Water Research Foundation
advancing the science of water

Proceedings of the 9th Water System Seismic Conference

October 14–16, 2015

Sendai, Japan

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CONTENTS

PAPERS FOCUSED ON TAIWAN

Agenda

Time	Title	Name	Affiliation	Country
14-Oct-15				
Keynote Presentations				
9:10	Fault Crossing Pipeline	Masakatsu Miyajima	Kanazawa University	Japan
9:30	Have We Adequately Mitigated Inter-sector Dependencies of our Critical Infrastructure?	Xavier Irias	East Bay Municipal Utility District	USA
9:50	Toward Sustainable Water Supply System in Seismic TAIWAN	Yang-Long Wu	Chinese Taiwan Water Works Association	Taiwan
15-Oct-15				
Topic 1:Pipeline behavior in Earthquake Events Chair: Hayato Nakazono				
9:00	The Damage Analysis of Distribution Pipes in Artificial Ground	Shu Kikuchi	Sendai City Waterwworks Bureau	Japan
9:15	Non-linear Pushover Analysis of Water Pipelines under Soil Liquefaction	Lap-Loi Chung	National Center for Research on Earthquake Engineering	Taiwan
9:30	The Abnormal Behavior of Water Supply Systems Just after Earthquakes in Case of Saitama City	Akihisa Ishida	Kanawaza Univercity	Japan
9:45	New Study on Soil Liquefaction Susceptibility Categories	Chin-Hsun Yeh	National Center for Research on Earthquake Engineering	Taiwan
10:00	Fragility Models that Reflect Pipe Damage in the Seismic 2014 Napa M 6.0 Earthquake	John M. Eidinger	G&E Enginnering Systems Inc	USA
Topic 2：Countermeasures for Fault Crossing Pipelines Chair: Yu-Tang Huang				
10:45	Design and Seismic Prevention of Water Main Crossing Faults Cases in Taiwan	Jiunn Liang Lin	CECI Engineering Consultants, Inc., Taiwan.	Taiwan
11:00	Research of Earthquake Resistant Ductile Iron Pipe (ERDIP) for fault crossing	Keita Oda	KUBOTA Corporation	Japan
11:15	Seismic Upgrades to an Existing 180 MGD Water Treatment Plant near the San Andreas Fault	Calvin Huey	San Francisco Public Utilities Commission	USA
11:30	Development of Low-reaction Type of Steel Pipe for Crossing Fault	Hayato Nakazono	JFE Engineering Corporation	Japan
11:45	Seismic Enhancement Framework and Screening of Critical Water Mains, A Proposal	Gee-Yu Liu	National Center for Research on Earthquake Engineering	Taiwan
Topic 3：Seismic Programs for Water Supply System Chair: Gordon L. Johnson				
13:00	Introduction to the Earthquake Resistance Capacity Assessment and Reinforcement of Taipei Water Department Office Building	Yu-Ting Kuo	Taipei Water Department	Taiwan
13:15	Report on the seismic reinforcement work of Sagamihara Sedimentation Basin	Tomomi Suzuki	Yokohama Waterworks Bureau	Japan
13:30	The earthquake damage and reinforced method of combined water tank	Yu-Tang Huang	Taiwan Water Corporation	Taiwan
13:45	Seismic Resistance Design of the Higashiyama No.3 Service Reservoir	Yasuhiko Sugiyama	Worterworks and Sewerage Bureau, City of Nagoya	Japan
14:00	Seismic Assessment of Steel Chemical Storage Tanks	Chun-Wei Chang	Taipei Water Department	Taiwan
Topic 4：Mitigation Program of Seismic Damages Chair: Toru Tomioka				
15:45	Seismic Countermeasures and Strategies for Public Relations in Kobe City Waterworks Bureau	Takahiro Yamaguchi	Kobe City Waterworks Bureau	Japan
16:00	Water System Seismic Vulnerability Mitigation, The Sequel	William F. Heubach	Seattle Public Utilities	USA
16:15	Tokyo Waterworks' Earthquake Countermeasures:Towards Earthquake-resilient Water Services in Tokyo	Kaoru Mochizuki	Bureau of Waterworks, Tokyo Metropolitan Government	Japan

16:30	Mitigation of Potential Impacts of Large Seismic Events on a Regional Water Supply Conveyance System	Gordon L. Johnson	Metropolitan Water District of Southern California	USA
16:45	TSS Tokyo Water's Efforts for Earthquake Disaster Measures	Yoshinari Kawase	TSS TOKYO WATER CO., LTD.	Japan
16-Oct-15				
Topic 5：Preparedness and Resilient Programs to Earthquake Events Chair: Gee-Yu Liu				
9:00	Implementing a Seismic Resilient Pipe Network as Part of a Resilience Program in Los Angeles	Craig Davis	Los Angeles Department of Water and Power	USA
9:15	Evaluation of Fire Protection Capacity in Disasters Based on Disaster Resilience Curve	Nagahisa Hirayama	National Institute for Environmental Studies	Japan
9:30	The Estimated losses and Preparedness Strategy for Emergency Water Supply of Fire Fighting and Life Supporting in a Rupture Scenario of the Shanchiao Fault	Ban-jwu Shih	National Taipei University of Technology	Taiwan
9:45	Water Sector Emergency Preparedness and Response Standards – How an All-Hazards Approach Supports Seismic Preparedness and Response	Jian Zhang	Water Research Foundation	USA
10:00	Niigata as a temporary water works relay base: support for teams in a major seismic disaster	Etsuro Kawase	Niigata Water Supply Bureau	Japan
Topic 6:Information System and Resilient Programs to Earthquake Events Chair: John M. Eidinger				
10:45	Emergency Planning and Response Damage Prediction Modeling to Mitigate Interdependency Impacts on Water Service Restoration	Serge V. Terentieff	East Bay Municipal Utility District	USA
11:00	The Damaged Water Supply Facility for Repair or Reconstruction Evalution Program – Case Study of Nao-Guan Service Reservoir at Taichung, Taiwan	Kuo Ching Lin	Taiwan Water Corporation	Taiwan
11:15	Development of the New Disaster Information System of Osaka Municipal Waterworks Bureau	Hajime Nishikawa	Osaka Municipal Waterworks Bureau	Japan
11:30	The Application of Taiwan Earthquake Impact Research and Information Application (TERIA) Platform for Lifeline Systems	Carol C. Wu	National Science and Technology Center for Disaster Reduction	Taiwan
11:45	Damage of water works facilities caused by the Great East Japan Earthquake and future problem for reconstruction in Otsuchi town	Kimiyasu Ohtake	NJS CO.,LTD	Japan

Poster Session			
The evaluation of earthquake-resistant performance of basic facilities (ductile iron pipes with earthquake-resistant joints) which passed for 38 years after construction.	Yasutaka Uchimiya	Hachinohe Regional Water Supply Authority	Japan
The installation of emergency water supply taps passed through the Great East Japan Earthquake	Kazumasa　Hashiyada	Sendai City Waterworks Bureau	Japan
Hanshin Water Supply Authority Business Continuity Plan for earthquakes	Hiroyoshi Honjo	Hanshin Water Supply Authority	Japan
Damage to Water Supply Pipelines by the 2014 Kamishiro Fault Earthquake in Japan	Masakatsu Miyajima	KANAZAWA UNIVERSITY	Japan
Handbook of Emergency Water Supply Examples and New Concept for Portable Water Treatment Unit Technology	Yoshiaki Asaka	Japan Water Research Center	Japan
A Representable Way of Strain in the 2D Discrete Element Method for Numerical Simulation of Growth Fault Slip around Taipei Basin	Sheng-Shin Chu	Taipei Water Department	Taiwan

__Cover page__

Title: **Fragility Models that Reflect Pipe Damage in the Napa 2014 M 6.0 Earthquake**

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Fragility Models that Reflect Pipe Damage in the Seismic 2014 Napa M 6.0 Earthquake

John M. Eidinger*

ABSTRACT

The City of Napa, California was struck by a M 6.0 earthquake on August 24, 2014. The water system, having 380 miles of pipe, underwent about 163 pipe repairs within two weeks after the earthquake. Of these pipe repairs, about 18 were due to surface faulting, 23 from liquefaction, and 122 from ground shaking. This rate of pipe damage, especially that due to ground shaking, is very high. This paper examines the reason(s) for this high repair rate due to ground shaking. We tested the soils in Napa, and found that much of the soils in the Napa area are extremely corrosive. Many of Napa's water pipelines are older cast iron pipes, but even newer thinner-wall ductile iron pipes had been failing due to non-earthquake-related reasons at a high rate prior to the earthquake. The results from the soil tests (as measured by Rho, in ohm-cm, at the depth of the pipeline) were correlated with observed long term water leak rates. There is good correlation with the inverse of Rho with repair rates for un-protected metal water pipes, such as older cast iron pipes, and unprotected ductile iron pipes. Given these findings, this paper suggests updated pipeline seismic fragility models for ground shaking that account for Rho, as measured in ohm-cm, as well as peak ground velocity, as measured in cm per sec.

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CITY OF NAPA WATER SYSTEM

The City of Napa was incorporated in 1872. The Napa Water Department serves a population of about 84,000 people, via 25,000 services. The water system includes 3 water treatment plants, about 542 km (337 miles) of pipe, 12 storage tanks with a total of 113.6 million liters (30 million gallons) storage, 9 pump stations, 14 pressure regulating stations and is operated in 5 pressure zones. About 90% of the populations is served by gravity flow coming from the water treatment plants.

Water demand peaks at about 95 million liters per day (95 m^3/day, 25 MGD) during a hot spell in July and drops to about 26 m^3/day (7 MGD) during the winter months. Landscape irrigation represents about half of yearly water demand. All potable water is provided from three surface water sources; no ground water is used. Of the total demand, about 53% is single family residential, 16% is multi-family residential, commercial is about 15%, institutional about 7%, landscape about 5%, St. Helena about 2%, agricultural about 1%, construction about 0.3%.

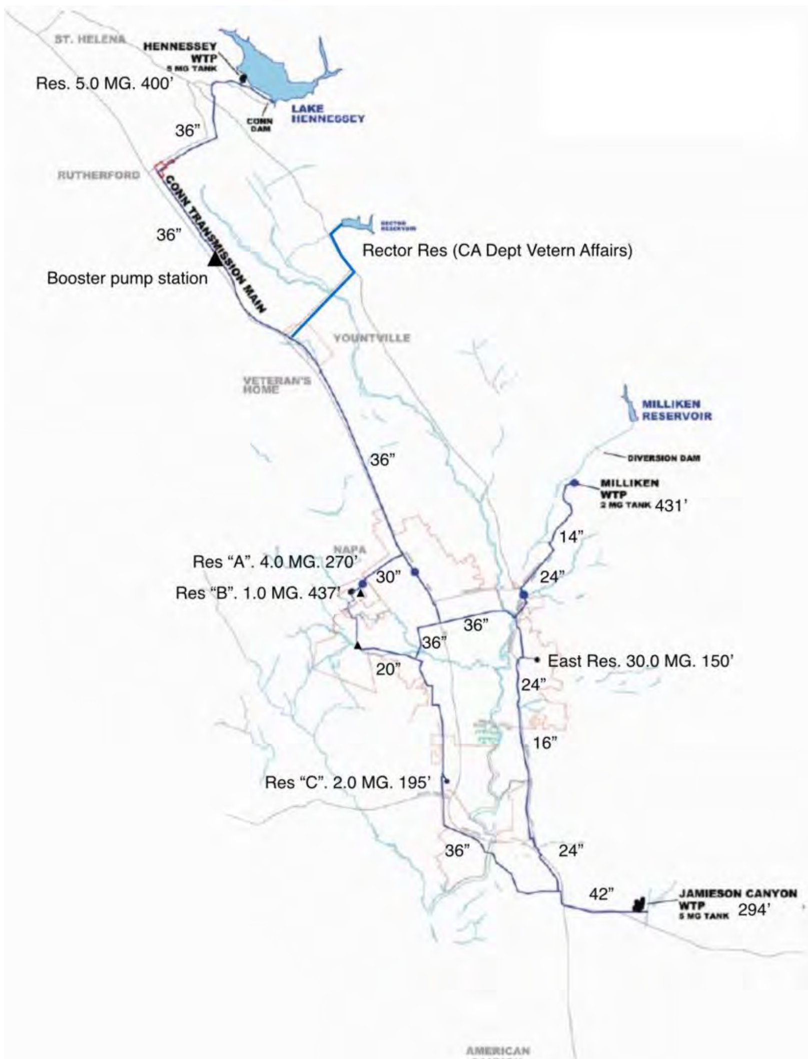

Figure 1. Napa Water System Major Pipelines and Location of Water Treatment Plants

As of September 30, 2014, Napa reported about 172 water pipe repairs. Through November 15, 2014, Napa reported 185 pipe repairs. Through late January 2015, Napa reported having completed 243 pipe repairs. By late January 2015, Napa reported that the repair rate for water pipes had reduced to "about" the long term average repair rate.

Table 1 lists the lengths of water pipes in the Napa water system (2012 data). Napa reports that in a typical year, there are about 80 to 100 pipe leaks in the city, system wide (about 0.21 to 0.26 repairs per mile per year). This leak rate for water pipes is consistent with industry average (about 0.24 to 0.27 leaks per mile per year). Other water departments in California with primarily cast iron pipe of similar vintages as in Napa (but with non-aggressive soils, Rho usually well over 5,000 ohm-cm) have system wide leak rates on the order of 0.06 leaks per mile per year. For example, the City of Burbank has zero pipe repairs in the 1994 Northridge earthquake, whereas neighboring Los Angeles had over 1,000 pipe repairs; both cities have similar-aged cast iron pipe, parts of both cities had similar levels of ground shaking, but Burbank's soils usually have higher Rho values than many parts of Los Angeles. This suggest that the rate of cast iron (and other metal pipe) pipe damage in earthquakes will tend to be relatively high, if Rho is low, or if the historical leak rate is high.

Age (years)	PVC	DI	CI	AC	RCCP	STL	Total	Pct of Total
< 20	6,600	225,600				100	232,300	13%
20-40	24300	370,500	83,400	14,100		100	492,400	28%
40-60		12,300	466,700	167,200	9,900	59,800	715,900	40%
60-80			173,100			100,400	273,500	15%
80-100			55,100				55,100	3%
> 100			10,300				10,300	1%
Total	30,900	608,400	788,500	181,300	9,900	160,400	1,779,500	100%
	2%	34%	44%	10%	1%	9%	100%	

Table 1. Length of Water Pipe Mains – Napa (Feet)

Table 2 lists the number of repairs by pipe material. The total number of repairs (163) reflects the amount completed as of about September 15 2015, at which time water was restored to essentially all customers. As discussed above, for several months afterward, the rate of pipe damage was about 2 to 3 times higher than normal: about 80 more repairs in about 4.5 months; whereas the long term rate was about 90 per 12 months.

This higher leak repair rate in the months following an earthquake is not unusual, reflecting that many pipes were highly stressed / deflected by the earthquake (but not immediately broken), but over time, these highly loaded pipes fail at a higher rate than normal. The City of Napa confirmed that the longer term pipe repair rate after the earthquake was higher than normal, with about an additional 50% of the immediate earthquake repairs (163) occurring by about late January 2015; after which the leak rate seemed to have reduced to about the long term rate.

Material	Repairs	% Repairs	% Pipe	Repair per Mile
AC	8	5%	10%	0.23
PVC	2	1%	2%	0.34
CI	123	75%	44%	0.82
DI	18	11%	34%	0.16
Steel	3	2%	9%	0.10
Other / unknown	7	4%		
Total	163	100%		

Table 2. Repair Rates for Water Pipe

Table 2 shows that CI (cast iron) is the most vulnerable of pipe materials, with AC (asbestos cement), PVC (polyvinyl chloride, C900), DI (ductile iron) and Steel (with corrosion protection) all performing much better than Cast Iron. Further examination of the repairs to correlate against location, in terms of peak ground velocity (PGV) and permanent ground deformation (PGD) and age (especially with respect to corrosion) is done later in this paper.

Figure 2 shows the level of ground shaking in the earthquake (in PGA, g), along with names of major cities and towns, and latest census populations shown in (brackets). The star shows the epicenter, with the rupture going northwards. Red areas show PGA > 0.7g. White areas show PGA < 0.05g. Black lines show boundaries of counties.

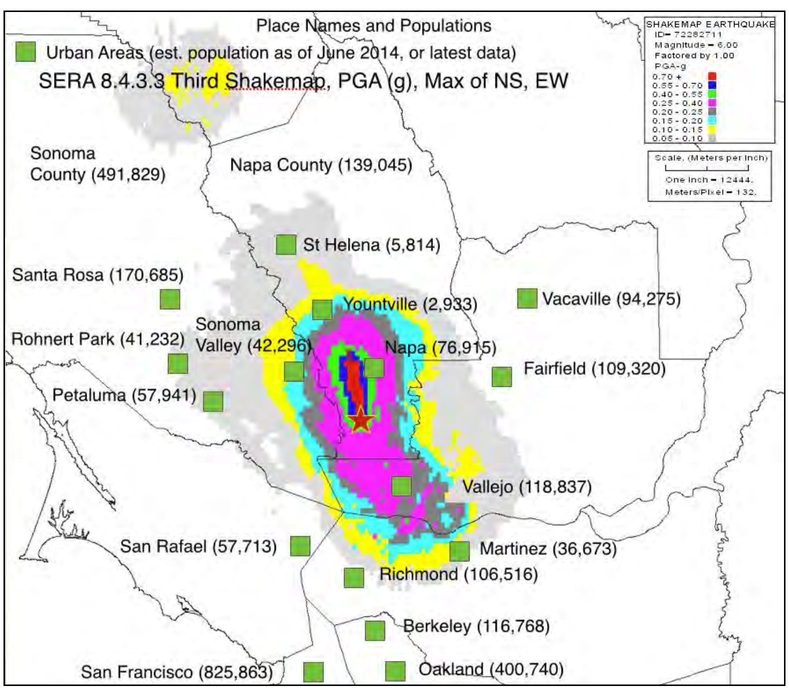

Figure 2. Ground shaking levels (PGA) on the Napa 2014 M 6.0 earthquake

Figure 3 shows the results from soil resistivity (Rho) tests performed in Napa after the earthquake. The locations of the Rho tests are indicated by small colored dots, and the actual test value at the depth of the water pipes (1.5 meters below grade is most common) is shown next to the symbol. The numbers in round circles are the highway numbers of major roads in and near Napa.

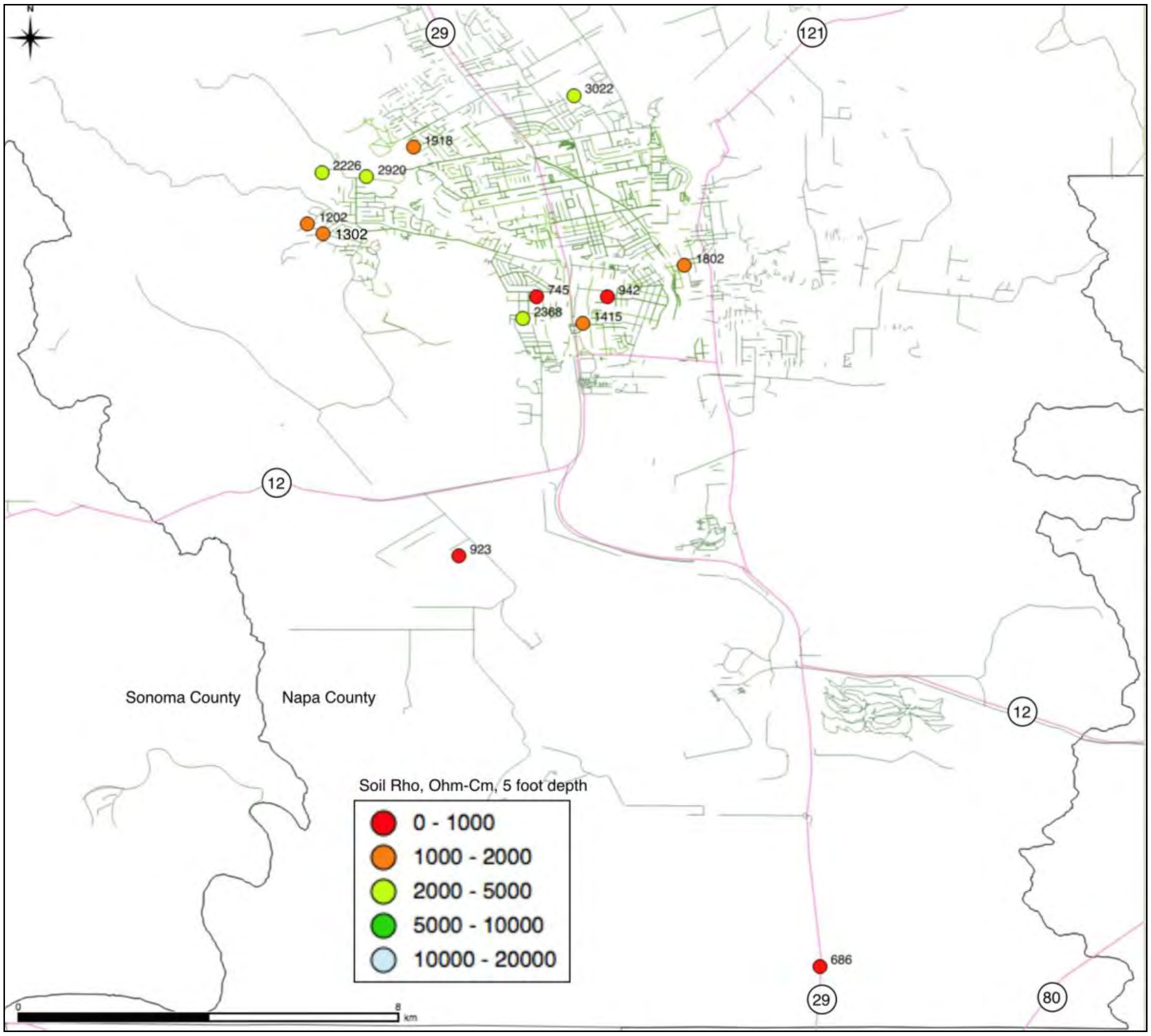

Figure 3. Soil Resistivity and Location of Pipe Repairs for Napa Water Pipe

Figure 3 shows that the soils in Napa are extremely aggressive. This may be in part due to the volcanic origins of the soils; many are clayey-in nature. At three test locations, Rho was under 1,000 ohm-cm (extremely corrosive); four more tests showed Rho from 1,000 to 2,000 ohm-cm (very aggressive); and four more tests showed Rho from 2,000 to 3,022 ohm-cm.

The Napa water department reports that their ductile iron pipe has had a fairly high leak rate, even without the earthquake, and this reflects that Napa apparently did not install polyethylene "baggies" over the ductile iron pipe. The very aggressive nature of the soils; coupled with the relatively thinner wall thickness of ductile iron pipe, under 0.5 cm (0.2 inches), relative older but thicker cast iron pipe that are commonly 1.27 cm (0.5 inches) or thicker.

In the northwest part of the water system, there was surface faulting. Figure 4 (left) shows a map of the 71 locations with observed surface faulting (yellow stars), along with the pipe repair locations. The light green lines indicate streets; light blue lines indicate major roads / highways.

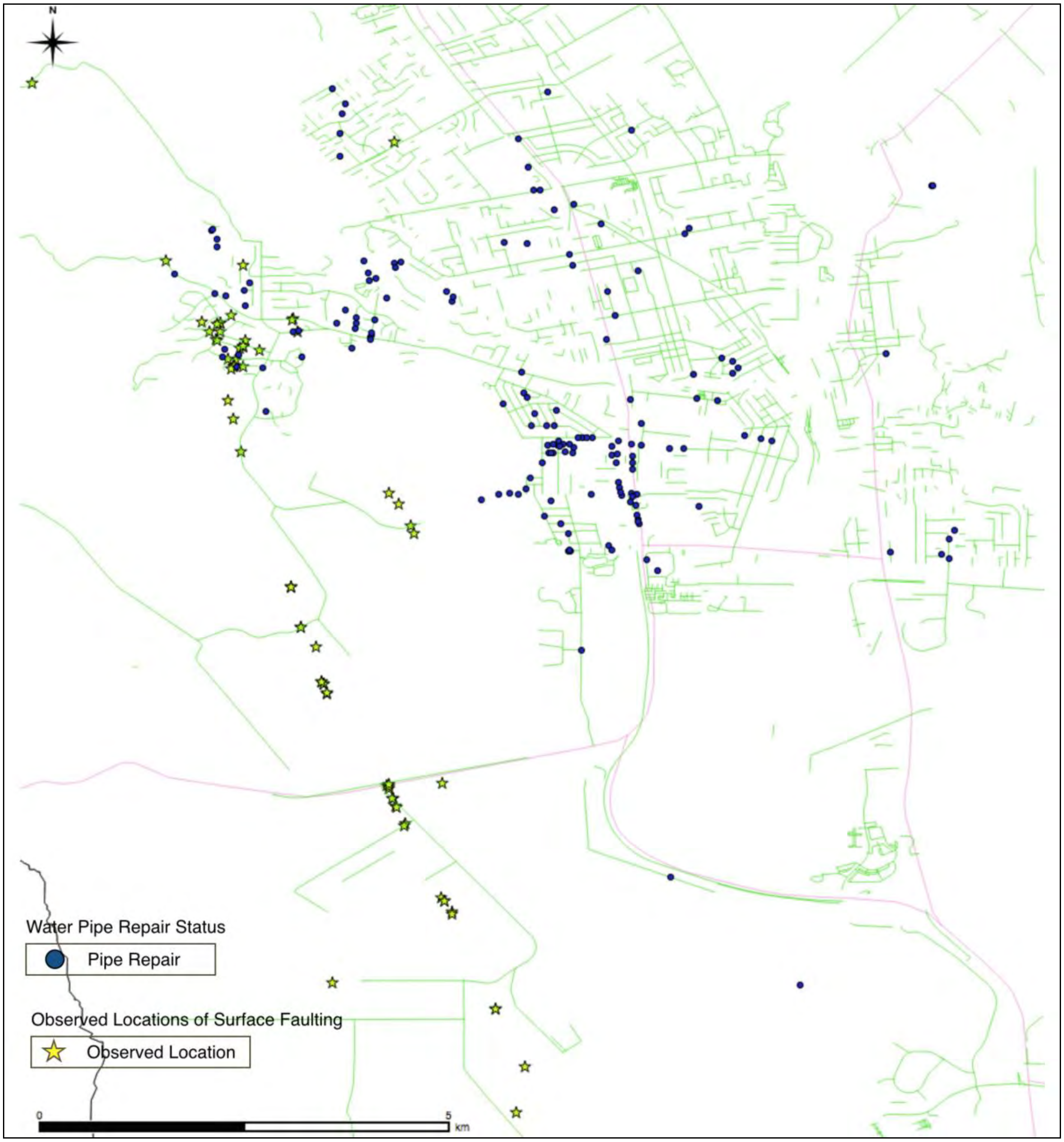

Figure 4. Location of Surface Faulting and Water Pipe Repairs

SEISMIC EVALUATION OF THE WATER PIPES

Figure 5 shows the Peak Ground Velocity (PGV) map for the Napa area due to the August 2014 earthquake. This map shows the maximum of north-south or east-west direction PGV. Each "box" represents an area of about 0.8 km (east-west) by 1 km (north-south). The symbols are at the locations of the pipe repairs as shown in Figure 4: solid dot: CI; triangle: DI; open dot = unknown; polygon: AC; square: PVC. The colors of the PGV shaking in Figure 5 correspond to: Red: PGV ≥ 85 cm/sec. Blue: PGV = 70 cm/sec to 85 cm/sec. Green: PGV = 55 cm/sec to 70 cm/sec. Magenta: PGV = 40 cm/sec to 55 cm/sec. Dark Grey: PGV = 30 cm/sec to 40 cm/sec. Cyan: PGV = 20 cm/sec to 30 cm/sec. Yellow: PGV = 10 cm/sec to 20 cm/sec

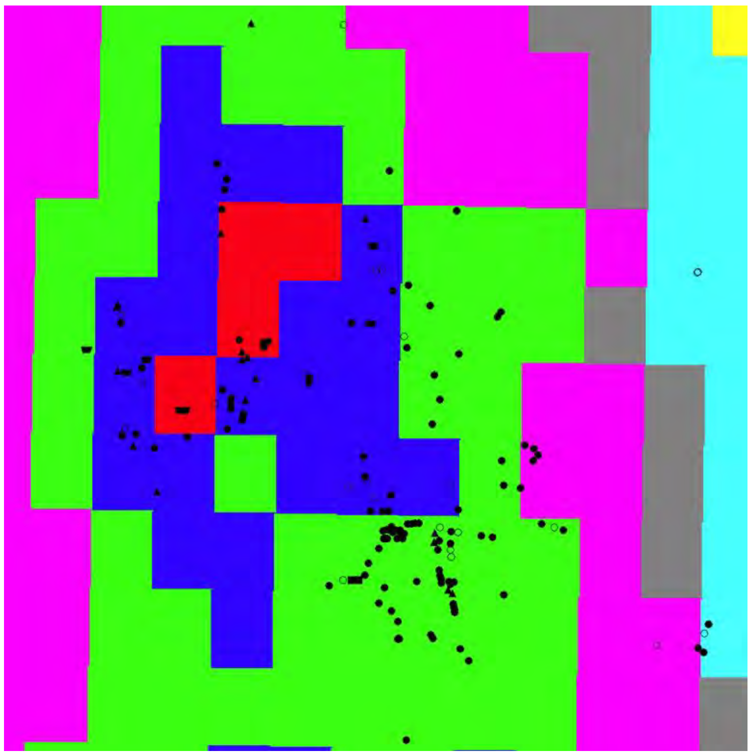

Figure 5. ShakeMap PGVs (Maximum of NS, EW)

Using the corresponding PGV ShakeMap levels of shaking from Figure 5, Table 3 shows the number of pipe repairs that were subjected to various levels of PGV (totals add to 164; 163 elsewhere in this report; the 1 pipe repair location had uncertain attribute as to whether there was 1 or 2 repairs at that location).

	20-30 cm/sec	30-40 cm/sec	40-50 cm/sec	50-60 cm/sec	60-70 cm/sec	70-80 cm/sec	80-90 cm/sec	Total
AC					2	2	3	7
CI	3		2	16	38	41	10	110
DI				2	4	4	7	17
PVC					2			2
STL					1	1		2
UNK	3	1	2	1	9	7	2	25
Total	7	1	4	19	56	55	22	164

Table 3. Water Pipe Repairs vs. PGV (cm/sec)

We reviewed the number of pipes that were located within about 152 meters (500 feet) from locations of surface faulting; and attributed that damage to surface faulting and not ground shaking or liquefaction effects. We also differentiated the number of pipes that were damaged due to liquefaction. Table 4 shows the results. The total number of pipes damaged from shaking was 122, with 23 repairs due to liquefaction, and 18 due to fault offset.

Pipe Type	Length, System-wide (miles)	Repairs due to Shaking (PGV)	Repairs due to Liquefaction (PGD)	Repairs due to Surface Faulting (PGD)	Total Repairs, August 24 to Sept 15 2014
AC	34.34	2	0	5	7
CI	149.34	86	19	5	110
DI	115.23	8	4	5	17
PVC	5.85	2	0	0	2
STL	30.38	2	0	0	2
RCCP	1.88	0	0	0	0
UNK		22	0	3	25
Total	337.01	122	23	18	163

Table 4. Water Pipe Repairs – PGV and PGD (faulting)

ALA (2001) provides pipe fragility models that factor in PGV and pipe material and diameter, but not the soil resistivity / corrosion effects. In Napa, the corrosion effects should be important, especially for Cast Iron and Ductile Iron pipes. We ran a forecast using modified ALA (2001) models, including the effects of corrosion, and the variations of ground shaking levels throughout Napa. The results are in Table 5.

Pipe Type	Length, System-wide (miles)	Actual Repairs due to Shaking	Forecast Repairs due to Shaking
AC	34.34	2	2.4
CI	149.34	86	88.5
DI	115.23	8	12.3
PVC	5.85	2	0.4
STL	30.38	2	5.0
RCCP	1.88	0	0.1
UNK		22	
Total	337.01	122	108.8

Table 5. Water Pipe Repairs – Forecast and Actual (due to PGV)

In preparing Table 5, the repair rate model for repairs due to shaking was assumed to be:

RR = k1 * k2 * k3 * 0.00187 * PGV, where

- RR = repairs per 1000 feet (305 meters) of pipe
- PGV = ground shaking, inches per second
- k1 = factor to account for corrosion (Table 6)
- k2 = factor to account for pipe diameter (Table 6)
- k3 = factor to account for pipe material (Table 6)

Pipe Type	This report k1 corrosion	This report k2 Diameter (≤ 12 inches)	This report k3 material	ALA 2001 Combined factor
AC	1.0	1.0	0.3	0.5
CI	1.0 to 3.0	1.0	1.0	1.0
DI	1.5	1.0	0.3	0.5
PVC	1.0	1.0	0.3	0.5
STL	1.0	1.0	0.7	0.7
RCCP	1.0	1.0	0.2	0.2

Table 6. Pipe Fragility Model due to Ground Shaking

Considering the situation in Napa, we suggest applying corrosion (k1) as follows for metal pipes:

- Rho < 1500 ohm-cm. Prior to 1920. k1 = 3.0. Post 1960. k1 = 1.0. 1920 to 1960, interpolate.
- Rho from 1500 to 2500 ohm-cm. Prior to 1920. k1 = 2.0. Post 1960. k1 = 1.0. 1920 to 1960, interpolate.
- Rho > 2500 ohm-cm. k1 = 1.0.

For ductile iron, asbestos cement and PVC, we suggest reducing the k3 factor from 0.5 to 0.3; this is in part offset by a corrosion factor, such that k1 * k3 is about the same as the combined factor in ALA

(2001). The main issues with shaking for these pipes is the pullout of joints, and all rubber gasketed pipes have similar joint pull out capabilities.

Based on the field observations in Napa we estimate the following lengths of pipe were subjected to liquefaction:

- Cast iron. 20,000 feet. Average PGD = 1 inch. Using the ALA (2001) models, this translates into a forecast total number of cast iron pipe repairs = 21.2.

- Ductile iron. 4,000 feet. Average PGD = 1 inch. Using the ALA (2001) models, this translates into a forecast total number of ductile iron repairs = 4.3.

Pipe Type	Length, System-wide (miles)	Actual Repairs due to Liquefaction	Forecast Repairs due to Liquefaction
AC	34.34		
CI	149.34	19	21.2
DI	115.23	4	4.3
PVC	5.85		
STL	30.38		
RCCP	1.88		
UNK			
Total	337.01	23	25.5

Table 7. Water Pipe Repairs – Forecast and Actual (due to Liquefaction PGDs)

NAPA WATER SYSTEM EMERGENCY RESPONSE

Figure 6 shows the restoration of water service after the earthquake.

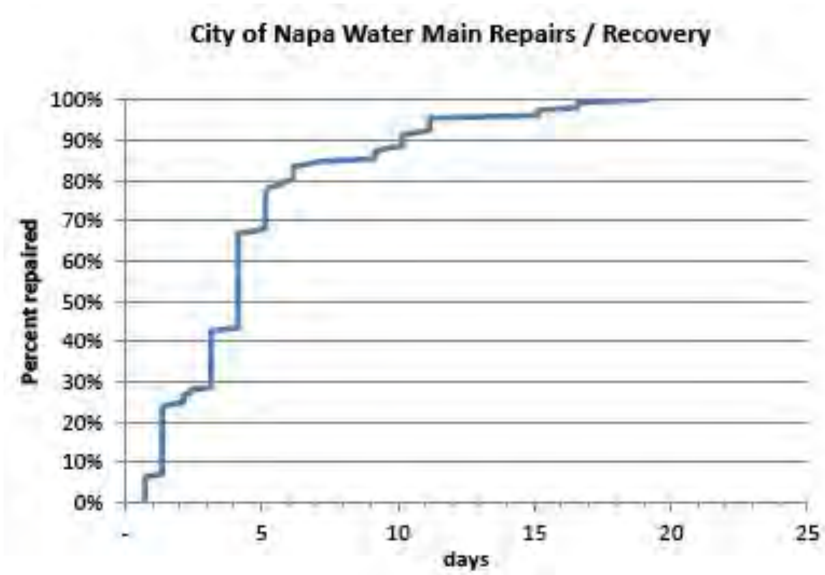

Figure 6. Napa Water Recovery

In making repairs, one of the required steps prior to digging up the area around the leaking pipe, is to perform "USA" markings (Underground Service Alert). This entails having each utility with underground facilities (gas, water, sewer, communications, etc.) to pre-mark the location of their pipes / conduits, prior to the commencement of digging to get to the leaking pipe. In the post-earthquake environment, when all utilities are also busy, this effort can slow down the entire restoration process. Following this process possibly slowed down the restoration effort for the water pipes. Still, the potential of accidently damaging a gas pipe, or otherwise damaging third party utilities, cannot be discounted, so this effort should be accounted for in emergency restoration plans.
Water demand increased by 200% or more immediately following the earthquake. This reflected normal overnight water demands, as well as water lost through leaking pipes, and some water being used for fire flows. As measured at the water treatment plants, the following water rates were recorded:

Time	Water Flows from WTPs	Then Known Water Leaks
Day 1. Sunday Aug 24	32 MGD	60 leaks
Day 2. Monday	28 MGD	90 leaks
Day 3. Tuesday	24 MGD	100 leaks
Day 4. Wednesday	22 MGD	105 leaks
Day 5. Thursday	20 MGD	110 leaks
Day 6. Friday	19 MGD	120 leaks
Day 20. Sept 12		167 leaks
Day 37. Oct 1		179 leaks
Day 68. Nov 1		193 leaks
Day 99. Dec 2		220 leaks
Day 153. Jan 26 2015		241 leaks

Table 8. Napa Water Flows, Million Gallons per Day, Number of Repaired Leaks

The average water demand for late August, without earthquakes is about 18 MGD. The actual water flows in the entire distribution system is uncertain, but in the first day would be much higher than the 32 MGD listed in Table 8, in that much of the water in the 12 storage tanks (with 30 MG capacity, mostly full at the time of the earthquake) also drained in the first few hours.

The Napa Water Department was aided by several regional utilities in making pipe repairs. Mutual aid (via Cal Warn) pipe crews were provided by:

- EBMUD: 5 crews. Three crews were initially dispatched within 24 hours of the earthquake, and two days later, two additional crews. EBMUD reports that the EBMUD crews helped make repairs for 56 pipe leaks.
- Contra Costa Water district: 1 crew
- City of Fairfield: 2 crews
- Alameda County Water District: 1 crew

All crews arrived with spare parts, trucks and equipment, typically 5 people per crew. All mutual aid crews were released by August 29 2014 (note the slow down in the rate of pipe repairs after Day 5, Figure 6). It was initially thought that the mutual aid crews were sufficient to effect nearly all the pipe repairs by August 29; however, over time, as the last pipe repairs were made, additional pipe leaks were identified as repaired pipes were re-pressurized.

The Napa Water Department estimated they spent about $200,000 on spare parts.

There were no regional-wide boil water alerts issued during or after the earthquake. Water quality at the water treatment plants was reported to be acceptable. The general population was encouraged to use bottled water (many did). There were boil water alerts to all customers who lost water supply, owing the concern of possible cross contamination from nearby potentially damaged sewer lines (no evidence that this occurred); or bacterial growth in empty water pipes.

The lack of a regional boil water alert was in part due to the negotiations between the Napa Water Department and other state-wide agencies. The state-wide agencies wanted a large scale boil water alert, being concerned that damaged sewer pipes might be leaking sewage into damaged water pipes. However, the City of Napa noted that they had no damage in the transmission pipes, and the water treatment plants were able to keep up with the increased water demand (for normal use lost water due to leaks, and fire fighting purposes), and positive pressure was maintained in the majority of the water system, so there was no need for such a regional boil water alert. Had the water transmission pipes been damaged, or the water treatment plants been unable to keep up with post-earthquake water demands, large portions of the water system would have become de-pressurized, and this would have had much more impacts on customers (more outages, boil water alerts, longer restoration times, etc.).

ACKNOWLEDGMENTS

The work reported in this paper was reviewed by Mr. Bruce Maison (EBMUD, Retired), and Prof. Mike O'Rourke (Rensselaer Polytechnic Institute). Mr. Maison and Prof. O'Rourke both participated in developing the ALA (2001) Water Pipeline Fragility report. Ms. Joy Eldredge, General Manager of the City of Napa City Water Department, provided pipe damage statistics.

REFERENCES

ALA, Seismic Fragilities for Water Systems, American Lifelines Alliance, March 2001.

SI UNITS

This paper uses both US customary and SI units of measure. The following are the conversions.

1" = 1 inch = 2.54 centimeters = 2.54 cm
1' = 1 foot = 0.3048 meters
1 mile = 1.609 kilometers = 1.609 km
1 MGD = 1 million gallons per day = 3,785,400 liters per day = 3,785.4 m^3/day.

Title: **Seismic Upgrades to an Existing 180 MGD Water Treatment Plant near the San Andreas Fault.**

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Seismic Upgrades to an Existing 180 MGD Water Treatment Plant near the San Andreas Fault

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ABSTRACT
The Harry Tracy Water Treatment Plant (HTWTP), capable of supplying 180 million gallons per day (mgd), is a critical component of the Hetch Hetchy Regional Water System that serves 2.6 million people in the San Francisco Bay Area. In 2002, the San Francisco Public Utilities Commission (SFPUC) launched the $4.8 billion Water System Improvement Program (WSIP) to provide improvements to meet level of service (LOS) goals established for seismic and delivery reliability, water quality and water supply. Under WSIP, the HTWTP Long Term Improvements Project (LTIP) was implemented to upgrade the existing plant to allow delivery of a minimum of 140 mgd within 24 hours after a major earthquake on the San Andreas Fault, located less than 1,000 feet away. Although the close proximity of the fault presented significant design challenges, the greatest project challenges related to two previously-unidentified traces of the Serra Fault that crosses the property. The identification of these traces resulted in the abandonment of two existing treated water reservoirs, and replacement with an 11-million gallon (MG) treated water reservoir (TWR), designed to resist high vertical and lateral seismic forces. The $278 million project was dedicated in 2015, marking the completion of four years of construction.

INTRODUCTION AND PROJECT DESCRIPTION

The Hetch Hetchy Regional Water System serves on average 260 mgd of drinking water to 2.6 million people in the San Francisco Bay Area, home to some of the world's largest technology corporations. The system is critical to the economic viability of the area and the public health and safety of the region's population. Built in the early 1900s, it is considered by many to be an engineering marvel for its great efficiency and the high-quality water it delivers. The system, shown in Figure 1, is supplied by pristine snowmelt accumulated in Yosemite National Park and stored in the Hetch Hetchy Reservoir, and carries water 167 miles across California—all via gravity. Although the system has performed extremely well for nearly a century, it is vulnerable to seismic events as it crosses three of the United States' most active faults: the San Andreas, Hayward, and Calaveras Faults. In 2008, the United States Geological Survey (USGS) predicted a 63 percent chance that a major earthquake could strike one of those three faults in the next 30 years [1].

Water System Improvement Program (WSIP) and Level of Service (LOS) Goals

In 2002, recognizing the need for major upgrades to the aging water system, the SFPUC initiated the WSIP to ensure water delivery following a major earthquake in the San Francisco Bay Area. The WSIP is a $4.8 billion multi-year program including 83 projects over seven counties—from the Sierra mountain range to the City of San Francisco. The WSIP includes a wide variety of improvements such as upgrades to and addition of new water treatment, transmission (pipelines, tunnels, pump stations), and storage (dams, reservoirs, tanks) facilities. It is the largest capital program ever undertaken by the SFPUC, and one of the largest water capital improvement programs in the United States (U.S.).

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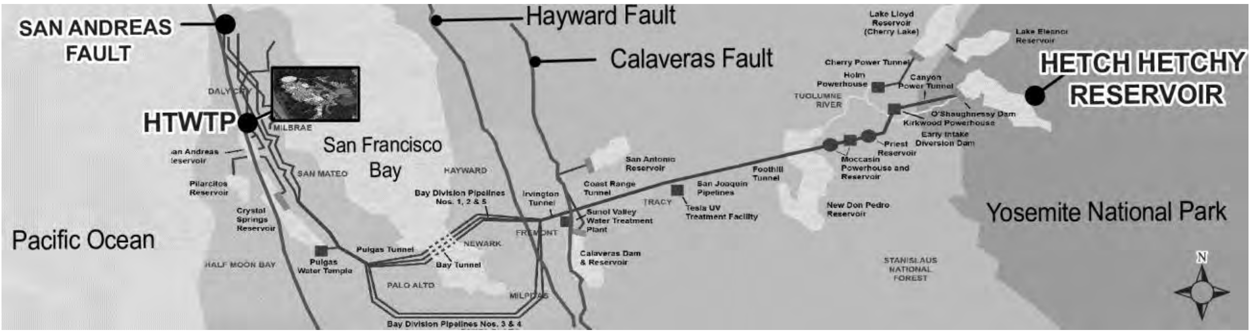

Figure 1: Hetch Hetchy Regional Water System

The overall scope of the WSIP was developed to meet four types of LOS goals: seismic reliability, delivery reliability, water quality, and water supply. The goals establish specific performance criteria for the system, and also provide quantifiable means to define and rank projects and select design criteria. The seismic reliability LOS goal category establishes the required delivery capability of the system following a major seismic event. Specifically, it requires delivery of basic service (average winter-month usage) within 24 hours following a pre-determined event on any of the three aforementioned active faults. It also specifies that facilities must be restored to meet the system's average-day demand within 30 days of such an event.

Harry Tracy Water Treatment Plant (HTWTP) Long Term Improvements Project (LTIP)

The HTWTP is a 180 mgd peak-capacity surface water treatment plant located in an unincorporated area of San Mateo County, near the Cities of San Bruno and Millbrae. The HTWTP delivers water stored in the Crystal Springs and San Andreas Reservoirs to over one million people on the San Francisco Peninsula. It is also the only source providing emergency water to the San Francisco Peninsula. HTWTP was originally constructed in 1972 (and originally named the San Andreas Water Treatment Plant), with major expansions in 1988 and 1990. The HTWTP is a direct filtration plant with pre-ozonation: raw water undergoes pre-ozonation, flocculation, filtration, and disinfection via chloramination before entering the system.

The HTWTP is a critical component of the Hetch Hetchy Regional Water System and therefore the $278 million HTWTP LTIP was developed as an important part of the WSIP. The primary objective of the HTWTP LTIP was to identify and upgrade specific deficiencies at the plant that restricted it from sustaining operations to meet the defined LOS goals.

LOS Goals for the HTWTP LTIP. Under the "*WSIP System Assessment for LOS Objectives*" [2], performance measures were outlined for the HTWTP LTIP with regard to water quality and seismic and delivery reliability required for HTWTP. The LOS goals for the HTWTP LTIP are twofold:

- <u>Delivery Reliability Goal</u>: Provide net water production of 140 mgd for a minimum of 60 days under typical water quality conditions. Typical water quality conditions are defined as a raw water turbidity of 10 NTU or less and less than 2 million algae cells per cubic meter. The treatment plant will be required to produce more than 140 mgd to account for in-plant uses (i.e., filter backwashing). Counting in-plant water uses, the total sustained treatment capacity is 153 mgd.
- <u>Seismic Reliability Goal</u>: Increase seismic reliability of new and modified facilities to sustain limited damage following a major earthquake and be able to deliver 140 mgd within 24 hours of such an earthquake. The specified major earthquake is an approximate magnitude 7.9 earthquake on the San Andreas Fault, which is considered a Basic Safety Earthquake (BSE)-2 event (an 84^{th} percentile deterministic Maximum Considered Earthquake [MCE]) for existing facilities as specified in the American Society of Civil Engineers (ASCE) Standard 41, and the MCE specified in the 2007 California Building Code (CBC) for new facilities.

Summary of HTWTP LTIP Improvements. The HTWTP LTIP included major treatment process changes as well as substantive site improvements, all constructed to withstand earthquakes and meet the LOS goals previously described. Capital improvements of water treatment plant facilities were also included in the project due to scheduling constraints, construction cost efficiencies, impending facility needs, and anticipated reduction in near- and long-term operational disruptions.

The original design of treatment process improvements for the LTIP, as outlined in the 2008 Conceptual Engineering Report (CER) [3], included replacement of a raw water pump and ozone generation equipment; conversion of the ozone system from a combination air/oxygen gas feed to oxygen-only gas feed system; five new filters; a second parallel backwash system; spent washwater clarification modifications; a new solids dewatering system; and new calcium thiosulfate and polymer filter aid chemical systems. The project also included major site improvements, including structural strengthening of key structures with identified seismic weaknesses, such as the 8- and 6.5-MG reservoirs, as well as modifications to selected major pipelines to allow interior repair access.

The HTWTP is located between the Holocene-Active San Andreas and Serra Faults, as shown in Figure 2. Although the close proximity of the San Andreas Fault presented significant design challenges due to high seismic forces, the greatest project challenges of the HTWTP LTIP design were related to the presence of two previously unidentified traces of the lesser-known Serra Fault that cross the HTWTP property and are capable of movement in conjunction with an earthquake on the San Andreas Fault.

Geologic and geotechnical work performed as part of the CER phase of design included a study of two faults on the HTWTP property as well as an investigation of slope stability at and around the 8- and 6.5-MG reservoirs and two washwater clarification basins. The results of these investigations determined the need for additional treatment plant improvements to the LTIP to meet the LOS goals. These additional areas of improvement included retrofit of large-diameter transmission pipelines within the boundaries of fault traces; installation of seismic isolation valves to protect residential and school properties; and modifications to the design of new filters to avoid intersecting a fault trace. Most significant was the abandonment of two existing treated water reservoirs due to unacceptable ground deformations in the hillside below the foundations. These reservoirs were replaced with an 11-MG treated water reservoir (TWR) on the opposite side of the plant from the fault traces.

Seismic upgrades to the Plant were designed to essential facility seismic standards and included structural retrofits where necessary. Essential facility seismic standards were determined by interpreting codes and standards specific for HTWTP, using the General Seismic Requirements for Design of New Facilities and Upgrade of Existing Facilities Revision 1, December 22, 2008 [4, 5, 6] as a basis for determination.

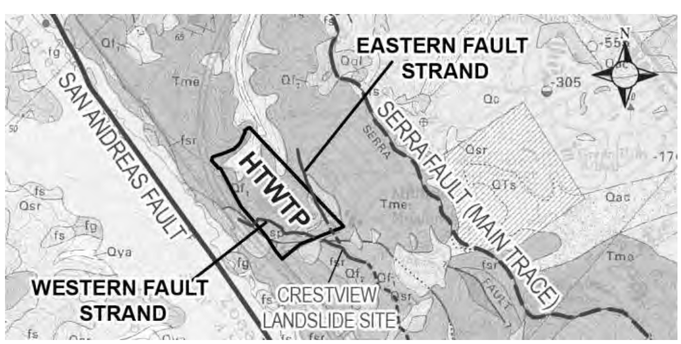

Figure 2: Faults near the HTWTP

GEOTECHNICAL INVESTIGATION

The project's seismic challenges stemmed from the treatment plant's location within the seismically active San Francisco Bay Region and the close proximity (approximately 1,000 feet) to the San Andreas Fault. This active fault governed the determination of seismic criteria (including seismic response spectra and design accelerations) for structural analyses and improvements, and studies of slope stability and risk of seismically-induced landslides. The seismic design loads determined from the site-specific seismic requirements were much higher than the design loads of the existing facilities designed between the late 1960s and early 2000s.

As part of the CER [3], a geotechnical study of two fault strands on the HTWTP property was conducted. There are two known fault strands on the HTWTP property, termed the Eastern and Western Faults—also known as "Serra Faults" as they may be branches of the Serra Fault passing through nearby City of Millbrae. Figure 3 shows the locations of the Eastern and Western Faults. Both faults slope under the main HTWTP facilities at steep angles and deemed capable of movement in conjunction with an earthquake on the San Andreas Fault.

Eastern Fault

The Eastern Fault has been only relatively recently identified on the HTWTP property. Estimated horizontal displacements from movement on this fault range from 6 inches (475-year return period San Andreas Fault earthquake) to 11 inches (2,475-year return period San Andreas Fault earthquake) and vertical displacements are approximately 2 inches (475-year return period San Andreas Fault earthquake) to 3 inches (2,475-year return period San Andreas Fault earthquake). Implications of this fault for the HTWTP LTIP are noted below:

- A portion of the 60-inch San Andreas No. 3 Raw Water pipeline adjoins the Eastern Fault area and is possibly susceptible to damage from the movement of off-site landslides. Residential and school properties are downhill of this pipeline and this pipeline could release large volumes of water from San Andreas Reservoir if ruptured. This could create life safety and property damage hazards depending upon the amount and duration of water release.
- The 60-inch Sunset Branch (Treated Water) pipeline crosses this fault and has important facilities directly over the fault zone. This pipeline also passes through an off-site landslide area from the 1970s, expected to be susceptible to movement from earthquakes. Residential and school properties adjoin this pipeline and this pipeline could release large volumes of water from the water transmission system if ruptured.

Western Fault

The Western Fault has been typically interpreted as inactive (last movement 20,000 to 5,300,000 years ago) based upon geometry and slip direction. This secondary fault is considered capable of some slip during a major earthquake because it represents a pre-existing plane of weakness.

Estimated horizontal displacements from this fault are approximately 2 inches (475-year return period San Andreas Fault earthquake) to 4 inches (2,475-year return period San Andreas Fault earthquake) and vertical displacement estimates are approximately 1 inch (475-year to 2,475-year return period San Andreas Fault earthquakes).

Although the SFPUC General Seismic Requirements [4] do not specifically require special measures for secondary inactive faults, implications of this fault on the existing and proposed facilities include:

- The five new media filters could not be located at the previously planned expansion location since they would have been astride the Western Fault, and were therefore moved to the existing (unused) sedimentation basin footprint.

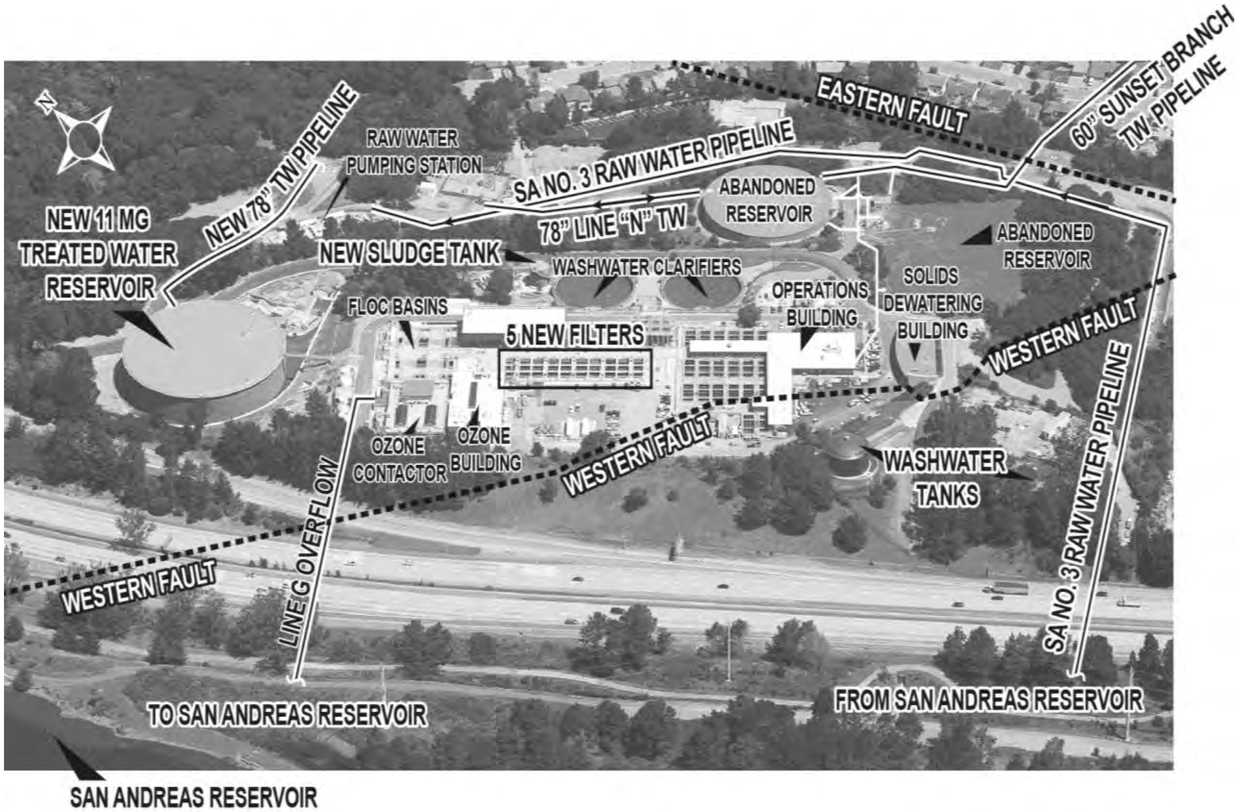

Figure 3: HTWTP Site Plan showing Eastern and Western Faults

- Serious damage of the existing water conduits, channels, and filters could take place if estimated fault displacement occurs and structures do not maintain their integrity at the displacement. Rupturing of certain channels and conduits could flood the filter galleries and take the HTWTP out of service for months.
- The 72-inch San Andreas No. 3 Raw Water pipeline crosses the Western Fault near its tunnel portal. A ground displacement at this location presents of risk of damage and possible pipeline rupture. Failure of this raw water pipeline could drain a significant volume of San Andreas Reservoir toward residential and school properties.

Slope Stability Analysis

A dynamic slope stability analysis [7] identified the need for slope improvements to reduce potential displacements from the MCE/ BSE-2 event. Study implications included:

- Portions of the fabricated and natural slopes adjoining the existing 8- and 6.5-MG reservoirs could experience landslides or deformations. Deformation could be relatively minor (i.e., surface cracking) or major (i.e., where landslides damage the reservoir structures, downhill pipelines, roads, and other facilities). It is also possible that reservoir water could be released, compounding the potential damage and hazard.
- Portions of the fabricated slopes adjoining the washwater clarifiers and main plant access road could experience landslides. Although deformations could be relatively minor in some cases, others could be major (e.g., landslides that damage structures and pipelines, releases of large volumes of water causing cascading damage to utilities, access, and other structures).
- Landslides or slope displacements put the adjoining treated and raw water pipelines at risk for rupture and compounding failures.

- Measures to increase the slope stability surrounding the existing reservoirs and washwater clarifiers and to reduce the potential for pipeline damage were required. Measures included drilled micropiles, piers or caissons, tie-backs, rock anchors, and other means to reduce displacements.

Fault Rupture Hazard Assessment of New TWR Site

The nearby San Andreas and Serra Faults and secondary Eastern and Western Faults constitute a fault surface-rupture hazard during large earthquakes on the San Andreas Fault. Therefore, although the HTWTP is outside the California State Alquist-Priolo Earthquake Fault Zone (A-P Zone) for the San Andreas Fault, it was determined that a site-specific fault rupture hazard investigation should be performed for the proposed improvements to the site to minimize the surface-fault rupture hazard from possible secondary faults.

Specifically, the rupture hazard investigation was performed to evaluate the proposed location for the new TWR—designed to replace the existing 8- and 6.5-MG reservoirs that were at risk for landslides or deformations as previously described. Although previous investigations had determined the proposed TWR site was located about 200- and 800-feet from the Western and Eastern Faults, respectively, the presence or absence of additional secondary faults had not yet been determined. A rupture hazard assessment was therefore performed to evaluate the presence and displacement potential of minor shears and shear zones that may underlie the TWR site within the Merced Formation sandstone, as suggested by similar features previously identified in the direct vicinity of the TWR site. The following are conclusions and recommendations resulting from this assessment:

- The known primary and secondary faults on or near the HTWTP do not constitute a rupture hazard to the proposed TWR site.
- The rupture hazard from secondary faults within the TWR footprint is very low.
- The proposed TWR footprint overlies individual shears and minor shear zones within Merced Formation sandstone and minor conglomerate. Such minor shears can be assumed to underlie the entire site and cannot be avoided.
- The rupture hazard associated with the minor shears is low, but it is possible that they can accommodate minor secondary (sympathetic) movement during or following a large earthquake on the San Andreas Fault.

The results of rupture hazard assessment suggested the TWR design accommodate 1 to 2 inches net, including 0.5- to 1-inch vertical displacement within the footprint on individual shears or shear zones, with no more than two shears or shear zones spaced at approximately 100-foot intervals being capable of such displacements. Thus, given a proposed 240-foot tank diameter, a major (i.e., BSE-2 or 2,475-year) event may produce one to two individual displacements of 2 inches net and 1-inch vertical each beneath the TWR, for a total cumulative offset of 4 inches net and 2 inches vertical [8].

OVERVIEW OF HTWTP LTIP UPGRADES

As noted above, the purpose of the HTWTP LTIP was to upgrade the HTWTP to meet the delivery and seismic reliability LOS goals, which required major treatment process upgrades as well as substantial site improvements. In order to meet the LOS goals, not only was new and existing equipment installed and retrofit to withstand earthquakes (hardening and bracing of existing equipment and structures), but significant redundancy was built into HTWTP processes. For example, HTWTP includes 15 filters, two parallel washwater systems, six megawatts of standby power, and an emergency chlorination system, allowing for chlorination of untreated San Andreas Reservoir water in the event of a major disaster and the need to send untreated water through the transmission system. Additional design and construction challenges stemmed from the requirement to keep the plant operational during construction. Only six major outages were allowed during the four years of construction, typically, between October and March of each year with outages ranging from 4 to 10 weeks.

The HTWTP LTIP improvements modified the treatment process for functional, seismic strengthening, and reliability reasons and included the following upgrades [9]:

- Raw Water Pump Station: Addition or replacement of variable frequency drives for six raw water pumps (45 and 15 mgd pumps).
- Ozone System: Replacement of liquid oxygen storage tanks, vaporizers, ozone generation and destruction equipment. Conversion of the ozone system from a combination air/oxygen gas feed to oxygen-only gas feed system.
- Filters: Addition of five gravity, dual media filters for a total of 15 filters; with new applied water channel, filtered water conduit, Filter Effluent Chamber, and blower room.
- Washwater Supply: Addition of second 0.5 MG washwater storage tank and replacement of existing 0.5 MG washwater storage tank.
- Washwater Treatment: Conversion of two existing washwater clarifiers to serve as washwater equalization basins. Addition of four Parkson high-rate clarifiers; second sludge storage tank and associated pumps; centrifuge dewatering equipment and conveyor system.
- Treated Water Reservoir: One new 11 MG TWR with associated piping and chemical application mixing. Keeping the system as gravity-fed, with equivalent hydraulic head as the existing system, drove the TWR site selection.
- Chemical Systems: New caustic soda, sodium hypochlorite, aqua ammonia, calcium thiosulfate, washwater ferric chloride, washwater polymer, hydrofluosilicic acid, and filter aid polymer chemical facilities. Replacement of existing chemical tanks for higher seismically reliable storage tanks.
- Emergency Chlorination: Emergency chlorination facility to allow for chlorination of untreated San Andreas Reservoir water in the event of a major disaster and the need to send untreated water through the transmission system.
- Pipelines: Replacement of major portions of on-site raw and treated water transmission pipelines for seismic reliability.
- Electrical: All new main switchgear and electrical service equipment in the Standby Power Building. An additional 2-megawatt diesel-engine driven electrical generator. Wide-ranging infrastructure improvements across the site for electrical and instrumentation service, SCADA, piping, pumping, and HVAC purposes.
- Structural: Structural strengthening of the Operations Building complex, Ozone Building, Ozone Destruct Room, Ozone Contactor Structure, inlet water channels, the overflow junction box, and valve vault.
- Site Improvements: Micropiles to strengthen the hillside beside the washwater equalization basins and sludge storage tanks; drilled piers to support the retaining wall system along the Standby Power Building.
- Existing equipment/pipe/conduit/duct support evaluations and strengthening.

Seismic Performance Category

Seismic criteria were developed for the LTIP based on importance factors to either: (1) ensure restoration to a level of service consistent with adopted post-earthquake goals within 24 hours for primary facilities; or (2) experience damage but retain the capability to restore service within 30 days for secondary facilities. Therefore, all structures at the HTWTP were classified as either Seismic Performance Category (SPC) II (equivalent to the 2007 CBC Occupancy Category III) or SPC III (equivalent to Occupancy Category IV).

- SPC II: The performance goal of the SPC II classification is to provide life safety protection against earthquakes likely to affect the site. Therefore, structures classified as SPC II may experience damage but should be capable of restoration to service within 30 days.
- SPC III: The performance goal of the SPC III classification is to provide life safety protection against earthquakes likely to affect the site, but includes reasonable expectations of post-earthquake operability of SPC III classified facilities. Therefore, structures classified as SPC III should be capable of restoration to a level of service consistent with adopted post-earthquake level of service goals within 24 hours.

DESCRIPTION OF SELECT KEY IMPROVEMENTS

Descriptions of improvements to the Operations Building Complex, large diameter transmission pipelines and the new TWR follow.

Operations Building Complex

The Operations Building complex consists of several buildings, including the Operations Building, Basement, Filter Gallery, and Office and Storage Building. The complex includes the plant control room, offices, a workshop, restrooms, a laboratory, and other facilities on the ground level, in addition to a mezzanine level, and a lower level connecting the filter galleries and equipment rooms. During preliminary design it was determined various components of these buildings required seismic upgrading. For example, the small separations between the various buildings did not meet the project-specific criteria. Additionally, due to the project requirement to keep HTWTP operational during construction, replacing the existing complex with a new, seismically sound facility would not meet project schedule, and therefore retrofit of the existing building was included in the project.

To address these issues, the project included the following seismic improvements:

- Added steel wall columns and knee braces to brace masonry walls for out of plane forces.
- Added transverse and longitudinal roof collectors to engage masonry walls.
- Structurally joined the buildings by closing roof joints.
- Removed some infill walls, and removed and replaced all partition walls.
- Braced lighting fixtures and provided emergency lights.
- Replaced all exterior cladding with drift tolerant materials and replaced plaster soffit over entrance.
- Braced mechanical, electrical, and plumbing equipment as needed.
- Braced fire sprinkler piping and modified ceiling tile penetrations for sprinkler heads.

In addition to these improvements to the building itself, a buried geofoam pier wall was constructed between the Western Fault and the Operations Building complex foundation, to protect the building from movement during a seismic event. The geofoam pier wall consisted of 48-inch diameter intersecting geofoam piers buried 17 feet and extending a length of 90 feet.

Large Diameter Transmission Pipelines

During the preliminary stages of design of the HTWTP LTIP, multiple large diameter pipelines at the site were determined to be in close proximity to the Western and Eastern Faults and therefore at risk for failure during a seismic event. The 72-inch San Andreas No. 3 pipeline (SAPL3, raw water pipeline) was found to cross the Western Fault and then run parallel to Eastern Fault, and was located within a steep slope at risk for landslides in a seismic event. The 60-inch Sunset Branch (treated water) pipeline was found to cross the Eastern Fault, while the 78-inch Line 'N' (treated water) was found to run parallel to and cross the Eastern

Fault. In order to strengthen the raw and treated water pipelines, LTIP construction improvements included:

- Raw Water Pipelines: The existing 60-inch SAPL3 was abandoned and a new 72-inch raw water pipeline was installed. The pipeline was installed partially above ground on pipe saddles set on caissons and was buried for the remainder of the alignment.
- Treated Water Pipelines: A new 78-inch treated water pipe was constructed to deliver water from the new 11 MG TWR. Additionally, portions of the existing 60-inch Sunset Branch (treated water) pipeline was sliplined with 48-inch, polyurethane-lined pipe 220 feet in length. The existing Sunset Branch pipeline is a cement mortar lined and coated steel pipe. Because the original alignment included a 53 degree slope that transitioned to a 33 percent slope, an anchor block was constructed on the top and bottom of the pipeline alignment and reinforced with drilled caissons. The sliplined pipe was then installed from either end of the existing pipe (top of slope and bottom of slope) and was exposed in the middle to enable welding of the two ends of pipe together.

Treated Water Reservoir [10]

Replacing the two existing reservoirs with a new 11 MG TWR was the largest major seismic component of the LTIP. The new TWR was designed as a reservoir with an integral chlorine contact basin. The chlorine contact basin is configured as a long single-pass raceway, created as a ring outside the circular reservoir-portion of the structure, with the outside wall of the contactor being the outside wall of the TWR tank and the inside wall being the outside wall of the operational storage portion of the reservoir. The water storage reservoir is located in the center of the TWR. See Figure 4 for the components of the TWR.

A raceway contactor configuration was selected because of its hydraulic efficiency due to its superior flow path for chlorine contact effectiveness. This configuration provides a smooth flow path, given the minimal difference in inner to outer radius on such a large-diameter tank, and provides uniform contact across the flow path cross section with minimal mixing in the direction of flow. This configuration begins to approach the hydraulic design of a pipe or conduit.

The bypass piping configuration allows for the following operational configurations:

- Bypassing the entire TWR structure.
- Taking the contactor off-line while leaving the reservoir portion of the structure on-line.
- Taking the reservoir portion of the structure off-line while leaving the contactor on-line.

Filtered and chlorinated water flows into the TWR from the filter effluent chamber through a 96-inch filtered water line and is then conveyed through piping and associated valves as follows:

- Chlorinated filtered water enters the annular raceway contactor located along the perimeter of the TWR through a grated pipe opening in the TWR floor.
- The filtered water is distributed across the annular raceway cross-section through a perforated baffle wall and flows around the raceway and through a second perforated baffle wall.
- At the end of the annular raceway, the disinfected water flows over a weir, which maintains the required water level in the contactor section at all times before the water enters a pipeline. Disinfected water is delivered to the external pump mixing system for chemical mixing.
- After the chemicals disperse into the water, the chloraminated and pH-adjusted water enters the TWR storage area in the center of the structure for operational storage prior to distribution.
- Treated water flows to distribution through a new 78-inch pipeline, which includes a new 78-inch Venturi flow meter.

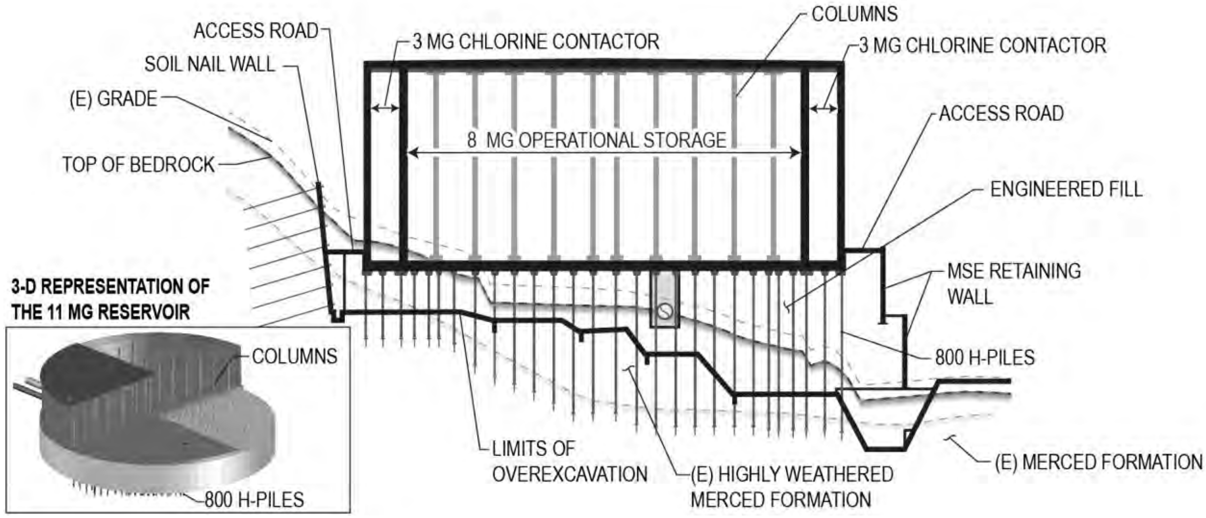

Figure 4: Treated Water Reservoir Design

Chemical additions of ammonia and caustic are assisted by an external pump mixing system for effectively mixing in the injected ammonia (to produce a chloramine residual) and caustic (for corrosion control through pH adjustment) in the chlorinated water before it enters the storage reservoir portion of the TWR.

Structural components. The 11-MG structure is circular, with an integral chlorine contact basin, an inside diameter of 240 feet, and a height of 48 feet (including 3 feet of freeboard). Its capacity is divided into 3 million gallons (MG) for the chlorine contact basin and 8 MG for operational storage. The chlorine contact basin consists of an outer annular raceway approximately 16 feet wide around the perimeter of the reservoir. Design of the reservoir included a feature for draining completely either the chlorine contact basin or operational storage basin while the remainder of the tank remains full and in service. The reservoir was constructed at a new site, with the exterior walls completely exposed for monitoring and repairs.

Foundation. The TWR was constructed on a hillside that required extensive cut to create a stepped excavation and partial engineered fill to develop the foundation pad for the reservoir, resulting in a potential for differential settlement across the cut/fill transition. A soil nail retaining wall, rising up to 65 feet tall and supported by approximately 1,000 soil nails up to 70-feet long, was constructed directly uphill of the TWR to support the cut face of the excavation. A mechanically stabilized earth (MSE) wall, located downhill of the TWR, was utilized to support the engineered fill for the tank pad and separates the reservoir from the main plant access road.

A pile-supported reinforced concrete mat slab foundation was found to be the most-economical foundation type that would address up to 4 inches of potential differential settlement due to the cut/fill transition and would also mitigate seismic settlement caused by sympathetic movement on secondary faults near the tank site. Final design of the pile-supported reinforced concrete mat slab required more than 800 steel H-piles, at approximately 10-feet on center, and driven to depths of 20 to 60 feet, including up to a depth of 12-feet into the Merced Formation bedrock unit below the overlying engineered fill. The piles were designed to support the reservoir's vertical and lateral loads, including high seismic loads. The reinforced concrete mat slab was constructed on top of the pile caps, with a gravel subgrade for an underslab drainage system. Footings for more than 80 interior columns supporting the reservoir roof were placed monolithically with the reinforced concrete mat slab.

Tank Design. The circular reservoir is a "tank within a tank," with a strand-wound, pre-stressed, cast-in-place reinforced concrete exterior wall with vertical post-tensioned tendons and a galvanized steel diaphragm, and a conventional, cast-in-place reinforced concrete interior wall with vertical post-tensioned tendons. The interior wall separates the contactor portion from the operational storage portion of the reservoir. Internal weir walls are conventional cast-in-place reinforced concrete walls, while internal baffle walls are constructed of fiberglass reinforced plastic (FRP).

The design of both the pre-stressed exterior and interior walls include an anchored flexible base in accordance with ACI 350.3, Type 2.3(1), to allow the tank to expand and contract during filling and draining. All reservoir walls are anchored to the foundation via reinforcing dowels and seismic cables in order to transfer seismic loads from the roof and the walls themselves to the foundation, and to prevent the reservoir from sliding off the foundation (See Figure 5). The pre-stressed exterior and interior walls, which have flexible bases, are isolated from internal concrete and baffle walls with non-flexible bases via expansion joints with waterstops and slotted connections. The exterior concrete wall and floor of the contactor are coated with an elastomeric polyurethane coating, while the internal and external walls of the reservoir is coated with a crystalline waterproofing coating system to minimize leakage and protect the concrete surfaces from the corrosive water. The pre-stressed exterior wall was placed against the galvanized steel diaphragm, which wraps around the outside face of the wall. The diaphragm lies in between the wall and the post-tensioned strands to provide additional protection for the strands against any seepage. Shotcreting via the wet-mix process was used to encapsulate the post-tensioned strands to protect them from corrosion. The concrete reservoir walls are designed to resist temperature gradients radially through the thickness of the walls.

The reinforced concrete reservoir roof is designed to be weather-tight in order to prevent leakage and contamination of the reservoir contents. It is also designed to accommodate thermal stresses from an 85 degrees Fahrenheit temperature differential. The structure of the roof is a two-way slab supported on top of the pre-stressed exterior and interior walls and more than 80 interior reinforced concrete columns at approximately 20-foot centers inside the operational storage portion of the reservoir. The roof rests on bearing pads on top of the walls and is positively connected to the top of the pre-stressed exterior wall via flexible pinned connections. For drainage, the top of the roof has a minimum slope of 1.5 percent (an approximately 22-inch difference in elevation from roof center to roof perimeter).

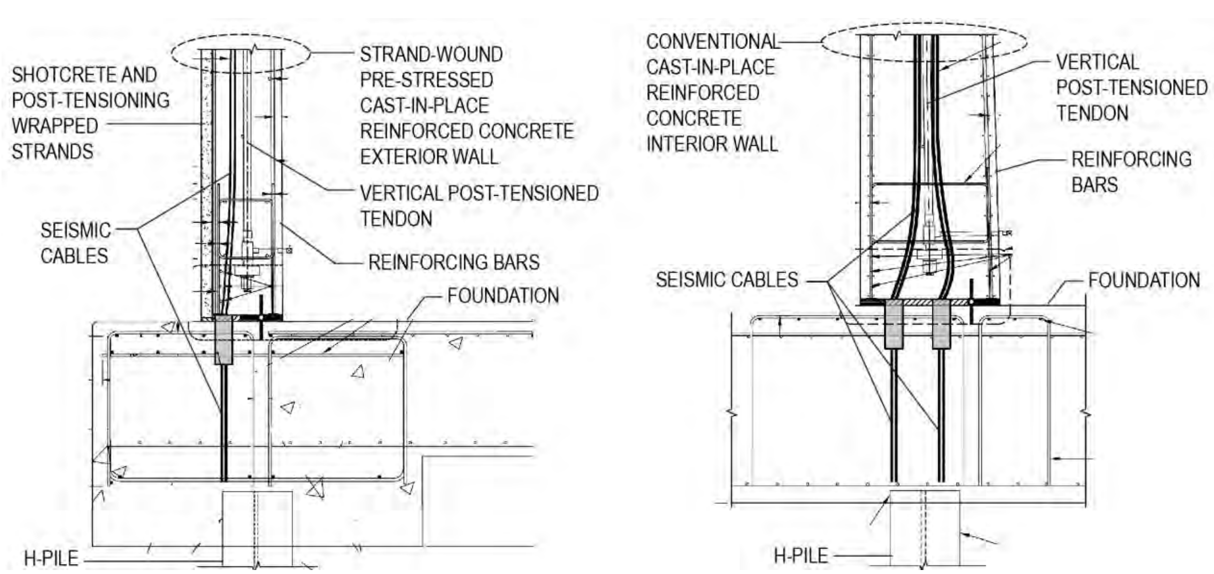

Figure 5: Connection of Exterior and Interior Walls and Foundation

Appurtenances and Underdrain. The tank appurtenances of the reservoir include the inlet, outlet, drain, and overflow piping; overflow weir; valves outside the tank; piping in the tank roof and walls for sensors and sampling; roof openings for access hatches and ventilators; and locking and safety devices. All piping is concrete-encased beneath the tank floor slab. Flexible joints are provided outside the wall footing to accommodate any movement caused by differential settlement or seismic activity. Materials and coatings utilized in the reservoir's construction satisfy the requirements of National Sanitation Foundation (NSF) 61.

The reservoir includes an underdrain system configured to collect water and detect leakage from isolated areas of the TWR. Groundwater levels may result in hydrostatic uplift under the tank; therefore the underdrain system was designed to prevent hydrostatic uplift and detect potential floor leakage.

CONCLUSION

The improvements constructed as part of the HTWTP LTIP allows the SFPUC to supply emergency water to over one million people after a seismic event on the San Francisco Peninsula. Design challenges included seismic retrofit of existing facilities and locating a new 11 MG TWR at site with limited space, near the San Andreas and Serra Faults, and with the requirement to maintain operation of the existing plant 7 days a week, 24 hours per day. The $278 million project was dedicated at a public ceremony in 2015, marking the completion of nearly four years of construction.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the contribution of the following organizations that participated in the HTWTP LTI Project: SFPUC, CDM Smith, Inc., Kennedy/Jenks Consultants, Geotechnical Consultants Inc., William Lettis & Associates, Inc., Exponent, Inc., G&E Engineering Systems, Inc., Degenkolb Engineers, Jacobs Associates, as well as engineers of record Rosanna Tse, P.E. (overall design coordinator), Scott Dittman, P.E. (overall plant process) and Don Barraza, P.E. (11 MG TWR).

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Title: **Seattle Public Utilities - Water System Seismic Mitigation – The Sequel**

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Seattle Public Utilities – Water System Seismic Vulnerability Mitigation, The Sequel

William F. Heubach

ABSTRACT

Seattle Public Utilities (SPU) provides water to over 1.3 million people in the central Puget Sound area. Based on a 1990 seismic vulnerability assessment by Cygna Energy Services, many SPU water facilities were seismically upgraded. This assessment was focused on "vertical" facilities. Major transmission and distribution pipeline performance, and overall system response were only briefly considered.

Since 1990, earthquakes in Northridge, Kobe, Christchurch and the Tohoku regions, and hydraulic modeling done for a postulated earthquake in the Puget Sound regions have shown the effects that distribution pipeline failures can have on system response and recovery. Additionally, seismologists have determined that there are active surface faults running through the Puget Sound area that are capable of producing earthquakes of M7.0 or greater.

Consequently, SPU is re-evaluating the seismic vulnerability of its system and updating its seismic mitigation strategy. Five major objectives have been defined for this project:

1. Define post-earthquake water system level of service goals.
2. Perform seismic vulnerability assessments of SPU water system facilities.
3. Use hydraulic modeling to estimate post-earthquake system performance.
4. Develop planning level mitigation measures and cost estimates.
5. Develop seismic standards for new SPU water system facilities.

This paper describes the approach SPU is using to increase the seismic resiliency of its water system.

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INTRODUCTION

Seattle Public Utilities (SPU) provides potable water to over 1.3 million residents in the central Puget Sound region [1]. Approximately half of these residents are served directly by SPU. SPU wholesales water to nineteen other municipalities and special purpose districts, and to the Cascade Water Alliance, that serve the other residential customers. The average daily demand is approximately 135 million gallons (500,000 cubic meters).

Two watersheds in the Cascade Mountains east of Seattle are the sources of Seattle's water supply (see Figure 1). The Cedar River Watershed is located approximately 40 miles (65 kilometers) southeast of Seattle and provides approximately two-thirds of Seattle's water supply. Masonry Dam was constructed on the Cedar River in 1914 to raise Chester Morse Lake by approximately 35 feet (10 meters) and provide 13 billion gallons (50 million cubic meters) of usable storage. A pumping plant on the reservoir allows SPU to pump the reservoir even lower, if needed.

Water releases into the Cedar River from Chester Morse Lake are managed to provide water for the Cedar River fishery and for diversion into the SPU water transmission system at the Landsburg Diversion Dam, 14 miles (23 kilometers) downstream of Masonry Dam. Water diverted at the Landsburg Diversion Dam is piped to Lake Youngs which has an additional usable storage capacity of 1.5 billion gallons (5.5 million cubic meters). The Cedar River Water Treatment Plant at Lake Youngs uses ozonation and ultra violet processes to treat the water. The Cedar River Pipelines deliver treated water to SPU's direct service area and wholesale customers.

The Tolt River Watershed, located approximately 40 miles (65 kilometers) northeast of Seattle, was developed in 1962 to meet the rising water demands from population growth in the central Puget Sound region. The Tolt River Watershed supplies approximately one-third of SPU's water supply. The Tolt Reservoir provides approximately 18 billion gallons (70 million cubic meters) of storage. The Tolt River Water Filtration Plant, located approximately 5 miles (8 kilometers) downstream of the Tolt Reservoir, is used to treat Tolt Reservoir water. The Tolt pipelines are used to transport water to the northern portions of SPU's direct service area and wholesale customers.

In addition to the Tolt and Cedar River watersheds, SPU maintains two well fields approximately 10 miles (16 kilometers) south of downtown Seattle. The Riverton and Boulevard Park well fields can supply up to 10 mgd (40,000 cubic meters per day) in emergency and drought conditions.

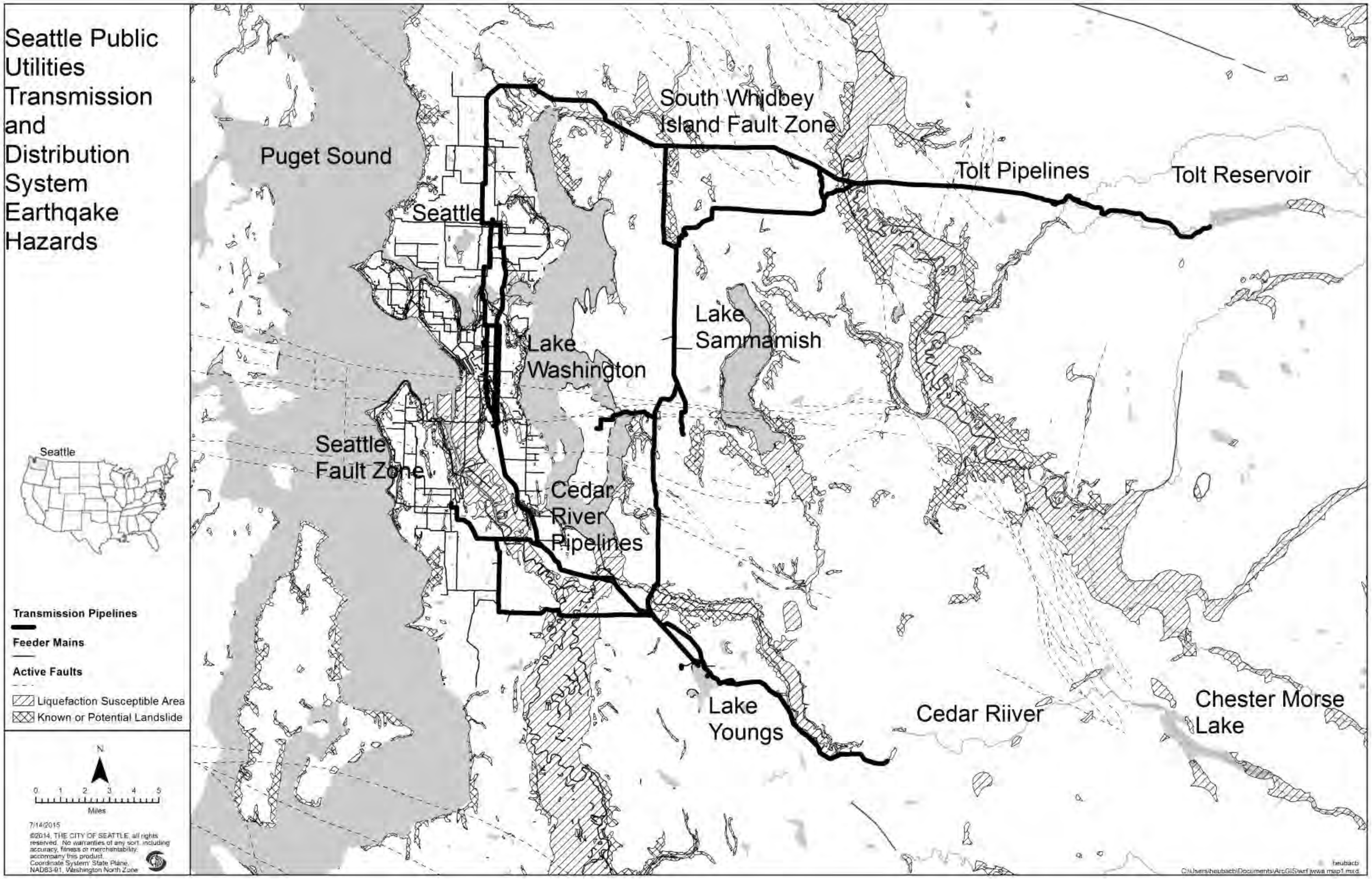


Figure 1. Seattle Public Utilities Transmission and Distribution System and Area Earthquake Hazards

The Great Seattle Fire of 1889 was the impetus for developing a reliable water system for Seattle. Consequently, some SPU water system facilities are more than 100 years old. Currently, SPU's distribution system consists of

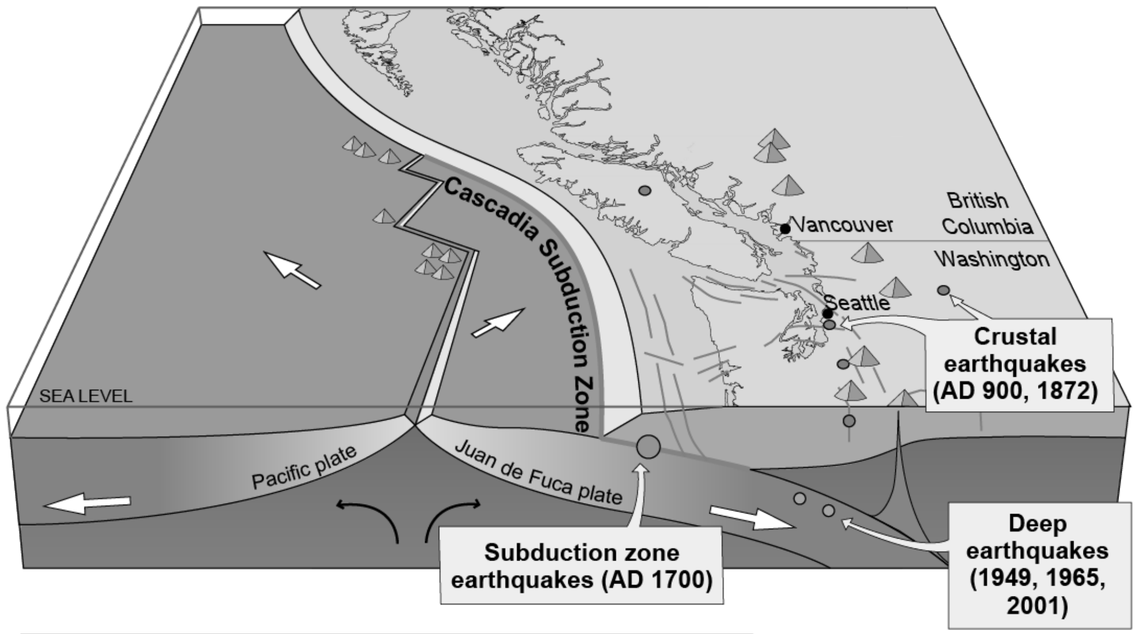
- 1700 miles (2700 kilometers) of distribution pipelines
- Ten at-grade terminal storage reservoirs ranging in size from 5 million gallons to 60 million gallons (19,000 cubic meters to 227,000 cubic meters)
- Six standpipes and elevated tanks
- Sixteen pump stations
- 21,000 valves
- 19,000 fire hydrants

PUGET SOUND REGION SEISMICITY

The SPU water transmission and distribution system lies over a subduction zone. As Figure 2 shows, there are three earthquake mechanisms that threaten the Puget Sound region:

- Deep intraplate earthquakes in the Juan de Fuca plate are caused by fracturing of the Juan de Fuca Plate as it is being subducted below the North American Plate and the Puget Sound. The M7.1 1949 Olympia, M6.5 1965 Seattle and M6.8 2001 Nisqually Earthquakes were intraplate earthquakes. Although the epicenters of these three earthquakes were located within the Puget Sound region, the hypocenters of Juan de Fuca intraplate earthquakes are typically 30 to 80 kilometers (20 to 50 miles) below the earth's surface. Consequently, peak ground accelerations in most locations are less than 0.2g. Damage from these earthquakes to SPU water system facilities has been minimal and has not significantly affected water system functionality.
- Megathrust subduction earthquakes are possible below the Pacific Northwest coastal zone where the Juan de Fuca Plate is being subducted by the North American Plate. The locked boundary between the North American Plate and Juan de Fuca plate extends more than 700 miles (1100 kilometers) and is capable of producing earthquakes of M9.0 or greater. Because the interplate fault rupture would not occur in the immediate vicinity of Seattle, peak ground accelerations would likely only be on the order of 0.2g to 0.3g in SPU's service and transmission area. However, strong ground shaking may last as long as three or four minutes and would increase the likelihood and extent of soil liquefaction, damage to buried pipelines and above ground structures. Under the worst case scenario, the western regions from Northern California to Southern British Columbia would be significantly impacted.
- Several active surface fault systems in the Puget Sound region have produced M7.0 to M7.5 earthquakes. Although these surface faults are responsible for most of the earthquakes in the Puget Sound area, most of these earthquakes are too small to produce significant damage. The last major earthquake from a surface fault in the Puget Sound area is believed to have occurred over 1100 years ago in the Seattle

Fault Zone. The Seattle Fault Zone runs directly through Seattle and possibly all the way east to the Cedar River Watershed. In addition to strong ground shaking that may exceed 0.6g, the Seattle Fault Zone may produce surface expressions of faulting.



Source	Max. Size	Recurrence
Subduction zone	M 9+	200–600 years
Deep Juan de Fuca plate	M 7+	30–50 years
Crustal faults	M 7+	Hundreds of years?

Volcano

Active crustal fault

Active plate boundary fault

*figure modified from USGS Cascadia earthquake graphics at http://geomaps.wr.usgs.gov/pacnw/pacnweq/index.html

Figure 2. Puget Sound Earthquake Source Zones (Source: USGS [2] and Washington State Department of Natural Resources [3])

SEATTLE PUBLIC UTILITIES SEISMIC PROGRAM – THE PAST

Cygna Energy Services [4] was hired by SPU to perform a seismic vulnerability assessment of SPU's water system facilities in the late 1980's. Almost all of SPU's water system facilities were assessed by Cygna. Seismic hazards were identified by Shannon and Wilson, a geotechnical engineering consultant.

Although some surface faults had been identified in the Puget Sound region prior to 1990, these faults were not considered capable of producing large, damaging earthquakes at the time. Although the Cascadia interplate subduction zone had been identified prior to 1990, Cascadia interplate subduction earthquakes were believed to be limited to approximately M8.0 to M8.5. Cygna evaluated SPU's facilities for two levels of ground shaking:

- 0.50 probability of exceedance in 50 years ground motions (72 year average return interval)
- 0.10 probability of exceedance in 50 years ground motions (475 year average return interval)

The postulated mechanisms for these ground motions were M6.5 and M7.5 intraplate earthquakes that would occur 30 to 50 miles directly below the facilities that were assessed.

The Cygna study focused on distinct water system facilities and a few discrete transmission pipeline locations. Based on the Cygna study, several facilities were seismically upgraded. These upgrades ranged from improving structural component connections at pump stations to installing seismic base isolators on two elevated tanks. Additional emergency preparedness measures such as purchasing flexible hose to use as temporary water mains and water blivets that could be used to provide temporary drinking water sources were also implemented.

SEATTLE PUBLIC UTILITIES SEISMIC PROGRAM – THE PRESENT

In 2014, SPU decided to take a fresh look at the seismic vulnerability of its water system and to develop a long term mitigation plan. There were several reasons behind SPU decision to re-evaluate the seismic vulnerability of its water system. First, in many of the several large earthquakes since the 1990 study was completed, water systems had continued to perform poorly. Complete restoration of water system service has taken upwards of two months in some instances. The indirect economic effects on Seattle's businesses and industries would be enormous if complete water system restoration took two months or more. If the post-earthquake recovery took too long, Seattle could risk outward migration of both businesses and residents.

There were also several important lessons learned in these earthquakes [5]. Although water distribution pipelines continued to perform poorly, particularly in areas were permanent ground displacement occurred, some distribution pipelines such as those made from earthquake resistant ductile iron pipe performed exceptionally well. Other United States utilities have conducted pilot projects with earthquake resistant ductile iron pipe and United States pipe manufacturers have begun developing their own earthquake-resistant water distribution pipe.

Although facility criticality was considered in the Cygna study, overall water system performance was not considered. As the 1994 Northridge, 1995 Kobe, and 2011 Christchurch and Tohoku earthquake demonstrated, distribution system pipeline breaks can have a major effect on water system reliability and restoration. A 1988 USGS sponsored study [6] looked at how distribution pipelines might affect system response in a portion of the SPU water system. As part of a Water Research Foundation study [7], SPU evaluated the effect of distribution pipeline damage on the entire water system. As Figures 3 and 4 show, it will likely take only a few hours for large areas of the SPU direct service system to lose water pressure after a major earthquake. Six to ten hours after an earthquake, most of the system could lose water pressure.

Finally, the understanding of the seismicity of the Puget Sound region has changed dramatically since 1990. Earthquake design codes have undergone significant revision. When the 1990 SPU seismic study was completed, the only two mechanisms believed capable of producing damaging earthquake in the Puget Sound region were the Cascadia interplate and intraplate zones. Although the most common type of earthquake in Western Washington are small, shallow earthquakes and a shallow M7.2 earthquake occurred in Eastern Washington in 1872, in 1990 it was not believed that large, shallow earthquakes were likely in Western Washington. However, since 1990, paleoseismic evidence has been discovered that indicates that large shall earthquakes have occurred in Western Washington in the past and will occur in the future. One of the active surface fault zones that seismologists have identified, the Seattle Fault Zone, runs directly through Seattle and bisects the Cedar River pipelines and the Eastside Supply Line, the transmission pipeline that supplies SPU's eastside wholesale customers. Another fault zone, the South Whidbey Island Fault Zone, bisects the Tolt River pipelines.

Figure 3. Estimated SPU System Water Pressure Three Hours After Major Earthquake (Darkest Areas Denote Water Pressure = 0)

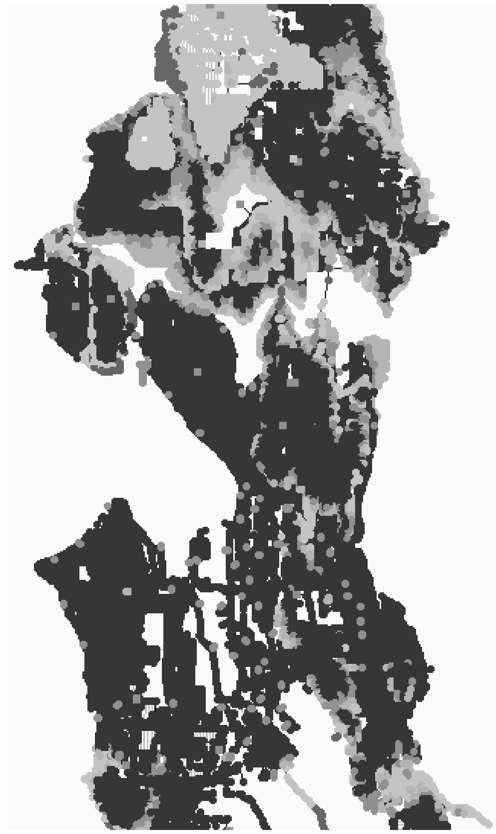


Figure 4. Estimated SPU System Water Pressure Ten Hours After Major Earthquake (Darkest Areas Denote Water Pressure = 0)

In addition to possible surface expression of faulting that could damage SPU water system facilities, the Seattle and South Whidbey Island fault complexes have dramatically increased the ground motions. Additionally, the building codes [8] have gravitated from considering 0.10 probability of exceedance in 50 years (475 year average return interval) ground motions to 0.02 probability of exceedance in 50 years (2475 year average return interval) ground motions. Consequently, the design level ground motions for SPU water system facilities has increased from approximately 0.2 to 0.3g, to 0.5 to 0.6g.

SEATTLE PUBLIC UTILITIES SEISMIC PROGRAM – THE FUTURE

Recognizing the current seismic vulnerability of SPU water system, SPU has established five objectives for its seismic program/study.

Post-Earthquake Level of Service Goals

Clear, concise post-earthquake water system performance objectives are being defined. The purposes of these objectives are to define obtainable goals and to communicate these goals to SPU's stakeholders. The performance objectives need to be realistic in terms of available funding. The objectives also need to recognize that due to the high costs, it will take many years to upgrade SPU's water system to meet the objectives. Consequently, the objectives will be divided into (relatively) near-term objectives for the next 20 years and longer term objectives for the next 50 to 60 years.

The different SPU stakeholders have been identified and their input is being solicited. Major stakeholder groups include

- Seattle Fire Department
- Retail Customers
- Wholesale Customers
- City and SPU Leadership
- SPU Staff

Stakeholder engagement includes meeting with stakeholders and soliciting their input. Because any mitigation strategy that is implemented by SPU will require some level of rate-based funding, a choice experiment will be developed to help determine retail customer willingness-to-pay for improved water system seismic performance.

Water System Facility Seismic Vulnerability Assessments

The seismic vulnerability of each SPU water system facility will be assessed. The facilities will be evaluated with three different sets of criteria: two scenario events and the code level 0.02 probability of exceedance in 50 years (2475 year average return interval) ground motions. The first scenario event is a postulated M9.0 Cascadia interplate subduction earthquake that would occur off the Washington coast. Fault rupture could extend over 700 miles (1100 miles) from Southern British Columbia to Northern California. Although the 0.2 to 0.3g ground shaking intensity in the SPU transmission and distribution area is similar to the shaking intensity used in the 1990 Cygna study, strong ground shaking may last for three or four minutes. The long ground shaking duration has significant implications for less ductile facilities that may not be able to withstand repeated excursions into the inelastic range. Additionally, the long duration ground motions will likely result in more widespread liquefaction and landslides, larger permanent ground displacements and more extensive pipe damage. The M9.0 Cascadia scenario is believed to be representative of a scenario with an approximately 500 year average return interval.

The second scenario is a M6.7 Seattle Fault Zone earthquake. The Seattle Fault Zone will be assumed to rupture within SPU's direct service area. In addition to strong ground motions in the vicinity of the fault rupture, the fault ruptures surface expression will be assumed to sever the Cedar River pipelines. This M6.7 Seattle Fault Zone scenario is consistent with the type of event that may be expected to occur every 1000 to 2500 years.

Each facility will also be assessed in accordance with current building code and standard ground shaking levels. Although the current U.S. codes are in the process of migrating from 0.02 probability of exceedance in 50 years ground motions to 0.01 probability of collapse in 50 years ground motions, the 0.02 probability of exceedance ground motions, which will likely be similar to the 0.01 probability of collapse ground motions in the Puget Sound region.

Although all SPU facilities will be considered, the level of analysis for each facility will vary. Facilities that have been recently constructed and/or upgraded to current codes will be assumed to remain functional during the scenario and code level analyses. Whenever possible, information and analyses developed by Cygna or other seismic evaluations will be used in the assessments. Critical facilities that have not been previously analyzed for the current ground motions will be analyzed in most detail. ASCE 41-13 procedures [9] will be used as a guideline. Site-specific evaluations will be conducted for critical transmission pipelines. Distribution pipeline damage will be estimated with the American Lifelines Alliance (ALA) water distribution system pipeline fragility models [10]. The fragility models will be modified to reflect SPU water distribution pipeline characteristics and lessons learned about water distribution pipeline damage since the 2001 ALA guidelines were published.

Water System Post-Earthquake Response

Water system performance in past earthquakes has shown that distribution pipeline breaks can heavily influence post-earthquake water system performance and recovery. Unmitigated, distribution pipeline damage can quickly drain reservoirs and lead to loss of system pressurization. This behavior is consistent with the hydraulic modeling results from the 2009 Water Research Foundation study. Consequently, the facility earthquake scenario vulnerability assessment results will be used to estimate overall system response. A “skeletonized” system hydraulic model will be used to hydraulically model the system response. The major difference between the approach used in this study and the 2009 Water Research Foundation study is that a “skeletonized” hydraulic model that essentially models each pressure zone as a single node will be used in this study. With the full system EPANet model used in the previous Water Research Foundation study, EPANet has trouble converging and remaining stable once pressures reach 0 psi in large areas of the system. A simpler EPANet model is expected to remain more stable under the extreme conditions created by a large earthquake.

In addition to assessing the current water system vulnerability, the hydraulic model will also be used evaluate the effect of mitigation options on system response. Hydraulic modeling of the system response to various mitigation solutions will help identify cost effective mitigation strategies that are consistent with the post-earthquake level of service goals.

Earthquake Mitigation Strategy Development

Mitigation solutions will be developed that are consistent with the post-earthquake level of service goals. If the mitigation solutions are unrealistically expensive, there will be some iteration/modification of the post-earthquake level of service goals. As mentioned previously, there will be a near-term set of post-earthquake level of service goals and a longer term set of post-earthquake level of service goals.

Because SPU has committed to limit rate increases through 2020, the near term mitigation measures are expected to include less expensive strategies such as improvement of emergency preparedness and response procedures, and implementation of post-earthquake operation and control strategies.

Seismic Standard Development for New Water System Facilities

As part of the long-term approach to reducing the seismic vulnerability of SPU's water system, an important component of SPU's current seismic study is to develop seismic standards for new water system facilities. Because buildings, building contents and reservoirs are already covered by existing codes and standards, the emphasis will be on the development of standards for pipelines. It's expected that the standards for distribution system pipelines will be largely prescriptive. That is, in areas where permanent ground displacement is possible, some type of earthquake resistant pipe will be required. As pipe criticality and size increases, the level of analysis will increase. For transmission pipelines, the requirement of a complete seismic analysis is anticipated.

Previous earthquakes experienced by other water utilities and the 2009 Water Research Foundation study suggest that SPU would likely experience more than 1000 distribution pipeline failures in a major earthquake. Because it is not practical to replace large amounts of vulnerable distribution piping in a short amount of time, one purpose of the standards will be to ensure that as SPU replaces pipelines as part its normal replacement process, seismic resistant pipelines are installed so the vulnerability of SPU's pipeline system can gradually be reduced.

SUMMARY

Seattle Public Utilities is reevaluating the seismic vulnerability of its water system and developing a new mitigation strategy because:

- The understanding of the seismicity of the Puget Sound region has changed dramatically since SPU's 1990 study.
- Recent earthquakes have shown that although water systems remain seismically vulnerable, there are practical strategies that can be used to decrease vulnerability.
- In addition to individual facility evaluation, the response of the entire water system needs to be considered.

The objectives of SPU's seismic program are to:

- Define post-earthquake water system level of service goals
- Evaluate the seismic vulnerability, consistent with the current understanding of seismicity in the Puget Sound region, of SPU's water system facilities
- Estimate SPU's water system response to two earthquake scenarios
- Develop a mitigation strategy and program to enable SPU to meet its post-earthquake level of service goals
- Define seismic design standards for water system facilities with an emphasis on design standards for pipelines.

Ultimately, over time, SPU is aiming to develop a seismically resilient water system that is able to function as needed after a major earthquake so that life safety and property damage effects are minimized. Additionally, the time fully restore the system should be minimized to reduce societal impacts.

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Title: **Mitigation of Potential Impacts of Large Seismic Events on a Regional Water Supply Conveyance System**

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Mitigation of Potential Impacts of Large Seismic Events on a Regional Water Supply Conveyance System

Gordon L. Johnson*, Albert J. Rodriguez**

Abstract

The Metropolitan Water District of Southern California owns and operates the Colorado River Aqueduct (CRA), which is one of the main imported water conveyance facilities for Southern California. The aqueduct traverses a seismically active area and crosses a number of active faults, including the San Andreas Fault. During design and construction of the CRA, which occurred from 1933 to 1941, accommodations were provided to mitigate the risk posed by active fault traces and to enable rapid repair of the aqueduct. However, since that time, knowledge regarding geology and seismicity within Southern California has greatly increased, while significant advancements have occurred in earthquake engineering and design. Due to this continual increase in knowledge, Metropolitan maintains a program to periodically reassess the seismic vulnerability of its facilities. The most recent evaluation of the seismic vulnerability of the CRA assessed the potential vertical and horizontal surface deformation that could occur from a Magnitude 7.8 earthquake on the San Andreas Fault, and the potential impacts of this deformation on the CRA. This paper will present Metropolitan's strategy for improving the seismic reliability of the CRA, along with steps being taken to mitigate the potential impacts of a large earthquake on the aqueduct.

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INTRODUCTION

The Metropolitan Water District of Southern California is a consortium of 26 cities and local water agencies that provides drinking water to 18 million people over a 13,470 square kilometer (km) (5,200 square mile) service area within Los Angeles, Orange, Ventura, Riverside, San Bernardino, and San Diego Counties. On average, Metropolitan delivers 6.4 million cubic meters (1.7 billion gallons) of water per day to its customers. Metropolitan owns, operates, and maintains five conventional water treatment plants, nine pumping plants, 15 hydroelectric plants, 33 dams and reservoirs, over 1,335 km (830 miles) of large diameter pipelines and tunnels up to 6.25 m (20.5 feet) in diameter, and the 390 km (242 mile) Colorado River Aqueduct (CRA).

Metropolitan imports Colorado River water from the border of California and Arizona into coastal Southern California via the CRA. Metropolitan also imports water from Northern California, which is conveyed through the California Department of Water Resources' (DWRs) California Aqueduct. In an average year, these two conveyance facilities supply 50 percent of the water used within Southern California.

Metropolitan's service area is crossed by a number of known faults with varying degrees of activity. The major imported water conveyance systems into Southern California and the major regional faults are shown in Figure 1. The recently released Uniform California Earthquake Rupture Hazard Forecast (UCERF) [1] estimates a 93 percent likelihood of a magnitude (M) 6.7 or greater earthquake occurring within Southern California within the next 30 years. Specifically for the Southern San Andreas Fault, which is crossed by all of the water conveyance facilities into the region, UCERF estimates a 19 percent likelihood of a M 6.7 or greater earthquake within 30 years.

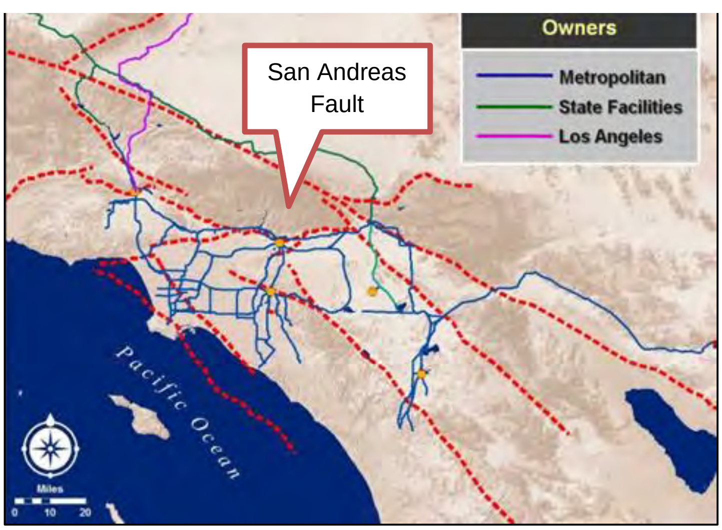
As a regional provider of drinking water, Metropolitan recognizes the importance of continued water deliveries following a major seismic event. Water will be a vital resource for both general welfare and fire suppression. This paper will provide an overview of Metropolitan's approach to ensuring reliable deliveries and mitigating potential impacts from a seismic event, focusing specifically on the CRA and a recent vulnerability study that assessed potential impacts to the CRA from a large earthquake on the Southern San Andreas Fault.

COMPREHENSIVE RELIABILITY STRATEGY

Metropolitan has developed a comprehensive approach to system reliability through a collaborative effort with its 26 member agencies. The strategy was first developed as an element of the Integrated Area Study, which aims to maximize the coordination between Metropolitan and its member agencies to meet the region's future water supply needs. System reliability has five principal components:

- Water Supply Reliability – the ability to obtain water to meet member agency demands under all foreseeable hydrologic conditions.
- System Capacity – the ability to convey, treat, and distribute supplies to meet firm demands under peak conditions.

Figure 1: Regional Faults within Metropolitan's Service Area in Southern California



- Infrastructure Reliability – the ability to maintain facilities in a state of readiness to make water deliveries.
- System Flexibility – the ability to respond to short-term changes in water supply, water demands, and water quality; and the ability to meet member agency needs during planned outages.
- Emergency Response – the ability to respond to unplanned outages and restore service quickly.

Metropolitan's strategy to ensure the reliability of its conveyance facilities and distribution system following an earthquake is carried out through actions taken under the Infrastructure Reliability, System Flexibility, and Emergency Response functions. Following are descriptions of these three functions.

Comprehensive Reliability - Infrastructure Reliability Component

Seismic preparedness activities under the Infrastructure Reliability function include Metropolitan's long-term Seismic Upgrade Program and periodic Vulnerability Assessments.

Seismic Upgrade Program. For over 25 years, Metropolitan has maintained a Seismic Upgrade Program to harden its above-ground facilities against potential earthquake damage. Metropolitan's system was constructed over a period of 80 years in conformance with then-current building codes. Over time, building codes have evolved as engineering capabilities and the industry's knowledge of earthquake hazards have advanced. The goal of the Seismic Upgrade Program is to maintain water deliveries immediately following a code-level earthquake.

The Seismic Upgrade Program utilizes a systematic approach to identify and prioritize facilities in need of seismic retrofit. In California, buildings constructed in the 1990's or later are generally considered to have reasonable assurance of withstanding a code-level earthquake without catastrophic structural failure. As a result, the Seismic Upgrade Program focuses on Metropolitan facilities constructed prior to 1990. Facilities are divided into three groups – 1) those related to water delivery, 2) those not related to water delivery but which are essential to Metropolitan's business operation, and 3) those that do not fall within the first two groups. Facilities within the first group receive the highest priority for evaluation.

To date, Metropolitan has invested over $230 million to enhance the seismic performance of its existing facilities, including $135 million at its five regional treatment plants. All facilities related to water delivery have been evaluated, and the identified upgrades have either been completed or are currently underway.

Vulnerability Assessments. Metropolitan conducts vulnerability assessments to identify potential impacts to its ability to deliver water following various postulated hazards including large seismic events. Vulnerability studies can focus on individual facilities (i.e. treatment plants) or assess the system as a whole. The findings of vulnerability studies can lead to new operation and maintenance procedures, new design guidelines, new projects within Metropolitan's Capital Improvement Program, or can provide guidance for emergency response planning. One example of a vulnerability study is the recently completed CRA Seismic Assessment, which will be detailed later in this paper.

Comprehensive Reliability - System Flexibility Component

As Metropolitan has expanded its distribution system over the decades, it has incorporated both flexibility and redundancy to allow for temporary shutdown of facilities and pipelines with minimal impact to its member agencies. This flexibility and redundancy will be vital for Metropolitan to maintain water deliveries following a seismic event.

As stated previously, Metropolitan imports water from multiple areas within California for treatment and distribution into its service area. Water from Northern California can supply all five of Metropolitan's regional water treatment plants and therefore reach the entire distribution system. With recent upgrades to this distribution system, CRA water can now supply most of the service area. These modifications have helped Metropolitan meet member agency needs during the current long-term drought in the American West.

The concept of system flexibility has also been promoted between Metropolitan's member agencies. These agencies are encouraged to develop interconnections between systems, and to ensure that they have adequate local back-up supplies. One of Metropolitan's core strategies is to help member agencies develop these local supplies. As a minimum, member agencies are required to maintain seven days of storage for temporary shutdowns and emergency repairs.

Comprehensive Reliability - Emergency Response Component

Metropolitan's Emergency Response Program focuses on maintaining the capability to execute multiple simultaneous repairs, conducting emergency planning and training events, and maintaining storage of emergency water supplies.

Repair Capabilities. Metropolitan has protocols to inspect and monitor its conveyance facilities and distribution system, and to distribute resources following a major seismic event. The repair response will depend on a number of factors including the extent of damage and repairs needed, the back-up capabilities of member agencies, and the immediate delivery benefits provided by individual repairs. To execute urgent repairs, Metropolitan would first rely on its own construction forces and utilize its existing supply of materials and heavy equipment. If necessary, Metropolitan would then turn to its existing construction contracts. As a standard provision in all of its construction contracts, Metropolitan retains the ability to mobilize contractors to perform emergency work on an as-needed basis. In addition, Metropolitan maintains a list of prequalified contractors for emergency repairs. Lastly, Metropolitan maintains mutual aid and mutual assistance agreements with state and local agencies to share available resources during emergencies.

In addition to its construction forces, Metropolitan owns and operates its own machining, fabrication, and coating shops located centrally within the distribution system. These shops have the ability to respond on short notice to either Metropolitan's or its member agencies' emergency needs. Metropolitan recently invested $40 million to upgrade manufacturing equipment and seismically strengthen and expand this facility, and plans to invest $10 million to purchase additional equipment. The investments in these shops allow Metropolitan to fabricate large-diameter pipe to repair at least two simultaneous pipeline breaks utilizing in-house capabilities.

Emergency Response Planning and Training Events. To prepare for major earthquakes, Metropolitan has developed an Emergency Response Plan which documents the assessment and reporting guidelines following a seismic event, and identifies the structural hierarchy of the response teams and their responsibilities. The Emergency Response Plan specifies the level of seismic event for which emergency response activation is required, based on the magnitude and proximity of an earthquake to conveyance and distribution facilities.

In addition to the Emergency Response Plan, Metropolitan conducts annual emergency response exercises to evaluate the plan's effectiveness, train staff, and identify potential areas for improvement. The exercises can be either table-top, in which a response to an emergency scenario is talked through, or a more elaborate simulated event in which Metropolitan's various emergency operation centers (EOCs) are activated. For these simulated exercises, the EOCs must coordinate amongst each other as damage information is submitted by Damage Assessment Teams. Metropolitan encourages member agencies and State of California representatives to participate in the simulations.

Emergency Storage. Metropolitan has long recognized the potential for a major earthquake to occur on the Southern San Andreas Fault System (SSAFS), which may interrupt deliveries from the CRA. In 2000, Metropolitan completed construction of Diamond Valley Lake (DVL), which is Southern California's largest surface water reservoir. DVL was constructed on the coastal side of the SSAFS and the San Jacinto Fault Zone (SJFZ) in order to supply the region in case CRA deliveries are interrupted. Water stored in DVL can directly supply four out of Metropolitan's five water treatment plants. With the completion of DVL, Metropolitan nearly doubled the available surface water storage in the region. In conjunction with local production and conservation, DVL and other local reservoirs can provide the region with six months of emergency water supply.

COLORADO RIVER AQUEDUCT SEISMIC ASSESSMENT AND MITIGATION

The CRA conveys water from the Colorado River across the California desert to Lake Mathews in Riverside County. As noted above, Metropolitan recognizes the potential for water deliveries from the CRA to be disrupted by a major earthquake on the SSAFS or the SJFZ. During the original design and construction of the CRA in the 1930s, Metropolitan engineers incorporated measures to mitigate potential impacts from surface displacement due to an earthquake on the SSAFS or SJFZ. These measures included: providing 2.3 meters (7.5 feet) of additional head (allowable loss) in the hydraulic profile of the aqueduct as it crosses the SSAFS zone; utilizing inverted siphons or shallow conduits for crossing identified active traces of the fault, in order to make damaged areas more accessible; and utilizing segmented conduit sections rather than typical monolithic construction to reduce potential damage from displacements [2][3]. Recent advancements in earthquake engineering and design, and increased knowledge regarding geology and seismicity within Southern California, have prompted Metropolitan to periodically reassess the seismic vulnerability of the CRA and its related facilities, and the potential impacts to CRA deliveries from a major earthquake.

Seismic Upgrade of CRA Facilities

Upgrades to CRA facilities to date have largely focused on the five aqueduct pumping plants. Upgrades completed at these facilities include seismic strengthening of the pump buildings, the discharge pipelines from the pumping plants, electrical switch houses, and various appurtenant structures. Figure 2 shows the Hinds Pumping Plant's main building after completion of the structural upgrades. Buttresses were added to withstand the out-of-plane seismic loading, and to minimize deflection.

In addition to seismically upgrading the pumping plants, Metropolitan constructed a new outlet tower for the Lake Mathews Reservoir, which is the terminus of the CRA. The original tower was constructed in 1940, and the seismic evaluation found it to be deficient. Figure 3 shows the original Lake Mathews outlet tower and the new outlet tower that was completed in 2003.

Figure 2: Seismic Upgrade of CRA Pumping Plant

Figure 3: Original and New Lake Mathews Outlet Towers

Colorado River Aqueduct Seismic Vulnerability Study

The CRA crosses the SSAFS in an area known as the San Gorgonio Pass. In recent years, there has been a significant increase in knowledge regarding the structure of the SSAFS within the San Gorgonio Pass. As a result, Metropolitan recently conducted new vulnerability studies of the CRA to reassess the risk and nature of a potential rupture of the San Andreas Fault, and to reexamine previous assumptions about damage to the CRA and potential delivery impacts. The recently completed CRA Seismic Vulnerability Study was conducted in two phases. The first phase of the study modeled potential displacements from a rupture of the San Andreas Fault using the United States Geological Survey's Coulomb 3.3 software [4]. The second phase applied the results of the model to the CRA to determine potential damage and service impacts.

Phase 1 - Modeling of the SSAFS within the San Gorgonio Pass. The San Gorgonio Pass area is the most complex portion of the SSAFS and has been the least understood. Outside of the pass, the SSAFS is a northwest trending, right-lateral strike-slip fault. Within the pass, the San Andreas Fault bifurcates into northern and southern branches of discontinuous fault segments as shown in Figure 4. The bifurcation creates a leftward stepover of the fault. The south-eastward movement of the North American Plate and the north-westward movement of the Pacific Plate compress the area within the San Gorgonio Pass, forming a zone of transpression (Figure 5). A rupture of the SSAFS through this zone of transpression can cause broad regional uplift. This uplift is potentially significant because the water flows by gravity through the CRA in a westerly direction downstream of the Hinds Pumping Plant toward Lake Mathews. Consequently, broad regional uplift within the San Gorgonio Pass could have implications on the hydraulic capacity of the CRA. To evaluate the potential horizontal and vertical deformation that may occur from a rupture of the San Andreas Fault and the impact to the CRA, Metropolitan initiated the Colorado River Aqueduct San Gorgonio Pass Seismic Event Vulnerability Study (SEVS) [5]. The study was led by a team of geoscientists experienced in assessing the potential for fault displacements along the SSAFS in the San Gorgonio Pass area, and was presented by GeoPentech, Inc. Using recently available data, estimates for post-seismic event ground deformation were developed following a five-step approach.

Step 1 – Analysis and Integration of Geologic, Seismologic, and Geodetic Data – The SEVS incorporated the most recent information available relating to the seismicity of the area including: geology, tectonics, paleoseismology, seismicity, and geodesy.

Figure 4: CRA Crossing of Southern San Andreas Fault System and San Jacinto Fault Zone

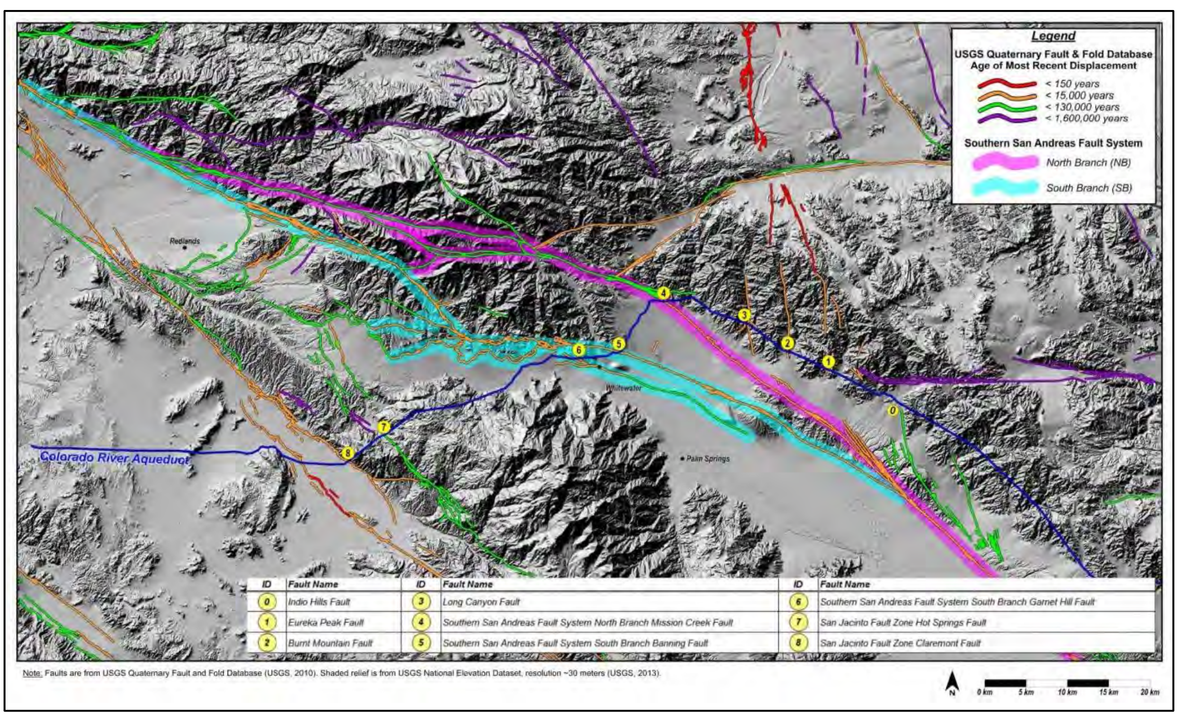
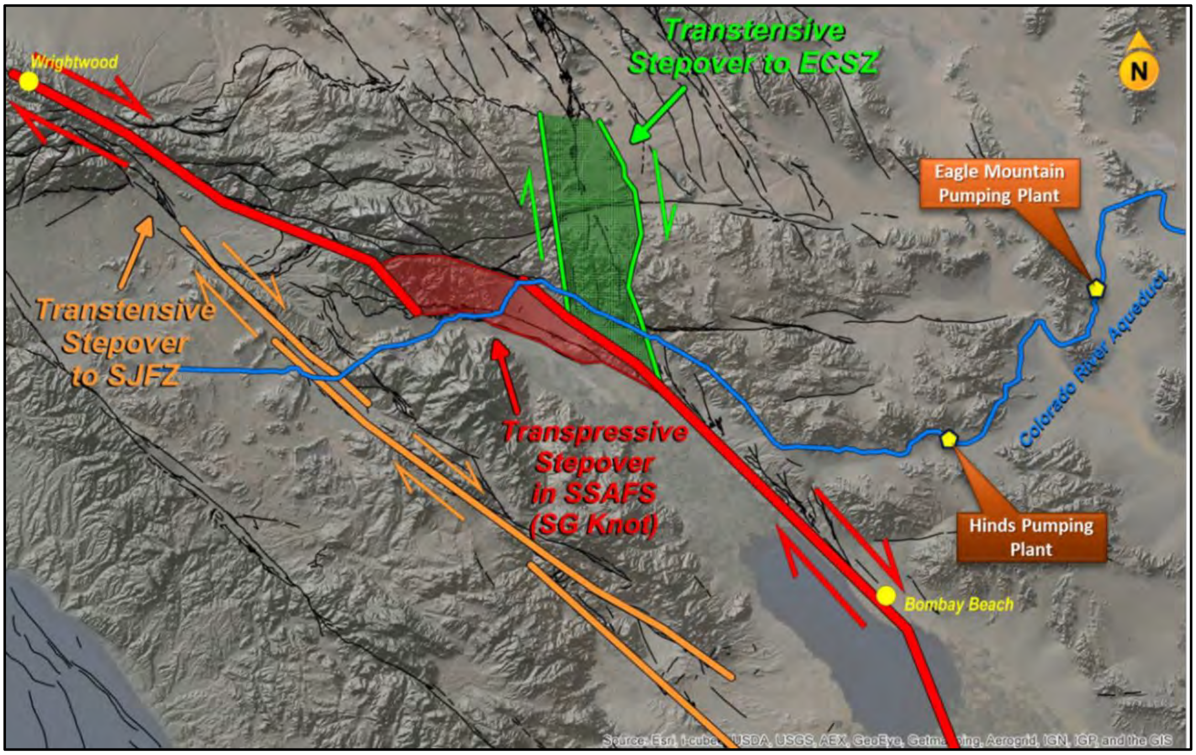


Figure 5: Southern San Andreas Fault System Directional Motion Showing Zone of Transpression



Step 2 – Three Dimension Construction of San Gorgonio Pass Subsurface Geometry **–** The second step in the modeling process was to incorporate the information gathered from Step 1 and develop a three-dimensional (3D) graphical representation of the subsurface geometry of the faults beneath the San Gorgonio Pass area.

Step 3 – Configuration of the Deformation Model **–** Step 3 involved building a model for the Coulomb 3.3 software based on the final 3D graphical representation.

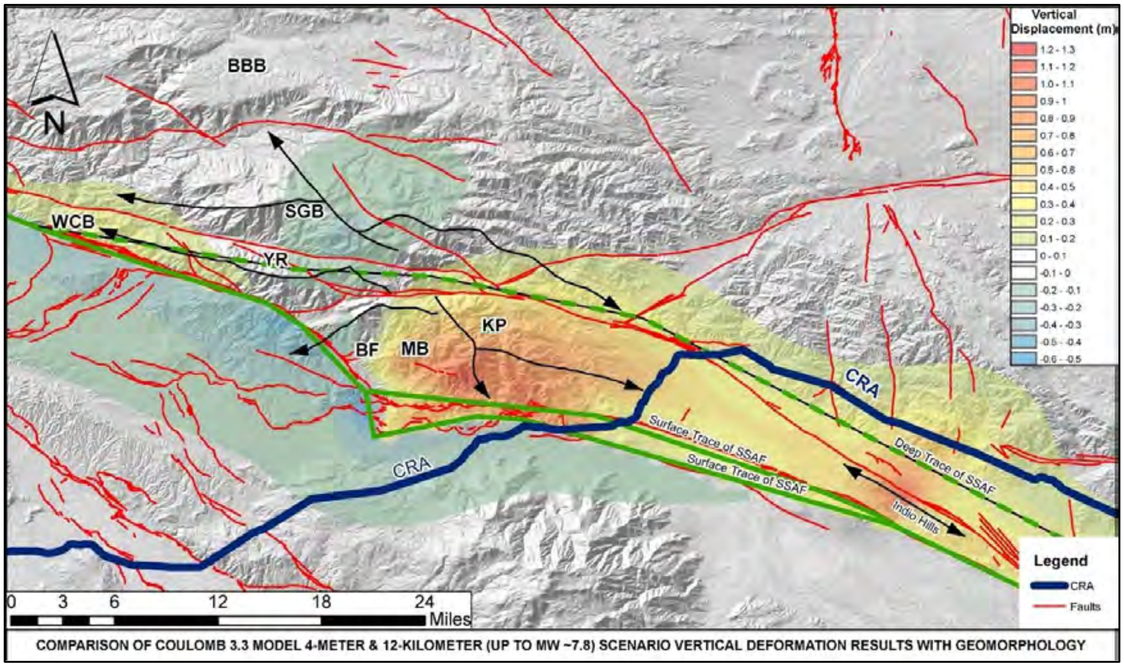
Step 4 – Model Runs for Three Earthquake Scenarios **–** While the focus for this study was to determine impacts to the CRA from the Maximum Considered Earthquake (M_W 7.8) on the SSAFS, three earthquake scenarios were identified in order to bracket the results. The study included the following model scenarios:

- Scenario 1 – Approximately 1 m (3 feet) of slip at and above 12 km (7.5 miles) in depth, tapering to no slip at the surface, representative of a M_W6 to M_W6.5 event with an estimated recurrence of several decades, similar to a North Palm Springs type event.
- Scenario 2 – Approximately 4 m (13.1 feet) of right lateral strike-slip at and above 12 km (7.5 miles) in depth, representative of a M_W7 to M_W7.8 event with an estimated return period of 500 to 1,000 years.
- Scenario 3 - Approximately 8 m (26.2 feet) of right lateral strike-slip at and above 25 km (15.5 miles) in depth, representative of a M_W8.5 event with an estimated return period of greater than 5,000 years.

Scenario 3 was considered improbable by the team of geoscientists due to geologic complexities within the San Gorgonio Pass and magnitude/displacement scaling relationships for 8 m (26.2 feet) of average displacement.

Step 5 – Critical Review and Documentation of Results **–** The results of the model were compared against specific geologic, geomorphic, and paleoseismic data from the San Gorgonio Pass Area. In Figure 6, the results from the Coulomb 3.3 model of vertical deformation for Scenario 2, M_W7-M_W7.8, are superimposed on a map showing geomorphic expressions within the San Gorgonio Pass. The black arrows were taken from a study by Yule and Seih [6] and approximate the broad, regional flexure associated with crustal shortening at and near the stepover. The

Figure 6: Comparison of Coulomb 3.3 Model Results for Scenario 2 and Existing Geomorphology



arrows point down-gradient. There is a strong correlation between the model results and the existing geomorphology. The greatest model uplift coincides with the location of Kitching Peak, which is approximately 1,200 meters (4,000 feet) higher than the eastern arrow tip touching the CRA.

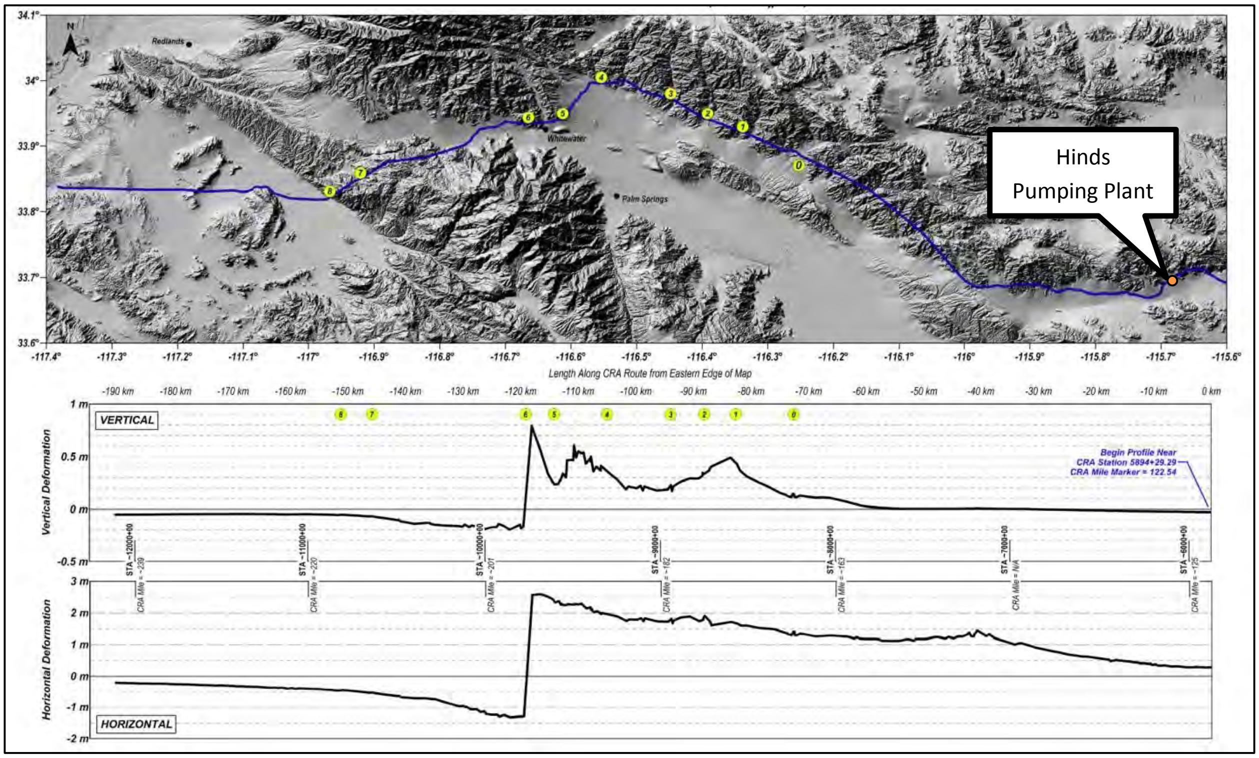
Phase 2 - Application of Coulomb 3.3 Model Results. The second phase of the CRA Seismic Vulnerability Study applied the modeled deformation results to the CRA. Figure 7 shows the change in the horizontal and vertical profiles of the CRA due to the modeled Scenario 2 event, M_W7-$M_W7.8$, on the SSAFS. At the crossing of the Garnett Hills fault and the CRA, the model results identified a 3.75 meter (12 feet) horizontal and 1 meter (3 feet) vertical gross displacement. Focusing specifically on vertical displacement, the CRA experiences uplift over an approximate 60 kilometer (37 mile) distance with three distinct peaks. The highest and most westerly peak is located at the crossing of the CRA and the Garnett Hills Fault, and is 0.8 meters (2.6 feet) above the baseline CRA elevation. This information was used to assess hydraulic impacts to the CRA as well as the potential repair time following the postulated earthquake.

CRA Hydraulic Impact Analysis – The CRA has a design flowrate of 45,450 Liters per second (lps) [1,605 cubic feet per second (cfs)]. The CRA's five pumping plants, all of which are located east of the SSAFS, are capable of lifting the aqueduct's design flowrate a combined height of 493 meters (1,617 feet). As stated previously, water discharged from the Hinds Pumping Plant flows by gravity through the San Gorgonio Pass area to the remainder of Metropolitan's system. Uplift of the CRA would have the effect of reducing the water delivery capa- city of the aqueduct.

Metropolitan conducted the CRA Hydraulic Impact Analysis [7] to determine the extent of flow reduction resulting from the Scenario 2 modeled uplift, which approximates the MCE for the SSAFS. The hydraulic analysis utilized a smoothed version of the vertical displacement profile of the CRA shown in Figure 7 in order to determine the loss in capacity. The original design roughness coefficient was applied to the various aqueduct components (i.e. tunnel, siphon, or covered canal) and the emergency repairs were assumed to maintain the original component cross-sections. The analysis also maintained the original design freeboard, retaining the original intent of non-pressurized free-water-surface flow.

The result of the hydraulic impact analysis indicated that the capacity of the CRA would be reduced to 36,800 lps (1,300 cfs) – an approximate 20% reduction. This result shows that despite the uplift, Metropolitan would be able to

Figure 7: Deformation Profile of Colorado River Aqueduct for Scenario 2 San Andreas Fault Rupture Event (Mw 7 to Mw7.8)



convey significant amounts of water through the CRA following any initial repairs required to re-establish service. Thus, Metropolitan could continue to supply the Southern California region with water from the Colorado River while long-term repairs to restore the original design flow are planned and executed. Long-term repairs would take advantage of the available head in the CRA's hydraulic profile to compensate for uplift resulting from the earthquake.*Estimation of Potential Damage and Repair Times* – The next step was to determine the potential damage that could occur to the CRA from the modeled seismic event. Figure 8 shows the location of the CRA relative to various fault segments within the San Gorgonio Pass. The CRA was designed to cross the Mission Creek and Banning Faults perpendicular and in shallow, readily accessible conduits. The CRA parallels the main strand of the Garnett Hills Fault on the hanging-wall side of the fault. The Garnett Hills Fault has one hanging-wall splay fault that crosses downstream of the Whitewater Tunnel No. 2. An additional hanging-wall fault, alternatively mapped as a fold by Yule and Seih [6], crosses through the Whitewater Tunnel No. 2 upstream of its west portal. From the SEVS study, the likely path for a continuous rupture of the SSAFS through the San Gorgonio Pass is the Garnett Hills Fault segment, which is the most recently active strand. However, the Coulomb 3.3 model is not precise enough, and there is insufficient information available, to determine how the displacement would be distributed among the main fault trace and its splay faults.

Given the location of the Garnett Hills Fault's hanging-wall splay or fold within the Whitewater Tunnel No. 2, the specialized nature of tunnel repair, and the access challenges of repairing a tunnel compared to a siphon or conduit, it was assumed for planning purposes that the worst-case scenario would be for the primary fault rupture to occur on the Garnett Hills Fault's hanging-wall splay or fold within the Whitewater Tunnel No. 2. It was also assumed that repair of the Whitewater Tunnel No. 2 would be the critical path to restoring deliveries from the CRA.

Additional research was conducted to determine the type of damage that might occur within a tunnel from different seismic hazards (i.e. shaking, ground failure, fault rupture). Previous studies have shown that tunnels perform well during earthquake shaking when compared to above-ground structures [8][9][10]. Much of the heavy damage to tunnels from earthquake hazards is attributable to heavy shaking in areas of shallow overburden (i.e. near portals) or

Figure 8: CRA Southern San Andreas Fault System Crossings in the San Gorgonio Pass

ground failure (i.e. landslide or liquefaction)[9][11]. In addition to damage that may occur near the portals, the high levels of shaking during the earthquake could result in minor-to-moderate cracking or spalling of the tunnel liner.

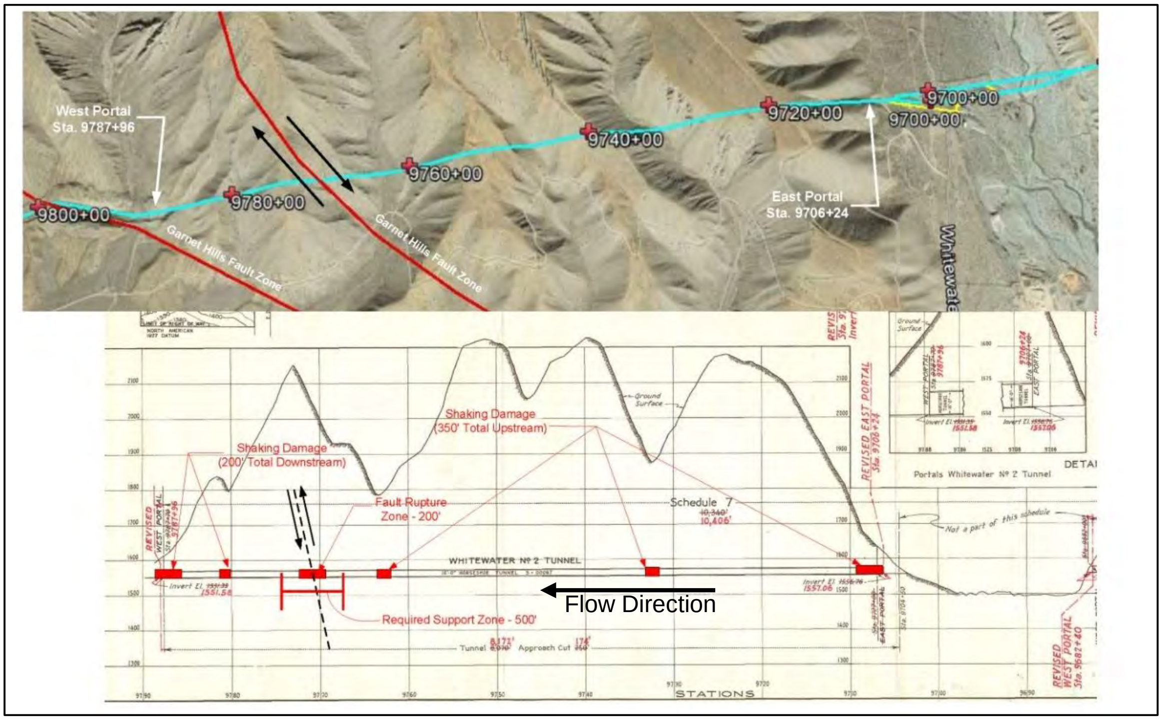
A Tunnel Repair Workshop was conducted [12] to identify realistic repair requirements and to estimate times to re-establish service. The Tunnel Repair Workshop was conducted by a team with expertise in geology, tunnel engineering, tunnel construction and repair, and hydraulics. Workshop participants received a detailed presentation of the Whitewater Tunnel No. 2 construction and geology, and were provided a damage scenario as shown in Figure 9.

The damage scenario assumed the tunnel experienced the full 3.75 meter (12 feet) horizontal and 1 meter (3 feet) vertical displacement on the Garnet Hill Fault from the Coulomb 3.3 model results. The scenario also assumed that displacement at the rupture zone collapsed the tunnel and blocked the flow of water. Additional shaking and ground failure damage was assumed to occur throughout the tunnel with major damage occurring at the portals and the shallower portions of the tunnel. In addition, the sudden blockage would cause a backup at the upstream east portal location that would wash out the access road to the portal.

Two options for repair were identified during the workshop to address the severe damage incurred at the fault rupture zone. Option 1 involved direct mining through the damaged tunnel section (i.e., through the destroyed concrete liner, steel and timber, backfill muck, etc.) to restore the original tunnel. Option 2 would construct a new bypass tunnel around the rupture zone. Due to the uncertainty in mining rate caused by the range of materials encountered and safety issues under Option 1, the team concluded that Option 2 would be the preferred option.

For the damage scenario under Option 2, the tunnel contractors were confident that repairs to the Whitewater Tunnel No. 2 could be completed within a 6-month period. However, they stressed the benefits of pre-planning the repair activities including prequalification of tunnel repair contractors, stockpiling of steel sets for support of damaged tunnel areas to facilitate rapid inspection and repair, and completion of design in advance for a junction structure between the existing tunnel and the new bypass tunnel. The conclusion of the tunnel repair workshop regarding the time to re-establish service was consistent with previous estimates of repair times used for planning purposes.

Figure 9: Whitewater Tunnel No. 2 Rupture Damage Scenario



CONCLUSION

Metropolitan's strategy to ensure reliability of its conveyance facilities and distribution system in the event of a major earthquake includes the hardening of essential facilities; continual reassessment of the system as new research and data become available; conducting emergency response exercises and planning; maintaining the capability to perform emergency repairs; and maintaining stockpiles of key supplies and equipment. For the CRA, Metropolitan has completed seismic upgrades to key structures at its pumping plants and has constructed a new outlet tower for the Lake Mathews Reservoir. These upgrades will enable specific essential CRA facilities to better withstand a major earthquake.

The recently conducted SEVS identified the potential surface deformation that could result from the MCE on the SSAFS, and the potential impact to CRA deliveries. A rupture of the Garnett Hills Fault's splay fault or fold located within the Whitewater Tunnel No. 2 could severely damage the tunnel, and while unlikely, could result in a 3.75 meter (12 feet) horizontal and 1 meter (3 feet) vertical offset within the tunnel. In addition to the localized damage within the tunnel at the fault crossing, the earthquake could cause a regional uplift within the San Gorgonio Pass area and along a 60 kilometer (35 mile) stretch of the CRA that would reduce the flow capacity of the CRA by approximately 20%.

With adequate pre-event planning, localized damage to the CRA could be repaired within six months. While the initial repairs are underway, Metropolitan would continue to supply the Southern California region with water from emergency supplies that it holds in local reservoirs such as Diamond Valley Lake. Following completion of the initial localized repairs to the CRA, Metropolitan could continue to supply a significant amount of water to the region from the CRA while long-term repairs to restore the aqueduct's original design flow are planned and executed.

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Implementing a Water System Seismic Resilience and Sustainability Program in Los Angeles

Craig A. Davis

ABSTRACT

The Los Angeles Water System is implementing a Seismic Resilience and Sustainability Program as part of a larger plan to improve the City's seismic resilience as outlined in the *Resilience by Design* report released by the Mayor [2]. The Water System Resilience and Sustainability Program comprehensively integrates into all aspects of water system business. The purpose is to continually improve the Water System seismic resilience in a manner that ensures its sustainability and improves the resilience and sustainability of Los Angeles. Water System resilience is critical for providing the water delivery, quality, quantity, fire protection, and functionality service categories, all necessary for supporting community resilience. The goal of a resilient Water System is to limit the total number of service losses and restore the water service categories as rapidly as possible while protecting property, life safety, and the regional social and economic stability. This paper reviews Water System resiliency and sustainability then provides brief descriptions of recommendations and potential tasks which may be implemented to accomplish the recommendations.

INTRODUCTION

The Los Angeles Department of Water and Power (LADWP) Water System (Water System) is undertaking a seismic resilient and sustainability program at the request of the Mayor [1]. Los Angeles City Mayor Eric Garcetti established a 1-year partnership in 2014 between his administration and United States Geologic Survey (USGS) seismologist Dr. Lucy Jones to develop earthquake resilient strategies for Los Angeles by focusing on three main components: water, communication, and building structures. The main focus for the water component is creating a seismically resilient and sustainable Water System which supports the resilience of Los Angeles.

The Water System Seismic Resilience and Sustainability Program (Program) purpose is to continually improve the Water System seismic resilience in a manner that ensures its sustainability and improves the resilience and sustainability of Los Angeles. This is viewed as an effort to make the implementation of resilience activities a standard of practice, building upon seismic improvements implemented over the past century.

Program development is being accomplished through a management team effort investigating three requisites: (1) defining characteristics of a seismically resilient Los Angeles Water System, (2) identifying the current status of Water System seismic resilience, and (3) recognizing aspects which may improve Water System seismic resilience. To proceed with the Program six initial

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recommendations are identified as follows:

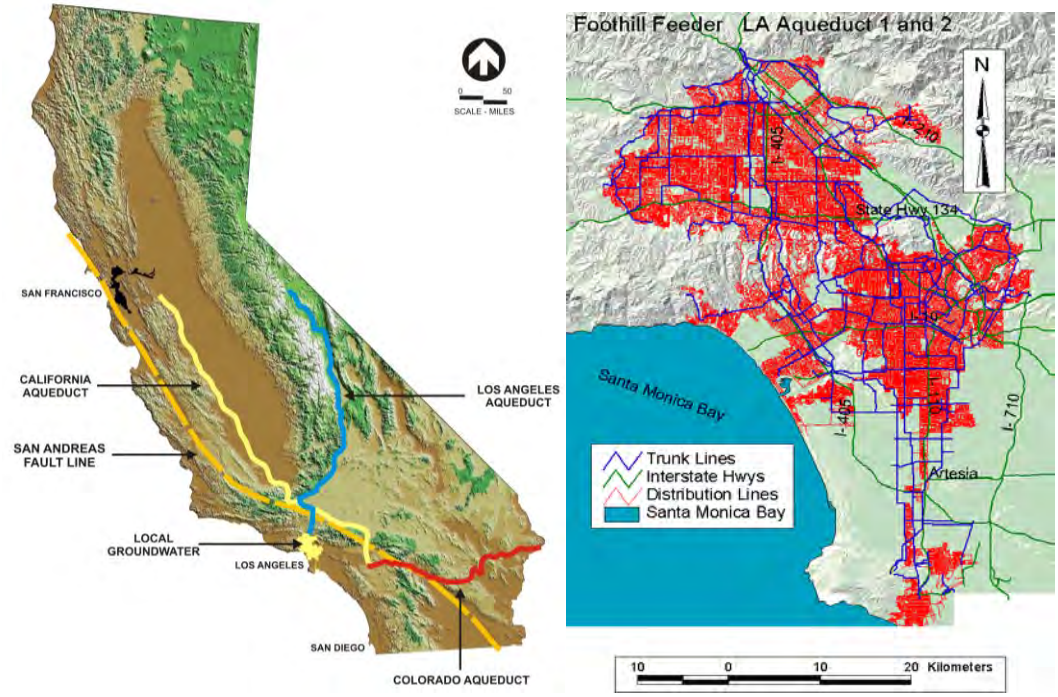
- Establish an LADWP-wide Resilience Task Force to oversee and provide resources to lead, support and ensure accomplishment of the Program.
- Prepare a plan for implementing the Program.
- Implement Water System seismic planning, evaluation, and monitoring to identify needed mitigations throughout the City and along the Los Angeles Aqueducts (LAA).
- Develop a seismically resilient pipe network.
- Increase water supply and storage reliability, including
    - Identify mitigation alternatives for LAA crossing the San Andreas Fault.
    - Enhance the Dam Safety Program using risk-based methods.
    - Identify alternative water supply sources for firefighting.
    - Develop local supply sources to reduce dependence on imported water and enhance water availability in emergencies.
- Enhance emergency response capabilities.

From this outline, the Mayor made some specific recommendations in the *Resilience by Design* report released in December 2014 [2]. This paper provides an overview of the Program purpose and implementation.

LOS ANGELES WATER SYSTEM OVERVIEW AND SEISMIC HAZARDS

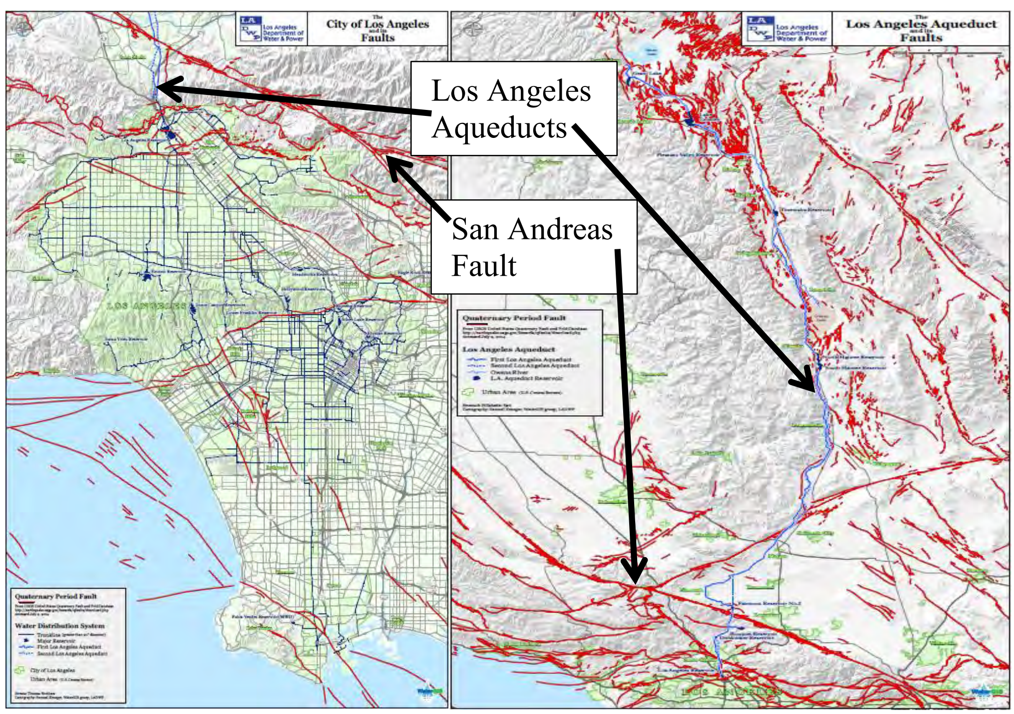
The Los Angeles Department of Water and Power (LADWP) is the largest municipal utility in the United States, and provides critical water and power services to support the local economy and wellbeing as well as in support of the supply of goods and products throughout the United States and the Pacific rim. The LADWP was founded in 1902 and is a primary reason for the growth and expansion of Los Angeles. Los Angeles covers an area of 1,214 km^2 with a population of about 4 million people. Figure 1 shows the approximate 12,000 km of pipe within the city used to transmit and distribute water to customers. The transmission and distribution networks also contain numerous tanks, reservoirs, pump stations, and regulating stations. Water quality is maintained with treatment plants, chloramination stations and chlorination stations.

The Los Angeles Water System has annual water sales of about 678 billion liters. As shown in Figure 1, Los Angeles receives water from multiple sources including local groundwater, the Los Angeles Aqueducts, The Metropolitan Water District of Southern California (MWD), and recycled water. The great majority of supply, about 88% on average for the five years 2008 to 2013, for Los Angeles is imported through the Los Angeles, Colorado River, and California Aqueduct systems. The Los Angeles Aqueduct (LAA) System [consisting of the First and Second Los Angeles Aqueducts], is owned and operated by the LADWP. The Colorado River Aqueduct (CRA) is owned and operated by the MWD. The California Aqueduct is owned and operated by the California Department of Water Resources and constructed as part of the California State Water Project (SWP). The MWD is a state-created regional water wholesaler that receives water from the SWP. The majority of local ground water comes from the San Fernando basin (SFB). The usable ground water volume has dwindled over the past several decades from contaminants in the SFB.



(a) (b)

Figure 1. (a) Water supply sources for Los Angeles. (b) Los Angeles Water System transmission and distribution pipe networks.



(a) (b)

Figure 2. Fault lines: (a) within the city of Los Angeles, (b) along the Los Angeles Aqueducts.

California is riddled with earthquake faults. Figure 2 shows the known 20 faults which can rupture the ground surface within the Los Angeles city boundaries and the nearly countless faults along the LAA. Additional blind faults not identified in Figure 2 do not rupture the ground surface. Earthquakes generated from these and other surrounding faults can cause severe ground shaking, and permanent ground deformations from liquefaction, landslides, differential settlement, etc. These movements threaten the Water System's capability to maintain service provision following an earthquake. The San Andreas Fault shown in Figures 1a and 2 poses the greatest risk to a regional disaster or catastrophe.

The combination of significant earthquake threats, major regional economy important to the USA and the Pacific rim, and Los Angeles' reliance on the Water System warrants the development and implementation of the Program.

RESILIENCY AND SUSTAINABILITY

Seismic resiliency and sustainability are achievable when the Water System:

- Has the systemic ability to provide water services in a manner allowing the community to effectively respond to earthquake events, recover quickly from them, and adapt to changing conditions, while also taking measures to reduce future seismic risks, and
- Is prepared to manage all threatening seismic hazards in a manner that minimizes and contains the hazard impacts while continuing a comprehensive approach to natural resource conservation and maintaining environmental quality.

To understand the inter-relation between resilience and sustainability following a significant natural hazard attack such as an earthquake, Figure 3 shows different possible trajectories of economic activity recovery [3,4].

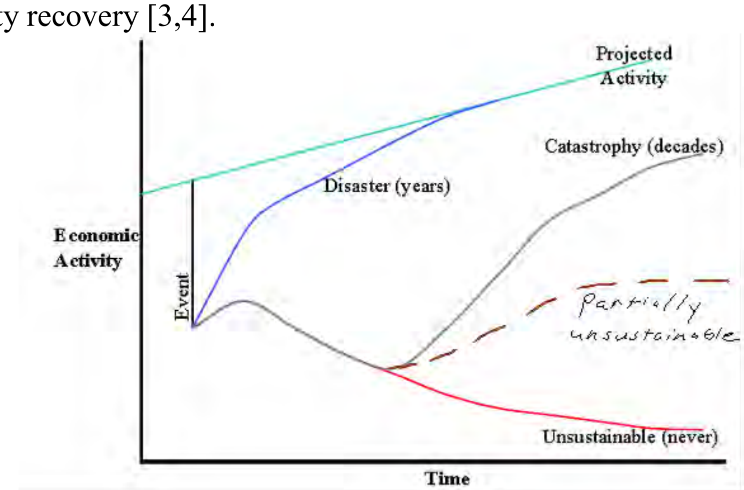


Figure 3. Economic resilience; trajectories of possible economic recovery [3,4].

When a damaging earthquake strikes there is an immediate drop in economic activity. Resilience is measured by the amount of economic loss and the time it takes to recover. There are several possible trajectories the economic activity may take over time. For a fixed initial loss, the shorter the recovery duration the more resilient is the economy. The event is considered a disaster when recovery takes several years (upper curve in Figure 3). A more rapid recovery is considered a disruption. In great earthquakes, economic activity may not recover for several decades resulting in a catastrophe [5]. In some cases the economy remains functional but has a permanent long-term reduction compared to the pre-event levels. This condition shows a limited resilience because there is not complete recovery to pre-event conditions and the economy is understood to be partially unsustainable to the earthquake hazard. In the greatest extreme the economic activity may never recover, continuing to decline and disabling a safe and equitable lifestyle for city residents (lower curve in Figure 3). In such a case, the economy is not resilient or sustainable (this trajectory is for descriptive purposes and not anticipated for Los Angeles).

The Water System's resilience is dependent upon the amount of service losses suffered as a consequence of the event and the time required to reestablish the services. In a disaster, water services may be disrupted and their recoveries are described by five basic categories [6,7,8]:

Water Delivery: This service is achieved when the system is able to distribute water to customers, but the water delivered may not meet quality standards (requires water purification notice), pre-event volumes (requires water rationing), fire flow requirements (impacting firefighting capabilities), or pre-event functionality (inhibiting system operations).

Water Quality: This service is achieved when water quality at customer connections meets pre-event standards. Potable water meets health standards (water purification notices removed), including minimum pressure requirements to ensure contaminants do not leach into the system.

Water Quantity: This service is achieved when water flow to customers meets pre-event volumes (water rationing removed).

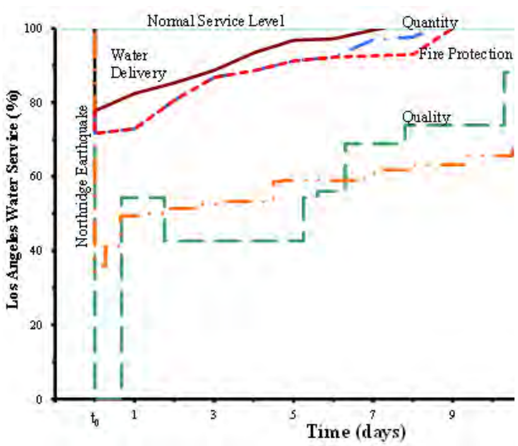
Fire Protection: This service is achieved when the system is able to provide pressure and flow of a suitable magnitude and duration to fight fires.

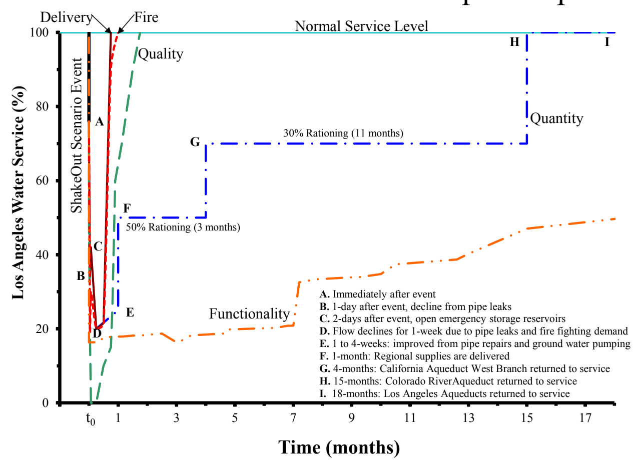
Functionality: This service is achieved when the system functions are performed at pre-event reliability, including pressure (operational constraints resulting from the earthquake are removed/resolved).

Each of these services can have an immediate loss and a recovery trajectory similar to that shown for the economy in Figure 3, including partial unsustainability. The goal of a resilient Water System is to limit the total number of service losses and restore the categories as rapidly as possible while protecting property, life safety, and the regional social and economic stability.

These services are best understood through example of Water System performance during and after the 1994 Northridge Earthquake. Figure 4a shows the 1994 earthquake service losses and restoration times. Total water system repair costs reached $41 million. The most significant water losses were in the highly residential San Fernando Valley impacting water services to an estimated 850,000 people, 670,000 of which lost water delivery for some period of time.

The water delivery service dropped to about 78%, with 22% of all Los Angeles customers receiving no water shortly after the earthquake due to water leaking from broken pipes. The quantity and fire protection services dropped to a low of about 72% on January 17, 1994. The quality service dropped immediately to zero because a water purification notice was issued across the entire city within 3 hours after the earthquake. As shown in Figure 4a, the water delivery service was restored to 100% at about 7 days, quantity and fire services at about 8.5 to 9 days, and quality service at 12 days after the earthquake. The functionality service initially dropped to about 34% and rapidly increased to about 60% once critical repairs were completed a few days after the earthquake and was 95% restored within 3 years. It took 6 years to return Functionality to 99% after completing a number of tank and reservoir repairs and replacements. Functionality was completely restored at about 9 years after relocating a major damaged trunk line and because of limited ability to remove the LAA channels from service to complete repairs.





(a) (b)

Figure 4. Los Angeles Water System service restorations: (a) following the 1994 Northridge Earthquake [7], (b) following the ShakeOut Scenario earthquake, based on analyses by [9].

Overall, the Los Angeles Water System is considered to have been highly resilient to the Northridge Earthquake because it was able to restore system operability within a relatively short period of time. Likewise, the Los Angeles economic system was also resilient to the Northridge Earthquake, resembling something like the upper curve in Figure 3. However, if the earthquake were larger or located elsewhere around the City the performance would have been different. The Water System will perform differently to different earthquakes based on shaking severity and locations of different vulnerabilities within the network. For example, Figure 4b shows results from simulated Water System performance subjected to a magnitude 7.8 earthquake on the southern San Andreas Fault. This earthquake scenario was developed for the 2008 ShakeOut event by a group of experts working with the USGS, and allows for independent assessment on how the Water System may perform in a great San Andreas Earthquake event.

Figure 5 maps the ShakeOut Scenario and shows the major water supply aqueducts crossing the San Andreas Fault. In the ShakeOut Scenario the San Andreas Fault damages the LAA, CRA, and California Aqueduct in a single rupture. As a result, in a matter of minutes all imported water is lost to Los Angeles and it may take over one year to return all of these aqueducts to operation [10]. In addition, the transmission and distribution systems suffer significant damage.

The Shakeout Scenario has greater impact on all services as compared to the 1994 Northridge Earthquake, mostly because the San Andreas Fault rupture has a regional impact while the Northridge Earthquake had a local impact to a portion of the Water System. Water delivery, quantity, and fire protection services drop to about 20% soon after the earthquake and water quality services are temporarily lost to all customers. Water delivery service is completely restored in about 3 weeks, fire protection service is restored in about 4 weeks, and water quality restored in about 7 weeks. Of great significance is the long quantity service restoration due to the need for long-term water rationing resulting from the water supply aqueduct damages. Water quantity services may not be restored for at least 15 months in this scenario. Functionality service initially drops to 16% and may take decades to restore, leaving the system more vulnerable during this timeframe.

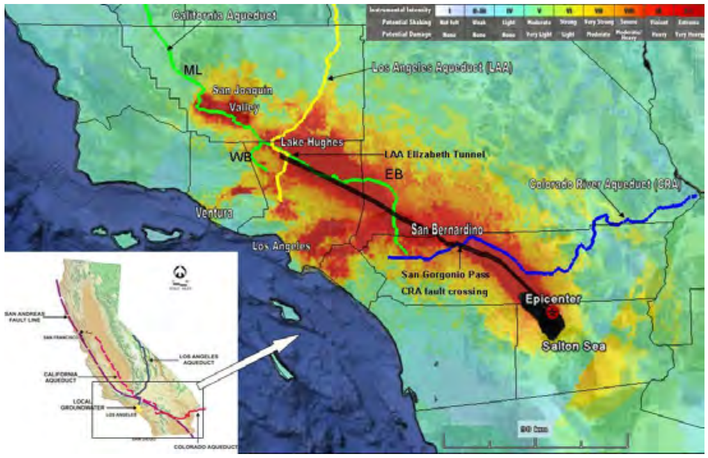


Figure 5. ShakeOut Scenario showing ground shaking intensity and fault rupture crossing the major water supply aqueducts.

The Water System is obviously less resilient to the San Andreas Earthquake scenario than it was to the 1994 Northridge Earthquake. Water service losses from a San Andreas event result in significant community impacts. Economic impacts include about $53 billion in direct and indirect economic losses throughout Southern California as a result of water loss alone, which is about 25% of the total $213.3 billion estimated losses to this event [5]. Business interruption from water loss is greater than 50% of the total business interruption losses for the entire event. This gross loss in output from water alone is sufficient to drive the region into a recession. Fire following earthquake results in significant social impacts having an estimated economic loss of about $87 billion, a large portion of this is within the City of Los Angeles. Considering the relation between fire and water service losses, the earthquake effects on the Water System has the greatest impact of all aspects considered in the ShakeOut Scenario. If unmitigated, the initial recession fostered by Water System losses could build toward a regional economic catastrophe [5] as defined in Figure 3. Further, it is unclear if some sectors in the City highly dependent upon water would be partially unsustainable. To achieve the Program goal, the water service losses and restoration times for the ShakeOut Scenario need to shift up and toward the left in Figure 4b. The target acceptable losses and restoration time, as well as strategies to shift these curves, needs to be determined as part of the Program.

A seismically resilient and sustainable Water System is achievable through:

- An organization capable of managing the planning and implementation of seismic resilience activities,
- Creating a seismically resilient pipe network,
- Increasing water supply reliability, and
- Ability to effectively respond after earthquakes followed by recovering and rebuilding to meet intended performance.

The Los Angeles Water System intends to put these resilience characteristics into action to secure a safe and reliable water supply against the threatening earthquake hazards and help protect the social and economic vitality of Los Angeles.

IMPLEMENTING PROGRAM RECOMMENDATIONS

The introduction to this paper outlines six initial recommendations for implementing the Program; additional background on these recommendations and associated tasks is provided in [1]. In addition, the Mayor's office made some specific recommendations to emphasize their priorities for improving the resilience to Los Angeles [2]. These include:

- Implement a Resilience by Design Program at the LADWP
- Improve the Water System's firefighting water supply
- Fortify the Imported Water Supplies and Water Storage
- Increase Local Water Sources
- Create a Seismic Resilient Pipe Network

The recommendations provided in [2] are consistent with those in [1], the primary difference is setting priority of focus from a city-wide perspective and the additional detail provided in by the Water System management group. Some of the plans and actions for implementing these recommendations are summarized in this section, with a primary focus of those given in [2]. The LADWP Water System has appointed a Resilience Program Manager to implement the Program.

Firefighting Water Supply

A preliminary plan to improve the Water System for managing the Fire Following Earthquake (FFE) Risks has been written. The goal is to develop a plan for addressing FFE risks by providing two end products:

I. A long-term plan for developing a resilient water system for firefighting
II. An emergency firefighting water supply plan

Both Plans I and II will address water supply for firefighting obtained through the distribution network and from alternate sources. Plan I primarily focuses on infrastructure development and improvement. Plan II primarily focuses on alternate water sources. As elements in Plan I are implemented to increase reliability, Plan II will be modified as necessary. The combination of both plans will work to build up and maintain capacity to fill, to the greatest extent possible, any potential gaps in firefighting water supply.

The LADWP and Los Angeles Fire Department (LAFD) are working collaboratively to undertake the steps needed to improve ability to reduce risks to FFE across Los Angeles. A key aspect for reducing FFE risks is to perform a risk assessment. This is recommended to be undertaken in three separate tasks: an assessment of FFE hazards, an FFE vulnerability study focusing on earthquake effects on Water System hydraulics and ability to meet fire protection services, and FFE consequence studies. Further, a program is being implemented to identify alternative water supplies throughout the city which can be used to fight fires. These include LADWP storage facilities, swimming pools, rivers, creeks, lakes, ponds, and temporary storage facilities (e.g., storm water detention basins).

Alternatives were identified as near-term, those which can be potentially implemented in a matter of years, and long term, those taking multiple years to decades to complete. Review of near-term alternatives identified the need to investigate: methods to improve access to existing storage and production facilities; methods to preserve water supply at storage facilities following a major earthquake specific to firefighting needs; feasibility of utilizing temporary storage facilities as alternate water sources for firefighting; feasibility of developing additional, new storage facilities for firefighting to provide an alternate water source in high risk regions; feasibility of developing drafting connections to rivers, creeks, lakes, and ponds; and procurement of additional water tankers in support of fire suppression. Long-term alternatives require the LADWP to: develop performance objectives for resilience improvements consistent with community resilience goals; develop a seismically resilient pipe network; incorporate seismic risk into pipe replacement evaluations when identifying and prioritizing pipe replacement projects; evaluate groundwater facilities to ensure operability following a major earthquake and to improve LAFD fire engine and helicopter access. The LADWP will also consider developing alternate water systems in support of firefighting such as using the recycled water system and developing a pressurized seawater system; both of these systems require feasibility studies. Additionally, the LAFD and LADWP will investigate feasibility of using large and ultralarge diameter hoses, and portable water supply systems [11].

Fortify the Imported Water Supplies and Water Storage

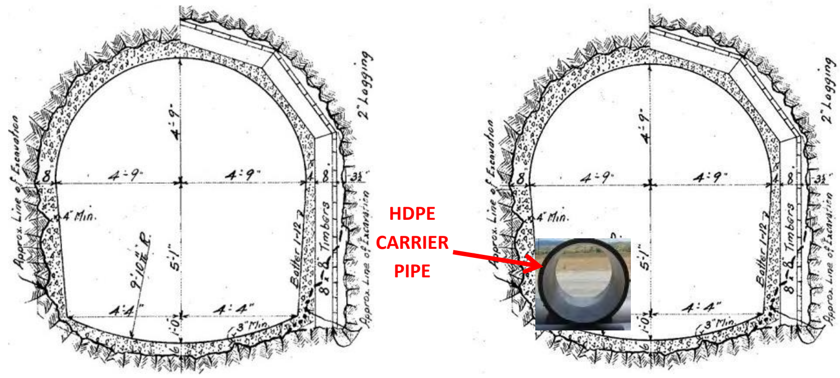
As shown in Figures 1 and 5, all imported water to Los Angeles crosses the San Andreas Fault, and as previously described some scenarios identify how this fault can damage all the aqueducts at the same time. This requires significant action to ensure adequate water supplies are available following a regional event. The primary items being undertaken to improve Water System resilience and sustainability are to: (1) investigate and implement cost effective measures where the LAA crosses the San Andreas Fault, (2) perform a systematic seismic assessment of the LAA, (3) establish a seismic resilient water supply task force consisting of LADWP, MWD, and DWR, and (4) Enhance the Dam Safety Program using risk-based methods. These four items are being implemented; only items (1) and (3) will be summarized in this subsection.

As seen in Figures 1, 2 and 5, the LAA crosses the San Andreas Fault nearly perpendicularly in an 8 km long approximate 3 m wide tunnel. Figure 6 shows a cross-section of the tunnel completed in 1913. The Elizabeth Tunnel is vulnerable to seismic shaking and may be subject to fault movements ranging from relatively small offset, to as much as approximately 12 m in any given earthquake. This range of fault rupture is capable of damaging the Elizabeth Tunnel to the point of failure, which would eliminate the LAA's ability to deliver water to Los Angeles.

Currently more than 15 alternatives are being investigated to identify the most cost-effective strategy to mitigate the San Andreas Fault rupture hazard. Due to the complexity of the San Andreas Fault rupture hazard, the problem is being approached using project-oriented risk-based methods, categorized within one of the two project types:

1. Risk reduction/retrofit project type to enhance seismic performance by evaluating measures that would increase the opportunities for continued water flow in the event of damage to the Elizabeth Tunnel in the near term.

2. Replacement/modification project type to provide an engineered solution to crossing the San Andreas Fault for the expected largest offset (approximately 12 m), which will minimize service disruption in the long term.



(a) (b)

Figure 6. Los Angeles Aqueduct Elizabeth Tunnel crossing the San Andreas Fault: (a) Typical cross section of Elizabeth Tunnel; (b) Example proposed retrofit with HDPE carrier pipe.

Figure 6b shows the proposed risk-reduction method by placing a highly ductile HDPE pipe within the tunnel to protect water flow in the event of relatively small fault movement or liner collapse. This solution does not prevent loss of water flow for large fault movements so in parallel more extensive alternatives are being pursued, but these take much more funding and longer to implement. In addition to the San Andreas Fault crossing, the LAA is being investigated for other vulnerabilities with an initial focus along the stretch from the San Andreas Fault to Los Angeles.

A seismic resilient water supply task force consisting of LADWP, MWD, and DWR is being created to address the seismic risks for each of the aqueducts individually and combined as a regional water supply system. Some key aspects these agencies will address are strategies for how to respond as a team once a major earthquake strikes, emergency preparedness and response, mutual aid and assistance agreements, pre-earthquake assessments of each aqueduct system, and potential mitigations which may be undertaken.

Increase Local Water Sources

To address the vulnerability and uncertainty of imported water supplies, LADWP is focusing on a combination of two important initiatives: the Local Water Supply Program and the San Fernando Groundwater Basin (SFB) clean up and remediation program. In the 2010 Urban Water Management Plan (UWMP) LADWP set goals for developing local water supplies through storm-water capture, water conservation, and water recycling. The 2010 UWMP also addresses the need to clean up and remediate SFB contamination and ensure extracted water meets safe drinking water regulations. A healthy SFB also sets a foundation for implementing conjunctive use, recycled water and storm water capture projects. Local supply development will enable LADWP to reduce reliance on imported water and cut purchases from MWD in half by 2035 or sooner. This enhances resiliency by improving the water quantity services (see Figure 4). Additionally, local supply development will enhance water availability in emergencies and help shift the post-earthquake service restoration curves in Figure 4b up and to the left. Water System resilience will be improved with continued implementation of the local water supply program and SFB clean up and remediation program. Additionally, Water System resilience can be improved by incorporating important resilience design aspects into these two programs during development, which may include, but not be limited to: emergency power, emergency production capacity, treatment plant bypass capabilities, and well placement.

Create a Seismic Resilient Pipe Network

A seismic resilient pipe network is designed and constructed to accommodate damage with ability to continue providing water or limit water outage times tolerable to community recovery efforts. The resilient network will include the use of earthquake resistant pipes placed at key locations to help increase the probability of continuous water delivery and reduce the time to restore areas suffering a total loss of water after an earthquake. Earthquake resistant pipes are designed to accommodate seismic forces meeting defined performance criteria, and may include Japanese manufactured Earthquake Resistant Ductile Iron Pipe (ERDIP), High Density PolyEthylene (HDPE), specially designed welded steel pipe, PolyVinylChloride (PVC) and others providing sufficient robustness against design level ground deformations. The proposed resilient network, as it relates to the fire protection service, will be developed by placing earthquake-resistant pipe in a grid to form an arterial sub-network at intervals consistent with capabilities of firefighting equipment to relay water and targeted system performance criteria. From the arterial sub-network earthquake resistant pipes can be placed to critical facilities such as hospitals, schools, and emergency evacuation centers to improve reliability of the water delivery, quality, quantity, fire protection, and functionality services. This network will also reduce restoration times for other less critical customers who may lose some water services. This minimizes economic disruptions and supports overall community recovery following an earthquake.

The Los Angeles Water System piping network is mostly built-out. As a result, improvements to create the seismic resilient pipe network will primarily consist of replacing existing pipe with earthquake resistant pipe in a manner consistent with on-going asset management and pipe replacement programs. Existing pipe must be replaced strategically to address regions with the greatest risk while simultaneously replacing deteriorating infrastructure to improve overall water system resilience. As an outcome, developing a seismic resilient pipe network will take decades and require significant continued investments. However, its development will make incremental and continuous improvements in prioritized areas throughout the entirety of its implementation. In the meantime, other tasks for improving service reliability need to be undertaken in parallel.

In 2011, LADWP initiated concepts on how to implement a seismic resilient pipe network and began developing a pilot project to investigate the use of ERDIP. The pilot project is on-going and initial results are described in [12]. Initial studies show the pilot projects are making incremental progress for increasing network seismic resilience. Evaluation of an ERDIP pilot project located at the Northridge Medical Center, located at the epicenter of the 1994 Northridge earthquake, indicates this critical facility may not loose water delivery, quantity, or fire protection if a repeat of this earthquake were to occur; whereas in 1994 it lost water delivery services for approximately three days, water quantity and fire protection services for approximately 3.5 days, and water quality services for approximately ten days.

CONCLUSIONS

The Los Angeles Department of Water and Power (LADWP) is highly exposed to numerous seismic hazards. The water supply is essential to the economic vitality of the city, much of the USA and the Pacific rim. As a result the LADWP is implementing a water system seismic resilience and sustainability program with a purpose to cost-effectively improve system resilience in a manner supporting the community resilience. Some key initial steps in this program improve the Water System's firefighting water supply, fortify the imported water supplies, increase local water sources, and create a seismic resilient pipe network.

ACKNOWLEDGMENTS

The Los Angeles Department of Water and Power Water System, Office of the Mayor, and Dr. Lucy Jones of the USGS are gratefully acknowledged for their input and assistance in developing the Resilience Program, which served as the basis for this paper.

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Water Sector Emergency Preparedness and Response Standards & Resources – How an All-Hazards Approach Supports Seismic Preparedness and Response

Mr. John Whitler, Water Research Foundation

ABSTRACT

This paper addresses the standards and resources that have been developed to support an all hazards preparedness planning and response framework for seismic hazards in the United States. The American Water Works Association (AWWA) has developed several standards that support the water sector to be prepared to respond to incidents, regardless of the type of hazard. This all-hazards approach enables utilities to efficiently and effectively prepare for and respond to the vast array of utility specific hazards, vulnerabilities, and consequences that they may face. Many of these standards can help utilities form a strong foundation for a seismic specific preparedness and response program. This presentation will provide an overview of these standards and explain their applicability to seismic events. The standards to be presented include: AWWA J100-10 (R13) Risk and Resilience Management of Water and Wastewater Systems (RAMCAP); AWWA G430-14 Security Practices for Operation and Management; AWWA G440-11 Emergency Preparedness Practices.

To support the implementation of these standards, the water sector in the United States has implemented a number of preparedness and response practices through mostly voluntary efforts. Many of these practices have been supported by tools, guidance and training developed by the federal government, state governments, water associations, individual utilities themselves, and other water sector entities. These products support an all-hazards approach that enables utilities to efficiently and effectively prepare for and respond to the vast array of utility specific hazards, vulnerabilities, and consequences that they may encounter. Many of these resources can help utilities form a strong foundation for a seismic specific preparedness and response program. This paper will provide an overview of the available tools and resources and explain their applicability to seismic events.

INTRODUCTION

Standards play a critical role in water utility planning and operations. Standards provide a baseline and target for performance to guide how a utility approaches different issues. While used by water utilities for decades and longer, most recently the water sector has developed standards that support an all-hazards approach to emergency preparedness and response. Led by AWWA, and using input from expert advisory committees, these standards were developed to fill a critical gap in the water sector's standards portfolio. These standards provide a flexible and adaptable approach to preparedness and response that are critical to a more resilient water sector. While developed with an all-hazards perspective, they are also very valuable for utilities with concentrated efforts on individual hazard types such as seismic events.

AWWA J100-10 (R13) RISK AND RESILIENCE MANAGEMENT OF WATER AND WASTEWATER SYSTEMS (RAMCAP)

The J100 standard was developed by AWWA to provide the water sector with a technically sound and consistent methodology to identify, analyze, quantify, and communicate the risks to operations from natural or manmade hazards (Morley, 2010). While several risk assessment methodologies were implemented by the water sector after the September 11th terrorist attacks, the J100 take an all hazards approach and provides a resilience assessment feature to enhance water sector preparedness and response. The three main upgrades include guidance for calculating the probability of an attack, calculating the probability of a specific natural hazard, and guidance for calculating asset and utility resilience.

The J100 standard is based on the seven step RAMCAP process (Morley, 2010).

1. Asset Characterization – What assets do I have and which are critical?
2. Threat Characterization – What threats or hazards may occur at my facility?
3. Consequence Analysis – What happens to my assets if a threat happens and how much money, lives, or injury damages will occur?
4. Vulnerability Analysis – What are my vulnerabilities that make a threat more likely to occur?
5. Threat Analysis – What is the likelihood of an incident at my facility?
6. Risk/Resilience Analysis – Risk is a combination of consequence, vulnerability and threat. Resilience is a combination of service outage, vulnerability, and threat.
7. Risk/Resilience Management – How you my utility reduce risk and increase resilience, and at what cost/benefit?

AWWA G430-14 SECURITY PRACTICES FOR OPERATION AND MANAGEMENT

The G430 standard defines the minimum requirements for a proactive security program at a drinking water or wastewater facility. It addresses key elements including worker safety, public health, public safety and confidence. The G430 standard is based upon the Key Features of An active and Effective Utility Security Program, which was originally developed by a workgroup formed by EPA's National Drinking Water Advisory Committee. The standard addresses many key areas for utilities to consider when developing their preparedness and response programs.

The elements addressed by the standard include the following (McLaughlin, 2010).

1. An explicit commitment to security – This would include something as simple as including security as part of a utilities vision, mission, or strategic planning efforts, or committing resources to a security program.

2. Maintaining a security culture – Does the utility maintain an active security program?
3. Defined security roles and employee expectations – Does utility staff know their role and have they been trained?
4. Maintaining an up-to-date vulnerability assessment – The standard recommends a specific timeline and triggers for when a vulnerability assessment should be updated.
5. Dedicated resources to security and implementation of key security priorities – Not only does the utility spend the time to identify its security issues, it also spends resources to address key vulnerabilities.
6. Access control and intrusion detection – Cyber security threats are growing and need to be a part of any security program.
7. Contamination, detection, monitoring and surveillance – The threat of intentional contamination is still active, and utilities need to take steps to prepare and respond to this threat.
8. Information protection and continuity – Utilities need to take steps to protect sensitive utility information, but also maintain access to key documents should there be an incident that disrupts normal means of access.
9. Design and construction – Security needs to be an explicit element in any new construction or utility asset.
10. Threat-level based protocols – EPA's small and medium sized utility guidance for emergency response planning includes protective measures utilities should take based on the level of threat currently being experienced.
11. Emergency response and recovery plans – These plans need to be maintained, updates, and exercised.
12. Internal and external communications – The utility needs to know who to call and how to communicate with key people during an emergency. This includes its own employees.
13. Partnerships – This includes participating in mutual aid and assistance networks, such as WARN.

The USEPA maintains a webpage of helpful utility resources that can support implementation of G430. A number of tools and guidance documents exist for each element of G430 that utilities can utilize. Those resources can be found here: http://water.epa.gov/infrastructure/watersecurity/features/utilitiesresources.cfm .

AWWA G440-11 EMERGENCY PREPAREDNESS PRACTICES

Once a utility has identified their risks, they need to implement and maintain an emergency preparedness and response program to address these risks. G440 establishes the minimum requirements for a utility when developing these preparedness programs. Some of the elements overlap with G430, like maintaining an explicit commitment to emergency preparedness and making employees aware of this commitment and programs that support it. G440 adds a level of specificity to some of the elements of G430. For example, utilities should not only perform a risk assessment, but this should be updated periodically when major systems changes or threats to the system occur, or no less than every 5 years. G440 identifies several types of preparedness plans, and recommends these plans are updated a minimum of once a year. It also states these plans should follow the National Incident Management System concepts and incorporate the Incident Command System into these plans. G440 addresses internal and external communication related to preparedness so customers and response partners are aware of the utilities preparedness plans. Another element in G440 is training, including exercises. Utilities should be trained on their role in the preparedness plan, and this training should be offered as a refresher at least once a year. The utility should have an exercise once a year, and an operation exercise with response partners every three years. The exercises should include an after-action report to ensure follow up actions to improve the preparedness plans are followed up on. Key partners should be identified and utilities should participate in mutual aid and assistance programs, such as a state based Water and Wastewater Agency Response Network (WARN).

While some of these elements may seem fundamental to some more advanced utilities, documenting these basic preparedness standards is a key action for the water sector. Following this standard should provide for a more resilient and robust utility if they were to be impacted by a seismic event.

RESOURCES AND PROGRAMS TO SUPPORT WATER SECTOR SEISMIC PREPAREDNESS

PLANNING TOOLS

Several guidance documents exist that help utilities develop plans to support their preparedness, response and recovery to seismic events. EPA offers two different guidance documents for developing emergency response plans, one tailored to large systems, and the other for small systems. One of the key elements of this guidance is the development of incident-specific emergency action procedures (EAPs). While the base part of the emergency response plan will contain information such as emergency contacts, partners, available equipment, chain of command, communication procedures, and basic system information, EAPs provide a plan of how to implement the plan for specific emergencies. Having an EAP for seismic events is something every utility with seismic risks should consider.

Another type of plan that utilities should consider for their seismic preparedness is a consequence management plan. Consequence management planning compliments other utility preparedness and response plans. Rather than focusing on an individual hazard, a consequence management plan focuses on the resulting problems or consequences that result from that hazard. Consequences that utilities may want to consider including service disruptions, infrastructure damage, loss of revenue or economic impacts, loss of power, and impacts to the workforce. Seismic events have the potential to cause many different consequences, but other disasters will also result in similar impacts. By taking a consequence based approach, utilities may be able to plan more efficiently because preparedness measures for these consequences will support many different disaster types.

Planning for recovery is also very important and guidance is available for utilities in the form of business continuity planning (BCP). BCPs help utilities maintain or restore normal financial, managerial, and functional operations after an incident. A few key elements of a BCP related to seismic events include: access to vital records, backup operating facilities, backup customer billing procedures, emergency acquisition protocols, and teleworking arrangements for displaced employees.

Key Resources:

Emergency Response Plan Guidance for Small and Medium Community Water Systems

Large Water System Emergency Response Plan Outline: Guidance to Assist Community Water Systems in Complying with the Bioterrorism Act

All-Hazard Consequence Management Planning for the Water Sector

Business Continuity Planning for Water Utilities: Guidance Document

RESPONSE TOOLS

After a seismic event, a utility may be short of staff, equipment, or other resources. One of the best ways to acquire support is through mutual aid and assistance. Essentially, prior to an emergency utilities make arrangements with other utilities to provide support to one another should they need it. This is extremely common in the fire and law enforcement sectors and has been steadily growing with the water sector within the United States since Hurricane Katrina in 2005. Referred to as WARNs, Water and Wastewater Agency Response Networks, exist in every state, but one, and ensure a more immediate and coordinate response to incidents.

Sometimes when an emergency happens, it is good to have a reminder of what actions are needed. EPA has created incident specific checklists, including one for earthquakes, which provides key examples of actions to take in responding to a seismic event. These checklists, along with other resources have been added to a smart phone application called, Water Utility Response On-The-Go. From a user's smart phone or tablet, they can access their key contacts, emergency response forms, and weather forecasting information. This is one of the first water utility specific disaster preparedness and response phone applications.

After a seismic event, there may be a disruption to water service. Although customers have been advised to have an emergency supply in their homes, many people will require water, especially if the disaster lasts for more than a few days. AWWA has developed a helpful guidance manual, *Planning for and Emergency Water Supply*, which contains information utilities can use to provide alternative water service during prolonged outages. One of the key takeaways from this document is that coordination with local and state emergency management agencies and public health departments is key to a successful operation. Also, planning for where people can get the water and how they will receive the water is also critically important. Some utilities have had practice drills to access the effectiveness of their alternative water delivery plans.

One key customer that relies on water utilities to keep operations going are hospitals. A guidance document has been created, *Emergency Water Supply Planning Guide for Hospitals and HealthCare Facilities*, to specifically address alternative water supplies for hospitals. This document contains an extensive list of alternative water supplies hospitals could potentially consider for use during normal supply disruptions. Case studies are also presented to show how other facilities have dealt with this issue.

Key Resources:

Utilities Helping Utilities: An Action Plan for Mutual Aid and Assistance Networks for Water and Wastewater Utilities

Water Sector Incident Action Checklist – Earthquake

Water Utility Response On-The-Go

Planning for and Emergency Water Supply

Emergency Water Supply Planning Guide for Hospitals and HealthCare Facilities

LEARNING FROM RECENT INCIDENTS

The AWWA, *Superstorm Sandy After-Action Report*, identifies a number of key lessons to improve on for future incidents. One of the key lessons was the need to increase coordination with the emergency services sector. In order to access resources to recover in a timelier manner utilities need to be connected to this group. This is particularly important for backup power and fuel, personnel access to utility facilities, and coordination on damage assessments. A guidance document was created to help support this improved coordination, *Coordination of the Water and Emergency Services Sectors: An Important Step to Better Response*, which provides easy to reference steps, case studies, and another mechanisms to improve this coordination. One key coordination step can be to have a water sector representative participate in the emergency management agencies emergency operations center. This help ensure the water sector is consulted on important decisions impacting their operations.

Key Resources

Superstorm Sandy After-Action Report

Coordination of the Water and Emergency Services Sectors: An Important Step to Better Response

CONCLUSION

This paper highlights the standards and just a few of the many resources that exist for water utilities to support their preparedness to seismic events. Capacity to implement these programs varies across utilities, with some being more sophisticated in their preparedness than others. Even without a sophisticated program, implementing actions from just a few of these resources will help a utility's preparedness to seismic events.

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Title: **Emergency Planning and Response Damage Prediction Modeling to Mitigate Interdependency Impacts on Water Service Restoration**

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Emergency Planning and Response Damage Prediction Modeling to Mitigate Interdependency Impacts on Water Service Restoration

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Yogesh Prashar[4], and Xavier Irias[5]

ABSTRACT

Interdependencies can significantly impact the time for the East Bay Municipal Utility District (EBMUD) to restore water service following a major earthquake. Knowing the types of interdependencies that are most likely to impact a utility's ability to quickly restore service to its disrupted lifelines is critical. The Association of Bay Area Governments (ABAG), in partnership with EBMUD and other utilities, has assembled a Regional Lifelines Council Workgroup to better understand impacts interdependent lifelines would have on expected utility restoration. As part of this effort, EBMUD is studying interdependencies between its water system and other critical lifelines such as line power and fuel. The goal of the study is to improve emergency planning and response efforts, including allocation of limited resources for post-disaster restoration purposes (repair crews, emergency pumps, generators, fuel, etc.).

EBMUD developed Marconi, a web-based application, to better plan, respond, and recover from various types of emergencies and hazards, such as a catastrophic earthquake event. Marconi computes rapid damage predictions using both readily available and facility specific customized fragility curves and real-time ShakeMap data to estimate potential damage to water facilities such as tanks, dams, pumping plants, and large diameter pipelines. Pacific Gas and Electric Company (PG&E), the utility that provides line power to EBMUD's service area, has also developed similar damage modeling capabilities for its power distribution system. EBMUD is actively working with PG&E to assess the water and power infrastructure systems interdependencies with a goal of using common input scenario earthquake events, overlaying damage prediction results, and setting common priorities for service restoration.

This paper discusses the importance of using an interdependencies-based regional risk assessment process to improve emergency preparedness. Damage prediction models can be used to both identify fragile components within the system as well as to assist in prioritizing emergency response efforts. A better understanding of interdependencies and associated vulnerabilities of critical facilities can help utility owners assess the need for additional pre-event mitigation or hardening of the system. Examples of proactive measures to reinforce the system are discussed and include adding electrical redundancy to critical facilities and making seismic improvements to reduce the risk of cascading failures resulting from collocated lifelines such as water and fuel. In addition, utility owners must be cognizant of public expectations by setting realistic timelines for service restoration and improving awareness at the local community and regional levels.

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INTRODUCTION

About EBMUD

The East Bay Municipal Utility District (EBMUD) provides drinking water to over 1.3 million people on the eastern side of the San Francisco Bay. The EBMUD water system comprises of 167 supply reservoirs, 132 pumping plants, 29 embankment dams, 7 water treatment plants, and approximately 4,200 miles (6,800 kilometers) of treated water distribution and transmission pipelines and 270 miles (435 kilometers) of raw water aqueducts. Figure 1 presents the EBMUD Location Map. The EBMUD service area encompasses a large and varying topography. With such a large water system to manage and operate in an area prone to destructive earthquakes, emergency response can be an overwhelming task in the minutes and hours following an earthquake. As a result, EBMUD created damage prediction models to prioritize field inspections of the water system and help accelerate emergency response and recovery time.

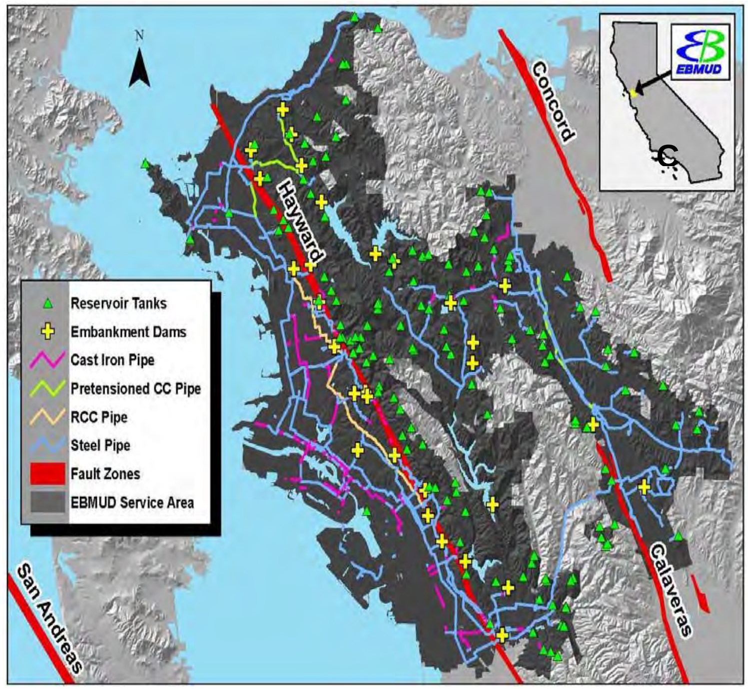

Figure 1. EBMUD Location Map

Background

The published documents entitled “Rapid Modeling of Seismic Damages to Water Infrastructure” [1] and “Water System Seismic Fragility of Embankment Dams, Tank Reservoirs, and Large Diameter Pipelines" [2] provide the introductory framework to this paper. As discussed in these papers, the anticipated performance of EBMUD’s facilities can be predicted using real-time ShakeMap data and customized fragility curves. Estimating the level of ground shaking (Peak Ground Acceleration [PGA]) at any particular facility is the critical input in developing rapid damage predictions. A better understanding of the specific interdependencies that can impact service restoration, in combination with the use of predictive models to estimate the level of water system damage, can be used for pre-event planning purposes, as well as to help prioritize inspections and deployment of limited resources immediately following a major seismic event.

Seismic Setting and Scenario Event for Damage Predictions

The highly active Hayward Fault dominates EBMUD’s risk profile. This fault, capable of earthquakes of M7.25, has produced major earthquakes on average every 140 years, with the last damaging earthquake occurring in 1868. The economic losses from a similar earthquake occurring today have been estimated at up to $200 billion. According to the United States Geological Survey (USGS), the overall probability of a magnitude 6.7 or greater earthquake in the greater Bay Area in the next 30 years is 63%. The earthquake probability is highest for the Hayward Fault system, at 31%. As shown on Figure 1, dozens of EBMUD’s critical facilities are located within a few hundred meters of the Hayward Fault.

Beyond the Hayward Fault, several other faults threaten EBMUD’s system, ranging from the larger San Andreas Fault west of the service area, to the Calaveras and Concord Faults in the eastern portion of the service area. While the San Andreas, Calaveras, and Concord Faults could also have a significant impact on EBMUD’s distribution system, the discussions on interdependencies and damage predictions presented in this paper are based on an assumed moment magnitude 7.05 (M-7) scenario event on the Hayward fault.

Goals of the Paper

This paper discusses different types of interdependencies that could impact service restoration for a water utility and includes examples of cascading outages and failures. Damage estimates, including results of a seismic evaluation of PG&E's substations and power outages for EBMUD's pumping plants, and estimates of the overall level of damage to water distribution mains, are presented.

This paper also presents results of recent rapid damage prediction modeling efforts for Large Diameter Pipelines (LDP), highlighting fragile components within the transmission system. Rapid damage modeling can assist in identifying vulnerable components of the system where physical improvements may be needed to promote resiliency. Similar damage prediction modeling efforts, using ShakeMap data, have been undertaken by PG&E for its power distribution system. EBMUD is working with PG&E to study the interdependencies between water and power infrastructure systems in more detail. The goal is to use common input scenario earthquake events, overlay damage prediction results, and develop common priorities for service restoration based on facility criticality and customer impacts.

A better understanding of interdependencies and associated vulnerabilities of critical facilities will help utility owners with emergency planning and response efforts. These efforts include the allocation of resources for post-disaster restoration purpose and assessing the need for additional pre-event mitigation or hardening of their system.

Based on damage predictions results and associated vulnerabilities, EBMUD is taking steps to mitigate impacts of interdependencies by improving robustness and/or adding redundancy to its critical facilities. These steps include adding flexible joints on large diameter mains located at fault crossings with collocated lifelines to reduce the risk associated with cascading failures, replacing critical estuary crossings that supply water to areas with no storage, adding electrical redundancy at water treatment plants, upgrading facilities, replacing large diameter pipelines, and installing new parallel transmission pipelines.

Finally, this paper discusses the need for utility owners to be cognizant of public expectations for service restoration following a catastrophic earthquake event. Despite making improvements to their systems, service restoration may take weeks or months. It is important to communicate realistic timelines by improving awareness and coordination at the local community and regional levels. The need for having an emergency drinking water distribution plan is also discussed, in the event of prolonged service disruptions.

INTERDEPENDENCIES

In a study published in 2014 [3], the City and County of San Francisco's (CCSF) Lifeline Council defined the interdependence between twelve important systems showing significant interactions with the fuel sector, and significant reliance by others on water, electricity, roads, and telecom (see Figure 2).

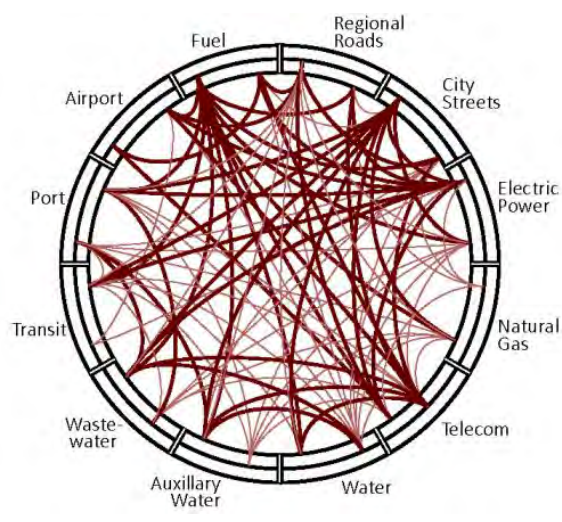

Figure 2. CCSF Matrix Information Illustrating Interdependencies of Infrastructure Systems

While there are many types of interdependencies, they can generally be categorized into four main types as defined in the Association of Bay Area Governments' (ABAG) recent study entitled "Cascading Failures: Earthquake Threats to Transportation and Utilities" [4]. Specific examples of cascading outage and cascading failures that apply to EBMUD's water distribution system are discussed in more detail in the following sections. These categories, and corresponding examples for EBMUD's water system, include:

Cascading outages, when failure of one system causes another to shut down until the system is restored, such as the impacts of electrical outages on pumping plants, which – depending on the scale and duration of the outage – could impact service to a large number of customers.

Cascading failures, when a failure results in physical damage to another, such as the impacts a catastrophic break on a water main could have on another adjacent lifeline, such as a gas or petroleum line.

Influence on recovery, when a system outage slows the repair of other systems, such as impassable roadways preventing repair crews from reaching a damage pipeline or pumping plant site.

Multi-system process, when a process requires two functional systems, such as a water treatment plant requiring the operation of an emergency generator to supply power during an outage, and the generator relying on fuel supply which can't be replenished if transportation does not work or fuel supplies run out.

Cascading Outages

EBMUD's distribution system includes over 120 different pressure zones delivering water to elevations that range from sea level to about 1,500 feet (460 meters). Nearly half of EBMUD's services rely on EBMUD's 132 pumping plants to deliver water to higher elevations, such as the Oakland-Berkeley Hills located along the Hayward Fault (see Figure 1). The average winter water consumption and number of services supplied by gravity zones and pumped zones are summarized in Table 1, with corresponding pressure zones illustrated on Figure 3.

Table 1. EBMUD Gravity vs. Pumped Zones

Pressure Zones	Avg. Winter Demand Consumption	Service Count
Gravity	65 MGD*	204,000
Pumped	52 MGD*	176,000
* MGD = Millions of Gallons/Day		

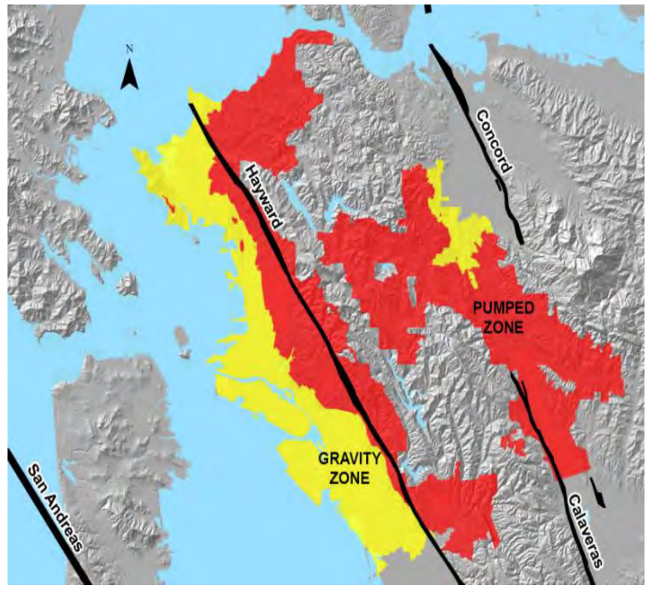

Figure 3. EBMUD Gravity vs. Pumped Pressure Zones

The impacts of power outages on EBMUD's water distribution system are discussed in more detail in the next section of this paper, titled "Damage Predictions". ABAG's 2014 report [4] provides an estimate of the potential impact of interdependencies on expected utility restoration as part of an exercise completed in 2008 with Southern California Edison (SCE), the power provider for Los Angeles, Riverside, and San Bernadino Counties. SCE held two panel discussions and concluded that "power restoration times are strongly interdependent with other lifelines and are particularly affected by damage to the water system, natural gas delivery, transportation network, telecommunication overload, and post-earthquake fires."

In their second panel discussion to estimate the potential time frame for restoration of their system after a massive Southern California M-7.8 San Andreas scenario, which took into account the impacts of external interdependencies, SCE estimated that the time it would take to restore service to 90% of its customers would increase from an estimated two weeks to over one-year after the scenario event, as illustrated in Figure 4 [4].

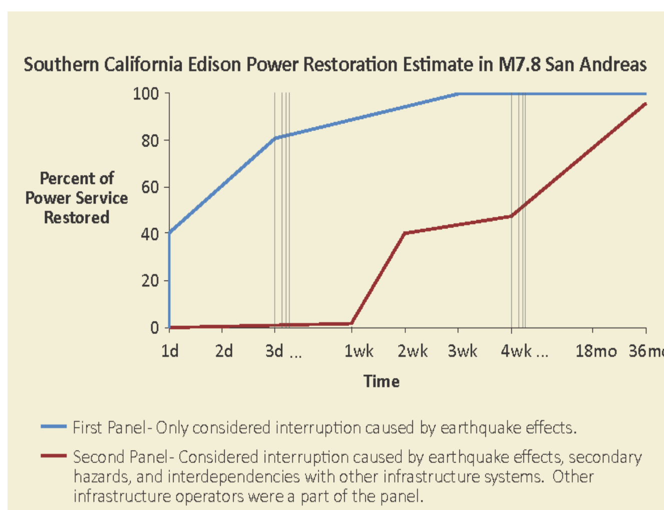

Figure 4. Power Restoration Estimate in M-7.8 San Andreas

Cascading Failures

One of EBMUD's 60-inch (1.5-meter) diameter LDP, located in El Portal Road in Richmond, failed in 2011 due to creep along the Hayward Fault. Resulting tensile stresses accumulated in the pipe. The ensuing sinkhole closed the road and resulted in significant damage to the roadway, adjacent utilities, and a creek bank. An adjacent 6-inch diameter petroleum product line operated by the Conoco Phillips Pipeline Company was damaged as well. The petroleum line had to be shut down and repaired prior to EBMUD crews being able to start repairs on the transmission main, which increased recovery time. Figure 5 shows the large sinkhole created by this break, with both the 60-inch (1.5-meter) pipe (seen in foreground) and 6-inch (0.15-meter) petroleum pipe exposed (in background). EBMUD was able to avoid any level of service impacts associated with this break by relying on an adjacent 24-inch (0.6-meter) diameter High Density Polyethylene (HDPE) bypass pipeline that had been installed at this location in 1997, as part of EBMUD's Seismic Improvement Program.

Figure 5. El Portal Main Break/Sinkhole and Mitigation Project
Example of Cascading Failures Associated with Collocated Utilities

Had the damage to the petroleum pipeline been more significant, the break in this water main could have caused more significant impacts on a nearby petroleum refinery as well as significant environmental damage. These collocated utilities also significantly slowed EBMUD's restoration efforts, as repair crews were delayed in order to first address safety concerns, and to allow Conoco Phillips time to repair its pipeline.

Due to the relentless creep of the Hayward Fault, it was estimated that a similar break could occur every few years. To reduce the risk associated with another break and the potential for damage to the adjacent petroleum pipeline, EBMUD recently installed a 48-inch (1.2-meter) diameter flexible expansion joint (Flex-Tend®), as shown in the right photo of Figure 5. The Flex-Tend® was installed with equipment to periodically monitor the creep displacement in the flexible joint and determine when the Flex-Tend® will require resetting. The San Francisco Public Utilities Commission recently installed a modified 72-inch (1.8-meter) diameter Flex-Tend® in Fremont, designed to absorb a large offset over a very short duration on the Hayward Fault.

Regional Lifelines Council Working Group

ABAG, in partnership with EBMUD, PG&E, and other local leaders and regional disaster resilience planners, recently assembled a Regional Lifelines Council Workgroup to better understand the impacts that interdependent lifelines would have on utility restoration. As part of this effort, EBMUD is studying interdependencies between its water system and other critical lifelines such as line power and fuel. The goal of the study is to improve emergency planning and response efforts, including allocation of limited resources for post-disaster restoration purposes (repair crews, emergency pumps, generators, fuel, etc.).

One of the main goals for this working group, which was formed in early 2015, is to provide guidance for communities and regional government agencies to better plan for emergencies and improve the resiliency of energy and water systems. This working group will build on the efforts from the CCSF Lifelines Council Interdependency Study [3], which was formed to better understand system interdependencies, help expedite response and restoration planning among agencies, identify key assets and restoration priorities, and develop a set of lifelines performance expectations.

DAMAGE PREDICTIONS

Following the 1989 Loma Prieta Earthquake, EBMUD completed a Seismic Evaluation Program (SEP) to examine the performance of its water distribution system [5]. As part of this SEP, which was the basis for EBMUD's 10-year, $189-Million Seismic Improvement Program that was completed in 1994, EBMUD also completed several studies to estimate the level of damage that would result from various scenario earthquake events. The results of these prior studies, as well as results from EBMUD's more recent damage prediction modeling efforts, are discussed below.

Power Outages

The SEP predicted a loss of power to a significant number of the District's 132 pumping plants serving the higher elevation pumped zones [5]. A vulnerability assessment was performed to estimate the availability of offsite power following various scenario events and included an estimate of the extent of damage to PG&E equipment, duration of outages, and number and location of impacted EBMUD facilities [6]. This assessment included an analysis using a model entitled "System Earthquake Risk Assessment" (SERA) that reflected actual substation equipment used by PG&E at the time (circa 1994). Some of the results from this study are summarized in Table 2, and indicate that over half of EBMUD's pumping plants may be out of power for 3 days or longer following a Hayward M-7 scenario event.

The specific pumping plants that are predicted to be out of service and the pressure zones that they serve are shown on Figure 6. These estimates suggest that on the order of 25% of EBMUD's services could be impacted by power outages as a result of a Hayward M-7 event. This estimate does not take into account service disruptions due to main breaks. The combined impact from both power outages and main breaks is likely to be significantly higher, on the order of 50% or more.

Table 2. Estimate of Pumping Plants that will Lose Power

Scenario Earthquake	Number of Pumping Plants Losing PG&E Power	Time to Restore PG&E Power to 95% of Pumping Plants (Days)
Hayward M-7	73-84	2.8-3.3
Hayward M-6	24-33	1.2-1.5
Calaveras M-6.75	11-22	0.9-1.2
Concord M-6.5	12-22	0.6-0.8

However, this prior study [6] may not have fully accounted for the interdependencies that may impede PG&E's ability to repair damaged substations. PG&E has a total of 17 substations that serve EBMUD's facilities, which have an estimated probability of power outage – based on the 1994 SERA model results – ranging from 4% to 78% as a result of a Hayward M-7 scenario event (11 substations with a probability of power outage ranging from 54%-78%, and 6 substations with a probability ranging from 4%-47%).

As previously discussed, recent studies suggest that power service interruptions as a result of a major earthquake – when accounting for other interdependencies – could last much longer (several weeks or more). Power outages as a result of a Hayward M-7 event may therefore be much longer than the estimated 2.8-3.3 days noted in Table 1, when taking into account interdependencies with other infrastructure systems and secondary hazards such as post-earthquake fires.

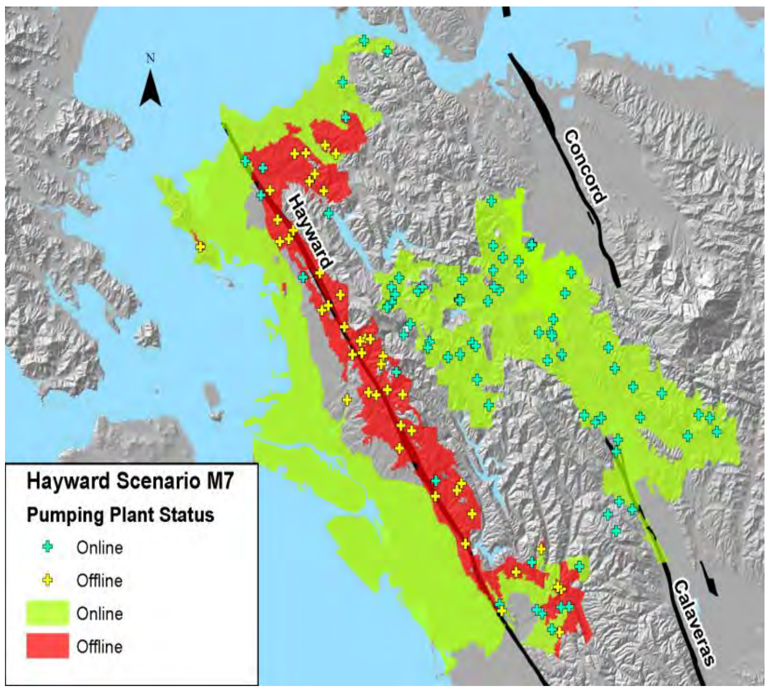

Figure 6. Pumping Plants with Power Outages and Impacted Pressure Zones

Assuming a winter or early-spring demand scenario, as summarized in Table 1, EBMUD could supply its customers for approximately 48 hours on a gravity-fed supply (using distribution reservoirs, with pumping plants out of service). After about 48-72 hours, only customers in pure-gravity zones shown on Figure 3 would be able to get water. Since only 2 of EBMUD's 132 pumping plants currently have permanent standby power, a majority of pumping plants impacted by prolonged power outages would therefore need to rely on emergency backup generators and portable pumps for operation.

EBMUD has a limited number of emergency backup generators (13) and portable pumps (22), which would be deployed as needed at pre-designated priority pumping plants locations shown on Figure 7. EBMUD, however, only has a limited amount of emergency fuel supply needed to power its emergency generators and portable pumps – only enough to last on the order of 24 to 48 hours. The same issue also applies to EBMUD's water treatment plants, which only have about 24-48 hours of fuel to power its backup generators. Depending on the extent and duration of PG&E power outages, EBMUD would therefore depend on external sources of fuel supply to keep its emergency backup generators and portable pumps in operation.

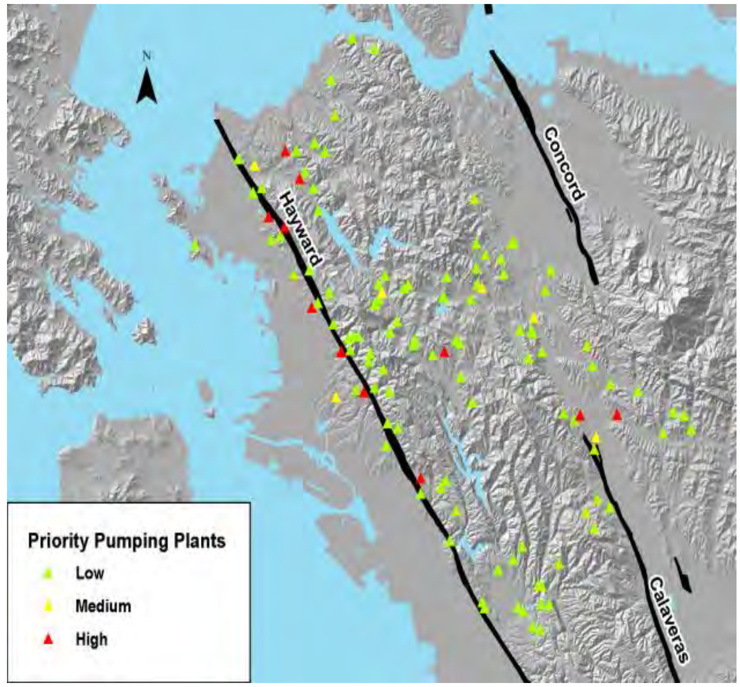

Figure 7. Priority Pumping Plants for Immediate Pumping, Hayward M-7 Earthquake

Main Breaks

Estimates of the extent of damage to EBMUD's distribution pipelines were also made as part of the SEP, and as summarized by pipe material type in Table 3. As indicated, it is estimated that EBMUD's distribution system would experience in excess of 4,000 leaks/breaks as a result of a Hayward M-7 event. Nearly 90% of pipe damage will result from breaks in the cast iron and asbestos cement pipe, which make up over 60% of the system. These pipes are generally older and more brittle pipe types when compared to other pipe materials [7]. This estimate is consistent with actual pipe damage observed during the Christchurch earthquake in New Zealand, where asbestos cement pipes had the highest break rate in liquefaction areas and cast iron pipes had the highest break rate in non-liquefaction areas [8].

This large number of breaks would quickly overwhelm EBMUD's four service centers and would require that aid be provided from outside sources. To address this emergency response issue, EBMUD has taken a number of steps including use of regional interties with adjoining water agencies and inter-agency cooperation and agreements, which are discussed in more detail in the next section of this paper, under "Steps to Improve Resiliency".

Results of a more recent analysis, using EBMUD's rapid damage prediction model, are also summarized in Table 3. As noted, this recent analysis focused on predicting damage to LDPs, which represents only 9% of EBMUD's distribution system but would have a more significant impact on EBMUD's system. The results of this more focused analysis are discussed in more detail below.

Table 3. Pipe Damage Predictions, Hayward M-7 Event

Pipe Material	Miles	% of System	Projected # of Breaks
1997 Estimates [6]			
Steel pipe	1,246	30	264
Cast iron pipe	1,357	33	2,451
Asbestos cement pipe	1,145	28	1,113
PVC	369	9	16
Other pipe (HPDE, copper, ductile iron, wrought iron, etc.)	11	<1	21
Large diameter pipe (reinforced, unreinforced, and pre-tensioned concrete cylinder pipe only)	21	<1	13
Total, all pipe materials	4,149		4,054
2015 Estimates – Based on Damage Prediction Model for Large Diameter Pipelines, using HayWired M-7 Scenario Event			
Steel (≥20-inch or 0.5-meter in diameter)	298	83	112
Cast Iron (≥16-inch or 0.4-meter in diameter)	37	10	164
Reinforced Concrete Cylinder (>24-inch or 0.6-meter)	14	4	54
Pre-tensioned Concrete Cylinder(>24-inch/0.6-meter)	10	3	4
Total, large diameter only	358		334

Rapid Damage Prediction Modeling and Marconi

Rapid modeling of seismic damage remains a very important area for water utilities seeking to maximize their reliability. It can greatly improve emergency response by allowing resources to be focused on the most important damage areas. Especially for large agencies that may have major assets spread over hundreds of square kilometers, timely estimates of earthquake damage can be invaluable since damage may vary substantially over a large area. For example, model results that show possible damage to key pipelines might prompt an agency to operate isolation valves immediately even before inspections can be completed.

Recent modeling efforts completed by EBMUD focused on estimating the extent of damage to LDPs as a result of a Hayward M-7 event. The subset of pipes that were included in this analyses includes approximately 358 miles (576-kilometers) of pipelines consisting of 20-inch (0.5-meter) and larger welded steel pipe, 36-inch (0.9-meter) and larger reinforced concrete cylinder pipe, 16-inch (0.4-meter) and larger diameter cast-iron pipe, and 20-inch (0.5-meter) and larger pre-tensioned concrete cylinder pipe (as summarized in Table 3).

This assessment is important for EBMUD to clearly identify areas in its pipeline network that are unlikely to perform adequately during a seismic event. The assessment also allows EBMUD to have a better understanding of various hazards including liquefaction-induced settlement, landslides, and fault crossings and how these hazards will affect EBMUD's water distribution capabilities.

The approach and analysis used to predict the number of LDP breaks summarized in Table 3 is discussed in more detail in EBMUD's paper entitled "Pipeline Fragility Assessment Against Liquefaction Induced Differential Settlement in City of Alameda, and Oakland, California" [9]. The spatial distribution of the projected LDP breaks within EBMUD's service areas, resulting from liquefaction, landslides, and fault crossings hazards as a result of an M-7 scenario event is illustrated on Figure 8.

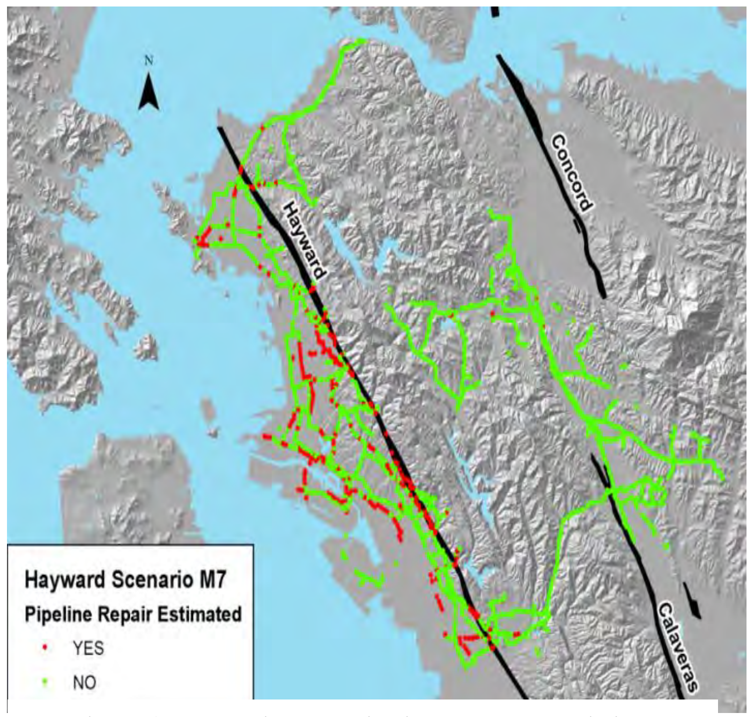

Figure 8. Large Diameter Pipeline Damage Predictions

Integration of Model Results with Emergency Response

As described previously, EBMUD uses an emergency response software called *Marconi* that integrates seismic model results with emergency response. Among its many capabilities is the ability to easily model historic or possible future earthquakes and quickly export damage prediction results. Marconi can also present actual damage reports on a map. However, rapid modeling, even at its best, remains an approximate prediction that might inform more detailed investigations. It is vital that the model results not be assumed true, but rather be interpreted in the light of real data as the data develop in the first hours and days after an earthquake.

In addition, the Marconi software has been licensed for open-source use and is being used by agencies besides EBMUD. This multi-agency use presents opportunities for collaboration in many areas, including seismic modeling and emergency response.

Damage Prediction Modeling and Interdependencies – Next Steps

PG&E has developed similar damage modeling capabilities for its power distribution system, using ShakeMap data to evaluate the likely level of damage to its substations and electric distribution system. In the near future, EBMUD will be working with PG&E to overlay its damage prediction scenarios for its water infrastructure system with PG&E's

electric distribution system. The goal is to use common ShakeMap data to estimate potential damage of the combined water and power infrastructure systems. As part of this effort, EBMUD is hoping to develop common priorities for service restoration based on customer criticality and other criteria. Being able to compare EBMUD's priorities for service restoration with PG&E's priorities for restoring gas and electric service and power generation, and critical business functions will be key to better understanding the interdependencies between the two systems.

STEPS TO IMPROVE RESILIENCY

While EBMUD completed a comprehensive, $189 Million Seismic Improvement Program (SIP) that included significant seismic upgrades to critical links to improve overall system performance, these improvements did not fix every component of the system that could be damaged in a major earthquake. Despite completing the SIP in 2004, it is predicted that the impacts on EBMUD's distribution system from a Hayward M-7 scenario event would still be significant, with an estimated number of leaks/main breaks on the order of 4,000. This damage includes over 300 breaks on LDPs and over 70 pumping plants potentially without line power for several days or longer. The additional steps that EBMUD is taking to further improve the resiliency of its distribution system are discussed below and include near-term projects to improve reliability as well as long-term improvements to improve robustness of EBMUD's distribution system.

Efforts to Improve System Reliability and Robustness

EBMUD has a large, ongoing capital improvement program that continues to improve the seismic reliability and robustness of its distribution system. Upcoming near-term projects include replacement of a vulnerable cast iron transmission pipeline and estuary crossing that supplies the island of Alameda, mitigation of liquefaction hazards, and electrical improvements at treatment plants to improve system redundancy and reliability. Longer-term improvements program also include:

- **Infrastructure Renewal Program:** In 2014, EBMUD initiated a new program to increase its rate of pipeline replacements from approximately 10 miles (16-kilometers) to a goal of as high as 40 miles (64-kilometers) per year. This program focuses on replacement of smaller diameter cast iron and asbestos cement distribution pipeline (pipes that are most likely to break as a results of an earthquake), and will gradually improve the earthquake resiliency and robustness of EBMUD's distribution system.
- **LDP Replacement Program:** A few years ago, EBMUD developed a new capital program to start replacing its LDPs at a rate of approximately 3 miles (4.8-kilometers) per year. Recent progress under this new program includes the Lincoln Avenue Pipeline Replacement Project in Alameda and the Dingee Pipeline and Claremont Center Aqueducts Replacement Project in Oakland, which included the replacement of over 5 miles (8-kilometers) of old LDPs. These recent improvements, and future projects under this new capital program will gradually improve the reliability of EBMUD transmission pipelines, which – as discussed in this paper – may experience a significant number of breaks as a result of a Hayward M-7 scenario event.
- **Other Capital Programs:** EBMUD has a number of other long-term and also recurring capital programs that will, over time, further improve the earthquake performance and reliability of its distribution system. These include open-cut, steel reservoir, and pumping plant rehabilitation projects (on the order of 6 facilities rehabilitated each year), as well as pther capital improvements including over $100 Million in transmission improvements, with over 23 miles (37-kilometers) of new LDPs scheduled to be completed in the next 15 years.

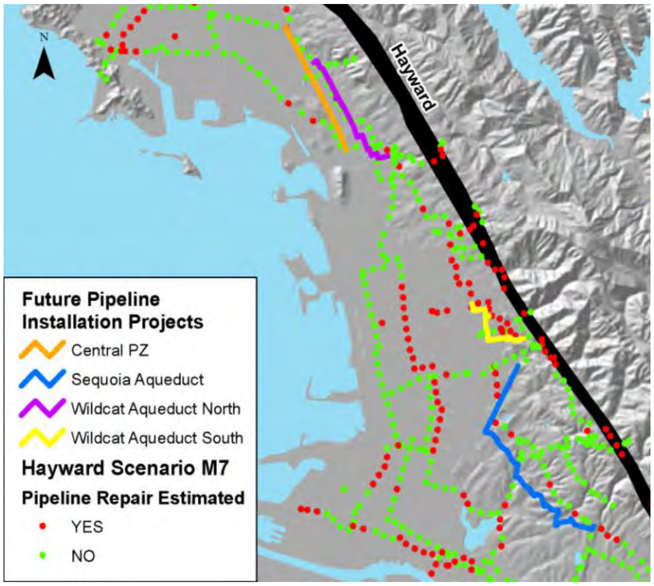

Figure 10. West of Hills Pipeline Improvement Projects

Figure 10 shows some of the transmission system improvements planned for EBMUD's "West of Hills" area, located along the Hayward fault. The new Wildcat Aqueduct South pipeline is currently being designed and will include approximately 1.7 miles (2.7-kilometers) of new 48-inch diameter transmission pipeline. This and other future improvements will not only improve transmission capacity for EBMUD but will also facilitate repairs on the existing parallel LDPs including the Wildcat Aqueduct, a reinforced concrete cylinder pipe projected to have a significant number of leaks as a result of a Hayward M-7 scenario event (as illustrated on Figures 8 and 10).

Emergency Response

General: EBMUD has a very well developed emergency preparedness program, including an Emergency Operations Plan (EOP). EBMUD recognizes that despite a high level of investment to harden its facilities, there will still be a significant level of damage following a major earthquake. For that reason, EBMUD has an overall EOP that describes how to respond to a major incident, trains staff to use the plan, and has regular exercises and drills to ensure staff understands the plan while providing an opportunity to identify where the program can be improved.

EBMUD also has hazard specific appendices to its EOP that describe how EBMUD would respond to specific types of incidents. Examples include a failure of a raw water aqueduct or threat to one of EBMUD's dams. In addition, there are functional appendices which describe specific tasks such as deployment of EBMUD flexible hose to temporarily restore service at fault crossings. EBMUD recommends to its customers to be self-sustaining for 3 to 7 days until water and food distribution centers can be set up.

EBMUD is also currently developing a pipe repair mitigation plan that includes improving its welding shop's capabilities to fabricate custom parts for repair, such as buttstraps, reducers, and manholes, and stockpiling limited quantities of LDPs with a pre-set reorder point to keep turnover in stock.

Regional Interties: EBMUD has 10 emergency interties with other local water agencies, which would allow for potable water to be shared if available, following a significant earthquake event that would affect one agency more than another. Figure 11 shows the approximate location and flow capacities that could be provided to or by EBMUD using these interties.

Inter-Agency Cooperation and Agreements: EBMUD is one of the original founding members of the California Water/Wastewater Agency Response Network (CalWARN), which was started in 1994 to increase planning and coordination between agencies, reduce administrative conflicts, and increase community and customer assistance. In response to the recent Napa earthquake, EBMUD sent crews to Napa via the CalWARN agreement, along with Alameda County Water District, Contra Costa Water District, and the City of Fairfield. EBMUD crews were in Napa the Monday morning after the earthquake, which occurred on a Sunday. EBMUD sent 5 crews, who repaired 56 leaks out of 144 total leaks, as well as an Incident Commander, Safety Officer, Logistics Chief/Liaison, and a Finance Chief (Accountant).

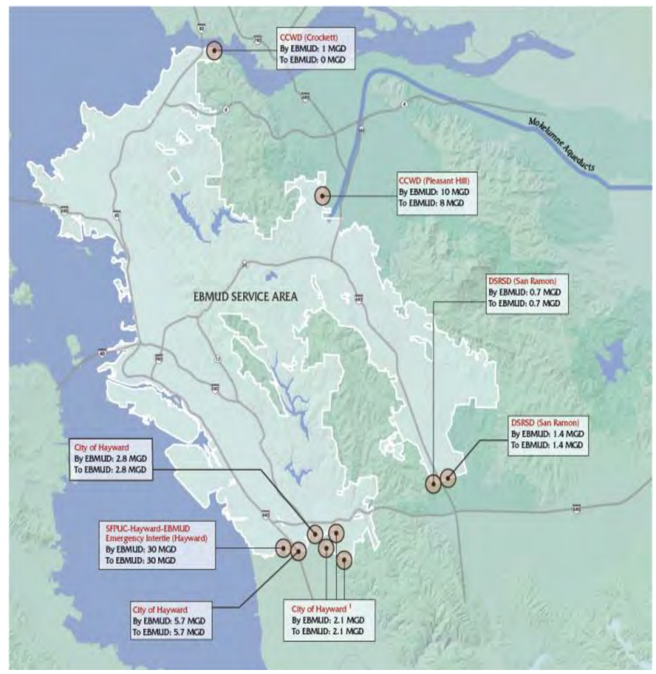

Figure 11. EBMUD Interties with Other Bay Area Water Agencies

In addition to being part of the CalWARN system, EBMUD has also entered into mutual assistance agreements with the Los Angeles Department of Water and Power (LADWP) and the Las Vegas Valley Water District (LVVWD), two other large water agencies that are not exposed to the same earthquake risk as EBMUD (i.e. geographically distant agencies, exposed to different sets of faults). This was done in recognition that a Hayward M-7 scenario event would likely overwhelm other local water/wastewater agencies that would be called to first respond to their own emergencies, before they could assist EBMUD.

In addition to these inter-agency agreements, EBMUD has also worked with other water agencies and the state to develop a statewide plan for emergency drinking water procurement and distribution. This is an important component of EBMUD's emergency response plan, and includes working closely with local cities and/or the counties to seek their assistance in procuring and distributing drinking water in the event that EBMUD cannot supply drinking water following a catastrophic earthquake event.

PLANNING FOR PROLONGED UTILITY SERVICE DISRUPTIONS

In the 2011 earthquake that devastated Christchurch in New Zealand, around 80% of residents were without a fully operational water supply for the first few days after the earthquake. Within a week, 50% of Christchurch had basic water supply and 75 per cent of the city had power, but people were still asked to conserve water and boil it before drinking. Progress to fully restore services was slow due to damage to roads and to the electric network, much of it underground.

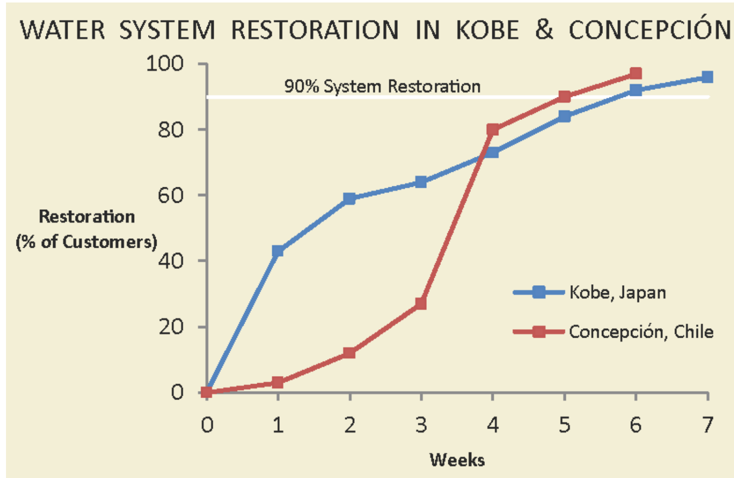

Figure 12. Water System Restoration Timelines in Kobe, Japan, and Concepcion, Chile [4]

Prior case studies for water system restoration following the 1995 M-6.9 earthquake in Kobe, Japan, and the M-8.8 earthquake in Concepcion, Chile, indicate that the time to restore service to 90% of customers took approximately 5 to 6 weeks, as illustrated on Figures 12 [4]. And based on the results from CCSF's study, the time to restore 90% of water service in San Francisco could take approximately 3-4 weeks, as illustrated on Figure 13 [3]. However, large-scale disasters such as Hurricane Katrina, the 2010 earthquakes which devastated Haiti, Chile, and Pakistan have demonstrated that recovery periods can be considerably greater than 3 weeks [10].

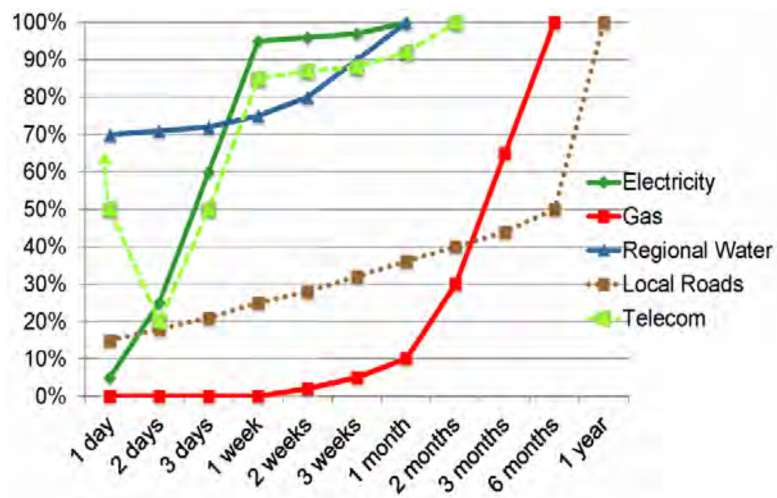

Figure 13. Timelines for System Restoration, CCSF Lifelines Council Interdependency Study, AICP Consulting | Research, January 2013 Progress Report [3]

The time to restore service to 100% of EBMUD's customers, following an M-7 Hayward scenario event, will depend on a number of factors. A catastrophic earthquake in the San Francisco Bay Area may require innovative solutions such as scaling up mobile water treatment units, or developing temporary distribution systems.

SUMMARY

In summary, despite water utilities' ongoing efforts to improve their distribution systems, not every component of the system can be hardened. Interdependencies significantly increase the potential for prolonged system outages following a major seismic event. AWWA's 2011 study entitled *Planning for an Emergency Drinking Water Supply* [10], illustrates how water from various sources could be distributed either through an existing, partially-operating distribution system, or via distribution sites. This study notes that depending on the nature of the damage and the ability of a utility to make functioning pipe connections, it may be impossible to transport water from functioning to non-functioning portions of the distribution system. If uncontaminated water is available in sufficient supply within the existing system but cannot be distributed as needed, the water may need to be tapped at fire hydrants or other locations within the functioning system for local distribution, and/or moved in bulk water tankers that would be accessible to local residents [10]. EBMUD has a water bagging station that could be deployed, to assist with distribution of water after an earthquake.

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The Damage Analysis of Distribution Pipes in Artificial Ground

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ABSTRAUCT

Many water distribution pipes were damaged by the Great East Japan Earthquake that happened on March 11th 2011. These pipes were mainly found at the artificial ground in developed land on hilly area in Sendai City, so it is assumed that the specific land characteristic is related to the damage of pipes. From the viewpoint of ground situation, there are few existing studies between pipe damages and land character such as an earthquake occurrence.

Those factors seem to be linked together, so we have researched following three points. Firstly, we estimate the thickness of cutting and filling ground in developed land by the topographic map surveyed before and after land development. According to the topographic map, we classify the developed land into cutting, filling and boundary area. Secondly, we calculate each damage ratio of the pipes for those three areas. Finally, we analyze the damage ratio for the thickness of land cutting and filling, the pipe kinds, and the land development ages.

According to the study, we conclude as follows. The filling ground has the highest damage ratio. The specific pipe kind has high damage ratio. The filling area developed before 1965 has high damage ratio.

INTRODUCTION

Sendai city has about a million of population and is the central city of Tohoku region. It is located in north area of Japan main land (Figure 1) and surrounded by the Ou Mountains in west and the Pacific Ocean in east. The water distribution area of Sendai is about 363km2 and our four main filtration plants are located in west area. So we supply water for customers with the effective utilization from west to east across Sendai. The water pipes are covered about 4,500km in Sendai and contributed to distribute water to citizens. The Great East Japan earthquake on March 11, 2011 had magnitude of 9.0 and the greatest earthquake ever recorded in Japan. It brought the intense shake and massive tsunami that caused lifelines cutting off over the long period of time. Especially, the tsunami hit the Tohoku and Kanto coast and caused the great damages and casualties.

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In Sendai, the suspension of water supply reached to two hundred thirty thousand houses with five hundred thousand people by those damages. This great damage restored by March 29, 2011 except some heavy damaged area.

Many distribution pipelines were broken and most of them were observed at an artificial ground. It is thought that distribution pipelines are influenced by ground damage. It is also considered that concentration of pipe break mainly was observed within the boundary area between cutting and filling in artificial ground when an earthquake happens. This reason is that strength in artificial ground is affected by backfilling materials and number of compaction at that time, so if the construction was not performed perfectly, strength against a shake in artificial ground is weak relatively. In 1965, Sendai city applied an Act on Regulation of Residential Land Development, the act decides technical standard for the construction. There are some developed areas where constructed for the past several ten years with no application of the construction act to the artificial ground. In addition, there are some distribution pipeline installed at the time of developed area, and they are reaching to service life. Fragility of water pipeline varies with the material and the joint, and the aging water pipelines do not have earthquake resistant performance.

Sendai waterworks bureau needs to replace such pipelines that will be easy to break with priority in keeping mind of installed ground condition. There are some cities in Japan which have the similar situation of Sendai. They will have the possibility of an intense shake of earthquake in the future like we have experienced. In that condition, it is important to analyze damage to pipeline in artificial ground. This analysis clarifies a damage tendency and allows preparing for future earthquake. Although there are some studies and investigations for the pipe breaks caused by the earthquake in Sendai city, they have rarely the focus on the viewpoint of ground condition and pipe materials and joints in detail. Therefore, in this study, to clarify a damage tendency about 409 water pipe breaks judged to be broken by the earthquake, the pipe breaks and the ground situation seem to be linked together, so we have researched the following points to verify the relation. We conduct the methods and procedures below.

Firstly, we estimate the thickness of cutting and filling ground in the developed land by the topographic map surveyed before and after development of land. According to the topographic map, we classify the developed land into three as cutting, filling and boundary area. Secondly, we calculate each damage ratio of the pipes for those areas. Finally, we analyze the damage ratio for the thickness of land cutting and filling, the pipe materials and joints, and the land development ages.

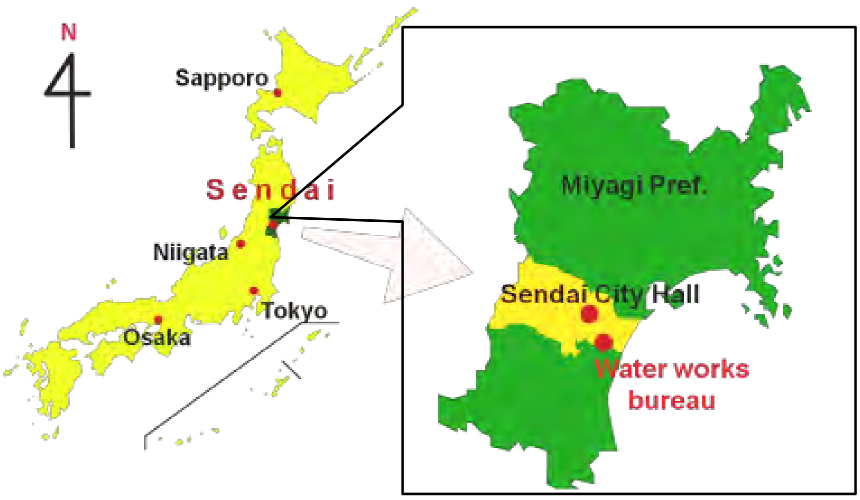


Figure 1 Location of Sendai City

METHODS

Damage Caused to Water Pipeline by the Great East Japan Earthquake

The Great East Japan Earthquake happened on March 11, 2011at 2:46 PM local time of Pacific Coast beside of Miyagi Prefecture. In Sendai City, there were few damages for main four purification plants but significant damages for water distribution pipelines. The number of breaks of the distribution pipelines by the earthquake reached to 409 except the auxiliary equipment broken. The pipe breaks of 317 cases were concentrated in developed artificial land, and it accounts for 80% of 409 pipe breaks.

Drawing up geotechnical map about the thickness of filling or cutting in developed areas

We designated the analyzing areas including the information map of residential land development record of Sendai City and the development land of adjoin Sendai where we supply the water. First, we calculate the surface elevation data before the land development and that of after. Table 1 shows materials for making the elevation data.

Table 1 Data about surface elevation

Item	Name
Before development	1/3000 City Planning Map
	Aerial photographs taken in 1940's
After development	5-m grid digital elevation model
	Data for permission for developed land

Then we estimate the thickness of filling or cutting land by the elevation data. Each data about surface elevation has an elevation error constantly, so the estimation may have an error in height of ±2.0m. Table 2 shows three classifications of ground condition by the estimation. In this table, B indicates the thickness of filling or cutting land.

Table 2 Classification of ground condition

Ground condition	Range of the thickness
Boundary area	Filling $0.0 < B \leqq 2.0$m, Cutting $0.0 \leqq B \leqq 2.0$m
Filling area	Filling $2.0\text{m} < B$
Cutting area	Cutting $2.0\text{m} < B$

Figure 2 shows cross section before and after land development, we classify ground condition into filling, cutting and boundary area by the thickness such as this figure. And we make a grand topography of developed residential land by the thickness as reduced scale about 1/2,500 (Figure 3).

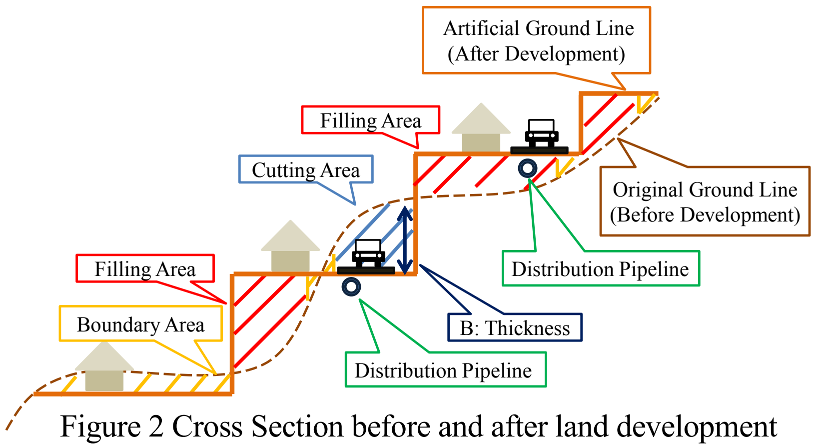


Figure 2 Cross Section before and after land development

Data and Analyzing points

We have researched for damage to pipeline to use the grand topography and below data. Table 3 shows data for using this study.

Table 3 Data

Data	Detail
(1)Damaged pipeline data	409 damaged water pipes repaired by the end of April, 2011.
(2)Pipeline data in Sendai City	Data for transmission, main distribution, distribution small distribution, conveyance and receiving pipe Sendai Waterworks Bureau has.
(3)Land development data	Data made by Fukken Gijyutsu Consultants Co., Ltd.

Table 4 shows classifications of pipe materials and joints. In these classifications, we calculate the damage ratio for distribution pipes with two analyzing points respectively.

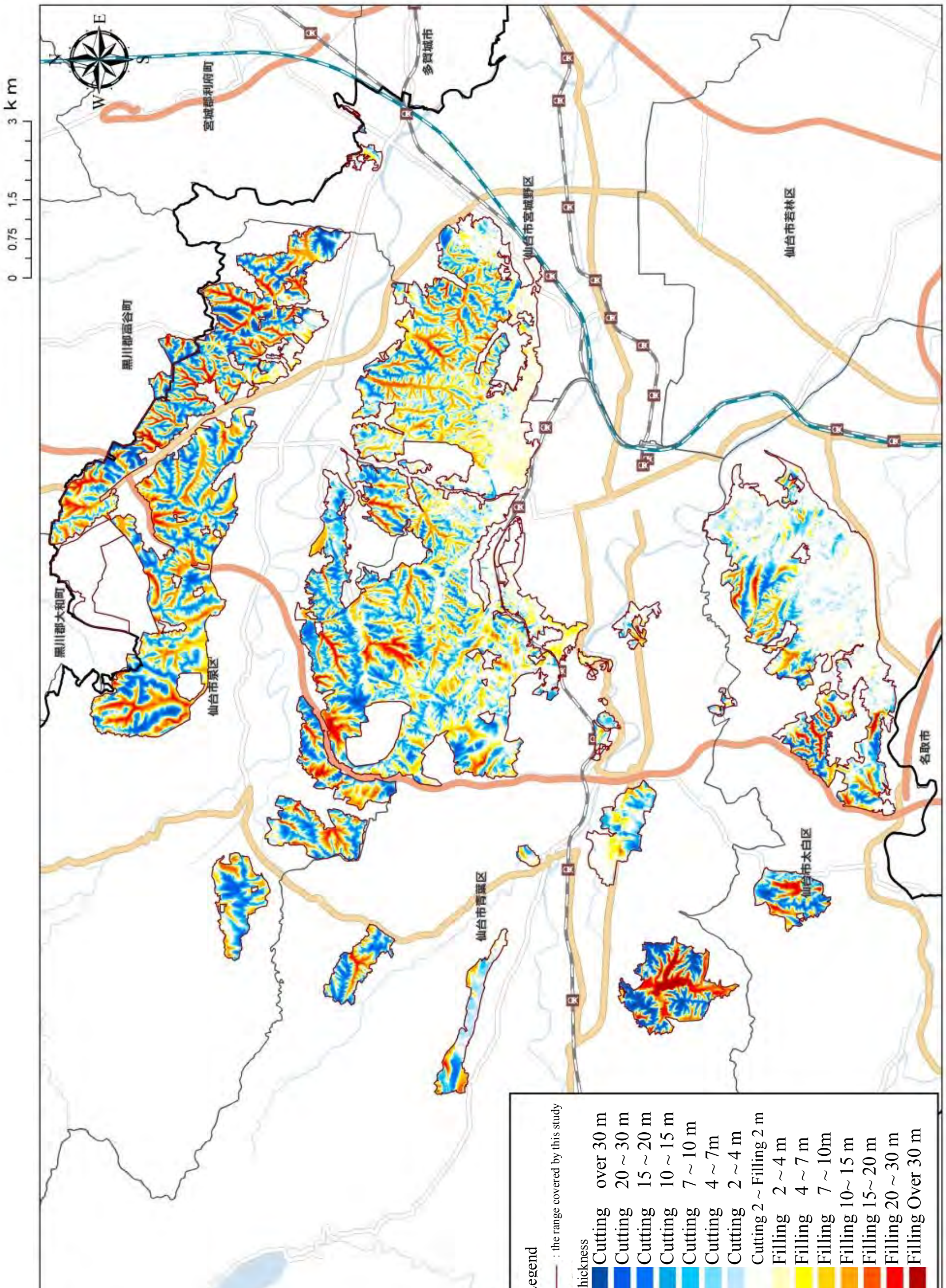
Table 4 Classifications of pipe materials ・ joints

Pipe materials・joints	Abbreviation	Characteristic
Ductile iron pipe（A, F and T type mechanical joint）	DIP (A, F, T)	They don't have anchor performance.
Ductile iron pipe（K type mechanical joint）	DIP (K)	Using retainer gland, they have anchor performance relatively.
Ductile iron pipe（KF・NS・S・S II type mechanical joint）	DIP（KF, NS, S, S II）	They have seismic resistant joint and have used general.
Rigid polyvinyl chloride pipe（rubber ring joint）	VP(RR)	The strength is weaker than Metal pipe. This has rubber ring socket but don't have anchor performance.
Rigid polyvinyl chloride pipe（taper socket joint）	VP(TS)	The strength is weaker than Metal pipe. Joint is fixed by taper socket.

Analyzing points:

(1) Damage ratio for the ground conditions (filling, cutting and boundary area)

(2) Damage ratio for the land development age



Background map made by ESRI JAPAN Co., Ltd.

Figure 3 The grand topography of developed residential land

RESULTS AND DISCUSSION

Analysis of the damage ratio for distribution pipes in artificial ground condition

Table 5 and Figure 4 show the damage ratio for distribution pipes in cutting, boundary and filling area. The damage ratio is 0.05 in cutting area, 0.13 in boundary area, and 0.36 in filling area respectably. When an earthquake happens, it is presumed that distribution pipelines are influenced by ground damage and broken mainly between cutting and filling area in artificial ground. It is so called the boundary area. However, this study shows a tendency that high damage ratio is cutting, boundary, and filling area in that order. Damage ratio in boundary area and filling area are 2.6 times and 7 times higher than that of in cutting area. Also it shows that the damage ratio in filling area is wholly high, and the highest damage ratio of the filling area is the thickness from 4 to 5 meter. This result shows that the damage to water pipelines varies to subsurface grand conditions even if the same shake happened in developed land. This result implies that filling area is affected with a shake relatively and pipelines installed in filling area were easy to break.

Figure 5 shows the damage ratio for pipelines each subsurface ground condition to different pipe materials and joints. Most pipe materials and joints have a tendency that damage ratio becomes higher in order of cutting, boundary, and filling area. Damage ratio of DIP (A, F, T) and VP (TS) are higher than that of the others. As a result, it is suspected that these pipes don't have earthquake resistant performance like DIP（KF，NS，S，SⅡ）. In addition, the material of VP (TS) is less stronger than the others, so the damage ratio of VP (TS) is the highest. Therefore, it implies that DIP (A, F, T) and VP (TS) installed in filling area have high priority to be replaced by earthquake resistant pipe.

Damage ratio for water pipelines in filling area according to land development age

Figure 6 shows number of pipe breaks and length of pipeline and Figure 7 shows the damage ratio in filling area according to land development age. The damage ratio in filling area is approximately 0.9 (breaks/km) before 1965, it is approximately 0.4 after 1965. Damaged water pipe installed in filling area was not found after 1990. It makes a clear tendency that pipes have lower damage ratio according to land development age. In 1965, Sendai city applied an Act on Regulation of Residential Land Development, the act decides technical standard for the construction. This suggests that strength of subsurface ground condition become higher after 1965, and also the figure shows there are few number of pipe breaks. Therefore, it is necessary to pay full attention to the pipes installed in filling area that developed for the past several years ago. Also, it implies that pipes installed in filling area have high priority to be replaced by earthquake resistant pipe.

Table 5 Damage ratio by the thickness of filling and cutting

Ground Condition	Thickness	Number of Breaks	Length (km)	Damage Ratio(breaks/km)	Summary
Cutting area	Over 21m	0	39.50	0.00	Total number of breaks : 40 Damage ratio : 0.05 (breaks/km) Total length : 735.97km
	20～21m	1	10.39	0.10	
	19～20m	0	12.15	0.00	
	18～19m	1	14.62	0.07	
	17～18m	1	17.17	0.06	
	16～17m	0	20.40	0.00	
	15～16m	0	22.98	0.00	
	14～15m	1	24.99	0.04	
	13～14m	0	27.70	0.00	
	12～13m	1	30.49	0.03	
	11～12m	1	33.89	0.03	
	10～11m	0	38.28	0.00	
	9～10m	2	41.36	0.05	
	8～9m	2	43.62	0.05	
	7～8m	0	48.00	0.00	
	6～7m	1	50.76	0.02	
	5～6m	6	53.56	0.11	
	4～5m	6	59.38	0.10	
	3～4m	4	66.20	0.06	
	2～3m	13	80.56	0.16	
Boundary area	1～2m	8	109.97	0.07	Total number of breaks : 60 Damage ratio : 0.13 (breaks/km) Total length : 459.09km
	0～1m	7	126.51	0.06	
	0～1m	22	119.59	0.18	
	1～2m	23	103.02	0.22	
Filling area	2～3m	27	76.59	0.35	Total number of breaks : 217 Damage ratio : 0.36 (breaks/km) Total length : 595.10km
	3～4m	17	60.64	0.28	
	4～5m	37	53.96	0.69	
	5～6m	16	46.83	0.34	
	6～7m	16	42.78	0.37	
	7～8m	18	38.00	0.47	
	8～9m	10	32.90	0.30	
	9～10m	7	29.87	0.23	
	10～11m	10	27.52	0.36	
	11～12m	13	26.93	0.48	
	12～13m	9	22.96	0.39	
	13～14m	9	20.99	0.43	
	14～15m	4	18.13	0.22	
	15～16m	4	15.25	0.26	
	16～17m	3	12.59	0.24	
	17～18m	4	11.34	0.35	
	18～19m	1	9.24	0.11	
	19～20m	4	8.15	0.49	
	20～21m	2	7.29	0.27	
	21～22m	1	6.27	0.16	
	Over 22m	5	26.87	0.19	
Summary except developed land		92	2624.56	0.04	-
Summary within developed land		317	1790.17	0.18	-
Total		**409**	**4414.72**	**0.09**	-

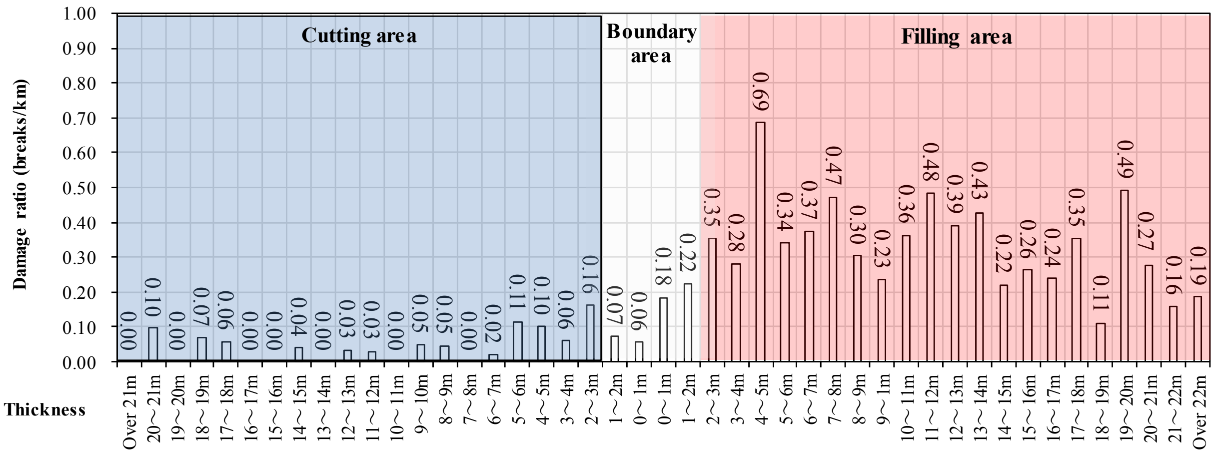


Figure 4 Damage ratio by the thickness of cutting and filling

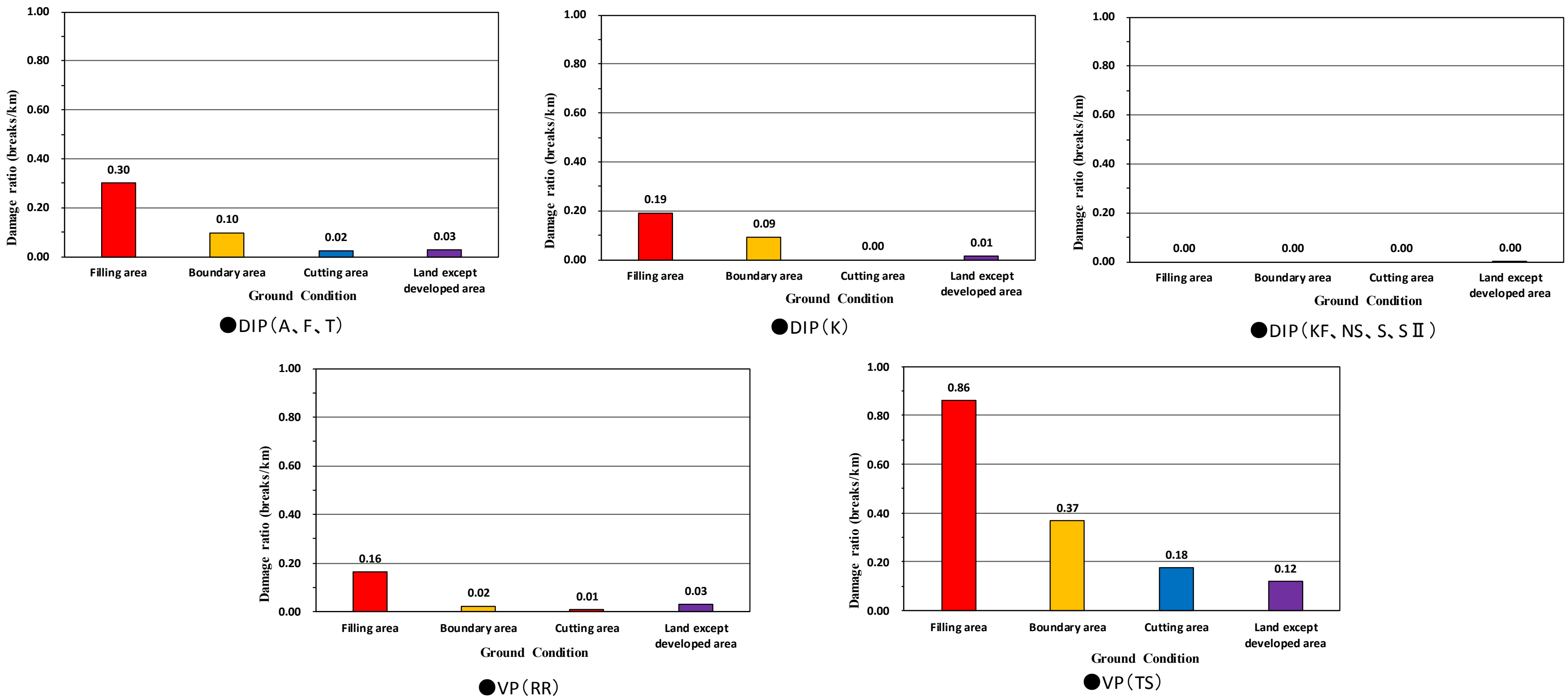
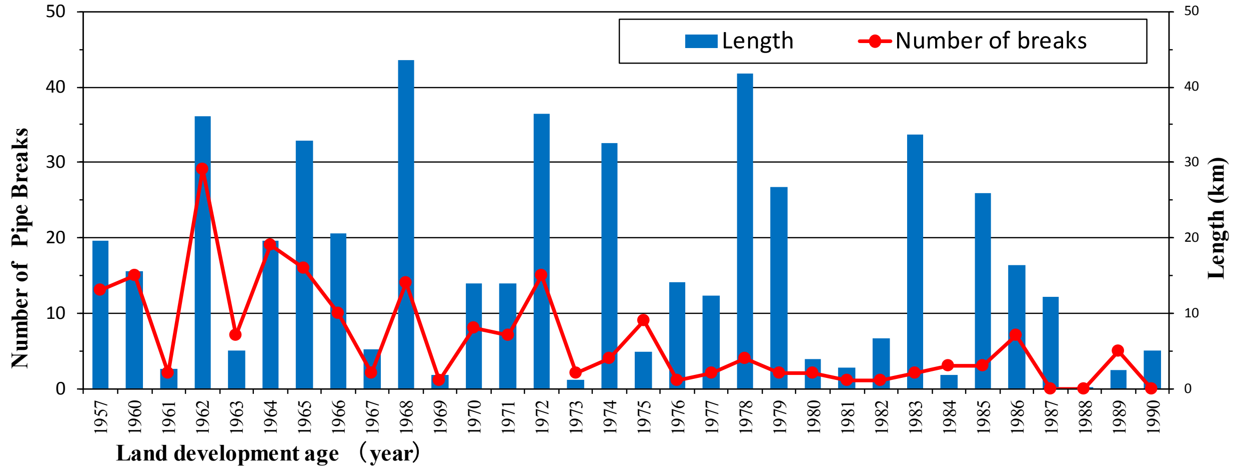
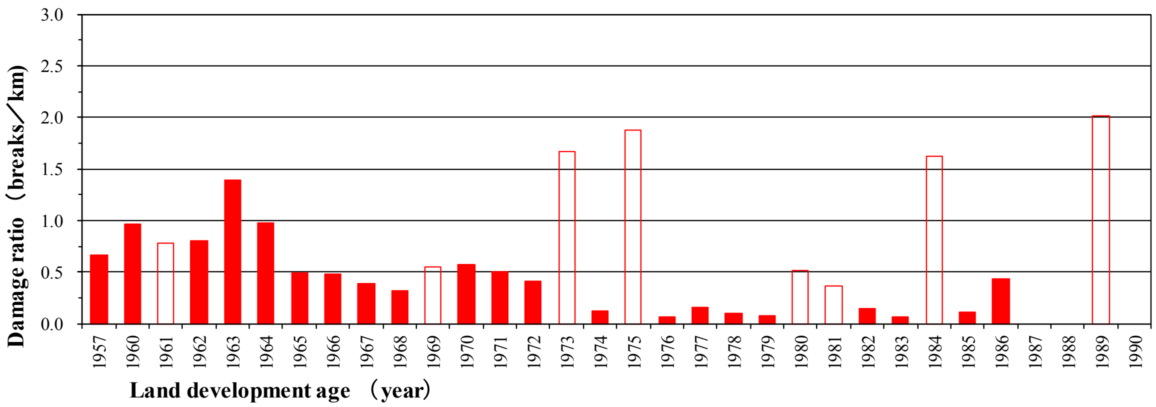


Figure 5 Damage ratio for pipelines per ground condition by pipe materials and joints.



・After 1990, damaged pipeline was not found in filling area.

Figure 6 Number of Pipe Breaks and Length in filling area



・Damage ratio for total length under 5km doesn’t deal with effective value, and the graphs of that are showed by erasing the color.

Figure 7 Damage ratio in filling area by land development age

CONCLUSION

We researched for the damaged pipeline by the Great East Japan Earthquake and calculated the damage ratio of pipelines from viewpoints of the specific characteristic of ground conditions, pipe materials and joints. According to the study, we concluded as follows. First, this study shows a tendency that high damage ratio is cutting, boundary, and filling area in that order. Second, especially it implies that DIP (A, F, T) and VP (TS) installed in filling area have high priority to be replaced. Lastly, Sendai City applied an Act on Regulation of Residential Land Development in 1965, so the damage ratio of pipeline that installed in filling area after 1965 is lower than that of others. Therefore, it implies that the pipes installed in filling area before 1965 have high priority to be replaced by earthquake resistant pipe.

Sendai Waterworks Bureau has set the priority for the pipelines to be replaced against the necessity and emergency of historical leakage of water. We would like to promote the earthquake resistant of the pipes effectively by utilizing this result.

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The Abnormal Behavior of Water Supply Systems just after Earthquakes in Case of Saitama City

Akihisa Ishida*, Mitsuyasu Tamase*, Masayuki Nagashima**, Masakatsu Miyajima***

Earthquakes cause rapid increase of water flow and rapid decrease of water pressure at water distribution system. Because that it causes the stop of water supply, we cannot send water to the areas that need water. However, we have never found out a cause of this abnormal behavior, therefore, we cannot take specific countermeasures against them on the present situation. The purpose of this study is to find out the cause of the abnormal behavior. We investigated the water flow and water pressure when the earthquakes occurred and seismic characteristics of earthquakes that occurred in Saitama city in 2011. We found out that the seismic motion of horizontal direction and the specific period gives a strong influence to water supplies.

1. INTRODUCTION

The 2011 Great East Japan Earthquake whose seismic focus was located at Oshika Peninsula offing has occurred on March 11th. The earthquake caused one of the biggest tsunami and tsunami inundation areas spread from the shoreline to 6km at most and it brought about sever damage. We focused on the damage of water supply among those damages. The earthquake caused rapid increase of water flow and rapid decrease of water pressure at water distribution stations even water pipes didn't get any damage such as a burst and leakage. Figure 1 shows the transition of water flow and water pressure at Seibu water distribution station at the 2011 Great East

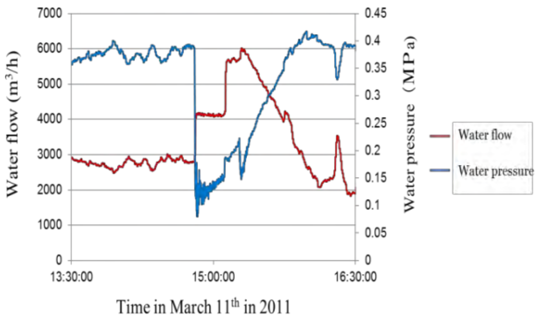

Figure 1 The transition of water flow and water pressure at Seibu water distribution station at the 2011 Great East Japan Earthquake

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Japan Earthquake. It caused the suspension of water supply and a malfunction of water supply systems. This abnormal behavior is similar to the behavior when a large scale of water leakage occurs on pipes and it would be difficult to confirm whether this behavior is caused by the damage of pipes or not. And also, a number of the damage of air valves has been reported and it is thought that the damage was caused by decrease of water pressure. This kind of damage is less influence when the scale of earthquakes are small but there is fear of extending secondary damage such as disrupting fire extinguishing in case of the seismic motions that bring out a lot of fires. Therefore, we need to take countermeasures to build water supply system which are strong enough against any earthquakes. The purpose of the study is to find out what kind of seismic motion effects the abnormal behavior. We analyzed the water flow and water pressure when the earthquakes occur and seismic characteristics of earthquakes that occurred in Saitama city in 2011.

2. RELATION BETWEEN ABNORMAL BEHAVIOR AND SEISMIC MOTION

Target Area

We selected Saitama city as a target area. Saitama city is located in the middle of Kanto Region, and 200km^2 in land area and has a population of 1,200,000. It is consisted of tableland and lowland, and doesn't have mountains and hills. Saitama city has 20 water distribution stations and filtration plants, and they send 538,000m^3 of water to the residents each day. Even among those stations, we focused on Seibu water distribution station. Seibu water distribution station utilizes force feed pump and sends 78,000m^3 of water each day. This station is supplying water the most and has the highest water supply function in Saitama city. We calculated the amount of increase of water flow and the amount of decrease of water pressure at each earthquake. We defined the amount of increase and decrease as the comparison of the mean of the value for 5 minutes till the earthquake occurs and that after earthquake.

Earthquakes in Saitama City in 2011

We compared water flow and water pressure when earthquakes occurred, and the data of seismic characteristics. We got the data of seismic waves from Strong-motion Seismograph Networks (K-NET) which National Research Institute for Earth Science and Disaster Prevention provides. The data of 87 earthquakes recorded at the Kawaguchi seismic observatory station which is 12km away from Seibu water distribution in 2011 are used in this study. There is the closest to Seibu water distribution station. The range of magnitude of the earthquakes used here is from 3.8 to 9.0 and instrumental seismic intensity is from 0.8 to 5. According to the investigation, we found out that there were 63 earthquakes which got the abnormal behavior of water flow and water pressure out of 87 earthquakes. It means that the water supplies in Saitama city were affected by the abnormal behavior in about 70% of earthquakes. In addition, the water flow increased from 3000m^3/h to 6000m^3/h and the water pressure decreased from 0.35MPa to 0.1MPa at the 2011 Great East Japan Earthquake. It took more than 1 hour to recover from the abnormal behavior completely. We consider that the abnormal behavior is severe problem for Saitama city from these things. We compared the data of water flow and water pressure, and seismic characteristics, and estimated what kind of seismic characteristics influence the abnormal behavior of water distribution systems.

Instrumental Seismic Intensity

We investigated the relations between the amount of increase of water flow or the amount of decrease of water pressure, and the instrumental seismic intensity of earthquakes. Figure 2 shows the relation between the amount of increase of water flow and the instrumental seismic intensity, and Figure 3 shows the relation between the amount of decrease of water pressure and the instrumental seismic intensity. The black lines show the approximate lines. According to these figures, it seems that if the magnitude of seismic intensity gets bigger, the amount of behavior increases as well. However, we can't say that instrumental seismic intensity of earthquakes strongly influences the behavior of water flow and water pressure because that it seems that the values are dotted sparsely, and the correlation coefficients of two figures are 0.54 and 0.59 each.

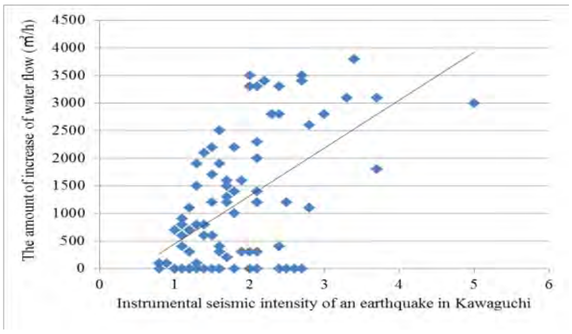

Figure 2: The relation between the amount of increase of water flow and the instrumental seismic intensity

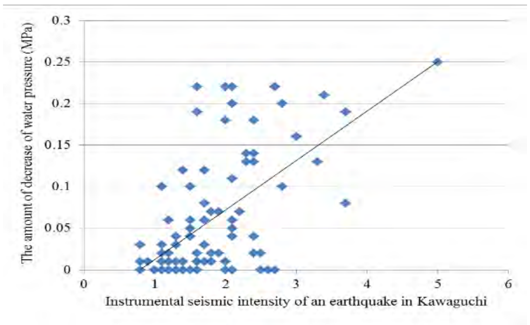

Figure 3: The relation between the amount of decrease of water pressure and the instrumental seismic intensity

Velocity Response Spectrum

We consider that there is another factor influences the abnormal behavior and we paid attention to the maximum velocity response spectrum of horizontal and vertical directions. We investigated the relation between these factors and the abnormal behavior of water flow and water pressure. Figures 4 and 5 show the relation between the increase of water flow and maximum velocity response spectrum of horizontal and vertical directions respectively. Figures 6 and 7 show the relation between the decrease of water pressure and maximum velocity response spectrum of horizontal and vertical directions respectively. It seems that the earthquakes with strong velocity response spectrum of horizontal direction tend to get the abnormal behavior according to Figures 4 and 6. By contrast, the values of maximum velocity spectrum of vertical direction are almost less than 5cm/s and it doesn't have a lot of difference from earthquakes. In addition, it seems that the values are plotted lengthwise and the abnormal behavior occurred even with small velocity response spectrum according to Figures 5 and 7. As results, we consider that water supplies tend to get the influence from the seismic motion of horizontal direction, and the vertical motion doesn't give a big influence to water supplies.

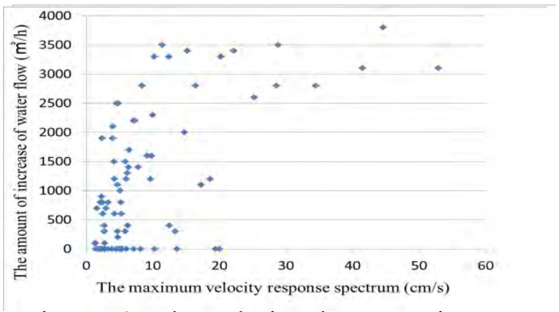

Figure 4: The relation between increase of water flow and the maximum velocity response spectrum of horizontal direction

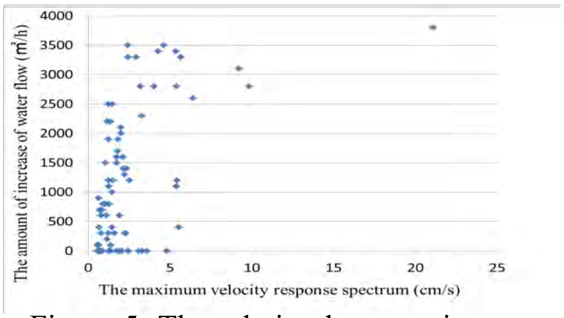

Figure 5: The relation between increase of water flow and the maximum velocity response spectrum of vertical direction

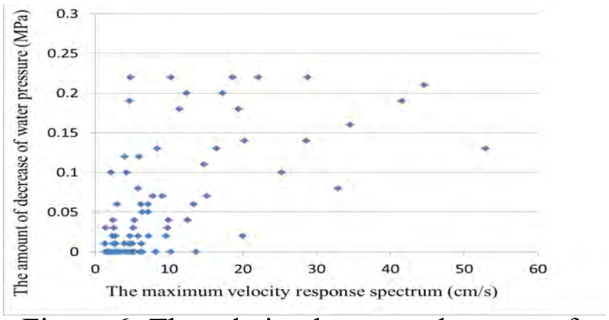

Figure 6: The relation between decrease of water pressure and the maximum velocity response spectrum of horizontal direction

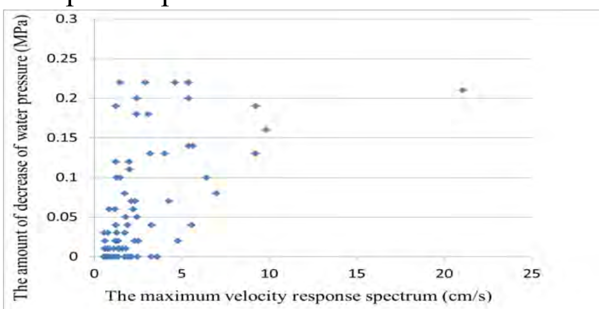

Figure 7: The relation between decrease of water pressure and the maximum velocity response spectrum of vertical direction

The Period

We focused on the period at the maximum value of velocity response spectrum and investigated the relation between the abnormal behavior and the period. Figure 8 shows the relation between the increase of water flow and the period of horizontal direction and Figure 9 shows the relation between the decrease of water pressure and the period of horizontal direction. According to the figures, the earthquakes with longer period which is around 1 second tend to get the abnormal behavior. The earthquakes with shorter period which is less than 0.5 seconds got less influence of earthquakes compared with the earthquakes with longer period.

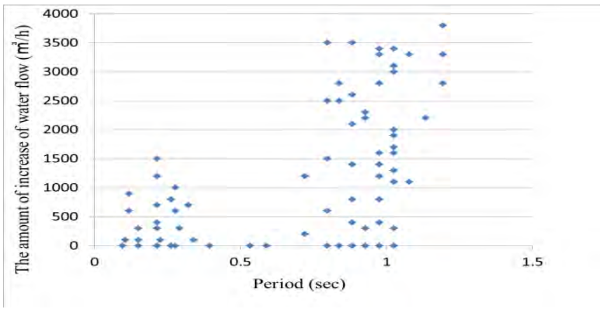

Figure 8: The relation between increase of water flow and the period of horizontal direction

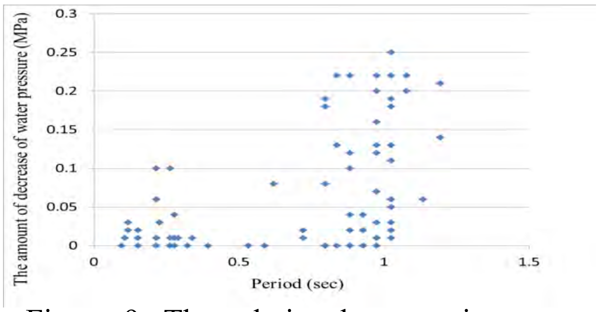

Figure 9: The relation between increase of water flow and the period of horizontal direction

The Velocity Response Spectrum and the Period

We analyzed each factor individually so we put two factors together and made the figures to see more details. We defined "behavior occurred" as the amount of increase of water flow exceeds 1000m^3/h, and the amount of decrease of water pressure exceeds 0.1MPa on this study. Figure 10 shows the relation between occurrence of abnormal behavior of water flow and seismic characteristics of horizontal direction. Figure 11 shows the relation between occurrence of abnormal behavior of water pressure and seismic characteristics of horizontal direction. These figures show that the earthquakes

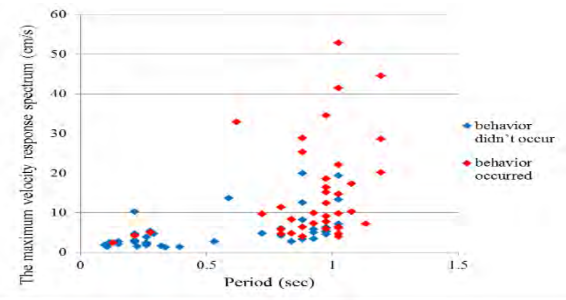

Figure 10: The relation between occurrence of abnormal behavior of water flow and seismic characteristics of horizontal direction

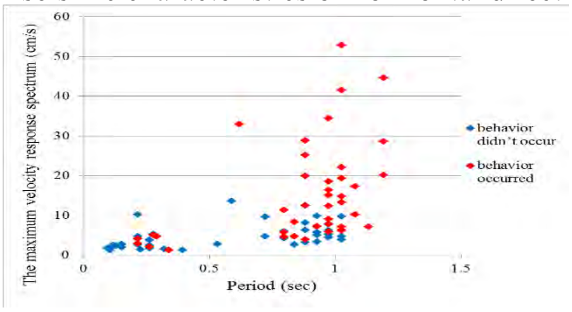

Figure 11: The relation between occurrence of abnormal behavior of water pressure and seismic characteristics of horizontal direction

with stronger velocity response spectrum and longer period give a lot of influence to water supplies. We found out that the tendency that the abnormal behavior didn't occur if the velocity response spectrum is low even if it is long period ground motion. Therefore, it is clarified that it is easy to influence the abnormal behavior if the earthquake is longer period motion and has larger velocity response spectrum.

3. CONCLUSION

First of all, we thought that the magnitude of seismic intensity in earthquakes influences the behavior of water flow and water pressure so we investigated the relation between them. We got the tendency that the stronger earthquake occurs, the stronger the behavior shows but the data is dispersing, and the mutual correlation is vague and we couldn't find a crucial proof with magnitude of the instrumental seismic intensity in earthquakes. Secondly, we focused on the velocity response spectrum and the period. We found out that the water supplies tend to get the abnormal behavior by seismic motion in horizontal direction and there is a tendency that if the velocity response spectrum increased, the behavior goes high as well. By contrast, the influence of that in vertical direction is not strong for water supplies. In terms of the period, we could see the tendency that the earthquakes with long period motion gets more influence compared with short period motion. Lastly, we investigated two factors together and made the figures to see the relation between the abnormal behavior and seismic characteristics. We could see the tendency that the earthquakes with longer period of horizontal direction and strong velocity response spectrum are easy to affect water supplies. According to these results, we consider that the water supplies get influence of sloshing in water tanks by resonance due to long period earthquake motion.

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Research of Earthquake Resistant Ductile Iron Pipe (ERDIP) for fault crossing

K. Oda*, T. Ishihara* and M. Miyajima**

Abstract

This study proposes a method for designing a water pipeline system against fault displacements by using Earthquake Resistant Ductile Iron Pipe (ERDIP). An ERDIP pipeline is capable of absorbing the large ground displacements that occur during severe earthquakes by movement of its joints (expansion, contraction, and deflection). Existing ERDIP pipelines have been exposed to several severe earthquakes such as the 1995 Kobe Earthquake and the 2011 Great East Japan Earthquake, and there has been no documentation of their failure in the last 40 years.

In the case of a pipeline that crosses a fault, there is the possibility of the occurrence of a local relative displacement of several meters between the pipeline and the ground. Hence, the present study was targeted at developing a method for designing an ERDIP pipeline that is capable of withstanding a strike-slip fault. This was done by FEM analysis, wherein 1500-mm shell elements were used to model the ERDIPs and spring elements were used to model the soil and ERDIP joints. An ERDIP pipeline can accommodate a fault displacement of about 2 m and the use of a “large displacement absorption unit” is an effective countermeasure for displacements exceeding 2 m.

INTRODUCTION

The 1995 Kobe Earthquake, which occurred just beneath the city, was caused by the movement of an active fault. In Awaji-shima Island, the movement of Nojima-fault affected the ground surface and it caused substantial damages to a lot of buildings [1], [2].

It has also been reported that the 1999 Chichi Earthquake in Taiwan and the 1999 Kocaeli Earthquake in Turkey induced surface fault displacements that damaged buried pipelines. The damages included compression and lateral deformations. Indeed, there have been instances when pipelines had to be installed across known faults and this required the design of the pipelines to absorb surface fault displacements.

An earthquake resistant ductile iron pipe (ERDIP) is capable of absorbing ground displacement in the event of an earthquake. This is achieved through a joint expansion/contraction and deflection mechanism. Over the past 40 years, ERDIP pipelines have been exposed to several earthquakes with seismic intensities of above 6, as well as accompanying severe liquefaction, such as occurred in the 1995 Kobe Earthquake and the 2011 Great East Japan Earthquake. Despite this, there has been no documented failure of an ERDIP pipeline. The earthquake resistance of ERDIP pipelines has been confirmed through observation of the pipe movement, joint movement, and pipe stress during earthquakes, as well as by liquefaction tests and post-earthquake surveys.

However, few studies have considered pipe movement and safety at fault crossings, and those that have were limited to small pipelines. In the present study, we focused on large-diameter pipes such as those of water systems, which could be damaged by an earthquake. We quantitatively measured the amount of fault displacement that a normal pipeline of such diameter could absorb and investigated countermeasures against large displacements.

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ANALYSIS OF PIPELINE BEHAVIOR AT FAULT CROSSING

Structure of ERDIP and its behavior

Fig.1 shows the joint behavior of a US-type joint, a type of an ERDIP joint, the performance of which was investigated in the present study. Table 1 gives the performance parameters of the joint. The joint is capable of expanding/contracting by 0.5% of its standard pipe length (e.g., 4 m in the case of DN1500). When the joint is fully expanded, the spigot projection and lock ring lock tightly together to prevent leakage resulting from pull-out of the joint.

Fig.2 shows the pipeline behavior during ground crack and subsidence. When a pipe joint is fully expanded or deflected, it may pull on other pipe joints one after the other to absorb the ground deformation. The pipeline is thus referred to as a “chain structure pipeline”. Buried ERDIP joints are not expanded by water pressure because the pipes are supported by the ground.

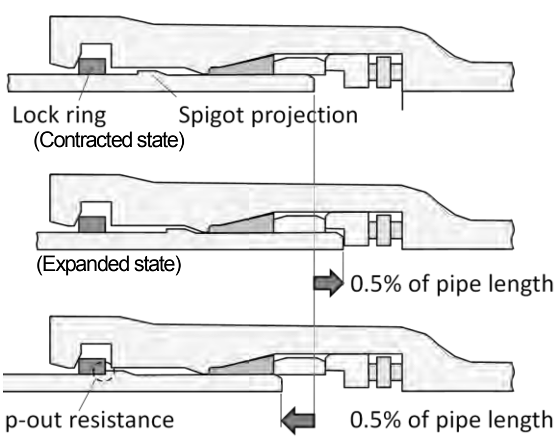


FIG.1 Joint behavior of US-Type joint

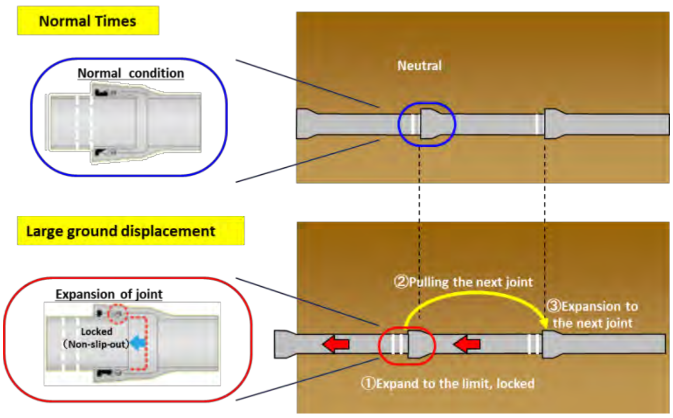


FIG.2 ERDIP pipeline behavior

Table.1 Joint behavior of US-Type joint

Property	Performance
Pull out resistance	3DkN（D：nominal daimeter mm）
Amount of expansion/contraction	±0.5% of pipe length
Deflection angle	4°(DN1500)

Table 2 Major fault in Los Angeles, US

Fault name	Slip rate (mm/year)	Average slip (m)
Newport Inglewood	1.5	1.7
Palos Verdes	3.0	2.8
Raymond	1.5	1.7
San Fernando	5.0	1.8
Santa Susana	5.0	2.1
Sierra Madre	2.0	3.3

Outline of fault model

Institute of Earthquake and Volcano Geology, a research institute of National Institute of Advanced Industrial Science and Technology (AIST), releases active fault database of Japan since 2005. As of Jan. 20, 2015, 389 cases are registered with fault displacement. Reverse fault is about 50% of all faults and 90% of inclination angles of these faults are 45°, 60° and 90°. Fig.3 shows distribution of displacement at active faults in Japan. According to this data, about 50% of active faults were displaced 2m or less. And about 75% of active faults were displaced 3m or less. In addition, Table 2 shows that the displacements of major faults in Los Angeles are mostly 3m or less.

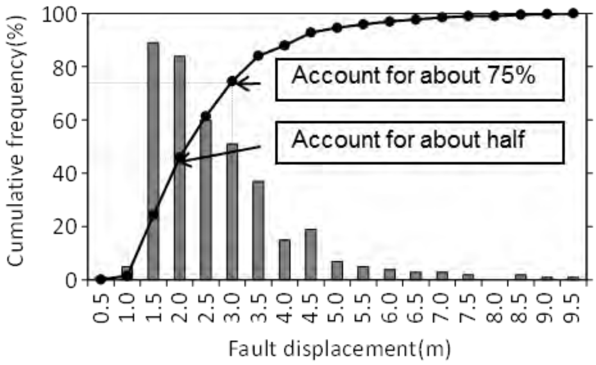


FIG.3 Fault displacement in Japan

Therefore, we set the upper limit of vertical fault displacement as 3m on this analysis model.

Analysis model

The analysis conditions are shown in Fig.4 and Table 3.

The pipeline model adopts DN1500 US-Type ERDIP which doesn't include the fittings such as bends and Tees. The location of fault displacement is set so that the fault plane crosses the joint. The target range of analysis is 200m pipeline in order not to affect the fault movement to both ends. The length of each pipe section is 4m which is standard length of DN1500 US type ERDIP.

Fig.5 shows outline of analysis model. The ductile iron pipes are modeled by 3-dimension shell element. The charac- teristic of joint and soil are modeled by joint spring and soil spring respectively. Geometric non-linearity and also material non-linearity to evaluate the large pipeline displacement are the considered in the FEM analysis. (Software: Marc. Mentat)

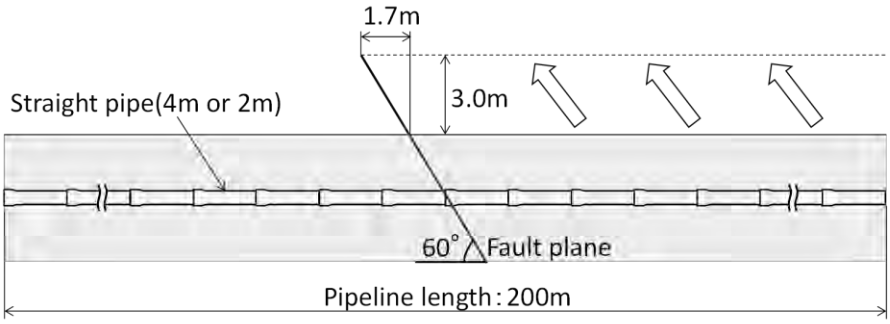


FIG.4 Analysis condition

Table.3 Analysis condition

Joint type	DN1500 US-Type joint
Pipe length	4m
Pipeline lengrh	200m
Amount of expansion/contraction	±0.5% of pipe length
Fault type	Strike-slip fault
Fault deflection angle	60°
Fault displacement	Orthogonal: 3m ,Axis: 1.7m
Coefficient of subgrade reaction	33,827 kN/m3

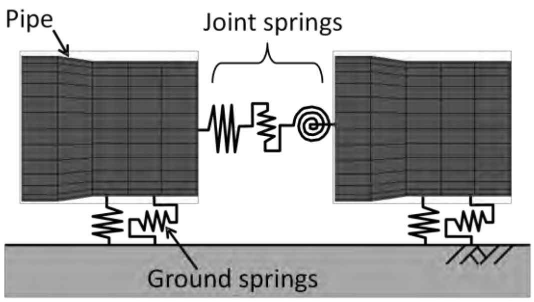


FIG.5 Outline of analysis model

Analysis condition

Criteria for evaluation. Table 4 shows the criteria for the evaluation. The stress generated on pipe body should be less than proof stress and the joint deflection angle should be equal or less than 4 degrees to keep the leak tightness performance. The axial force applied to the joint should be equal to or less than 3DkN (D: nominal diameter in millimeter)

Table.4 Criteria for evaluation

Joint		Pipe body
Axial force (kN)	Deflection angle (deg)	Stress (MPa)
4,500	4.0	270

Joint spring. The joint springs are defined based on the result of actual testing. Fig.6 shows the example of testing to determine the rotation spring of joint. Fig.7 shows the summary of joint spring. The axial direction spring has binary regions. In the 1st region (displacement 0 to δa), the joint can slide with small force because the resistance force is only friction between the pipe and rubber gasket. In the 2nd region (displacement over δa), the locking system of the joint can be activated, and the joint can't slide any more.

The rotation spring also has binary regions. In the 1st region, the joint can deflect with small moment because the spigot cannot touch the socket inside. In the 2nd region, the resistance of rotation will be

increased due to contact between the spigot and socket inside. The maximum deflection angle of DN1500 US-Type joint is 4 degrees.
Fig.8 shows the joint spring for shell element. They are set between each socket and spigot node with 3 directions (axial, normal and tangential direction) to coincide the characteristics of joint spring as shown in Fig.7. Fig.9 shows the comparison of joint rotation characteristic between the test result and joint spring. The joint spring is well accorded with test result.

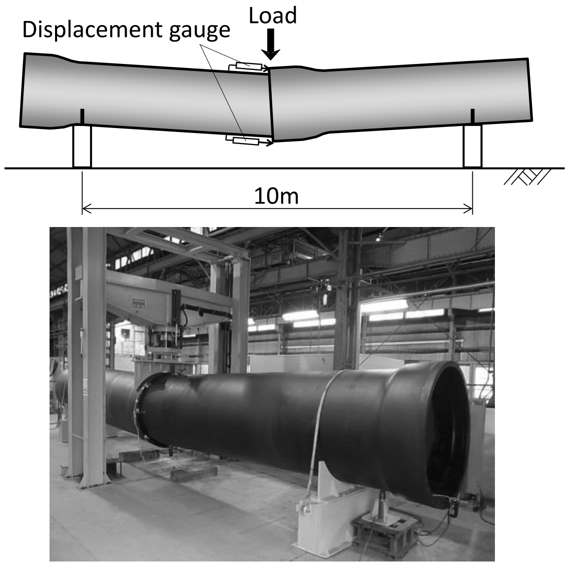


FIG.6 Test method to define rotation spring

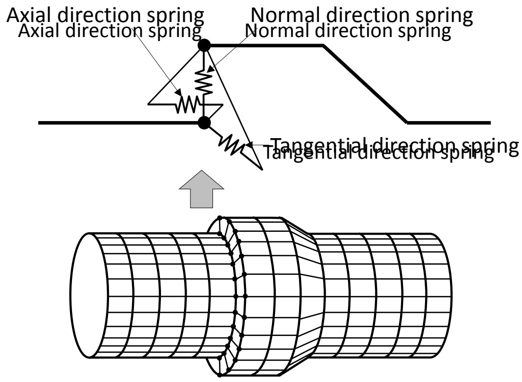


FIG.8 Joint spring for shell element

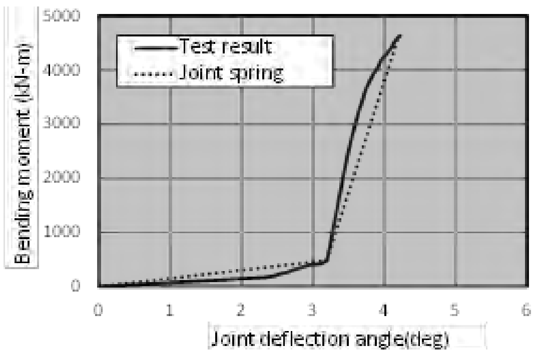
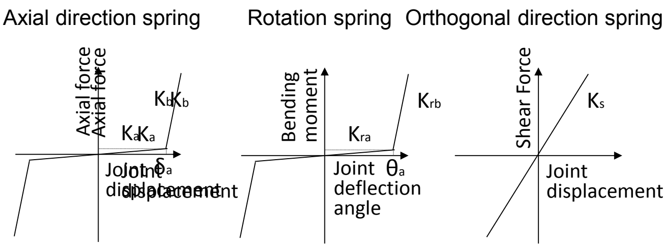


FIG.9 Comparison of joint rotation characteristic



Axial direction spring		Rotation spring		Orthogonal direction spring	
Ka	9.20 ×10^3(kN/m)	Kra	1.66 ×10^2(kN-m/deg)	Ks	2.0 ×10^6(kN/m)
Kb	1.98 ×10^6(kN/m)	Krb	4.28 ×10^2(kN-m/deg)		
δa	±0.0475(m)	θa	3.2(deg)		

FIG.7 Joint springs

Soil spring. Soil spring for axial direction is set as shown in formula (1a) based on previous study (See. Reference [14]). Internal friction angle of soil (Δ) is set 36 degrees based on the text (See. Reference [15]). In addition, soil spring is defined bi-linear model as shown in Fig.10 to be considered slip between the pipe and soil. Soil spring for orthogonal direction is set as shown in formula (2a) based on subgrade reaction modulus. In this study, soil springs are defined as general stiffness soil except to sufficiently high stiffness.

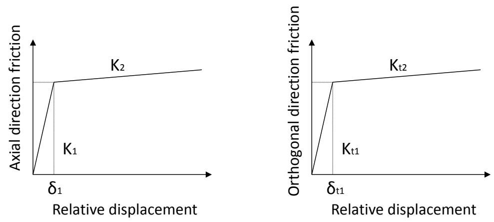
$$k_1 = \frac{\pi}{2} \cdot D \cdot \gamma \cdot \left(h + \frac{D}{2} \right) \cdot (1 + k_0) \tan\Delta \cdot \frac{\ell}{\delta_1} \tag{1a}$$

$$k_2 = 0.001 \cdot k_1 \tag{1b}$$

$$k_{t1} = K \cdot D \cdot \ell \tag{2a}$$

$$k_{t2} = 0.005 \cdot k_{t1} \tag{2b}$$

k1, k2	Constant of axial direction soil spring
kt1, kt2	Constant of orthogonal direction soil spring
D	Outside diameter of pipe
γ	Unit weight of soil (=16kN/m3)
h	Depth of earth cover (=3.0m)
k0	Coefficient of lateral soil pressure at rest(=1.0)
Δ	Internal friction angle of soil (=36°)
$\delta 1$	Inflection point of axial direction spring
K	Subgrade reaction modulus
ℓ	Unit length of pipe



Axial direction spring		Orthogonal direction spring	
K_1	3.66×10^4(kN/m)	K_{t1}	5.26×10^4(kN/m)
K_2	$0.001\times K_{g11}$(kN/m)	K_{t2}	$0.005\times K_{g21}$(kN/m)
δ_1	0.0005(m)	δ_{t1}	0.0005(m)

FIG.10 Soil spring

Results of analysis

Fig.11 to Fig.15 show the example of analysis results. Horizontal axis of each figure is axial distance. The positon of fault displacement is defined as 0m.

The ERDIP pipeline can deform in accordance with fault movement as shown in Fig.11. The portion of pipeline located near fault deform largely more than the fault displacement to orthogonal direction (bending outside).

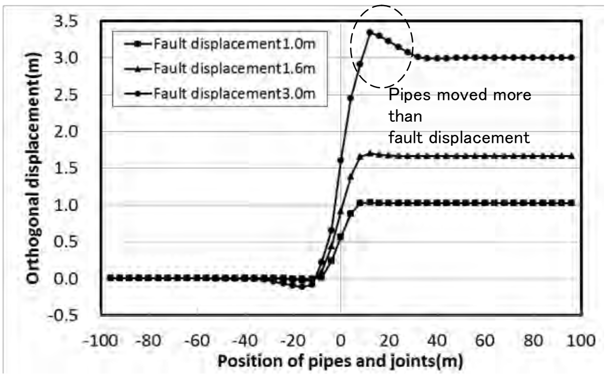


FIG.11 Pipeline displacement (Orthogonal direction)

Fig.12 shows the analysis results of joint deflection angle. The plus and minus mean the direction of joint deflection. In case of 3m fault displacement, 4 joints located near fault are deflected more than limit an gle (4 degrees).

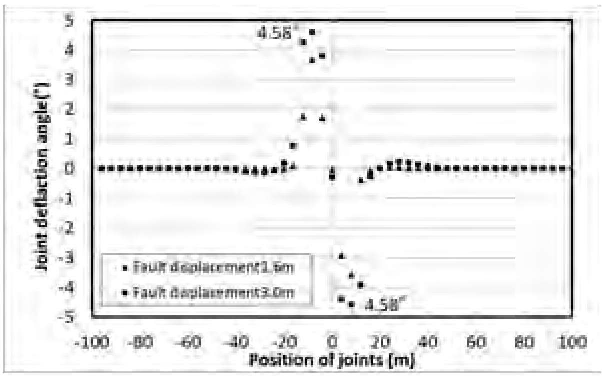


FIG.12 Joint deflection angle

Fig.13 shows the analysis results of axial force occurred at the joint. The plus and minus mean the expansion (+) and contraction (-) respectively. The maximum axial (contraction) force is generated at the joint located at the fault displacement. When the fault displacement is over 1.6m, the axial force exceeds 3DkN, which is performance limit of the joint. In case of 3m fault displacement, lots of joints exceed the 3DkN. This is because the total soil friction force generated on 140m of piping is acting on the joints near the fault location.

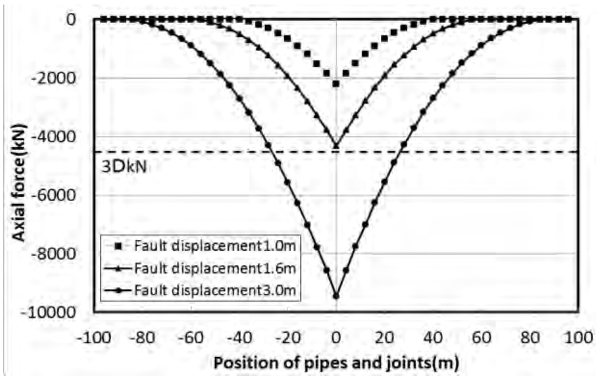


FIG.13 Axial force

Fig.15 shows the contour drawing of stress distribution generated in pipe body in case of 3m fault displacement. The stress generated in the portion of pipeline located 8m away from fault displacement is maximum stress, it is only 111MPa which is within elastic range.

The analysis results with respect to fault displacement are shown in Table 5. The ERDIP pipeline can withstand up to 1.6m fault displacement with its performance defined in Table 4. However, when the fault displacement exceeds 1.6m, axial force generated at joint is beyond performance limit (3DkN). Furthermore, in case of 3m fault displacement, not only axial force but also joint deflection angles exceed performance limit.

Table 5 Analysis results

Fault displacement (m)	Axial force (kN)	Stress (MPa)	Joint deflection (deg)
1.0	2,212	25	31
1.6	4,314	49	3.7
2.0	5,760	67	4.0
3.0	9,460	111	4.6
Allowance limit	4,500	270	4.0

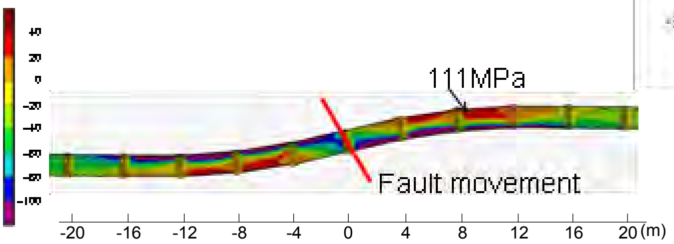


FIG.15 Stress distribution

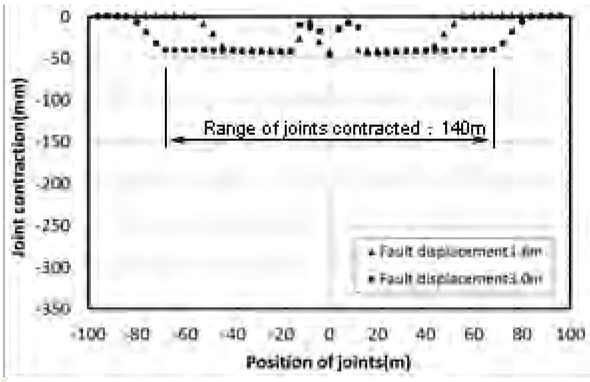


FIG.14 Joint contraction

ERDIP PIPELINE SYSTEM WITH 1.6M OR MORE FAULT DISPLACEMENT

Large displacement absorption pipeline system (LDAPS)

According to FEM analysis results in case of 1.6m or more fault displacement, the axial force generated at joints should be reduced because the axial force will reach 4,500kN which is the limit value of the joint. Also, the joints near the fault are subject to exceed the limit deflection angle due to the big axial force.

Therefore, we devise the large displacement absorption pipeline system (LDAPS) as shown in Fig.16. The LDAPS is ERDIP with large displacement absorption units (hereinafter, unit) as shown in Fig.17. The unit consists of long collar and ERDIP socket and spigot. The long collar has 10 times bigger expansion/ contraction amount (e.g. in case of DN1500, 600mm) and each ERDIP socket and spigot can deflect so that the unit can absorb locally-large relative displacement between ground and pipeline efficiently.

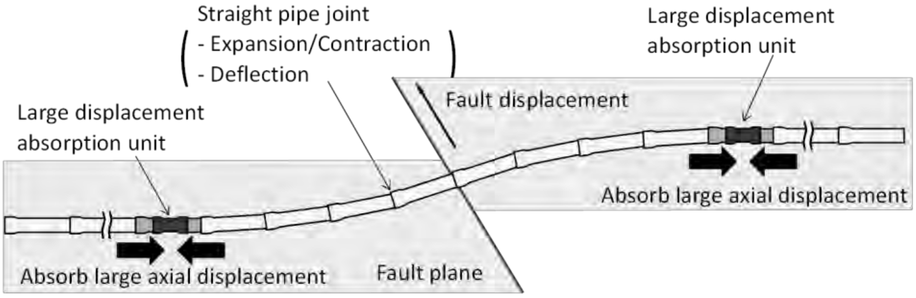
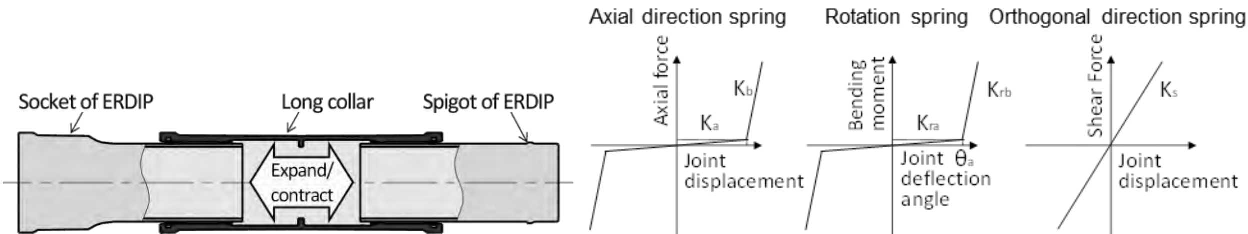


FIG.16 Large displacement absorption unit



Axial direction spring		Rotation spring		Orthogonal direction spring	
Ka	9.20 ×10^3(kN/m)	Kra	1.66 ×10^2(kN-m/deg)	Ks	2.0 ×10^6(kN/m)
Kb	1.98 ×10^6(kN/m)	Krb	4.28 ×10^2(kN-m/deg)		
δa	-0.3(m)	θa	0.5(deg)		

FIG.17 Large displacement absorption unit

The length of unit will be equal or less than pipe length so that the deflection performance of unit has equal to or more than pipe joint. Since there are no specialized pipes, the pipeline design and installation will be easy. The units should be placed where the joints are not subject to deflection angle of less than 1 degree. The span of each unit can be calculated as 36m (See Fig.18).

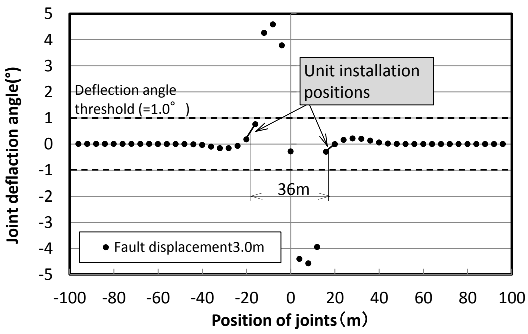


FIG.18 Unit installation

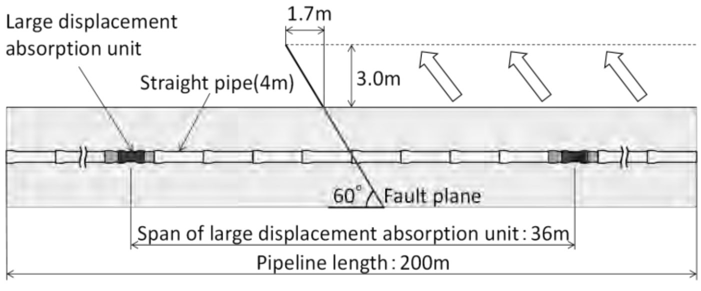


FIG.19 Analysis condition

Analysis results of LDAPS

To verify the effectiveness of LDAPS, we conduct FEM analysis. The analysis conditions are same as straight pipeline case (Table 3). The length of LDAPS is 200m. The units are placed at 36m intervals. The fault displacement is located in the center. Fig.19 shows analysis condition for LDAPS. The results of analysis are shown in Fig.20 to Fig.24. White plots in the drawing stand for the joint of long collar.

As shown in Fig.20, the range of joints contracted is reduced up to 72m.This is because the units absorb locally-large axial displacement. In consequence, the axial force can be dramatically reduced compared to regular ERDIP pipeline due to the reduction of friction force from the ground as shown in Fig.21. It was found that the span of units is important factor for the reduction of axial force. Because the axial forces are dramatically changed at the unit portion and increased from units toward fault movement.

Fig.22 shows the pipeline displacement. The pipeline displacement at the portion of “A” toward bending outside direction can be reduced due to the reduction of the axial f orce. In consequence, the joint deflection angle can be reduced less than performance limit (4 degrees).

Fig.24 shows the stress distribution on pipe body. The stress is totally-smaller than in case of regular ERDIP pipeline (Fig.15).

According to above results, it was found that LDAPS can be used for 3m displacement fault crossing pipeline as the pipeline stress keep within elastic range. Furthermore, the LDAPS is effective

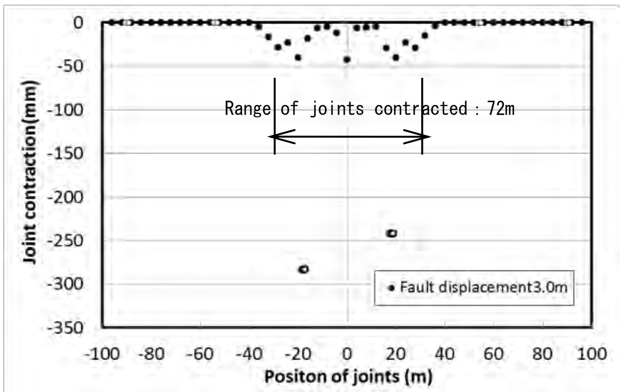


FIG.20 Joint contraction

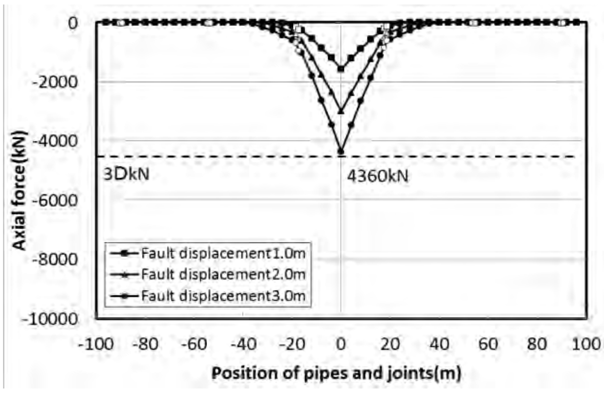


FIG.21 Axial force

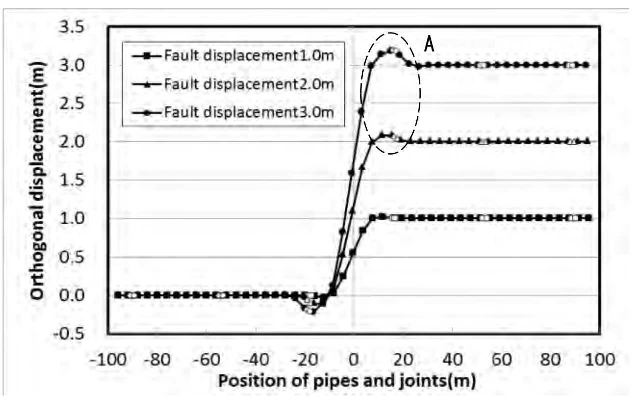


FIG.22 Pipeline displacement (orthogonal direction)

design method against larger fault displacement because the LDAPS can improve the performance with the number of unit and span of unit in accordance with fault displacement.

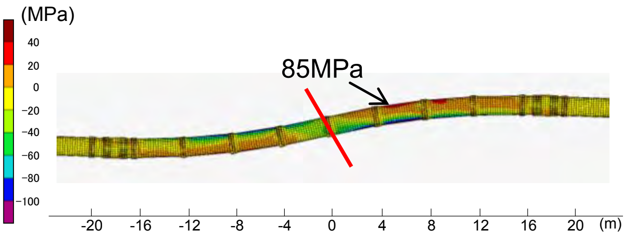


FIG.24 Stress distribution

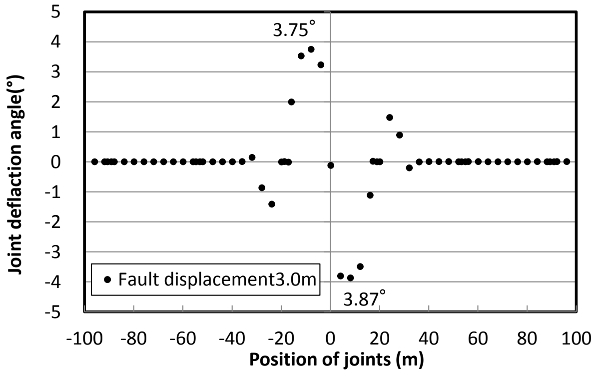


FIG.23 Joint deflection angle

DESIGN FLOW OF LDAPS

To design the pipeline with LDAPS, it is required that the unit should be placed with adequate span in accordance with anticipated fault displacement, fault crossing angle and ground condition. If the designed span is shorter than adequate span, it becomes excessive design. Meanwhile, if it is longer, it may not meet the required value on axial force, joint deflection angle and stress.
In this chapter, we describe the design flow of LDAPS using FEM analysis (Fig.25).

STEP 1 Analyze pipeline with standard length pipes [i) and ii) of Fig.25]
Performance evaluation of pipeline consists of standard length pipe is conducted through FEM analysis. The criteria are as follows;
Axial force: 3DkN and under
Joint deflection angle: limit joint deflection angle and under
Stress generated on pipe body: proof stress (270MPa) and under

STEP 2 Set preliminary span [iii) of Fig.25]
When pipeline with standard length pipes is not under the criteria, the span of unit should be decided so that the unit will be placed where the deflection angle is equal or less than threshold value θt (*2 of Fig.25). The span selected by this method tends to be same as adequate span or more than that.

STEP 3 Decide span [iv), v), vi), vii) of Fig.25]
Axial force, joint deflection angle and stress generated on pipe body are analyzed and evaluated again in a row. When axial force is not under the criteria, new span S1 is decided using the formula (3).

$$S_1 = S_2 \frac{f_1}{f_2} \tag{3}$$

where,
S1 New Span (m)
S2 Span on analysis condition (m)
f1 Axial force from analysis result (kN)
f2 Axial force at criterion value (=3DkN, D:diameter)

When axial force meets criterion value and joint deflection angle and stress do not meet the criteria, it is required that span or each pipe length should be shorter until it fulfills the criteria.
The flow of iv) through vii) of Fig.25 will be repeated until proper span is determined.

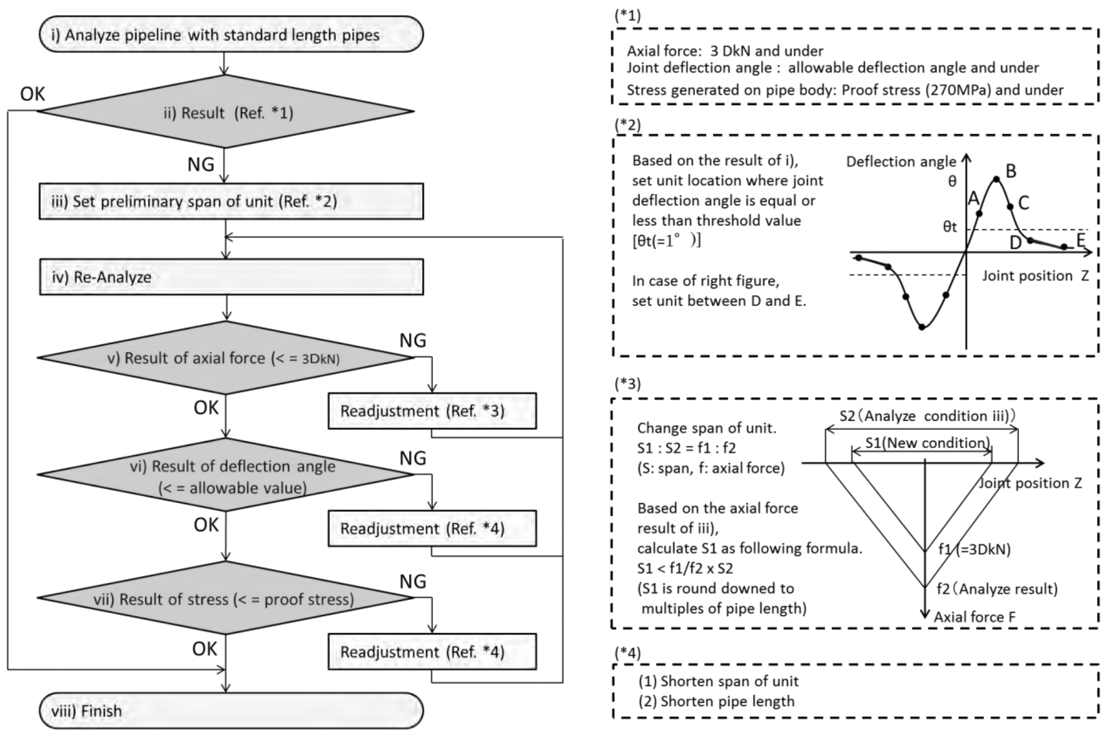


FIG.25 Design flow of LDAPS using FEM analysis

DESIGN METHOD WHEN A LOCATION OF FAULT IS NOT CLEARLY IDENTIFIED

On the above analysis, the location of fault was considered as the center of the span and the units are placed evenly. However, there are cases where the exact locations of fault cannot be identified. To handle this issue, we studied the safety of LDAPS under the situation. Fig.26 shows the analysis condition. We selected seven locations as a possible fault. No.1.3.4.5 and 7 are at joint portion, No.2 is at pipe body, No.6 is at unit. We conducted FEM analysis at each location. Analysis condition is same as that of Table 3 and Fig.19 except the fault movement location.

Fig.27 shows comparison of analysis result. Maximum axial force, maximum joint deflection angle and maximum stress are indicated. No.5 and No.7 showed relatively higher value than others, but still within the criteria. As a result of this analysis, we found all the locations to be safe if the fault cross the pipeline anywhere between the units.

Fig.28 shows an example of design at assumed area of fault. The key is to set a unit outside of assumed area on both side and some units inside the area. The span in the assumed area is S, whereas the span between a unit out of the area and a unit at edge is S’(<S). The S shall meet the criteria through FEM analysis. In case of above mentioned analysis, S will be 36m. Using this design method, “Large displacement absorption units” can be properly set and perform to secure the safety of water pipeline wherever a fault exists in the assumed area.

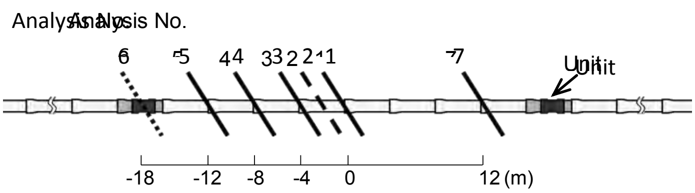


Fig.26 Analysis condition (Slash: Fault)

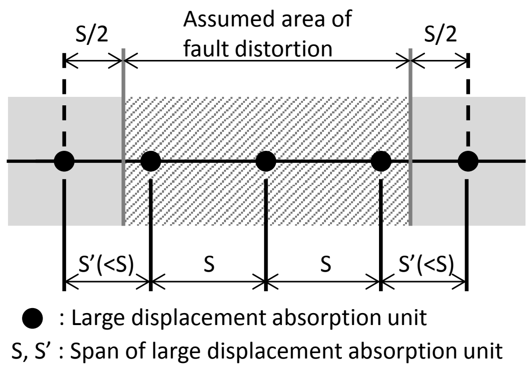


Fig.28 Design for assumed area of fault distribution

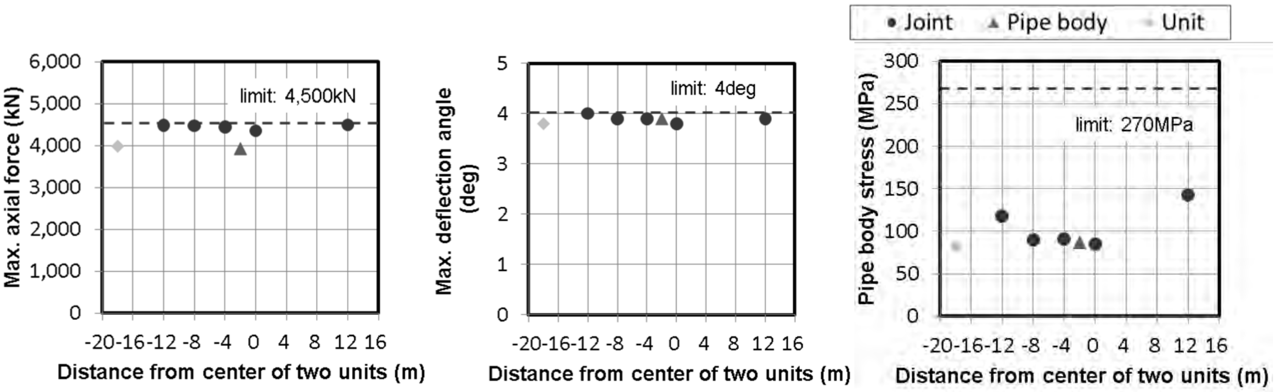


Fig.27 Comparison of analysis results

CONCLUSION

In this study, we focus on larger diameter pipe which cause serious damage to water system by earthquake and conduct FEM analysis to understand how much fault displacement the normal pipeline can absorb. Furthermore, we establish the countermeasure design method against such large fault displacement.

1) DN1500 US-type ERDIP pipeline can absorb 1.6m fault displacement by the joint expansion/contraction and deflection. The stress generated on pipeline by fault displacement is within elastic range.

2) As a countermeasure for 1.6m or more fault displacement, it was found that LDAPS is effective to absorb axial direction local-displacement and can accommodate the 3m or more ground displacement. LDAPS consists of "Large displacement absorption unit" which has 10 times bigger expansion/contraction amount than regular joint and ERDIP pipe.

3) "Large displacement absorption unit" should be placed on the both side of fault at the locations where they are not subjected to deflection of more than 1 degree based.

4) In case that the exact location of fault is not identified, we establish the design method using "Large displacement absorption units".

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Development of Low-reaction Type of Steel Pipe for Crossing Fault

H. Nakazono, N. Hasegawa , H. Nagamine, T. Imai

ABSTRACT

In response of pipe damages caused by fault offset, the authors had developed the normal type of SPF, as a countermeasure of water supply pipelines for crossing fault. However, in case of reverse fault in flexure layer, the compression force mainly works on the pipe in the axial direction, and the reaction force at wave-shaped pipe section is huge, and the strain at the sleeve pipe section is huge as well. Therefore, the low-reaction type of SPF has been developed, in order to have the capacity of normal type, to absorb the deformation of axial compression direction and to reduce the reaction force of the wave-shaped pipe section. The optimum shape of the wave-shaped pipe section has been determined by FE analysis, to put a value into the 2 variables; the height and the width. As the result, the low-reaction type could reduce the maximum reaction force by one third of the normal type. The axial compression test and the split-basin test have been carried out, in order to verify the deformation performance of the low-reaction type. Moreover, this paper introduces the case study to verify the low-reaction type on FE analysis.

INTRODUCTION

Recently, pipe damages, caused by fault displacement, had been occurred as one of earthquake damages. Water steel pipes, of which the diameter are 2,200mm and 2,000mm, had been damaged by Kocaeli earthquake of 1999 in Turkey and Chi-chi earthquake of 1999 in Taiwan. Therefore, the authors had developed steel pipe for crossing fault (hereinafter SPF) as a countermeasure of water supply pipelines for crossing fault (Hasegawa, 2009). The normal type of SPF has a structure to absorb bending deformation in case of reverse fault. However, in case of reverse fault in flexure layer, it is necessary to absorb bending and axial compression deformation, and to reduce the reaction force on axial compression deformation. Therefore, the low-reaction type of SPF has been newly developed.

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PIPE IN FLEXURE

Flexure

Flexure is a phenomenon that fault slips down and surface ground bends.

There are 2 types of flexures. 1st one is the case that the fault lies in the ground, as shown in the left side of Figure 1. 2nd one is the case that soil accumulates after the fault appeared on the ground surface, and the ground lifts up when the fault raises again, as shown in the right side of Figure 1.

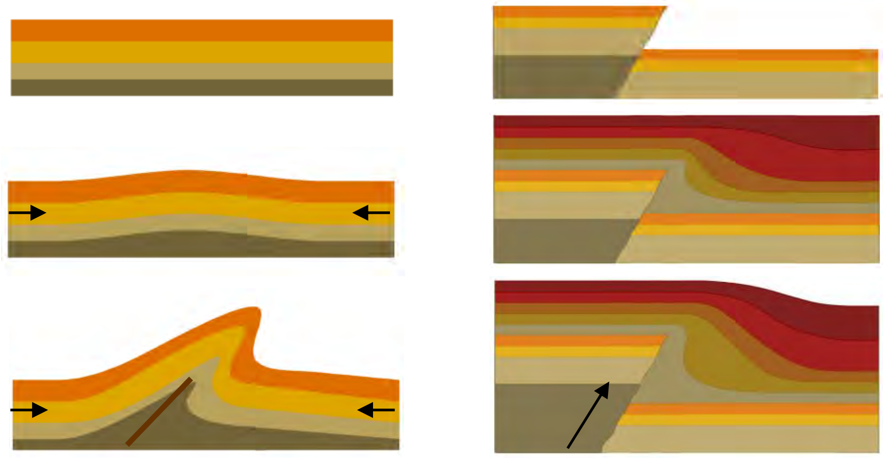


Figure 1 Flexure

Required Performance of Pipe in Flexure

In case of reverse fault in flexure layer, the fault plane does not reach to the ground surface because of a soft ground, although the fault displacement occurs.

If the pipeline is installed in the reverse fault of flexure layer, the compression force mainly works on the pipe in the axial direction. As it can be assumed that the fault plane newly appears in the flexure layer, it is necessary to absorb the bending deformation as well.

Moreover, the reaction force at wave-shaped pipe section (hereinafter WAVE) is huge, and the effect of the strain at the sleeve pipe section on the both sides of WAVE is huge as well, in case the axial compression deformation occurs.

Therefore, low-reaction type of SPF has been developed, in order to have the capacity of normal type of SPF, to absorb the deformation of axial compression direction and to reduce the reaction force of WAVE.

DEVELOPMENT OF LOW-REACTION TYPE OF SPF

Concept of Low-reaction Type of SPF

The WAVE, SPF has, is designed and manufactured, in order to be easy to deform. The optimum shape of the WAVE has been determined by FE analysis, to put a value into the 2 variables; the height and width of the WAVE, in order to absorb the axial compression deformation and to reduce the reaction force of WAVE in the axial direction. And, the allowable angle has been determined as 8 degrees, in order to absorb the bending deformation.

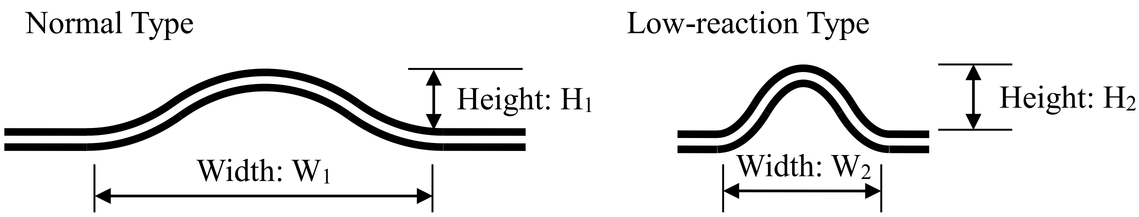


Figure 2 Reformed shape of Wave-shaped Pipe Section

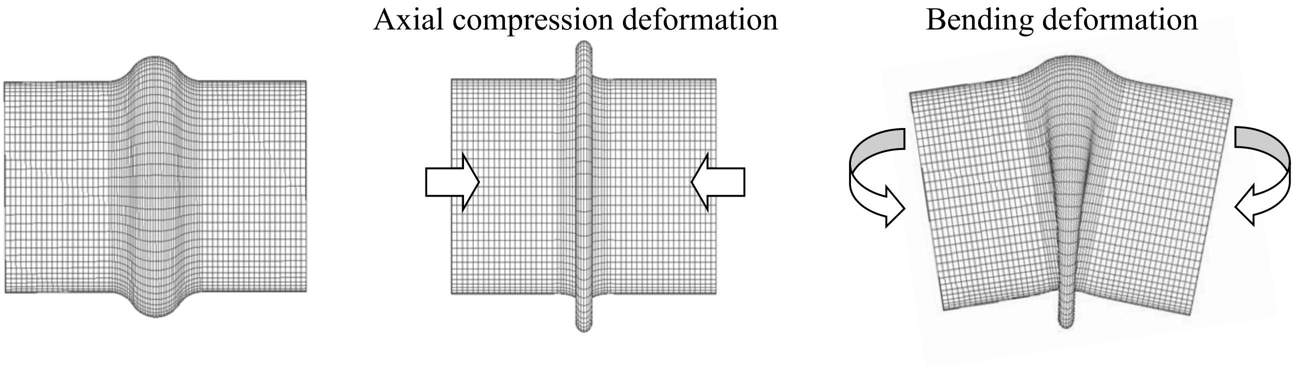


Figure 3 Deformation of Low-reaction Type of SPF

Compared with the reaction forces on the normal type and low-reaction type by FE analysis, the low-reaction type of SPF could reduce the maximum reaction force by one third of the normal type, as shown in Figure 3.

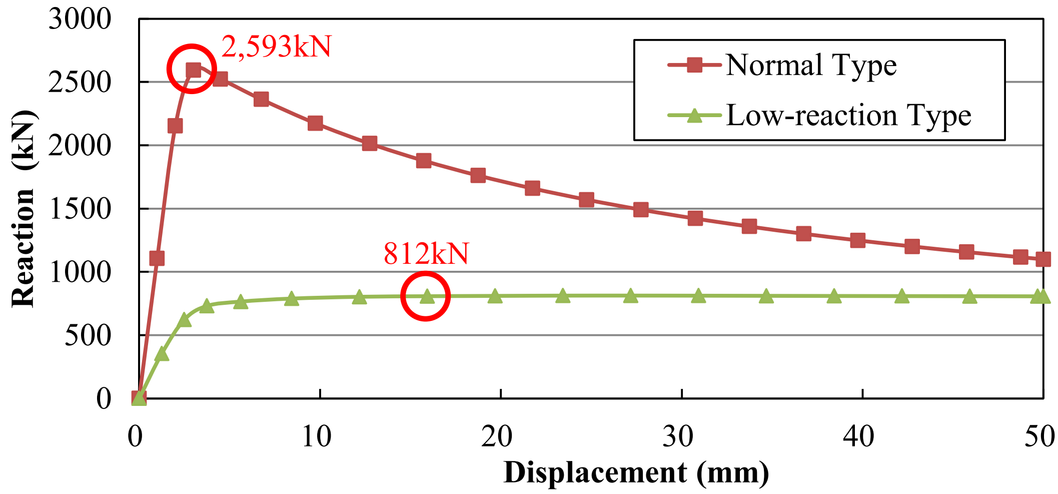


Figure 3 Comparison of Reaction by Displacement

Experiments

The axial compression test and the split-basin test have been carried out, in order to verify the deformation performance of the low-reaction type of SPF. In each experiment, there are 3 test pipes, of which the diameter is 100mm.

Axial Compression Test

The axial compression test has been carried out, by using the structural testing machine, as shown in Figure 4. In this experiment, 2 WAVEs were installed in the test pipe, in order to confirm the coupled deformation of the 2 WAVEs, as shown in Figure 5.

Figure 4 Structurral Testing Machine

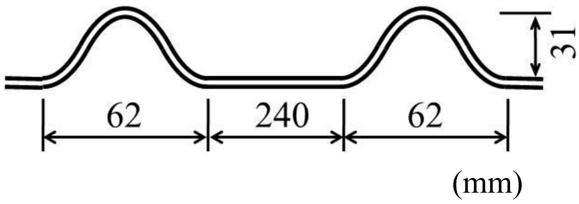
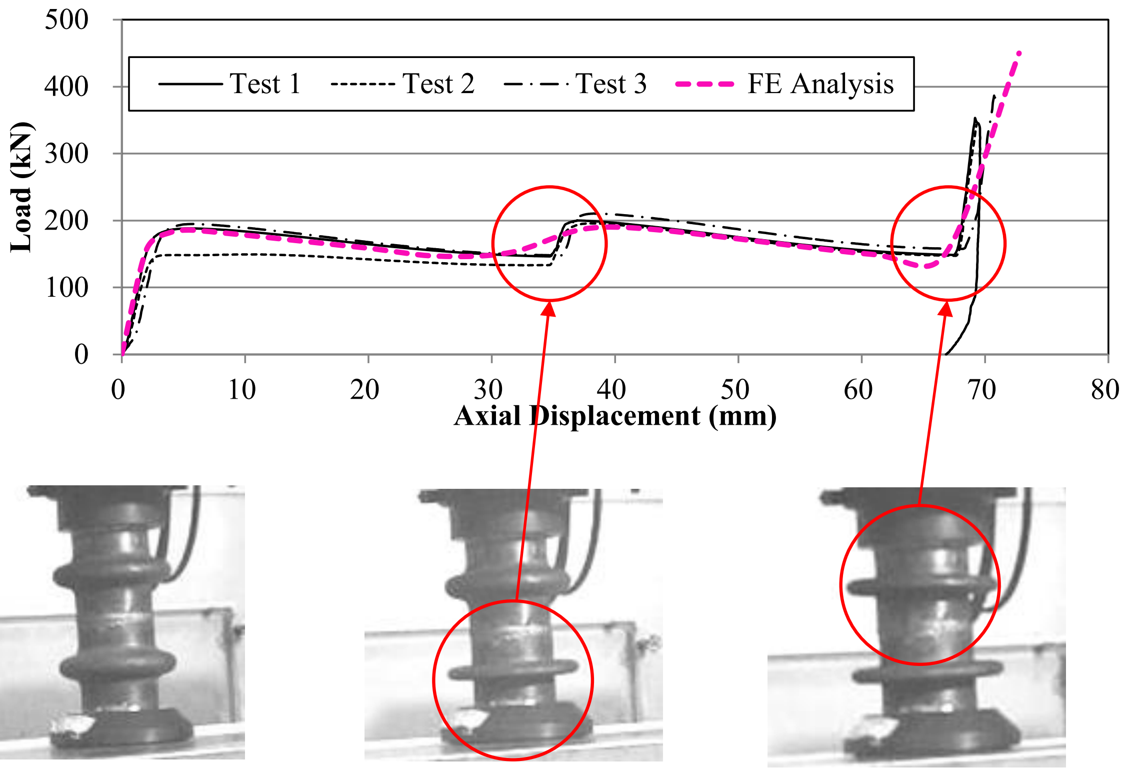


Figure 5 Shape of Test SPF

The load by the axial displacement is shown in Figure 6 in case of 3 test results and FE analsis result. One of test results was diferent from any other results at the maximum load, because the edge of the test pipe was not cut accurately. However, the results of 3 tests and FE anlysis have the same tendencies, especially at the 1st and 2nd points to contact the inner pipe walls. Therefore, it could be found that these results have highly-repeatable.



Initial State

Contact (Lower Wave)

Contact (Upper Wave)

Figure 6 Results of Axial Compression Test

Split-basin Test

The split-basin test has been carried out, in order to confirm the performance of SPF under the buried condition. The dimension of the basin is 1.0m as the width, 1.0m as the depth and 5.0m as the length. As shown in Figure 7, the partition plate was set as the fault plane in the split basin, and the load was forcibly applied to the left side of split basin by using the hydraulic actuator, as the displacement of reverse fault. The fault angle was assumed as 80 degrees.

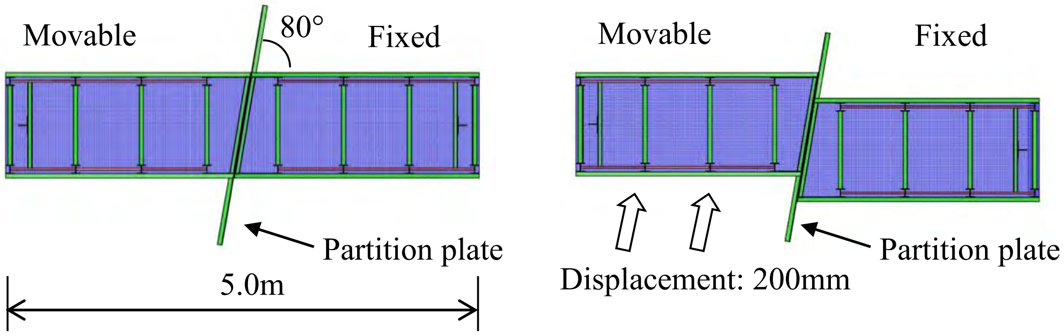


Figure 7 Plan of Split-basin Test

The diameter of the test pipe was 100mm (O.D.114.3mm, thickness 2.3mm, length 6m), in the assumption of one tenth model of 1000mm. As shown in Figure 8, the distance between 2 WAVEs was 600mm across the fault plane, according to FE analysis result. The test pipe was fixed in rotation direction and free in axial direction. Moreover, the amount of displacement was set as 200mm, as the result, the inner pipe wall contact angle was 18.5 degrees.

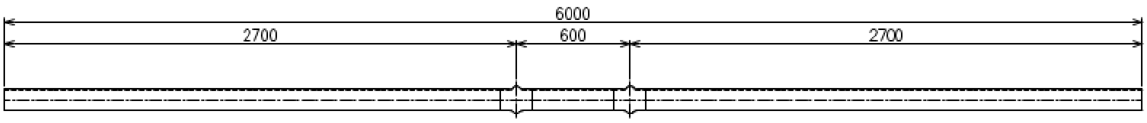


Figure 8 Pipe of Split-basin Test (100mm)

The test pipe after deformation is shown in Figure 10. The deformation of SPF appeared only at the WAVEs, which absorb the fault offset as bending deformation. The adequate result has been obtained about the installation position of the WAVEs, because the deformation concentrated only on the WAVEs and the WAVEs were deformed equally on both sides.

Figure 9 Overview of Split-basin

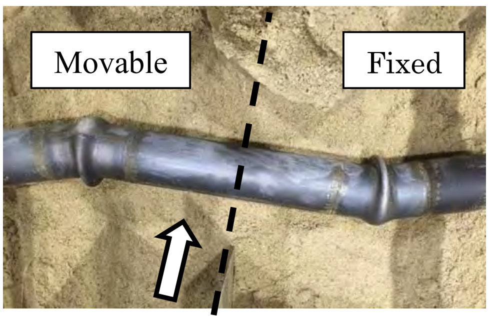


Figure 10 Test Pipe after Deformation

The result of FE analysis under same condition as the split-basin test is shown in Figure11. The adequate result also has been obtained that the deformation in FE analysis was closely similar with the deformation in the split-basin test, as shown in Figure 10.

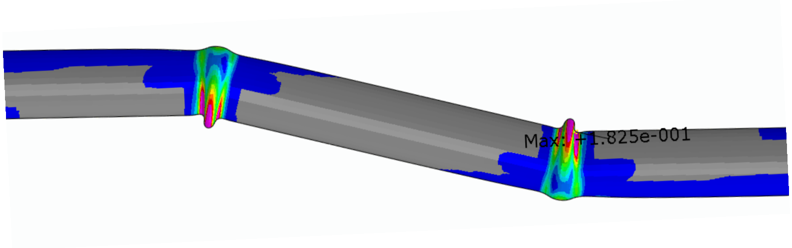


Figure 11 Result of FE Analysis in case of Spilt-basin Test

CASE STUDY

The low-reaction type of SPF was verified by FE analyses in 2 cases; deformation in flexure layer and deformation at fault crossing points. The status of inner pipe wall contact, water flow cross-section area and strain in sleeve pipe section were inspected in the above 2 cases.

Specification of SPF

The affected area (flexure zone) of upper layer, caused by fault offset, was calculated, by using the ground deformation analysis, in case the amount of fault offset is 3.6m. As the result, the length of flexure zone was assumed as 200m, as shown in Figure 11.

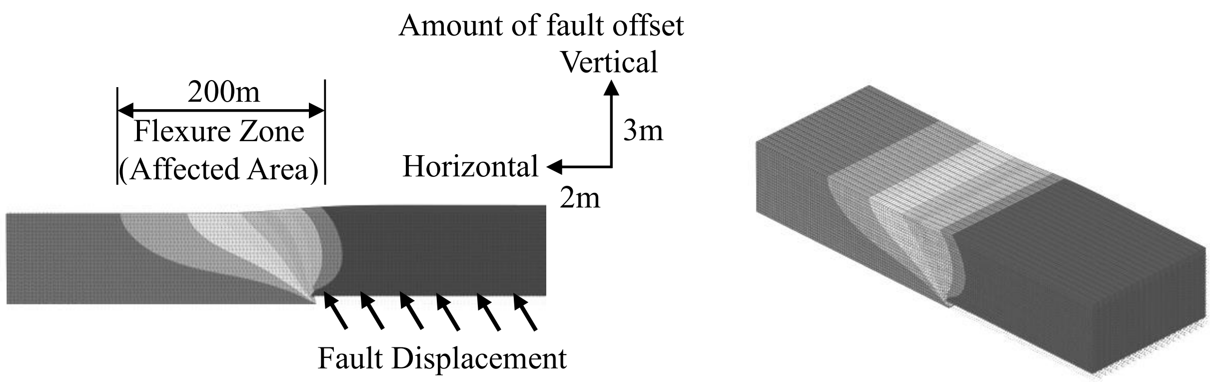


Figure 11 Distribution of Fault Displacement (Ground Deformation Analysis)

The straight pipe, of which the diameter is 2,000mm, was modeled on the FE analysis, and the pipe got the fault offset, of which the amount is 3.6m (Vertical:3m, Horizontal:2m). As the result, the plastic hinges occurred at the positions 6m-apart from fault plane, as shown in Figure 12. Therefore, the distance between plastic hinges was set as 12.0m as the installation positions of each WAVE.

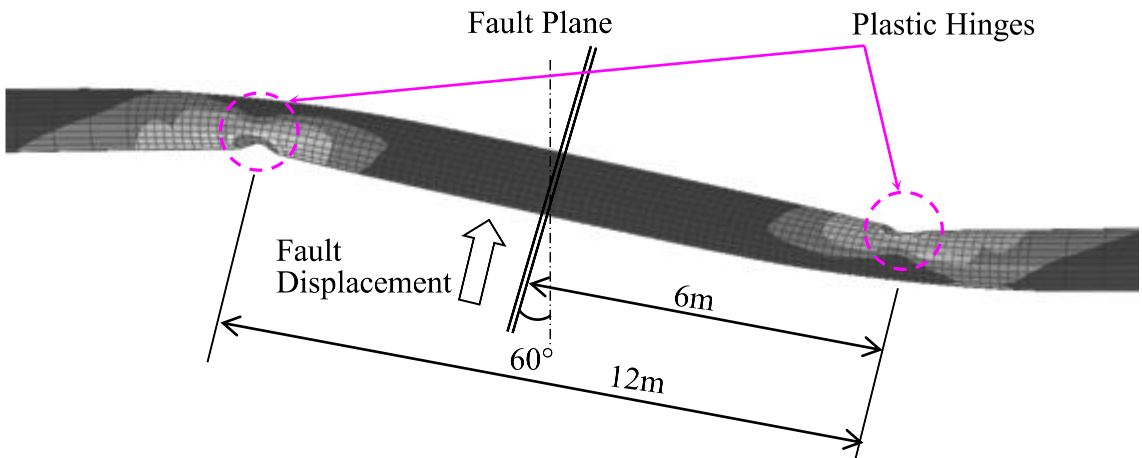


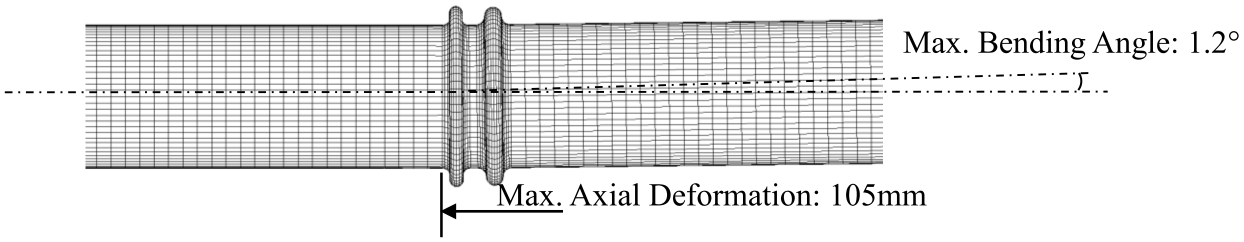
Figure 12 Distance between Plastic Hinges

In addition, the required number of the WAVE was set as 2 WAVEs per a SPF on each plastic hinge, from the results of axial compresstion displacement and bending displacement.

Verification by FE Analysis

Deformation in flexure layer

The analysis result in flexure layer is shown in Figure 13. 2 WAVEs were deformed one by one, not at the same time, as shown in Figure 13. The maximum bending angle was 1.2 degrees within 16 degrees as an allowable bending angle, and the maximum axial deformation was 105mm within 570mm as an allowable axial deformation. Moreover, the maximum strain in the sleeve pipe section occurred just by 0.03%, and it could be found that the WAVEs absorb the deformation in flexure layer.



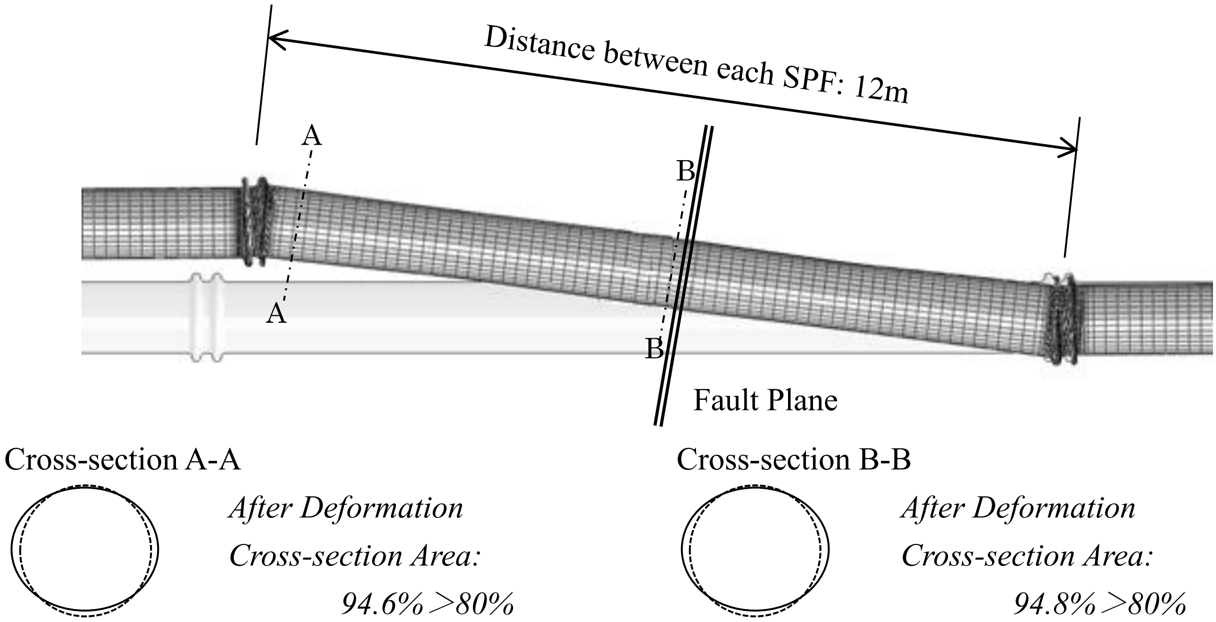
Max. Bending Angle	θ:	*1.2°*	<	$\theta_{a2} = 16°$
Axial Deformation	δ:	*105mm*	<	$\delta_a = 570mm$
Max. Strain at Sleeve Pipe Section	ε:	*0.03%*	<	$\varepsilon_a = 5\%$

Figure 13 Max. Axial Deformation

Deformation at fault crossing points

The analysis result at fault crossing points is shown in Figure 14. As shown in Figure 14, the WAVEs could absorb the fault offset as bending deformation. The bending angle was 14.5 degrees within 16 degrees as an allowable bending angle, and the maximum strain in the sleeve pipe section was 1.64% within 5% as an allowable strain.

The cross-section areas of A-A and B-B are shown in Figure 14, at the moment the amount of fault offset is 3.6m. The cross-section area of A-A and B-B were 94.6% and 94.8% of the area before deformation, even though the area became flattened due to bending deformation.



Bending Angle θ: 14.5° $< \theta_{a2} = 16°$

Strain at Sleeve Pipe Section ε: 1.64% $< \varepsilon_a = 5\%$

Figure 14 Cross-section area before and after fault offset

CONCLUSION

This paper introduces the low-reaction type of SPF corresponding to the deformation in flexure layer, though the experiment results and the case study based on FE analysis. We hope that it will be helpful to those who are engaged in the countermeasure of the pipe for crossing faults.

REFERNCE

N.Hasegawa, Development of High Seismic Performance Pipe for Crossing Active Fault, the 6th Taiwan-US-Japan Workshop on Water System Seismic Practices, 2009

Report on the seismic reinforcement work of Sagamihara Sedimentation Basin

Construction Section, Facilities Department, Yokohama Water Works Bureau
SUZUKI, Tomomi

Abstract

Sagamihara Sedimentation Basin is a structure of the earth-fill dam type for removing suspended solids in raw water via deposition. In FY 2011, the bank was inspected for seismic resistance. The inspection showed that the main bank lacked the required seismic resistance on the side facing the basin (referred to as the "upstream face").

By considering constraints on construction, etc., the basin was decided to be seismically retrofitted by replacing the outside part (referred to as the "downstream face") of the bank with reinforced embankment of soil cement.

1. INTRODUCTION

Yokohama Water Works Bureau supplies a daily average of approximately 1.15 million m^3 of drinking water to approximately 3.7 million citizens.

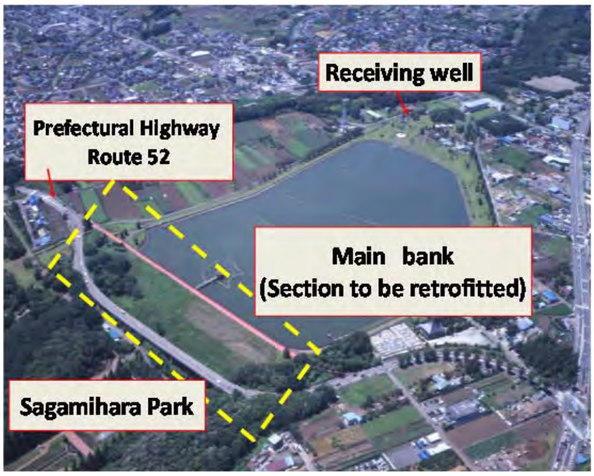


Fig. 1.1 An entire view of Sagamihara Sedimentation Basin

Since the establishment of waterworks in 1887, the Bureau has expanded its facilities eight times in order to respond to population growth and the expansion of the urban areas. Today, the facilities are being improved on seismic resistance and water treatment functions based on the "Long-term vision and 10-year plan", which was formulated in 2006.

This paper is a report on the seismic reinforcement work on the main bank of Sagamihara Sedimentation Basin.

2. OVERVIEW OF SAGAMIHARA SEDIMENTATION BASIN

Sagamihara Sedimentation Basin was constructed in 1954 by making use of the natural landform. This basin is located between Lake Sagami, which is one of water resources of Yokohama City, and Nishiya water purification plant (Fig. 2.1). Its structure is the earth-fill dam type. (Fig.2.2 and 2.3) It can store 883,000 m3 of water as emergency water storage and remove suspended solids in raw water via deposition. In case that the turbidity of the raw water becomes high such as during a typhoon or storm, the sedimentation is accelerated by adding PAC (Poly aluminum chloride).

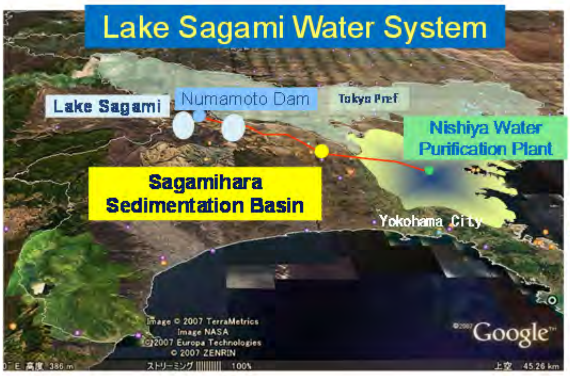


Fig. 2.1 Locality map of Sagamihara Sedimentation Basin

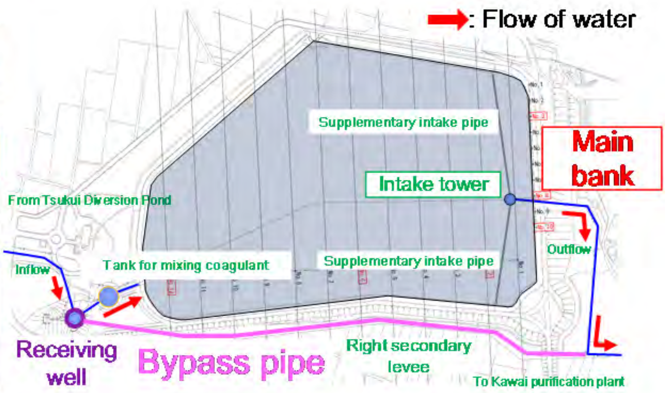


Fig. 2.2 Plan of Sagamihara Sedimentation Basin

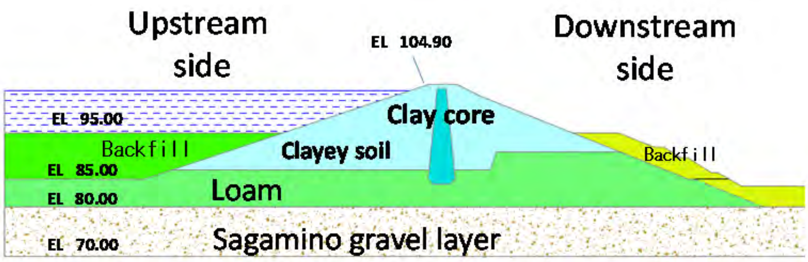


Fig. 2.3 Representative sectional view of Sagamihara Sedimentation Basin

3. CIRCUMSTANCES OF THE SEISMIC RESISTANCE INVESTIGATION

Yokohama Water Works Bureau examined the seismic resistance of Sagamihara Sedimentation Basin in 1982 and discovered that the slip surface of the downstream face of the main bank lacked seismic resistance. Therefore, the main bank was retrofitted by cutting and installing counterweight fill along the downstream face of the bank (Fig. 3.1). Later, in 1997 and 2009, the Seismic Design Guideline for Water Works Facilities (hereinafter referred to as the “Guidelines”) was revised requiring for a raised seismic resistance level. Because there are a university and Sagamihara Park, which is a governmentally designated evacuation site at the time of disaster, near the basin, collapse of the bank was feared to lead to secondary damage and affect people and properties. A dam which had a structure similar to that of this basin collapsed in the Great East Japan Earthquake. Therefore, the seismic resistance of the basin was checked based on the Guidelines (2009). The main bank was found to not have the required seismic resistance, and retrofit work started in 2013.

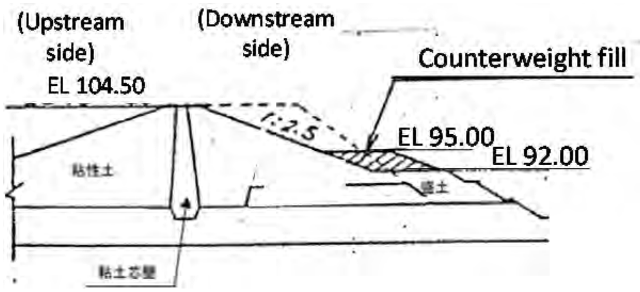


Fig. 3.1 Outline map of the retrofit work

4. VERIFICATION OF SEISMIC RESISTANCE

The main bank of Sagamihara Sedimentation Basin is an earth-fill dam structure. Therefore, the seismic resistance of the main bank was evaluated by referring to the standards for dams.

The basin is an important facility for lowering the turbidity of water as well as storing water for emergencies. Therefore, the stability of the main bank against Level 1 earthquake motions was analyzed by using the modified seismic coefficient method, which is a strict method for evaluating seismic resistance. The standards to conform to were those of the “Draft of Guidelines for Seismic Design of Embankment Dams” (1991, Japan Institute of Country-ology and Engineering), which refers to the inspection of seismic resistance of dams by using the modified seismic coefficient method.

According to the Guidelines (2009), the safety against Level 2 earthquake motions was analyzed by following the “Guidelines for Seismic Performance Evaluation of Dams During Large Earthquakes (Draft) and Explanation” (2005, Ministry of Land, Infrastructure, Transport and Tourism). An overview and the results of the evaluation are shown in Table 1.

Table 1 Overview of seismic diagnosis of the main bank and results

Item	Level 1 earthquake motion*		Level 2 earthquake motion**	
Inspection guideline	Draft of Guidelines for Seismic Design of Embankment Dam		Guideline for the Seismic Performance Evaluation of Dams against Large Earthquakes (draft)	
Inspection standards	Safety factor of the slip circle		Residual settlement, elevation difference	
Analytical standards	Fs≧１．２		No overflow, secured water storage function (settlement not exceeding 1.0m)	
Method of analysis	Slip circle method by the modified seismic coefficient method		Dynamic analysis by the equivalent linearization method, etc.	
Analytical model	Combined model of the dam and ground		Two-dimensional finite element model	
Target water level	Normal water level		Normal water level	
Inspection result	Upstream slip plane	Downstream slip plane	Upstream slip plane	Downstream slip plane
	✕	○	○	○

***Level 1 earthquake motion…**Out of the earthquakes that are assumed to happen in the area where the applicable facility is located, the earthquakes with the highest probability of occurring during the facility's in-service period.
****Level 2 earthquake motion…**The largest magnitude earthquake that is assumed to happen in the area where the applicable facility is located.

The seismic diagnosis showed that the main bank did not have the required seismic resistance against Level 1 earthquake motion at the slip surface on the upstream face that passes through the downstream slope (Fig. 4.1).

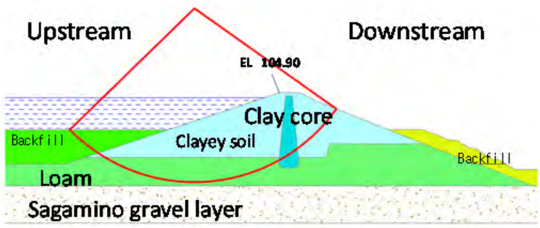


Fig. 4.1 Representative slip surface on the upstream face

5. INVESTIGATION OF RETROFITTING METHODS

The constraints on construction were organized based on the site conditions and survey results as described below in (1); methods for retrofitting the upstream and downstream side of the main bank were selected.

(1) Constraints on construction

①*Water supply control and management*. The raw water supplied from Lake Sagami accounted for at least 20% of the total water supply of Yokohama City. Therefore, it was difficult to cut off the water supply from Lake Sagami during the retrofit work.

②*Water quality*. It was possible to send the raw water directly from Lake Sagami to Nishiya water purification plant so as to bypass the basin by using only the bypass pipeline shown in Fig. 2.3. However, there are no sedimentation facility between Nishiya Water Purification Plant and Sagamihara Sedimentation basin. This would lower the performance of water treatment in the event that the turbidity of the raw water increased, for instance during a typhoon or a storm. Therefore, water could not be sent solely through the bypass pipeline over a long period of time.

③*Ground conditions, etc*. When the basin was completed approximately 60 years ago, cracks developed on the bottom surface of the basin. When the bottom surface was dried cracks were highly likely to develop again and cause water leakage. Furthermore, construction of temporary structures that were needed for the retrofit work had risks of inducing cracks and water leakage.

(2) Plans of retrofitting the upstream face

A common method for retrofitting a slip surface on the upstream face is to retrofit the edge of the slip surface. Because of the constraints on water supply control and management mentioned in ①, raw water transmission could not be halted. Therefore the three methods shown in Table 2 were investigated for retrofitting the upstream side.

Plan A involves emptying the basin and retrofitting the upstream side. As described above regarding constraints on ground conditions (③), the bottom surface of the basin was suspected to develop cracks and leak water. To empty the basin, it was necessary to solely use the bypass pipeline, but water could not be sent solely through the bypass pipeline over a long period of time as described in the constraints on water quality (②). Therefore, Plan A was rejected.

Plan B involves closing the area to retrofit by installing a temporary structure such as steel sheet piles and retrofitting the upstream side. However, as mentioned in the constraints on ground conditions (③), installation of a temporary structure was suspected to cause cracks on the bottom surface of the basin. Therefore, Plan B was rejected.

Plan C involves separating the area to retrofit by installing an underwater curtain and retrofitting the upstream side. However, insertion of the retrofitting materials was suspected to stir up sediments on the bottom of the basin and deteriorate the quality of water. Because the plan does not meet the constraints on water quality (②), Plan C was rejected.

It was thus judged very difficult to retrofit the upstream face.

Table 2 Plans of retrofitting the upstream face

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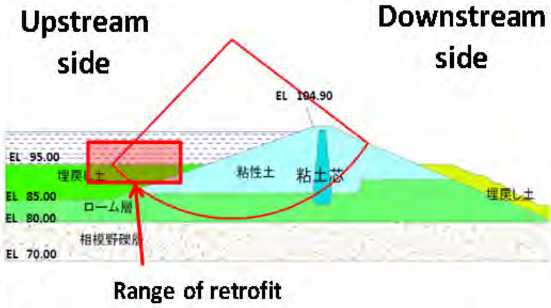
Plan of the range of retrofit</td>
<td colspan="2">

Cross section of the range of retrofit</td>
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<tr>
<td rowspan="2">Retrofit plan</td>
<td>Plan A</td>
<td>Plan B</td>
<td>Plan C</td>
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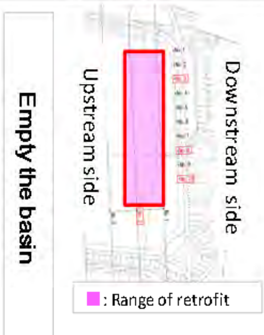
<td>
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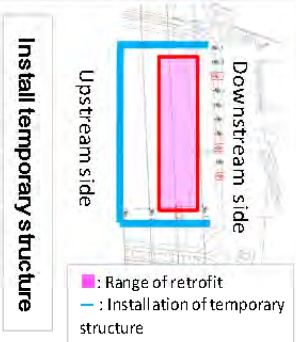
<td>
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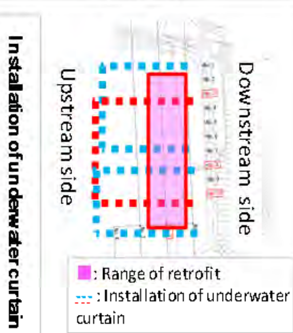
<td>
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<tr>
<td>Overview</td>
<td>The basin is emptied by using the bypass pipe. The embankment is then retrofitted by placing counterweight fill on the edge of the upstream slip plane.</td>
<td>The section to be retrofitted is separated from the basin with a temporary structure and emptied. The embankment is retrofitted by counterweight fill, etc.</td>
<td>The range to be retrofitted is separated with underwater curtain. The bank is retrofitted by counterweight fill, riprap work, etc. in the separated range.</td>
</tr>
<tr>
<td>Retrofitting method</td>
<td>・ Counterweight fill
・ Riprap work</td>
<td>・ Counterweight fill
・ Riprap work</td>
<td>・ Counterweight fill
・ Riprap work</td>
</tr>
<tr>
<td rowspan="2">Over-all judgment</td>
<td>✖</td>
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</tr>
<tr>
<td>・ Emptying the basin may cause cracks to develop on the bottom surface .
・ The bypass cannot be used for a long period of time.</td>
<td>・ Installing the temporary structure may cause cracks to develop on the bottom surface, creating a water leakage hazard.
・ Emptying the zone inside the temporary structure may cause cracks to develop on the bottom surface and result in water leakage.</td>
<td>・ Sediments flung up during the works may deteriorate the quality of water.</td>
</tr>
</table>

(3) Plans of retrofitting the downstream face

It was judged difficult to retrofit the slip plane (Fig. 4.1) that did not have the required safety factor on the upstream side (Plans A, B, and C).

Therefore, a method was investigated that involved increasing the resistance of the slip surface on the downstream face to ensure the required safety factor (Fig. 5.1).

Fig. 5.1 Schematic sectional view of the retrofit plan

This method improves the downstream slope where the slip surface passes through, increases the cohesion and thus enhances the resistance along the slip surface.

The downstream slope was decided to be improved through reinforced embankment by replacement. The method involves replacing the surface soil of the downstream slope with reinforced embankment. The uniaxial compressive strength of the reinforced embankment was increased by mixing cement to the excavated surface soil. The method has the following advantages among others:

* Work is performed only on the downstream side of the main bank outside the basin; and thus there are no limitations on water transmission method, such as having to solely use the bypass pipe, and no deterioration of water quality.
* The depth of improvement is 1 to 2m from the dam surface. Installation of temporary structures is not required and the materials of the existing bank can be used. Therefore, the method is economical.

As described, the reinforced embankment by replacement was judged to satisfy the constraints and to be economical and was thus adopted.

6. RETROFITTING WORKS

(1) Overview of the works

The working area was approximately 10,000m^2 on the downstream slope of the main bank of Sagamihara Sedimentation Basin. The uniaxial compressive strength

Counterweight fill	14,759m^3
Reinforced embankment	16,759m^3
Amount of cement added (Total)	3,965t
Area to be retrofitted	10,337m^2 (235m×23～52m)

Table 3 Major construction quantities of the retrofit work

levels required from the reinforced embankment in the three sections shown in Figs. 6.1 and 6.2 were set at 1,060kN/m^2, 920 kN/m^2 and 1,120 kN/m^2.

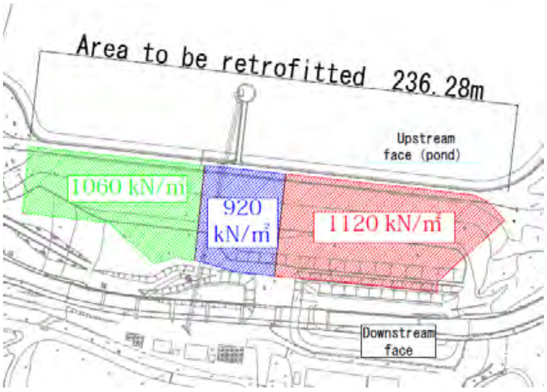

Fig. 6.1 Plan of the range of the bank to be retrofitted

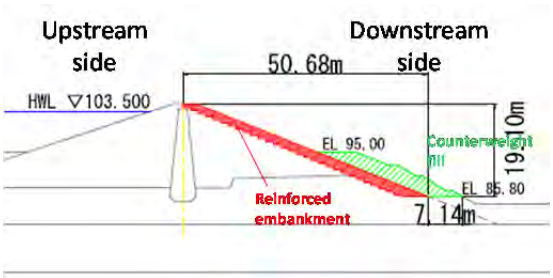

Fig. 6.2 Representative sectional view of the retrofit work

(2) Preparation of reinforced soil for embankment

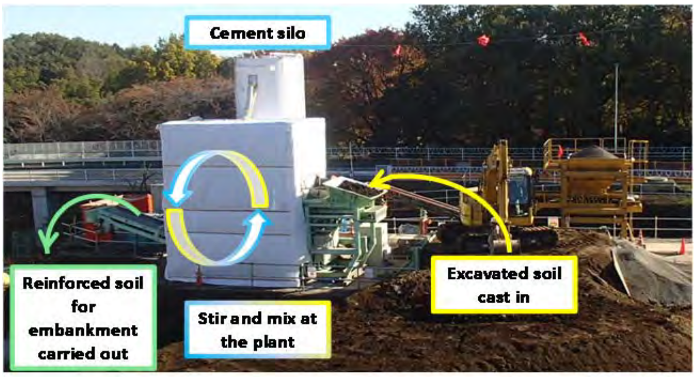

Fig. 6.3 Cement mixing plant

The mixture proportions of the reinforced embankment were decided based on the soil test results of the soil samples taken at the site. Cement can be mixed into soil either by using a backhoe to improve subgrade soil or by using a plant. The amount of cement that was to be added in this project was approximately 4 times the amount used for improving the subgrade soil in an ordinary road improvement project. Because the soil of the main bank was clayey, it was difficult for a backhoe to stir and uniformly mix the soil and cement. Moreover, the site was adjacent to a residential area, park, etc., and thus dust needed to be minimized as much as possible. Upon considering these conditions, a plant shown in Fig. 6.3 was assembled at the site.

(3) Workflow

The work involved removing the counterweight fill from the area to be retrofitted (Fig. 6.4 and the green section in Fig. 6.2) and excavating part of the bank within the range (red section in Fig. 6.2). To increase the stability of the main bank, the main bank was bench cut as shown in Fig. 6.5, and then chipping was performed.

The excavated soil was stirred and mixed with cement and prepared into reinforced soil for embankment. The reinforced soil and counterweight fill were banked on the main bank, and the slope was formed. The workflow is shown in Fig. 6.6.

Fig. 6.4 Excavating the bank

Fig. 6.5 Bench cutting

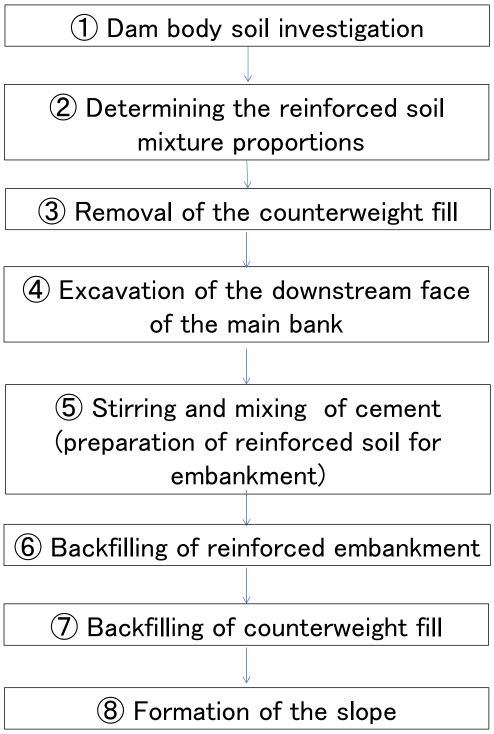

Fig. 6.6 Flow of the works

(4) Work control

① *Quality control of reinforced embankment*. The weight of the cement to be added was always monitored at the control room of the plant to ensure that the added material was consistent with the mixture design. A specimen was sampled for each 500m^3, and was subjected to an unconfined compression test.

② *Checking rolling and compaction*. The reinforced soil for embankment was banked on the main bank where the soil was excavated. Soil cement cannot manifest the target strength unless it is sufficiently compacted [1)]. Therefore, the soil cement was roll-compacted during backfilling at every 30cm in depth to ensure sufficient compaction. After completion of the backfill, the degree of compaction was properly checked by the RI method.

③ *Controlling the time from preparation of reinforced soil for embankment until backfilling*. Prepared reinforced soil for embankment starts hardening soon after preparation [1]. Therefore, the construction quantity per hour was adjusted so that the prepared reinforced soil was backfilled and roll-compacted within 6 hours of the preparation.

7. CONCLUSION

The retrofit work of the main bank of Sagamihara Sedimentation Basin is scheduled to be complete in March 2016. Holding up the goal of constructing an earthquake-resistant and reliable lifeline in the 10-year long-term vision formulated in 2006, Yokohama Water Works Bureau has promoted seismic retrofitting of its facilities.

This project is one of seismic retrofitting projects of its water conveyance facilities. The Bureau will continue this and other projects aiming at 100% earthquake-resistant facilities.

References

1) Fukutani, W. and T. Sakakibara: Study on the use of mortar mixed backfill soil for sewer installation, Technical Note of National Institute for Land and Infrastructure Management, No. 531, 2009.

Seismic Resistance Designs for the New Higashiyama Service Reservoir No.3

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Nagoya Waterworks & Sewerage Bureau, Japan

Abstract
Nagoya Waterworks & Sewerage Bureau plans to implement renewal work on a decrepit service reservoir that was constructed at the Bureau's foundation. This paper introduces a practical case of seismic resistance designs for the RC rectangle service reservoir according to "Guideline to and Explanation of Seismic Construction Method of Water Supply Facilities-2009."

INTRODUCTION

Fig.1, Location of Nagoya

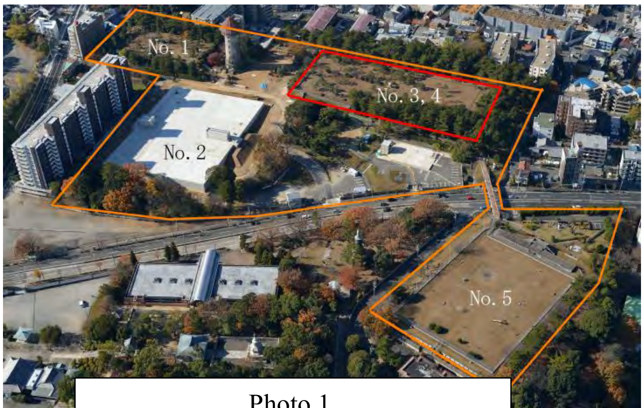

Photo 1,
The Higashiyama Service Reservoirs

Nagoya city, the third largest city in Japan, is located in the center of Japan islands. Fig. 1 shows the location of Nagoya, where the "Nankai trough" extends in the south and is concerned as a possible cause of a major earthquake in the near future. Waterworks of Nagoya started in 1914. Its Higashiyama service reservoirs, consisting of 5 reservoirs (shown in photo 1), were constructed between 1914 and 1934 and they are the oldest service reservoirs in Nagoya.

Table 1, Specific of the Higashiyama Service Reservoirs

No.	Constructed Year	Improved Year	Shape	Structure	Improving Method	Capacity(m^3)	Planned Capacity(m^3)
1	1913	1999	Rectangle	Plain Concrete	Interior Strengthening	6,860	6,860
2	1913	2013	Rectangle	RC	Renewal	23,500	23,500
3	1928	-	Rectangle	RC	Renewal	9,370	23,500
4	1928	-	Rectangle	RC		9,370	
5	1934	2001	Rectangle	RC	Interior Strengthening	27,000	27,000
					total	76,100	80,860

The Higashiyama service reservoirs have been distributing tap water to the center of Nagoya city by natural gravity for over 100

years. The specifics of the 5 service reservoirs are shown in Table 1.
Although seismic strengthening work on the interior of reservoirs No.1 & No.5 was implemented because of their seismic vulnerability, total-capacity enlargement work on the Higashiyama reservoirs has also been required for saving distribution energy since 2010. Due to this requirement, as shown in a red rectangle of Table 1, reservoirs No.3 & No.4 were chosen to be renewed as "new service reservoir No.3" together with seismic resistance designs.

SEISMIC RESISTANCE DESIGNS

According to "Guideline to and Explanation of Seismic Construction Method of Water Supply Facilities-2009" (hereafter "JWWA Guideline 2009"), the seismic resistance designs for the new service reservoir No.3 proceeded as shown in Fig. 2.

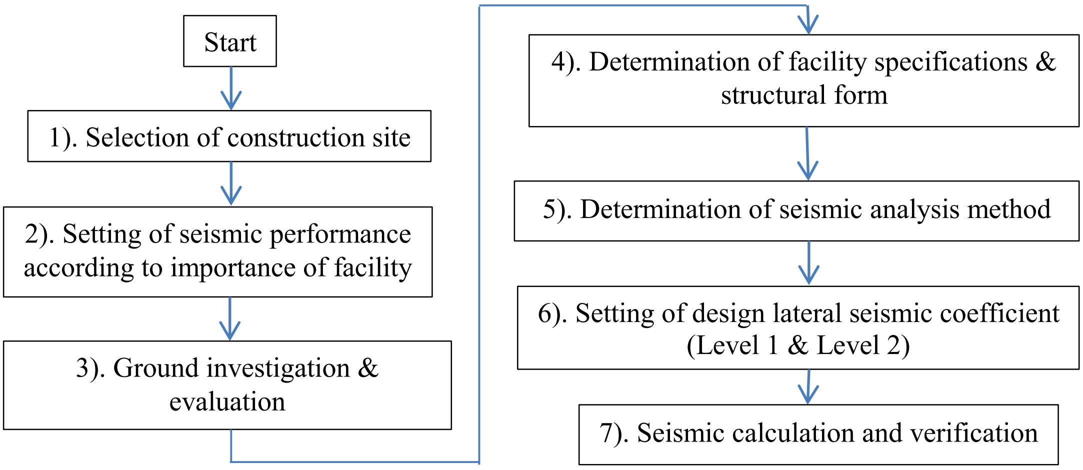

Fig. 2, Procedure of Seismic Resistance Designs

Selection of construction site

The construction site was limited to the existing service reservoirs No.3 & No.4, because of their altitude and facility capacity.

Table 2, Importance classification of service reservoir

Rank	Subject
A1	Having high probability of incurring serious secondary disaster if damaged
	Connecting to distribution main or maximum capacity and having no alternative facilities
A2	Connecting to distribution main and having alternative facilities
B	Other than those above

Table 3, Definition of seismic motion

Level 1	High occurring probability during operational period of subject facility
Level 2	Maximum intencity expected in the location of subject facility

Setting of seismic performance according to importance of facility

If damaged by earthquake, service reservoir No.3 may cause a major secondary disaster due to the collapse of the slopes from leakage. Thus, service reservoir No.3 is classified as "Rank A1." Table 2 shows classification of service reservoirs by importance according to JWWA

Guideline 2009.

Rank A1 facilities require “seismic performance 1” against “seismic motion level 1,” and “seismic performance 2” against “seismic motion level 2.” Table 3 shows the definitions of seismic motion level 1 and 2, and Fig. 3 explains seismic performance 1, 2, and 3 of RC service reservoir constructions. As shown in Fig.3, seismic performance 1 requires no leakage when small cracks occur. On the other hand, performance 2 allows small leakages which can be repaired within a short term.

Furthermore, Fig. 4 shows the concept image on the relation of response curvatures against bending moments for a part of a RC reservoir construction. Performance level 1 (Fig. 3, on the left) meets damage level 1 (elastic range), whereas performance level 2 (Fig. 3, in the middle) meets damage level 2 (in plastic range, less than max load bearing capacity).

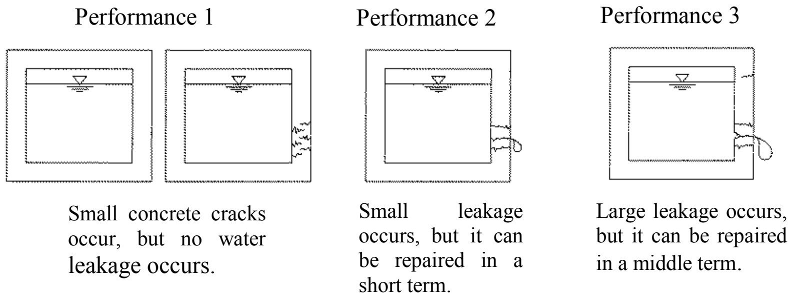

Fig. 3, Seismic Performance of RC Service Reservoir

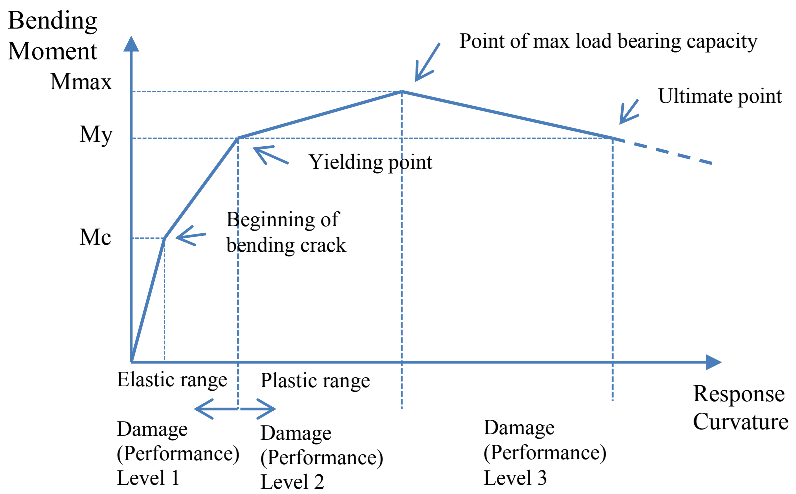

Fig. 4, Damage Level Against Bending Stress for a Part of Consruction

Ground investigation and evaluation

(1) Liquefaction

Based on a boring survey, it was determined that there were no sand layers which may cause liquefaction at the construction site.

(2) Surface of Engineering bedrock

The surface of engineering bedrock is an

Table 4, specific of basement of construction site

No. of layer	type of soil	H_i (m)	N value	V_S (m/s)	$4H_i/V_{Si}$ (s)	note
1	sandy	1.40	5	144.65	0.04	
2	sandy	2.90	35	319.71	0.04	
3	sandy	3.60	19	296.21	0.05	
4	sandy	1.00	11	276.65	0.01	
5	sandy	0.60	11	276.65	0.01	
6	sandy	2.20	10	273.37	0.03	
7	sandy	3.10	35	319.71	0.04	
8	cohesive	7.70	16	285.68	0.11	
9	cohesive	1.30	38	334.68	0.02	
10	sandy	0.90	54	337.52	0.01	
11	cohesive	2.30	35	329.68	0.03	
12	cohesive	1.90	18	291.91	0.03	
13	cohesive	0.50	22	302.83	0.01	
14	cohesive	1.60	26	312.23	0.02	
15	sandy	-	125	374.86	-	engineering bedrock
				T_G (s)	**0.43**	

upper surface of solid bedrock having enough large shear wave velocity compared with ground level, and it is used as reference bedrock for setting seismic motions. Usually, seismic waveforms used for seismic resistance calculation are ground level waveforms calculated with waveforms on the engineering bedrock. We set a series of bedrocks having more than 300m/s of shear wave velocity and more than 50 of N-value as engineering bedrock on this design.

(3) Basement Classification

Basement classification is used to calculate design lateral seismic coefficients or design displacement amplitude. As described hereafter, a static analysis method was adopted this time, which requires basement classification for calculating design lateral seismic coefficients. Basement classification is determined by the natural period of a basement "T_G." T_G is calculated by the formula (1) below. Table 4 shows the specifics of basement at the construction site.

$$T_G = 4\sum_{i=1}^{n} H_i / V_{Si} \quad \cdot\cdot\cdot\cdot (1)$$

where,

T_G: Natural period of basement (s)

H_i: Thickness of No.i layer (m)

V_{Si}: Mean shear wave velocity of No.i layer (m/s)

i: Layer number from ground surface, when basement is divided from ground surface to engineering bedrock by n layers

As shown at the bottom of Table 4, the natural period of basement "T_G" was 0.43(s), resulting in type II of basement classification in Table 5.

Table 5, Basement Classification

Type	Natural Period
I	$T_G < 0.2$
II	$0.2 \leqq T_G < 0.6$
III	$0.6 \leqq T_G$

Table 6, facility specifications & Structural form

capacity	23,500m^3
shapsize	49.000m×58.800m×4.550m×2tanks
structure	RC/flat slab
substructure	pile foundation(SC+PHC)

Determination of facility specifications & structural form

Table 6 shows facility specifications and structural form of service reservoir No.3. Facility specification is determined by the planned capacity, low water level of other service reservoirs, conditions of basement,

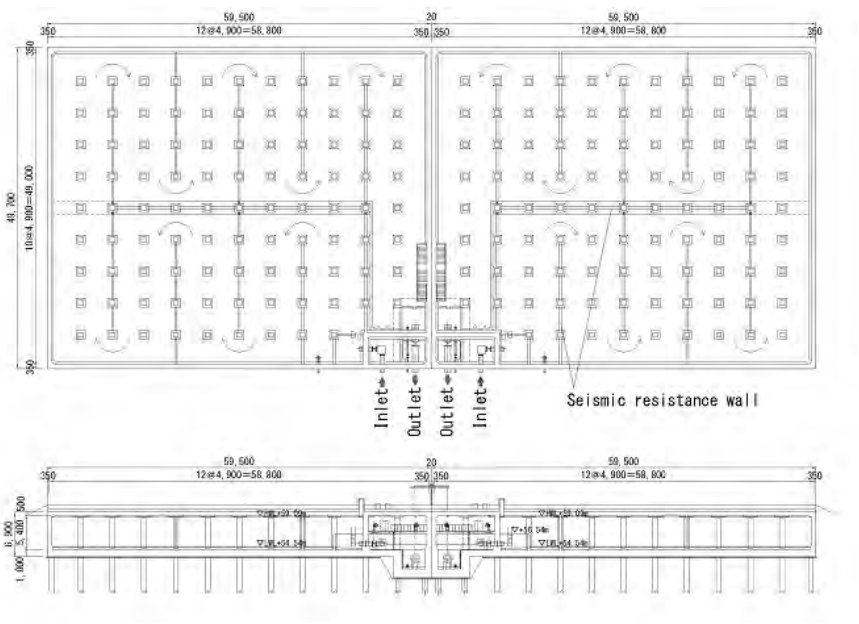

Fig. 5, Basic Structure

locations of existing pipes or facilities, and easy maintenance. Since RC rectangle service reservoirs have a structure with lower lateral stiffness than longitudinal stiffness against horizontal shaking in general, lateral shaking is the dominant influence. Thus, the effective seismic design is to allocate longitudinal & lateral seismic resistance walls in a good balance according to the shape of the service reservoir. From this reason, 5 lateral and 1 longitudinal seismic resistance walls were set for each tank as shown in Fig. 5.

Determination of seismic analysis method

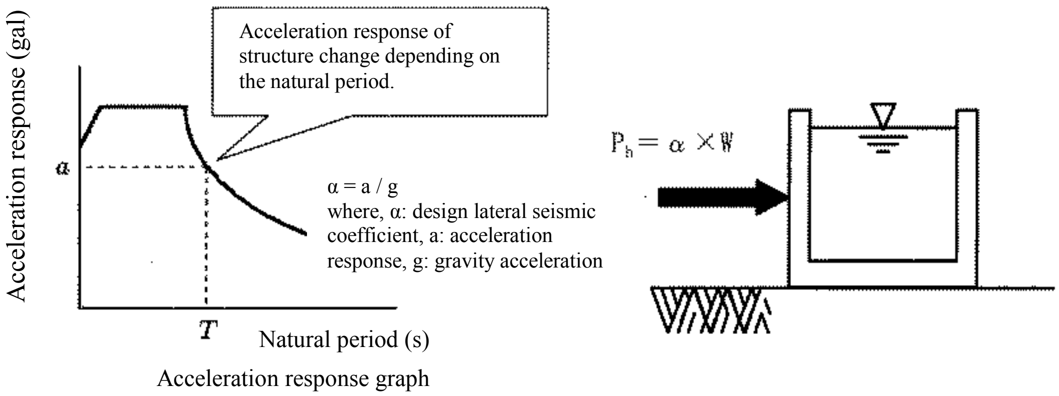

Fig. 6, Concept Image of Seismic Intensity Method

Service reservoir No.3 is an aboveground structure with soil cover, resulting in inertial force as the dominant influence during an earthquake. Therefore, we decided to apply a static analysis method (seismic intensity method). In the seismic intensity method, momentary force applied when the structure is displaced at maximum by earthquake is used as static horizontal force. Seismic force applied to the structure (= horizontal force "P_h") is calculated by multiplying a design lateral seismic coefficient "α" with the structure weight "W." A concept image of seismic intensity method is depicted in Fig. 6. Two-dimensional non-linearity frame,

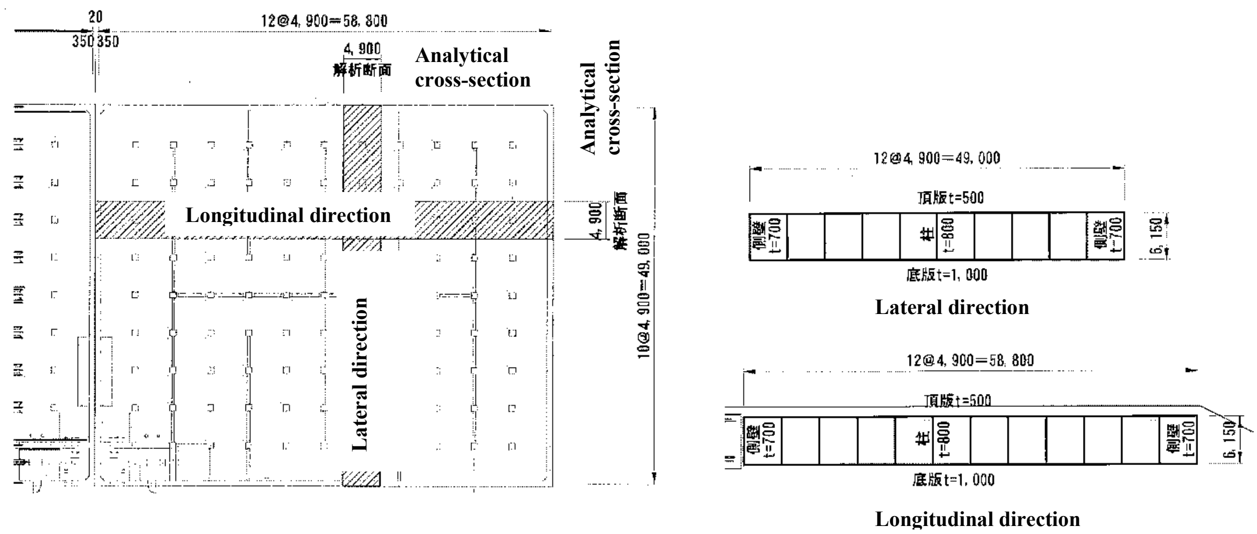

Fig. 7, Two-Dimensional Frame Model

used as analytical model, is shown in Fig. 7.

Setting of design lateral seismic coefficient

(1) Seismic Motion Level 1

According to JWWA Guideline 2009, a design lateral seismic coefficient of seismic motion level 1 "K_{h1}" is calculated by the following formula (2).

$K_{h1} = C_z \cdot K_{h01}$ ・・・・(2)

where,

K_{h1}: Design lateral seismic coefficient,

C_z: Area compensation coefficient (= 1.0 for No.3 construction site),

K_{h01}: Standard lateral seismic coefficient at gravity center of applicable structure

Table 7 shows the standard lateral seismic coefficients of seismic motion level 1 with the natural period of the structure "T," according to each basement classification. As mentioned above, the type of basement at the construction site is classified as type II. Based on eigenvalue analysis, the natural period of structure was calculated as 0.04(s) for lateral and 0.05(s) for longitudinal direction. Therefore, the design lateral seismic coefficient "K_{h1}" is calculated as below.

Table 7, Standard lateral seismic coefficient for aboveground structure (Level 1)

Basement classification	Kh01(corresponding to natural period T)		
Type I [TG<0.2]	$T<0.10$ $K_{h01}=0.431T^{1/3}$ $K_{h01} \geqq 0.16$	$0.10 \leqq T \leqq 1.1$ $K_{h01}=0.20$	$1.1<T$ $K_{h01}=0.213T^{-2/3}$
Type II [0.2≦TG<0.6]	$T<0.20$ $K_{h01}=0.427T^{1/3}$ $K_{h01} \geqq 0.20$	$0.20 \leqq T \leqq 1.3$ $K_{h01}=0.25$	$1.3<T$ $K_{h01}=0.298T^{-2/3}$
Type III [0.6≦TG]	$T<0.34$ $K_{h01}=0.430T^{1/3}$ $K_{h01} \geqq 0.24$	$0.34 \leqq T \leqq 1.5$ $K_{h01}=0.30$	$1.5<T$ $K_{h01}=0.393T^{-2/3}$

Tg: Natural period of basement (s)

- Lateral direction: $K_{h01} = 0.427 \times 0.04^{1/3} = 0.146 \rightarrow 0.20$, $K_{h1} = 1.0 \times 0.20 = 0.20$
- Longitudinal direction: $K_{h01} = 0.427 \times 0.05^{1/3} = 0.157 \rightarrow 0.20$, $K_{h2} = 1.0 \times 0.20 = 0.20$

(2) Seismic Motion Level 2

Based on JWWA Guideline 2009, a design lateral seismic coefficient of seismic motion level 2 was selected from the largest of the intensities calculated by two methods; (a) "calculation method from seismic ground level motions anticipated by the regional disaster prevention plan in Nagoya" and (b) "calculation method based on the observation record of the Great Hanshin-Awaji Earthquake." In the former method, two waveforms were

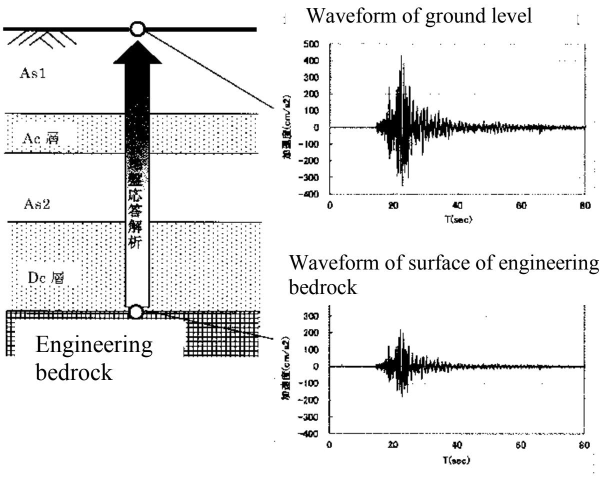

Fig. 8, Concept Image of ODERA

selected for “Nankai trough (see Fig. 1); the largest-class seismic ground level motion considered from the earthquakes in the past and the largest-class seismic ground level motion considered from every possibility.

(a) Design seismic lateral coefficient based on regional disaster prevention plan in Nagoya

Seismic ground level motion is amplified or damped while transiting trough subsurface ground. The maximum response acceleration can be determined by the one-dimensional earthquake response analysis (hereafter “ODERA”). Fig. 8 shows the concept image of this. In this design, ODERA was carried out to compute a ground level motion from the seismic motion of engineering bedrock of the “Nankai trough (see Fig. 1)” earthquake. Furthermore, because this analysis method has a variation in number of applications, convergence, and influence of frequency domain; three analysis methods were applied; “SHAKE*1,” “FDEL*2,” and “DYNEQ*3.” Table 8 shows maximum response accelerations computed by ODERA.

Table 8, result of ODERA

	Analysis code	Previouse earthquakes(gal)	Every possibility(gal)
Lateral (T=0.04)	SHAKE	296	319
	FDEL	326	373
	DYNEQ	317	352
Longitudinal (T=0.05)	SHAKE	305	328
	FDEL	351	421
	DYNEQ	351	381

As a result, the FDEL of every possibility showed the largest in both longitudinal & lateral directions, the design lateral seismic coefficient K_{h2} is calculated as below.

- Lateral direction: $K_{h2} = 373 / 980 = 0.38$
- Longitudinal direction: $K_{h2} = 421 / 980 = 0.43$

*1, University of California, Berkeley, USA, “A Computer program for earthquake response analysis of horizontally layered sites”

*2, Gifu University, Japan, a computer program based on “Frequency-Dependent Equivalent Strain for Equi-Linearized Technique”

*3, Tohoku Gakuin University, Japan, “A computer program for dynamic response analysis of level ground by equivalent linear method”

(b) Design lateral seismic coefficient based on the observation record of the Great Hanshin-Awaji Earthquake

Table 9 shows standard lateral seismic coefficients of Level 2 for aboveground structures according to JWWA Guideline 2009. These were developed based on the observation record of the Great Hanshin-Awaji Earthquake, which caused major damage to many structures. As mentioned above, the basement classification is type II, and the natural periods of structure T are 0.04(s) in the lateral, 0.05(s) in the longitudinal direction. Thus, a design

Table 9, Standard lateral seismic coefficient for abovegound structure (Level 2)

Basement classification	Kh02(corresponding to natural period T)		
Type Ⅰ [TG<0.2]	$T<0.20$ $K_{h02}=2.291T^{0.515}$ $K_{h02}\geqq 0.70$	$0.20\leqq T\leqq 1.0$ $K_{h02}=1.0$	$1.0<T$ $K_{h02}=1.000T^{-1.465}$
Type Ⅱ [0.2≦TG<0.6]	$T<0.20$ $K_{h02}=5.130T^{0.807}$ $K_{h02}\geqq 0.80$	$0.20\leqq T\leqq 1.0$ $K_{h02}=1.4$	$1.0<T$ $K_{h02}=1.400T^{-1.402}$
Type Ⅲ [0.6≦TG]	$T<0.30$ $K_{h02}=2.565T^{0.631}$ $K_{h02}\geqq 0.60$	$0.30\leqq T\leqq 1.5$ $K_{h02}=1.2$	$1.5<T$ $K_{h02}=2.003T^{-1.263}$

Tg: Natural period of basement (s)

lateral seismic coefficient K_{h2} is calculated as below.

- Lateral direction: $K_{h02} = 5.130 \times 0.04^{0.807} = 0.382 \rightarrow 0.80$, $K_{h2} = 1.0 \times 0.80 = 0.80$
- Longitudinal direction: $K_{h02} = 5.130 \times 0.05^{0.807} = 0.457 \rightarrow 0.80$, $K_{h2} = 1.0 \times 0.80 = 0.80$

By comparing the results of the two abovementioned methods, a design lateral seismic coefficient of seismic motion level 2 was determined as 0.80 in both directions.

Seismic calculation and verification

Firstly, prior to seismic calculation, the maximum bending moments under normal conditions were determined using the two-dimensional frame model (see Fig. 7) in order to verify that occurring degree of bending stress on the respective parts is below the allowable degree. Secondly, seismic calculation was carried out using lateral seismic coefficients of seismic motion level 1 and level 2, and then the maximum bending moments and maximum shear forces on the respective parts were calculated. Finally, it is verified if occurring degrees of bending stress or shear forces calculated satisfies the following 5 requirements. If any of the requirements wasn't satisfied, thickness of wall or installation of reinforced steel was changed until all the requirements were satisfied. Table 10 shows the seismic calculation results. The first row indicates analytical cross sections, and the second row shows the respective applicable parts. The first column from the left shows analytical conditions and judgement criteria, and the second column shows items.

Requirements

- ✓ Occurring degree of bending compressive stress by seismic motion level 1 is below the allowable degree of bending compressive stress (see the seventh and eighth row in Table 10).
- ✓ Occurring degree of bending stretching stress by seismic motion level 1 is below the allowable degree of bending stretching stress (see the ninth and tenth row).
- ✓ Occurring bending moment by seismic motion level 2 is below the max load bearing capacity (see the eleventh and twelfth row).
- ✓ Occurring shear force by seismic motion level 2 is below the shear capacity (see the thirteenth and fourteenth row).
- ✓ Bending fracture precedes shearing fracture by seismic motion level 2 (see the bottom row).

To avoid dangerous momentary collapse, it is desirable that the occurring bending fracture is earlier than shearing fracture, and the structure is made tenacious. Fig. 9 shows the concept image about

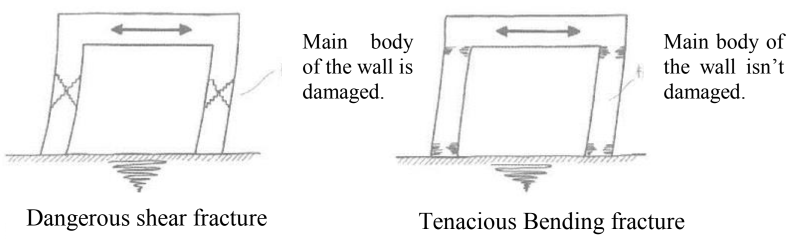

Fig. 9, Concept image of fracture mode

this. The verifying formula is as below.

$\gamma_i \cdot V_{mu}/V_{yd} < 1.0$

where,

γ_i: Structure coefficient (= 1.0),

V_{mu}: Shear force when the applicable part reached the max load bearing (kN),

V_{yd}: Shear capacity (kN)

Table 10, Results of seismic calculation

Analytical cross-section			Lateral direction						Longitudinal direction					
Judgement	Item	Part / unit	Upper slab	Side wall (downside)	Side wall (upside)	Column	Bottom slab (upside reinforcing steel)	Bottom slab (downside reinforcing steel)	Upper slab	Side wall (downside)	Side wall (upside)	Column	Bottom slab (upside reinforcing steel)	Bottom slab (downside reinforcing steel)
Normal (degree of stress ≦ allowable degree of stress)	Degree of bending compressive stress σ_c	N/mm^2	5.454	2.926	4.362	4.260	2.330	2.957	5.268	6.463	4.253	6.864	3.250	2.938
	Allowable degree of bending compressive stress σ_{ca}	N/mm^2	9.000	9.000	9.000	9.000	9.000	9.000	9.000	9.000	9.000	9.000	9.000	9.000
	Degree of bending stretch stress σ_s	N/mm^2	155.208	82.184	139.438	17.256	143.359	168.107	168.986	165.248	157.903	67.652	175.864	140.947
	Allowable degree of bending stretch stress σ_{sa}	N/mm^2	180.000	180.000	180.000	180.000	180.000	180.000	180.000	180.000	180.000	180.000	180.000	180.000
Level 1 (degree of stress ≦ allowable degree of stress)	Degree of bending compressive stress σ_c	N/mm^2	8.554	12.051	7.122	12.560	5.675	5.231	8.838	12.335	7.374	13.299	5.846	5.264
	Allowable degree of bending compressive stress σ_{ca}	N/mm^2	13.500	13.500	13.500	13.500	13.500	13.500	13.500	13.500	13.500	13.500	13.500	13.500
	Degree of bending stretch stress σ_s	N/mm^2	243.434	286.521	242.521	253.705	282.615	250.936	251.529	293.801	251.947	246.866	289.788	252.527
	Allowable degree of bending stretch stress σ_{sa}	N/mm^2	300.000	300.000	300.000	300.000	300.000	300.000	300.000	300.000	300.000	300.000	300.000	300.000
Level 2 (section force ≦ load bearing avility)	Bending moment M_d	KN・m	344.070	5797.975	2589.559	2406.938	4101.169	3991.563	361.350	5975.411	2727.907	2533.940	4271.427	4014.976
	Max load bearing capacity M_{ud}	KN・m	370.756	6460.747	3585.079	2575.248	4466.711	4083.872	430.775	6456.424	3574.343	2682.453	4501.010	4083.872
	Shear force V_d	kN	237.270	2528.451	1389.860	1506.488	1721.425	1721.425	245.320	2535.235	1481.556	1491.734	1741.932	1741.932
	Shear capacity V_{yd}	kN	355.725	2573.399	2341.170	1763.796	3111.185	2881.004	365.743	2576.919	2345.828	1765.184	3121.630	2881.004
Judgement of flacture mode ($\gamma i \cdot Vmu/Vyd<1.0$ ⇒OK)	Bending moment M_d	KN・m	344.07	5797.98	2589.56	3158.12	4669.78	3991.56	361.35	5975.41	2727.91	3277.75	4847.21	4014.98
	Max load bearing capacity M_{ud}	KN・m	440.63	4785.04	2664.33	2114.03	5399.09	4882.79	510.62	4783.03	2657.29	2111.68	5433.60	4882.79
	Shear force V_d	kN	237.27	3066.01	1389.86	1506.49	1721.43	1721.43	245.32	3070.74	1481.56	1491.73	1741.93	1741.93
	Shear capacity V_{yd}	kN	479.92	3437.35	3105.13	2277.35	4165.00	3850.77	494.14	3440.68	3111.74	2278.99	4177.97	3850.77
	Shear span $L=M_d/V_d$	m	1.45	1.89	1.86	2.10	2.71	2.32	1.47	1.95	1.84	2.20	2.78	2.30
	$V_{mu}=M_{ud}/L$	kN	303.90	2531.80	1432.40	1006.70	1992.30	2104.60	347.40	2452.80	1444.20	959.90	1954.50	2123.00
	$\gamma_i \cdot V_{mu}/V_{yd}$		0.63	0.74	0.46	0.44	0.48	0.55	0.70	0.71	0.46	0.42	0.47	0.55

SUMMARY

This paper explained an example of seismic resistance designs according to the JWWA Guidelines 2009. As design lateral seismic coefficients are the key factors, we implemented ODERA with three different methods, based on seismic motions of engineering bedrock anticipated for the “Nankai trough (see Fig. 1)” earthquake from the regional disaster prevention plan in Nagoya, in order to determine the design lateral seismic coefficient. However, the design lateral seismic coefficient based on the “observation record of the Great Hanshin-Awaji Earthquake” surpassed it, and was adopted for the data in seismic motion level 2. Now we are preparing the order of renewal for service reservoir No.3. It would be a great pleasure, if this paper would be of help for some other waterworks design.

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Seismic Countermeasures and the Public Relations Strategy of the Kobe City Waterworks Bureau

Takahiro Yamaguchi, Yasutaka Matsuda, Makoto Matsushita, Takamasa Tanaka

Abstract

This paper describes the tangible and intangible seismic countermeasures developed by the Kobe City Waterworks Bureau in the past 20 years since the Great Hanshin-Awaji Earthquake and their states of progress, as well as the City's efforts to secure general service water other than drinking water in anticipation of prolonged water outages. This paper also describes the strategic public relations activities (basic public relations plan) we have been conducting to gain understanding of these countermeasures and efforts by the citizens.

Introduction

From afterthoughts and lessons from the Great Hanshin-Awaji Earthquake, we developed the "Kobe City Basic Plan for Earthquake-resistant Water Supply Facilities" in July 1995. This basic plan aims to construct an earthquake-resistant water supply system that can be restored to its original state within a short period of time. Based on this plan, we have implemented various seismic countermeasures over the 20 years since 1995.

In addition to its tangible measures, we have recently been implementing intangible measures in order to enhance its capability of responding to disasters in collaboration with local communities. The intangible measures include the creation of community environments in which local communities can take the initiative in emergency water supply and the execution of emergency water supply practices in collaboration with the residents. However, the results of a survey conducted by Kobe City showed that the citizens' awareness of our seismic countermeasures is low. We are facing a challenge in how to make the citizens familiar with its seismic countermeasures.

This paper describes the tangible and intangible seismic countermeasures developed by the Kobe City Waterworks Bureau during the past 20 years and the progress of the countermeasures, as well as the Bureau efforts toward securing general service water other than drinking water on the assumption of prolonged suspension of water supply. This paper also describes the strategic public relations activities (basic plan for public relations) we have been promoting to gain the understanding of the citizens of Kobe regarding these countermeasures and efforts.

Seismic Countermeasures and the State of their Progress
Tangible Countermeasures

Kobe City Waterworks Bureau's tangible seismic countermeasures consists mainly of the "construction of an emergency water storage system" for emergency water supply immediately after disasters, the "construction of Large-Capacity Transmission Main" for emergency water supply to urban areas and immediate recovery from water outage, and the "improvement of the earthquake resistance of distribution pipes" for the minimization of damage to the water supply system and immediate recovery from water outage. We have been implementing these seismic countermeasures while maintaining consistency with water supply facility renewal works.

For the "construction of an emergency water storage system," we have installed emergency stop valves in distribution reservoirs and large-capacity storage tanks in parks and on other grounds owned by Kobe City. These pieces of equipment will serve as the bases for water supply by tank trucks and emergency water supply to the citizens. We completed the construction of the planned total number of 47 bases by the end of fiscal 2013. These bases can supply approximately 60,000 m^3 of drinking water during an emergency.

For the "construction of Large-Capacity Transmission Main," we are currently constructing a water main under the urban area along a route different from the existing water main passing through the Rokko Mountains. With a diameter of 2.4 m and an overall length of 12.8 km, the construction of the new water main will be completed within fiscal 2015. This large-capacity transmission main construction project was the first in Japan to be launched in compliance with the Law Concerning Deep Subterranean Utilization. Owing to the proactive use of the latest technologies and systems, such as Steel Pipe for Crossing Fault, this project won a Japan Society of Civil Engineers Prize for technology development.

For the "improvement of the earthquake resistance of distribution pipes," we have been improving the earthquake resistance of not only the distribution mains and major pipeline networks, but also the pipelines reaching elementary schools, hospitals, and other disaster prevention bases, to facilitate emergency water supply activities in the event of disasters. Within a limited budget, the Bureau has been improving the earthquake resistance of existing distribution pipelines in order of priority. In practice, aged distribution pipes are replaced with earthquake-resistant pipes. The percentage of earthquake resistant distribution pipes has increased from 9% at the time of the Great Earthquake to 35% as of fiscal 2015.

We have also been improving the earthquake resistance of existing water purification plants and distribution reservoirs.

Intangible Measures

As intangible measures for improving the earthquake resistance of water supply system, Kobe City Waterworks Bureau has been promoting "emergency water supply bases reconstruction and emergency water supply practice" and "Itsudemo Jaguchi" ("the drinking fountain can be used for drinking water at ordinary times, while it is used for emergency water supply in the event of disasters") projects. We have recently begun to make efforts toward securing general service water other than drinking water in anticipation of prolonged water outage.

For the "emergency water supply bases reconstruction and emergency water supply practice" projects, we have been working since 2008 to develop a culture that will encourage each local community to voluntarily begin emergency water supply as early as possible after disasters/accidents. In particular, we have been reconstructing material/tool storage warehouses for emergency water supply and emergency water supply ports so that local residents can access these pieces of equipment immediately after disasters. In the past, most of the emergency water supply bases were constructed in distribution reservoirs and were controlled so that a local resident alone could not access them for security reasons. The keys of material/tool storage warehouses for emergency water supply have been handed over to local disaster prevention organizations. Emergency water supply practice is conducted at regular intervals in collaboration between the Waterworks Bureau personnel and local communities.

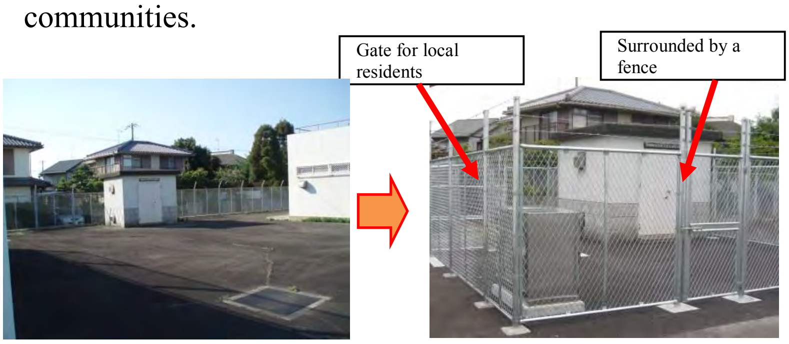

Figure 1　Emergency water supply base after its reconstruction

Figure 2　Emergency water supply practice in collaboration with local voluntary disaster prevention organization

For the “Itsudemo Jaguchi” project, we installed drinking fountains in elementary schools and junior high schools which are directly connected with reservoirs by earthquake-resistant pipes. These drinking fountains serve as emergency water supply bases. The purpose is to make the citizens familiar with the progress of our earthquake resistance improvement program in an easy-to-understand manner. The drinking fountain can be used for drinking water at ordinary times, while it is used for emergency water supply in the event of disasters. Emergency water supply practice is conducted at regular intervals in collaboration between the Waterworks Bureau personnel and each local community. The number of Itsudemo Jaguchi reached 36 by the end of fiscal 2014.

Securing General Service Water other than Drinking Water for Use during Disasters

As described above, we have implemented various measures to ensure the supply of drinking water even after the occurrence of disasters. In addition to the above measures, we are trying to provide information on both drinking water and general service water that can be used for daily life during disasters to further minimize the inconvenience of the citizens attributable to water shortage during disasters.

We have been working to establish a cooperation/contact system that will enable the related departments to share information on the following pieces of equipment, and thereby check mutually the damage to these properties and collaboratively respond to the damage at the time of a disaster.

(1) Emergency water supply bases and Itsudemo Jaguchi controlled and maintained by the Waterworks Bureau

(2) Wells controlled by the department in charge of health and welfare and made available for the citizens in the event of disasters (wells owned by citizens, companies, plants, and other organizations that can be made available to the public in the event of disasters)

(3) Facilities where the citizens can use rainwater and well water controlled by the department in charge of parks

(4) Temporary lavatories that are connected directly to a public sewage line controlled by the department in charge of the sewage system

The above cooperation/contact system will make it possible for disaster victims facing difficulty in obtaining water as usual after a disaster to obtain “water for use at the time of a disaster,” a general term for drinking water, daily life water, and general service water, from a total of 463 stations until the original function of the waterworks system is restored. The above 463 stations consist of 103 emergency water supply bases and Itsudemo Jaguchi that can supply drinking water, and 360 water supply stations. The water supply stations include 303 wells that can be made available for the citizens in the event of a disaster and facilities where the citizens can use rainwater and well water installed in parks. The total number of water supply stations that can be made available for disaster victims increases to 524 when 61 temporary lavatories that can be made available to the public in the event of a disaster are included. We believe that centralizing the information about the locations of these water supply stations and disclosing the information will help the citizens increase their options for access to water supply stations.

As described above, we have been promoting tangible and intangible seismic countermeasures in a unified manner. However, the results of a survey conducted by us showed that these seismic countermeasures have not been fully recognized by the citizens. One of our future tasks is to make the citizens aware of these countermeasures. It is indispensable for us to make the intangible countermeasures more effective and to sustainably promote the tangible countermeasures within a limited budget after gaining the understanding of the citizens. In particular, we should strategically publicize its seismic countermeasures.

Public Relations Strategy

Until recently, we performed public relations activities unsystematically with unclear objectives. Therefore, the activities were sporadic and lacked coherence. The activities were focused only on "how to transmit," and no attention was paid to "what should be transmitted and to whom." To improve our historical public relations strategy and thus maintain our water supply system sustainably by creating friendly relationships with water consumers, we developed the "Kobe City Waterworks Bureau Basic Plan for Public Relations" in March 2013. We intend to increase the number of water consumers who support our water supply operation and to maintain friendly communications with them. It is particularly important for us to get the citizens to understand that the water charges they pay are reflected reasonably in our water supply operation. Strategic public relations activities are also important to effectively continue the improvement of the earthquake resistance of water supply facilities. To deploy the public relations strategy systematically, we have adopted "fresh public relations" as a key word for its activities. This key word aims to encourage all spokespersons belonging to us to contact water consumers hospitably, to put forward all ideas on public relations activities based on this key word by introducing the senses of " fun," "laugh, and "humor," and to participate in the activities joyfully.

We believe that the "Kobe City Waterworks Bureau Basic Plan for Public Relations" conforms to the following objective of the "Project for promotion of earthquake-resistant waterworks," which was jointly launched by the Ministry of Health, Labour and Welfare and other organizations in Japan:

Objective: To achieve smooth operation of waterworks by building up trustful relationships with water consumers and stakeholders involved with waterworks and gaining their favorable responses to the necessity of renewing existing water supply facilities and improving their earthquake resistance. Increasing the number of the subjects of public relations from conventional water consumers to various stakeholders involved with waterworks and releasing information on waterworks including risk information to them are indispensable to achieving the above objective.

The succeeding sections of this paper describe a new public relations activity evaluation method developed by us, the results of public relations activity evaluation conducted by us in fiscal 2013, the citizens' awareness of our seismic countermeasures, and the new public relations strategy developed by us.

Public Relations Activity Evaluation Method

To apply the PDCA cycle approach to public relations, we tried to evaluate its public relations activities in terms of the "Mizumizu index" (effect of public relations) and the "efficiency of public relations activity."

The "Mizumizu index," which is an evaluation indicator, is determined from equation 1. We tried to use this index to digitize the direct and indirect effects of public relations on the public.

The "efficiency of public relation activity" is an index that is represented by the numerical figure obtained from equation 2. This equation digitizes the efficiency of public relations by comparing the effect of public relations with its cost.

$y = P \times T \times H$ (equation 1)

where,

y: Mizumizu index (effect of public relations)

P: Number of subjects

T: Depth of understanding

H: Degree of spread

Depth of understanding: Extent of the information understood by the person who received the information
Degree of spread: Number of friends and acquaintances to whom the person who received the information intends to transmit the information

A = Y/C (equation 2)
where,
A: Effect of public relations activity
Y: Mizumizu index
C: Cost

Evaluation of Public Relations Activity

To evaluate its public relations, we classified its activities into four primary categories according to characteristics and then further classified these primary categories into a total of 12 subcategories according to the measure.

"Event" ---------------------------------	Exhibition at event site (co-hosted event, etc.), event (hosted by us), waterworks week (event during waterworks week), hiking
"Visitingtalk A" -----------------------	Visiting talk, facility tour (upon request of the public), others
"Visitingtalk B" -----------------------	Facility tour (parent and child), facility tour (women's society), waterworks advisor
"Emergency water supply practice" -	Itsudemo Jaguchi, emergency water supply practice

We conducted a total of 97 public relations activities in fiscal 2013. These activities are divided into: (1) 20 events; (2) 29 visiting talks A; (3) 15 visiting talks B; and (4) 33 emergency water supply practices. The number of activities conducted on week days was 54, while the number of activities conducted on Saturdays and Sundays was 43. Excepting a few events, the Waterworks Bureau personnel talked about the improvement of the earthquake resistance of water supply system.

The measures in descending order of their average Mizumizu index scores (index per event) were "facility tour (parent and child)," "waterworks week," "exhibition at event site," and "hiking." In other words, the effect of public relations per event was in the descending order indicated above. The probable reasons were that the number of participants in these events was large and these events were covered widely in the media.

The measures in descending order of efficiency of public relations were "visiting talk," "Itsudemo Jaguchi," "waterworks week," and exhibition at event site." The Mizumizu index for "visiting talk" was small due to the small number of participants. However, the efficiency of public relations of this measure was high since most of them were held on weekdays, thus reducing costs including staff costs. The efficiencies of public relations of "facility tour (women's society)" and "waterworks advisor" were low because the cost of facility tours (women's society) per participant was high, and the cost of "waterworks advisor" events, most of which were held on Saturdays or Sundays, was also high. However, women's societies and waterworks advisors enhance the effect of our public relations strategy since they support and give advice on water supply operation. It may be necessary to increase the degree of dissemination of the above two measures.

Measure	Total for each measure			Numerical value per event (average)							
	Number of events held (media) (event)	Total number of participants (person)	Cost (×¥1,000)	Number of participants P (person)	Mizumizu index Y	Cost C (x ¥1,000)	Efficiency of public relations A=Y/C ×1,000	Saturday or Sunday (%)	Media (%)	Depth of understanding T	Degree of spread H
(1)Exhibition at event site	7 (1)	3,645	769	521	7,881	110	71.7	100	14	0.81	18.3
(2)Event	4 (1)	599	1,210	150	3,583	303	11.8	75	25	0.95	30.5
(3)Waterworks week	7 (0)	3,438	1,051	491	13,517	150	90.1	0	0	0.79	35.0
(4)Hiking	2 (2)	107	562	54	5,350	281	19.1	100	100	1.00	100.0
(5)Visiting talk	12(2)	558	88	47	984	7	133.6	17	17	0.95	21.1
(6)Observation of facilities (upon request of the public)	10(0)	588	77	59	155	8	20.2	10	0	0.78	4.1
(7)Observation of facilities (parent and child)	1(1)	277	722	277	27,700	722	38.4	100	100	1.00	100.0
(8)Observation of facilities (women's society)	9(0)	330	933	37	159	104	1.5	0	0	0.96	4.6
(9)Waterworks advisor	5(1)	88	301	18	379	60	6.3	100	20	0.84	28.0
(10) Itsudemo Jaguchi	7(1)	1,181	256	169	4,853	37	132.7	29	14	0.79	19.4
(11) Emergency water supply practice	26(5)	2,427	515	93	1,149	20	58.0	73	19	0.84	24.2
(12) Others	7 (0)	100	3	14	52	400	120.3	0	0	0.87	3.7
Total	97 (14)	13,338	6,486	138	2,922	67	43.7	43	14	0.86	21.3

Table 1 Evaluation result for public relations

The evaluation results for public relations are summarized as follows:

(1) Measures effective for spreading information [Mizumizu index ("index" for short) is large, efficiency is large)]

The "exhibition at event site" and "waterworks week" events are effective for grasping the public's awareness of waterworks and their needs. The reason is that we have a policy of conducting public relations without any limitation at these events in order to encourage even individuals with absolutely no interest in waterworks to participate in these events

(2) Measures that attracts public attention (efficiency is high)

"Visiting talk," "Itsudemo Jaguchi," "emergency water supply practice," and "facility tour (parent and child)" are highly efficient measures for our public relations. At the "visiting talk" events, the Waterworks Bureau personnel can talk about the topics requested by the citizens. "Itsudemo Jaguchi," "emergency water supply practice," and "facility tour (parent and child)" events give vivid impressions to the participants through practical experiences and observations.

(3) Increase in the number of waterworks supporters (index is small to medium, efficiency is low to medium)

"Hiking" provides many opportunities for us to hear the opinions of the citizens, since this event increases the number of repeat participants with whom the Waterworks Bureau personnel can communicate in a friendly manner. "Observation of facilities (women's society)" and "waterworks advisor" provide benefits higher than those represented by the public relation evaluation index, since these events deepen the visitors' understanding of water supply operation and they also support and give advice on our water supply operation.

Each measure (public relations means) has its own advantages and disadvantages. To enhance the effect of each public relations activity, it is important to hold the most appropriate event after considering the purpose and contents of the public relations, expected participants, and other factors. In other words, it is effective to combine an exhibition that inspires many people to participate with an unspectacular event, as in the past. The following section describes the citizens' awareness of the seismic countermeasures and the public relations strategy of us.

Citizens' Awareness of Seismic Countermeasures and the Public Relations Strategy of the Waterworks Bureau

To know the citizens' awareness of the seismic countermeasures, we conducted a questionnaire survey on the following four items before we publicized the countermeasures.

(1) We have been renewing or improving the earthquake resistance of aged water pipes.
(2) Improvement of the earthquake resistance of water supply facilities
(3) Large-Capacity Transmission Main
(4) Locations of emergency water supply bases

The questionnaires were handed out to event participants. As an example of our questionnaire survey, this paper describes the surveys conducted at the following five event sites:

Analysis of the questionnaire survey results showed that, though there was a slight difference between the events, approximately 70% of event participants knew little about our earthquake resistance improvement works (zero or one item). Their awareness of our works other than earthquake resistance improvement before these works were publicized was also surveyed. It was found from the survey that less than 40% of event participants knew little about the items covering the whole range of Kobe City's waterworks or such common items as tap water, while approximately 50% of them knew little about water quality improvement.

Compared with these percentages, their awareness of earthquake resistance improvement was substantially lower. A working group of the "Project for promotion of earthquake-resistant waterworks" conducted an Internet survey* asking 300 residents of Shizuoka Prefecture if they knew or heard of the ratio of earthquake-resistant facilities. The result showed that the percentage of the subjects who had been aware of the term before a waterworks PR campaign was 12%, while the ratio after the campaign was 20.3%.

* Waterworks PR campaign WG activities report Project for promotion of earthquake-resistant waterworks March 2014

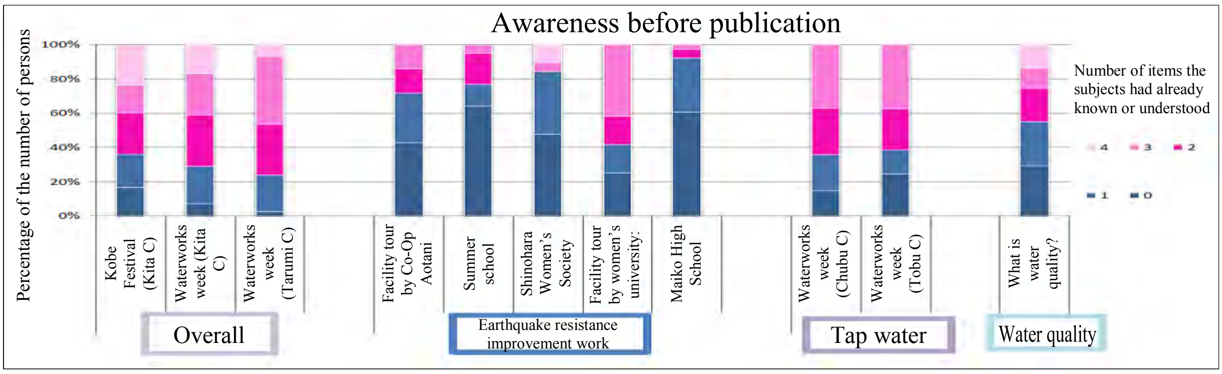

Figure 3 Subjects' awareness of earthquake resistance improvement work

The Waterworks Bureau further asked the event participants to answer the following questions to grasp their awareness of earthquake resistance improvement work by age. The result, which is shown in Figure 4, indicated that the event participants under the age of 40 were particularly poor in their awareness of "steadiness" (items 7 to 10), which is closely related to earthquake resistance improvement. Their awareness of the other items was also poor as a whole.

[Questions]

Questionnaire item	Theme	Question
7	Steadiness	In anticipation of earthquakes, earthquake resistance improvement has been promoted for water pipes and water purification plants.
8	Steadiness	The construction of Large-Capacity Transmission Main is a project launched on the basis of the lessons learned from the Great Hanshin-Awaji Earthquake.
9	Steadiness	In anticipation of earthquakes and other natural disasters, earthquake resistance improvement has been promoted for distribution pipes.
10	Steadiness	I know the location of the emergency water supply base nearest to my house.

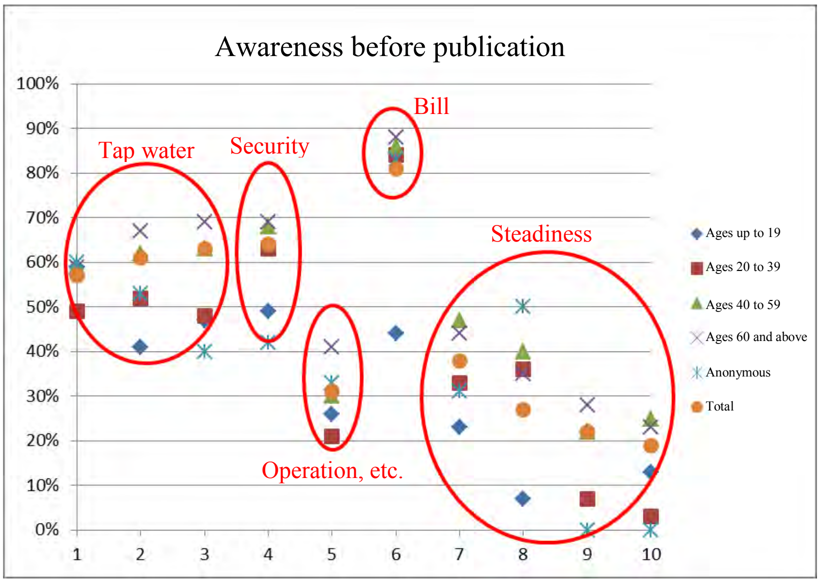

Figure 4 Analysis result of awareness by age

We analyzed the data obtained from a customer satisfaction survey on Kobe City waterworks that was conducted among 3,000 randomly selected ordinary citizens. The analysis results showed that the most important information they wanted to know or were interested in regardless of age was information on emergency water supply in the event of a disaster.

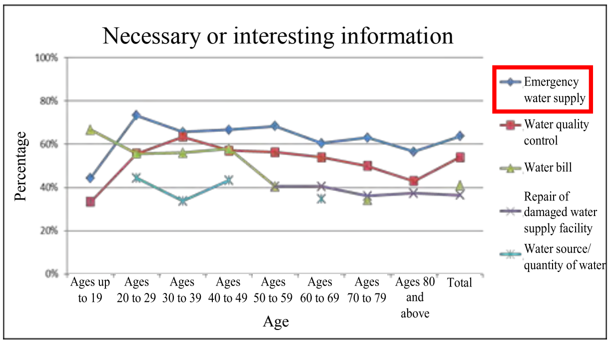

Figure 5 Necessary or interesting information

The analysis results are summarized as follows:

- Awareness of earthquake resistance improvement was lower than other topics.
- Awareness of earthquake resistance improvement (and other topics) by citizens of up to 39 years in age was lower than that of other age groups.
- Citizens of all age groups want to know the information on emergency water supply in the event of disasters.

Based on the above survey results, we studied the improvement of public relations on earthquake resistance improvement, the awareness of which was lower than the other topics. As a result, we concluded that it should improve the citizens' awareness of earthquake resistance improvement for water supply facilities by telling them about our actual experiences in helping the victims of the Great East Japan Earthquake and holding participatory events. More specifically, we should take the following measures:

- At "visiting talks" and other events, we will tell the participants about its earthquake resistance improvement efforts in combination with the real experiences gained in 2013 during its supportive activities following the Great Earthquake that hit the Tohoku Region.
  ⇨ Improvement of the depth of understanding

• We will hold participatory events that will provide the participants with special experiences or actual feelings. At these events, we will permit the participants to enter and see special facilities that are usually kept off limits to the public. The participants will gain a strong impression from these events and are likely to talk their friends and acquaintances about their impression.
⇨ Improvement of the depth of understanding and the degree of spread

• We will plan events that can be enjoyed by small children.
These events are expected to encourage thirty-something parents of small children to participate in the events and raise their limited awareness of our activities. Planning quiz games and other programs that will arouse the participants' playful spirit regarding emergency water supply practices is one of the ideas for promoting positive dialogue with the participants. We should also plan further new experience-based events at which children can dabble with and draw water, since these events are effective in helping young parents understand our various efforts.
⇨ Events for people of a specific generation

According to the result of a survey* conducted as a part of the "Project for promotion of earthquake-resistant waterworks," approximately 50% of water consumers are likely to accept a slight increase in their water bills for expediting the improvement of the earthquake resistance of water supply system. The working group in charge has confirmed that it is possible to have risk communication with water consumers. The above survey result suggests that it is important for us to steadily continue holding the events described above, thereby increasing the number of people who understand the necessity of improving the earthquake resistance of water supply facilities. It is also important to maintain good communications with water consumers in order to have them understand that their water bills are reasonably reflected in our water supply operation.

* Waterworks PR campaign WG activities report Project for promotion of earthquake-resistant waterworks March 2014

Afterword

At this turning point 20 years after the Great Hanshin-Awaji Earthquake, this paper described the earthquake resistance improvement works the Kobe City Waterworks Bureau has been promoting by integrating tangible and intangible measures, as well as our new efforts toward ensuring a stable supply of daily life water and its new public relations strategy.

As a earthquake resistance improvement strategy, we have been integrally implementing tangible and intangible measures. To pursue this strategy more efficiently, we are required to further improve its intangible measures and to gain the citizens' acceptance in order to secure the financial resources necessary to successfully implement its tangible measures.

While steadily improving the earthquake resistance of the water supply system by integrating the tangible and intangible measures, we will conduct research to determine information that will provide the citizens with a sense of ease during ordinary times and disasters, as well as the optimal timing and method for transmitting the information to them.

Tokyo Waterworks' Earthquake Countermeasures: Towards Earthquake-resilient Water Services in Tokyo

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Keywords: earthquake retrofitting; duplexing of conveyance pipelines; emergency water supply; backup agreement for disaster recovery

TOKYO WATERWORKS' EARTHQUAKE COUNTERMEASURES: CURRENT STATE AND CHALLENGES

In March 11, 2011, the Great East Japan Earthquake occurred, with a magnitude of 9 – the largest ever recorded in Japan. The big shakes and tsunamis due to the great earthquake inflicted enormous damage to the lifeline mainly in the Tohoku region. The water supplies to approximately 2.57 million houses were suspended, which led to the situation where water was unavailable even in shelters. Also, the quake caused damage that we have never experienced (e.g. leakage accidents due to ground liquefaction and turbid water associated with planned power outage) even in Tokyo – a place far distant from the epicenter. This shed light on the problem in securing water supply.

Meanwhile, in April 2012, the Tokyo Metropolitan Government (hereinafter, TMG) issued the Estimated Damage from a Tokyo Inland Earthquake and conducted a review of the situation where the worst possible damage can be caused in the future in a more realistic manner. As a result, we found that the damage will be larger than estimated before: the maximum seismic intensity 7 to be observed in certain places and the intensity 6 upper in broad areas, and the maximum tsunami height of TP 2.61 meters to be observed along the coast of Tokyo Port.

Under such a situation, in February 2015, Tokyo Waterworks formulated the Master Plan for Tokyo Water Supply Facility Development (hereinafter, Master Plan) in order to respond to various challenges such as the Tokyo Inland Earthquake, the urgency of which has been pointed out, thereby announcing the facility development policies including earthquake-resistance measures. Also, in March 2015, we reviewed the Tokyo Waterworks Earthquake Emergency Response Plan in order to more quickly and effectively recover the normal water supply and secure drinking water in case of earthquake damage.

Towards earthquake-resilient water services, it is important for us – a waterworks operator of the capital city Tokyo – to ensure the measures from both tangible and intangible perspectives.

TOKYO WATERWORKS' EFFORTS

At the previous Japan-US-Taiwan Workshop on Water Supply System Seismic Practices (2013), We made a presentation titled "Tokyo Waterworks' Earthquake Countermeasures Based on the Tokyo Waterworks Management Plan 2013." This time, I will report mainly on the details of such earthquake countermeasures and introduce the countermeasures that have been taken since the previous presentation.

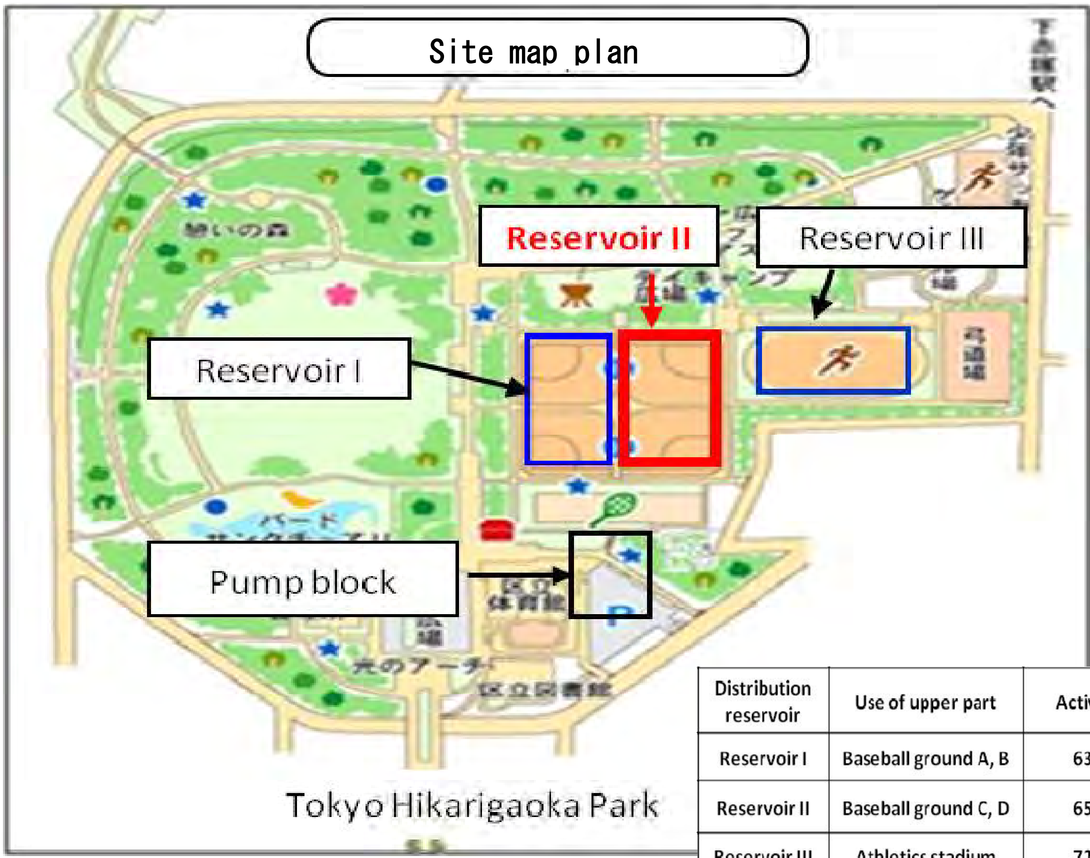
Promotion of earthquake countermeasures

Promotion of earthquake retrofitting at water purification plants and water supply stations

Many of the purification plants and water supply stations are becoming older because they were built around 1960, a half century ago. If a disaster (e.g. Tokyo Inland Earthquake) causes damage to those facilities in such a situation, their facility capacities will significantly decline due to damage caused by their lack of strength. We are, therefore, promoting earthquake resistance of facilities towards the development of such facilities with proper seismic capacity in a planned manner.

In terms of the promotion of earthquake resistance of purification plants, we are effectively carrying out earthquake retrofitting in light of the continuity from receiving wells to filter basins, internal connection pipes and wastewater treatment stations. Also, as for distribution reservoirs at water supply stations, we are prioritizing those without supporting functions, facilities related to water supplies to the capital's main organizations and emergency medical institutions, and facilities in areas with high liquefaction potential.

For example, the Nerima Water Supply Station that was built in 1980 is an important water distribution base in Tokyo, with three distribution reservoirs under the ground of the Tokyo Hikarigaoka Park, the total capacity of which is the largest in Tokyo (200,000 m^3). In preparation for disasters such as the expected Tokyo Inland Earthquake, the urgency of which has been pointed out, we have promoted earthquake retrofitting works in order since 2008, completed Reservoirs I and III, and are currently constructing Reservoir II.



Distribution reservoir	Use of upper part	Active storage
Reservoir I	Baseball ground A, B	63,000 m^3
Reservoir II	Baseball ground C, D	65,000 m^3
Reservoir III	Athletics stadium	72,000 m^3

Figure 1. Site plan of the Nerima Water Supply

The major earthquake retrofitting works carried out include shear reinforcement, concrete deck-slab reinforcement, installation of flexible expansion joints, and inner corrosion protection.

Shear reinforcement: improving the earthquake resistance by inserting reinforcing steel bars from the sides to increase the amount of reinforcing steel.

Figure 2. Sidewall boring

Concrete deck-slab reinforcement: improving the earthquake resistance of posts by casting concrete to the bases of posts

Figure 3. Concrete deck-slab reinforcement

Installation of flexible expansion joints: The joints compensate the displacement due to earthquakes, thereby reducing impacts on structures.

Before installation

After installation

Figure 4. Concrete deck-slab reinforcement

Inner corrosion protection: removing deteriorated internal coating and repairing it with mortar.

Coating removal

Mortar corrosion protection

Figure 5. Inner corrosion protection

Before earthquake retrofitting

After earthquake retrofitting

Figure 6. Earthquake retrofitting work (Nerima Water Supply Station)

Promotion of earthquake-resistant water pipes

In response to the lessons learned from the fact that many water pipe joints were slipped off due to the Great East Japan Earthquake, the TMG decided to implement the “10-year project to promote earthquake-resistant joints” aiming to complete the replacement of existing joints on pipelines of 5,000 kilometers in length by earthquake-resistant joints with the slipping-off prevention function in 10 years. As of end-March 2014, the share of earthquake-resistant joints has reached 35 percent. We have further promoted the use of earthquake-resistant joints aiming to increase the replacement rate up to 59 percent by March 2025 as planned in the Master Plan.

In terms of the promotion of earthquake-resistant joints, we have given priority to supply routes to important facilities such as the capital's main organizations and emergency medical institutions. In response to the lessons learned from the damage caused by water outage at shelters at the time of the Great East Japan Earthquake, we have newly included shelters and main stations in the list of the priority facilities, thereby working on promoting earthquake-resistant joints at these facilities.

For information on the promotion of earthquake resistant water pipes, please also refer to the Earthquake countermeasures as an affiliated corporation of the TMG (TSS Tokyo Water Co., Ltd.).

Figure7. Pipe jointing by earthquake-resistant joints in water supply pipes connected to major facilities

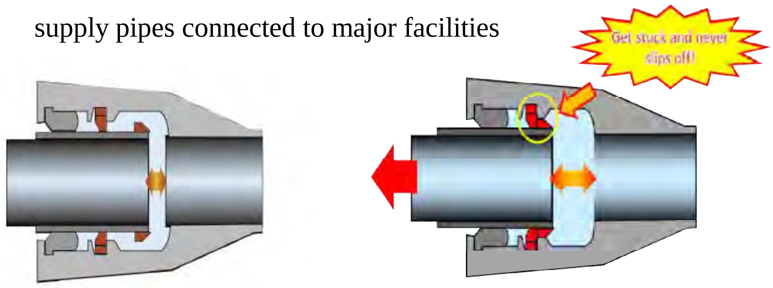


Figure 8. Structure of earthquake resistant pipe joint

Ensuring a stable water supply

Duplexing of conveyance facilities

The conveyance facilities are important facilities that convey raw water taken at water intake facilities to purification plants. The TMG takes 78% of water from the Tonegawa and Arakawa River systems and 19% from the Tamagawa River system.

In 1964, in order to enable mutual transmission of raw water between river systems as a measure against drought, Tokyo Waterworks developed the raw water connection pipeline between the Asaka Purification Plant that conveys raw water from the Tonegawa and Arakawa

River systems, and the Higasimurayama Purification Plant that conveys raw water from the Tamagawa River system. This is the only pipeline that enables mutual transmission between the Tonegawa and Arakawa River systems, and the Tamagawa River system.

At normal times, we work on securing a sufficient amount of water in the Tamagawa River system by transmitting raw water from the Tonegawa and Arakawa River systems that are relatively abundant in water to the Higashimurayama Purification Plant.

Also, at the time of drought or accident along the Tonegawa and Arakawa River systems, we ensure stable water supply by transmitting water from the Tamagawa River system to the Asaka Purification Plant.

The raw water connection pipeline is more than 50 years old and subject to concerns about the progress of aging and the seismic vulnerability; therefore, we conducted interior and exterior inspections and seismic diagnosis in 1999. As a result, we found four places that urgently require repairs due to problems in their seismic resistance, and carried out emergency repair works.

In this way, although the raw water connection pipeline is a crucial facility for Tokyo Waterworks, it has problems: lack of alternative pipelines, lack of option of long-term facility closure during water supply operations and vulnerability against the Tokyo Inland Earthquake that is of concern.

In order to resolve these problems, we decided to develop a new connection pipeline of raw water (hereinafter, Second connecting pipes of raw water) which have the backup functions .

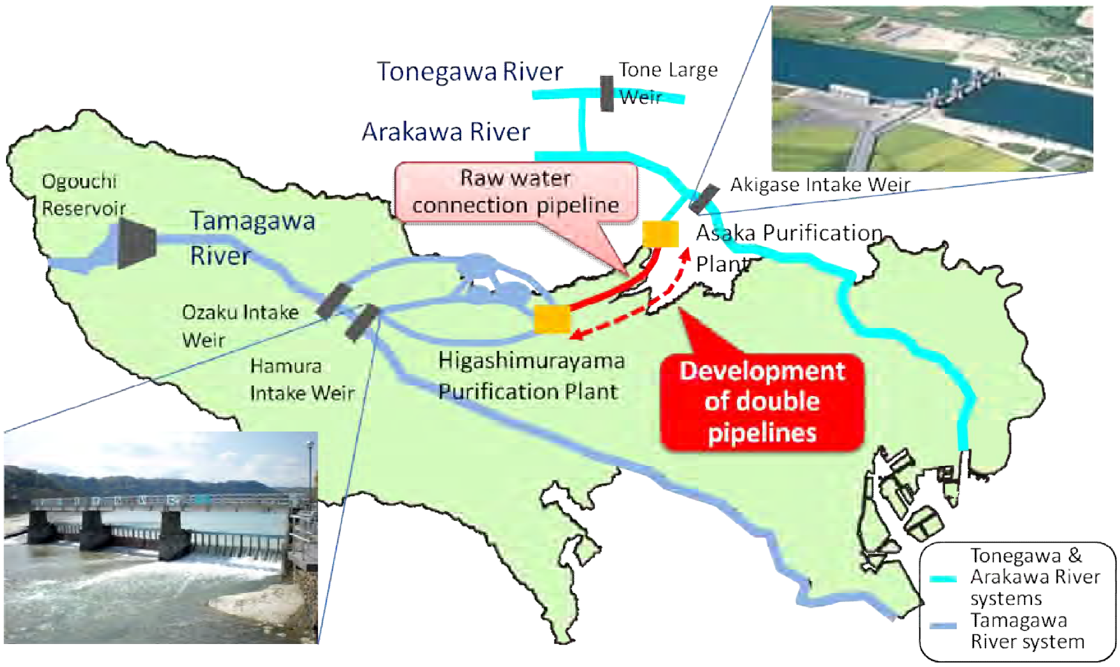


Figure 9. Duplexing of conveyance facilities

We lay Second connecting pipes of raw water on the same route as the conventional pipeline considering economic efficiency and workability. Whereas the conventional pipeline is laid under the earth covering of 3-meter depth, Second connecting pipes of raw water is to be laid around 30 meters below the ground by the shield tunneling method.

Projecting period and the scale of facilities

Projecting period

From 2010 to 2018

The scale of facilities

Pipe diameter: 2,000 mm

Total extension: about 16 km

We adopted the slurry shield construction method in all the construction sites.

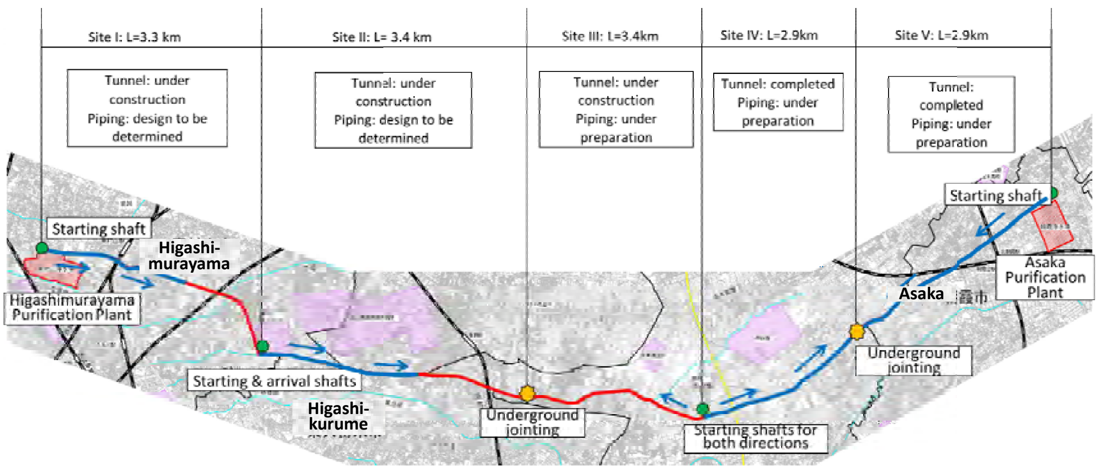
The construction sites are divided into five considering the shortening of the construction period. We build a 2,200-millimeter-diameter tunnel in each construction site by the shield tunneling method and lay earthquake-resistant pipes of 2,200 millimeter diameter inside it.

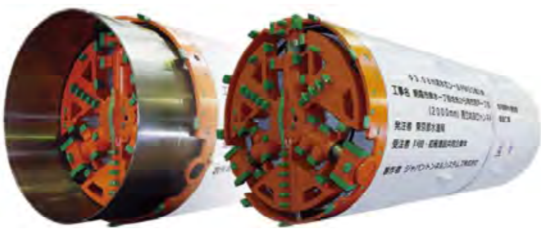
We are able to secure only four vertical shaft sites for the construction route and the distance between the sites is six to seven kilometers long. Thus, we adopt the underground jointing method that requires no arrival shafts between Sites II and III, and Sites IV and V.

As of October 2015, the tunnel constructions at Sites IV and V have been completed, and those at Sites I, II and III are under construction.

We are laying earthquake resistant pipes in order after the completion of the tunnels aiming to complete all the works in 2018.

Overview of the route





Underground jointing Tunneling

Shield machine

Construction status

Inside a shield tunnel

Figure 10. Overview of the second raw water connection pipeline

Establishment of emergency water supply system

Reorganization of emergency water supply bases

There are 203 emergency water supply bases in Tokyo (as of April 1, 2015). As for earthquake emergency water supply activities at purification plants and water supply stations, Tokyo Waterworks is responsible for unlocking the key to gates and setting up equipment, while municipalities are responsible for distributing water. In this regard, however, there used to be a problem that municipalities could not carry out emergency water supply activities until the arrival of Tokyo Waterworks' personnel who are familiar with how to enter into the base, where to store equipment, and how to start pumps.

Thus, we separated the area for emergency water supply activities and installed permanent hydrants (water taps) there within the facility site using dividing fences so that municipalities and local residents can promptly carry out emergency water supply activities without our staff. Also, we newly installed the emergency water supply pump unit within each site to supply water to these hydrants. This pump allows us to supply water just by opening the faucet without start-up operations and enables power supply from the non-utility power generator, which can work even in power outage in time of disaster. Thus, even those who have not mastered its operation can easily carry out emergency water supply activities.

In addition, we ensure the working of the security system by installing sensors on the dividing fence to prevent the general public from entering into the site of the purification plant or water supply station. We manage the entrance keys in accordance with agreements concluded with municipalities and local community associations.

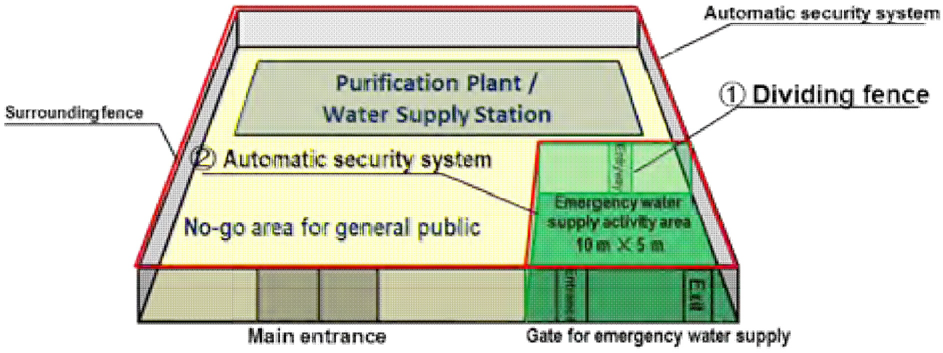


Figure 11. Area for emergency water supply activities

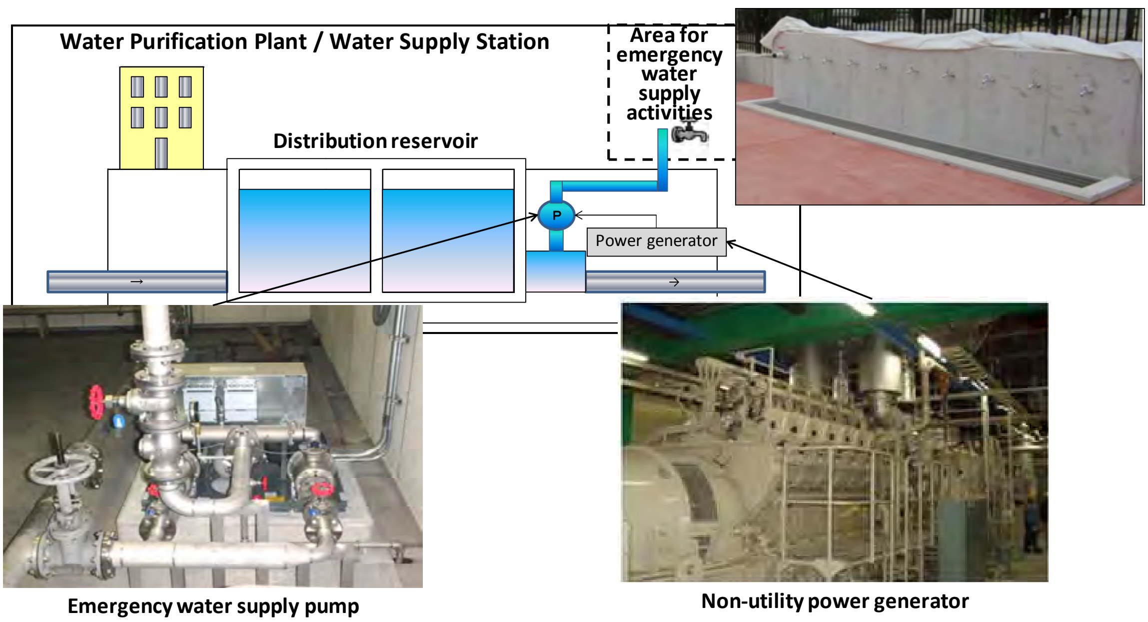


Figure 12. Illustration of the facility

Temporary hydrants

In order to provide rapid and smooth emergency water supply, the cooperation from local residents is essential. For the purpose of complementing emergency water supply bases, Tokyo Waterworks lends municipalities sets of equipment that are necessary for emergency water supply activities utilizing fire plugs around shelters.

The sets of equipment for temporary hydrants are composed of the following:

- Installation table for water supply pipes,
- Water supply pipes, and
- Hoses for water supply and faucets.

It is very easy to set up the hydrant that just requires us to connect pipes, and then turn over and fix pull rings. For emergency water supply using the temporary hydrant, water distribution pipes must be sound even if a service pipe is damaged; thus, securing the supply route to shelters as I mentioned earlier in the “10-year project to promote earthquake-resistant joints on water pipelines” is a crucial prerequisite.

Figure 13. Temporary hydrant

Joint trainings with local residents

Tokyo Waterworks has implemented joint trainings with municipalities and local residents at each emergency water supply base. We have provided not only trainings using normal hydrants (water taps) but also experimental programs of setting up temporary hydrants and of emergency water supply using fire plugs. In this way, we have promoted the improvement of disaster response capability by establishing the emergency water supply system in cooperation with local communities.

Below are images from the training held at the emergency water supply base in the Tama area in February 2015. On that day, the participants included staff members of Tokyo Waterworks (including affiliated corporations), City Hall staffs, local community associations, and local fire stations. We implemented the training for checking the performance of the normal hydrant, and the experience of setting up the temporary hydrant. We also train participants in measuring the residual chlorine concentration to confirm the compliance with the water quality standard (0.1 mg/L or more) before supplying water.

Figure 14. Information board of the emergency water supply base

Figure 15. Permanent hydrants

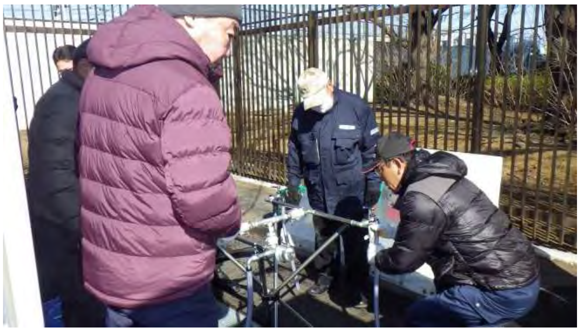


Figure 16. Experience of setting up temporary hydrants

Figure 17. Checking of water flow

Cooperation and collaboration with other cities and organizations

Agreements and memoranda of understandings

For appropriate implementation of emergency measures during disasters, we have made effort to establish the cooperative system with other cities and private businesses by concluding not only outsourcing contracts but also agreements or memoranda of understandings (MOUs) in advance, thereby ensuring post-earthquake emergency response activities. The followings are main agreements and MOUs that Tokyo Waterworks has concluded with other cities for the purpose of emergency water supply and recovery supports.

- MOU on Mutual Disaster Support between Waterworks Bureaus of 19 Cities (Tokyo, Sapporo, Sendai, Saitama, Kawasaki, Yokohama, Niigata, Shizuoka, Hamamatsu, Nagoya, Kyoto, Osaka, Sakai, Kobe, Okayama, Hiroshima, Kitakyushu, Fukuoka, and Kumamoto)
- Basic Agreement on the Establishment of the Asaka Connection Pipeline (Saitama Prefecture)
- Basic Agreement on the Establishment of the Connection Pipeline between Tokyo and Kawasaki City (Kawasaki City)

In addition to agreements with other cities, we have also concluded agreements or MOUs with private businesses (e.g. the Agreement on Disaster Emergency Services with TSS Tokyo Water Co., Ltd.) for the purposes of emergency response activities, and supply of materials for pipe recovery, vehicles and petroleum fuel.

Staging-area waterworks operators

In addition to agreements and MOUs, in September 2014, Tokyo Waterworks and the Ibaraki Prefectural Government Public Enterprise Bureau concluded the MOU on Activities as Staging-area Waterworks Operators, which is the first case in Japan.

The system of staging-area waterworks operators was instituted by the Japan Water Works Association because, in the aftermath of the Great East Japan Earthquake, support teams headed to affected areas could neither fully understand the disaster situation nor settle their activity bases as intended. Under this system, if the area of one waterworks operator is affected by a disaster, the other operator plays the function of a staging-area operator who provides a staging area as a parking or rest place for support teams who are dispatched to affected areas.

Trainings with other cities

Based on the agreements and MOUs, Tokyo Waterworks has regularly conducted joint trainings with other cities.

In the training with Ibaraki Prefecture held in January 2015, we conducted the information communication training of the process from making a request for the provision of a staging area to the Ibaraki Public Enterprise Bureau to the decision-making on a staging area, with the assumption that the Sendai City Waterworks Bureau that is our main support city is to dispatch its support team to Tokyo.

The training has been conducive to enhancing the effectiveness of the MOU by allowing better understanding of the procedure concerning the request to staging-area water operators.

Disaster emergency activities

Based on agreements with other cities and private trade associations, Tokyo Waterworks has conducted emergency supply of water and recovery of water facility in areas affected by disasters such as the Great East Japan Earthquake.

Table 1 below shows our major achievements:

Table 1. Major achievements based on agreements between Tokyo Waterworks, and other cities or private trade associations

Earthquake	Date of earthquake	Period of dispatch and the number of dispatched staff	
		Tokyo Waterworks	Private businesses

		(Emergency water supply support)	(Emergency recovery support)
Southern Hyogo Prefecture Earthquake (Great Hanshin-Awaji Earthquake)	Jan 17, 1995	254	598
		Jan 21-Mar 31, 1995 (70 days)	Jan 23-Mar 31, 1995 (68 days)
Niigata Chuetsu Earthquake	Oct 23, 2004	24	12
		Oct 24-Nov 15, 2004 (23 days)	Oct 30-Nov 15, 2004 (17 days)
Chuetsu Offshore Earthquake	Jul 16, 2007	34	42
		Jul 18-31, 2007 (14 days)	Jul 19-31, 2007 (13 days)
Tohoku-Pacific Ocean Earthquake (Great East Japan Earthquake)	Mar 11, 2011	36	49
		Mar 16-Apr 6, 2011 (22 days)	Mar 18-Apr 6, 2011 (20 days)

CONCLUSION

In 2012, the estimated damage from a Tokyo Inland Earthquake was reviewed in light of the Great East Japan Earthquake. As a result, the new estimate suggested more serious damage than the previous one. Tokyo Waterworks has also reviewed its conventional earthquake measures, thereby revising the Master Plan and the Earthquake Emergency Response Plan.
In the Master Plan, we newly added the goals in 10 years considering the achievements of the current facility development plan. In many cases, facility development takes a long period of time; thus, it is necessary to steadily implement the project by setting an order of priority on a limited budget.

In the Earthquake Emergency Response Plan, we changed our organizational structure in order to smoothly and flexibly carry out emergency response activities. Also, in 2014, we promoted cooperation with other cities, such as by concluding the MOU on activities by staging-area water operators with the Ibaraki Public Enterprise Bureau. The key to minimize damage is how to develop cooperative relations with other local governments, private businesses and all the citizens in Tokyo.

In this way, we have been making efforts to take earthquake disaster countermeasures from both tangible and intangible perspectives. We will continue to achieve the earthquake-resilient water services in Tokyo by further promoting various measures such as raising awareness related to self-help, co-help, and rescue and assistance by public bodies in times of disaster, along with the infrastructure development from a tangible perspective.

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TSS Tokyo Water's Efforts for Earthquake Disaster Measures

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Abstract
TSS Tokyo Water Co., Ltd. is taking responsibilities for important fundamental operations of waterworks management to conduct comprehensive operation and maintenance of overall waterworks facilities, taking advantage of its abundant experiences and high technical skills about waterworks and flexibility as a private entity.

Among the undertaking works from Tokyo Metropolitan Waterworks Bureau, TSS has recently expanded ones concerning reinforcement of earthquake-resistance, additionally concluding an agreement which enables TMWB and TSS to collaboratively and positively conduct necessary measures in the event of earthquake disasters.

This article reports introduction of some major examples of TSS's efforts including earthquake disaster measures. After "development of systems for entrusting works" is outlined, at "reinforcement of earthquake-resistance of pipelines," pipe network planning / designing and construction site supervision works as 10 Year Project for the Use of Earthquake-resistant Joints in Pipelines, and Adjustment Project of Service Pipes under Private Roads are explained, followed by "utilization of various pipe inspection data" with its examples such as pipeline diagnosis work and mobile mapping system. Lastly at "Collaboration with TMWB in earthquake disasters" efforts are introduced including reinforcement of collaborative system, practice of training against earthquake disasters, and development of circumstances concerning devices etc. for earthquake disasters.

INTRODUCTION

TSS Tokyo Water Co., Ltd. (hereinafter referred to "TSS") is playing a part as a partner company of Tokyo Metropolitan Waterworks Bureau (hereinafter referred to "TMWB"), in managing Tokyo Waterworks to support 13 million metropolitan residents' daily lives, urban activities, and central functions as the capital of Japan, collaboratively with TMWB. TSS has been undertaking a wide range of technical works such as O/M of facilities, pipe network planning / designing, and construction site supervision works "from water resources to taps," which were formerly conducted by TMWB.

In addition, TSS has another aspect as a Tokyo Metropolitan Government's supervised organization† (hereinafter referred to "Supervised Organization") which should contribute to efficient operation of waterworks by securing both publicness and efficiency. To accomplish these roles successfully, TSS is striving for showing comprehensive technical skills about waterworks operations which have been cultivated and making efforts for establishing an efficient business operation system which is characteristic of private companies.

Meanwhile, from both tangible and intangible viewpoints, TMWB has been dealing with various earthquake disaster measures against a local earthquake on metropolis which has been recently pointed out to occur, for establishing an earthquake-resistant waterworks which is

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desirable for the capital Tokyo. Among these leading measures, "reinforcement of earthquake-resistance of pipelines" is being implemented.

This article reports progress status of earthquake disaster measures including a leading project for reinforcement of earthquake-resistance of pipelines named "10 Year Project for the Use of Earthquake-resistant Joints in Pipelines" (hereinafter referred to "10 Year Project") which TSS involves in.

† Supervised Organization of Tokyo Metropolitan Government: an organization which receives investment and continuous fiscal expenditure from Tokyo Metropolitan Government, as well as supervision and guidance from all bureaus of Metropolitan Government

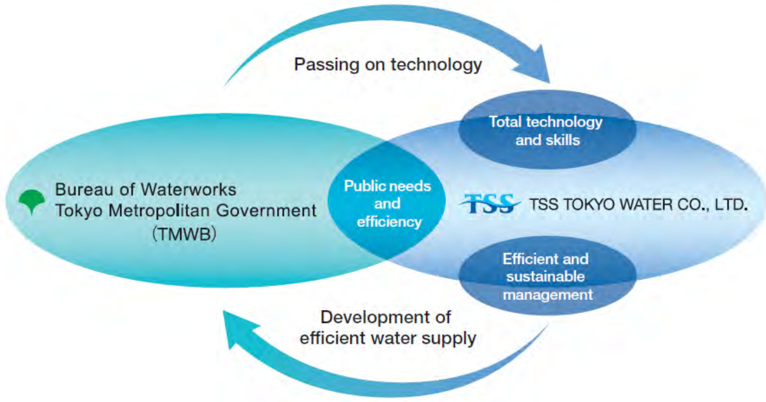

Figure-1: Partnership between TMWB and TSS

DEVELOPMENT OF SYSTEMS FOR ENTRUSTING WORKS

In 1987 TSS was established as "Waterworks Comprehensive Services Co., Ltd." before changing its company name to "TSS Tokyo Water Co., Ltd." in 2001. In 2006, "Integrated Operation System" was decided to establish, which specifies that fundamental waterworks operations should be conducted by TMWB and Supervised Organizations in order to be responsible for stably supplying Metropolitan residents with safe and drinkable water for the long future, securing both publicness and efficiency in administration.

As for entrusting works from TMWB, they are divided and separately contracted in two respective areas called Tama area and 23 Ward area, while TSS provides appropriate manpower to deal with work volume of each area. Tama area has 3.9 million population

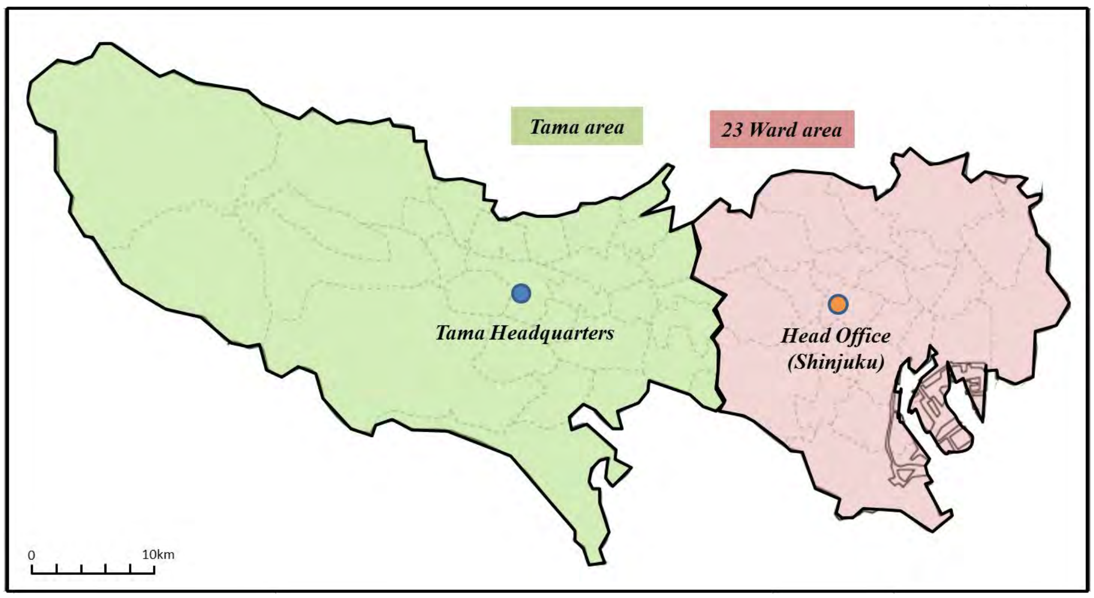

Figure-2: Operation system of TSS in Tokyo Metropolitan Government served, which is almost equivalent to those of Yokohama, the second largest city in Japan.

In Tama area each waterworks was formerly individually administrated by municipality. But after 1955 as the rapid urbanization progressed, waterworks utilities of 26 municipalities have joined TMWB to secure stable water supply. For a period of time even after the unification into TMWB, based on Local Autonomy Law, entrustment of business affairs to each municipality has been applied to works including O/M of waterworks facilities, water charge collection which needs close relationship with customers, and approval of new installation of service connections.

After that, based on “Master Plan for Improving Waterworks Management of Tama Area” which was established in 2003 for further satisfactory customer services and more efficient waterworks management, all entrustment of business affairs has resolved at the end of 2011 FY so that technical works can be entrusted from TMWB to its TSS as a Supervised Organization. To follow this, Tama Headquarters of TSS made a lot of efforts for arranging branch offices and procuring necessary staff to overcome difficulties together such as drastic increase of work volume, developing planned reinforcement of earthquake-resistance of pipelines.

On the other hand, as recruiting of necessary staff is difficult because of recent shortage of civil workers in Japan, flexible and efficient work performance are being carried out; valve operation works during water suspension etc. with much work force are undertaken by TSS’s partner companies with reliable work records, and routine works in planning / designing such as close figure examinations of paving area and materials are charged by temporary-hired part-timers.

As undertaken works have expanded, TSS has as many as about 1,500 staff, including part-timers (as of the end of 2014 FY) in the whole company.

REINFORCEMENT OF EARTHQUAKE-RESISTANCE OF PIPELINES

Transition of Ductile Cast Iron Pipes in Tokyo Waterworks

Pipe bodies of ductile cast iron pipes have much more strength for earthquake-resistance than those of conventional cast iron pipes, while on pipelines without the slipping-off preventing function at their fittings, much damage by slipping-off occurred in Great Hanshin-Awaji Earthquake Disaster in 1995.

TMWB has adopted “pipes with NS type earthquake-proof joint” which has the slipping-off

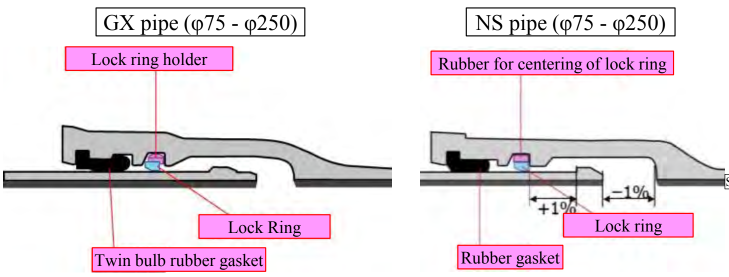

Figure-3: Structure of pipe fittings

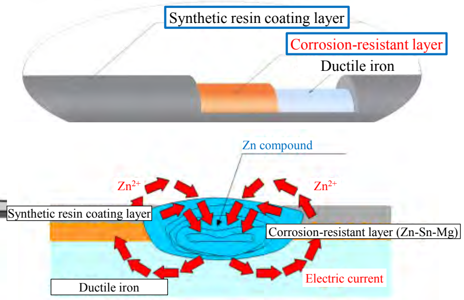

Figure-4: Mechanism of corrosion-resistance of GX pipes preventing function at their fittings gradually from pipes of smaller diameter since 1996.

Afterwards in October 2010, Japan Ductile Iron Pipe Association standardized GX type ductile iron pipes (hereinafter referred to “GX pipes”) which has as much earthquake-resistance as NS pipes and excellent in work efficiency, economic efficiency, and long duration. Then in order to verify such efficiency etc., TMWB conducted a trial construction of GX pipes from December 2010 in Tama area. According to this verification results, after Tama Headquarters of TSS started planning / designing and construction site supervision works of GX pipes gradually from the next fiscal year, in 2014 FY GX pipes (φ250 mm and smaller) became fully adopted in the whole Tokyo Metropolitan area.By the way, the verification results of the trial construction was reported in public by TMWB.

The following reported activities are mainly conducted in Tama area.

10 Year Project for the Use of Earthquake-resistant Joints in Pipelines
Great East Japan Earthquake Disaster revealed the importance of water supply at evacuation centers and major stations which accommodate many people in disasters, and hospitals as bases for first-aid medical care.

In addition, as the updated projection by Tokyo Government Disaster Prevention Council showed that seismic intensity of upper 6 may be recorded in a large number of areas with high liquefaction risks, more preparation of earthquake-resistance activities against a local earthquake on metropolis, which is pointed out to occur, is found to be necessary.

Based on such situations, for more efficient reduction of damage by water suspension, considering liquefaction risks and progress of reinforcement works of earthquake-resistance of pipelines, TMWB is promoting 10 Year Project (from 2013FY to 2022FY) in which evacuation centers, major stations, and so on have been newly positioned to be preferentially reinforced as earthquake-resistant facilities, in addition to conventionally positioned capital’s central agencies.

This project sets the target that the rate of pipes with earthquake-resistant joints (on φ350mm and smaller) in Tama area should increase from 35% in 2013 FY to 51.8% in 2022 FY with installation of about 2,100 km for 10 years or about 210 km per year. The status of progress is shown in Table-1. The both lengths of construction site supervision in 2013 and 2014 which are placed as 10 Year Project exceed 210 km as the target figure.

Table-1: Actual record of planning / designing and construction site supervision works (as for distribution sub-main)

	Designing / Planning (km)	Construction Site Supervision (km)
2014 FY	224	**230**
2013 FY	202	**239**
2012 FY	257	226
2011 FY	**358***	163
2010 FY	235	63
2009 FY	84	39

* The pipeline length of planning / designing of 2011 FY includes estimated increase in the next fiscal year because works in all of municipalities were succeeded to Tokyo Waterworks at the end of 2011 FY.

Planning / designing works: The planning / designing and construction site supervision works for distribution sub-main (φ350 mm and smaller) in Tama area have been gradually undertaken by TSS since 2004 as the entrustment of business affairs was succeeded from each municipality to TMWB. After the entrustment completely resolved at the end of 2011 FY, TSS has been undertaking all of such works. TSS has been also undertaking the similar works for distribution main (φ400 mm and larger) by about 50% since 2010 FY, sharing all works with TMWB.

When TSS began to undertake planning / designing works, about only 5 staff were in charge of them. Young career staff have gradually improved their technical skills under the guidance for the work by experienced staff who were formerly working for TMWB.

Picture-1: designing room

The standard number of planning / designing works in charge per staff is set; at the first year from new employment, 1 or 2 works of relatively short length; at the second year, 2 to 4 works considering each learning level; and at fourth year or further, 10 to 15 as the goal, with guidance mainly by intermediately experienced staff. Consequently, after 2011 FY when the work volume has fully increased, they are not only capable of designing targeted length at 10 Year Project, but also have even advanced planning / designing knowledge including difficult excavation works with complicated underground facilities and pipe jacking method without excavation, so that they have acquired ability for planning / designing works which is almost equivalent to that of TMWB staff.

In 2011 the transition of earthquake-resistant pipes from NS pipes to GX pipes started as a trial in Tama Area prior to 23 Ward area. TMWB held briefings of the designing procedure of GX pipes and others about how to connect cut pipes and revised items of specifications from those for NS pipes. It took some terms to learn them, but eventually the transition was successfully done.

Construction site supervision work: Construction site supervision work by TSS staff needs the viewpoints from an ordering party because besides securing of both publicness and efficiency, a fair and strict stance is indispensable in the amount settlement works on the basis of contract articles and specifications, and securing of safety for construction works. In addition, deliberate management according to individual situations is required at communication with customers and instruction to many contractors with different amounts of experience.

Capacity development for young staff as construction site supervisors is conducted from long-term viewpoints, which consists of participation to in-house and outside training sessions, on-the-job training considering each participant's characteristic by staff who were formerly working for TMWB. Consequently, nowadays many of them have grown into intermediately experienced staff who are acting in the forefront of construction site supervision works.

Picture-2: witnessing of pipe jacking work

By the way, TMWB is promoting "Image Improvement of Waterworks Construction" which helps local customers understand waterworks more to safely and smoothly carry out constructions. Along the policy, annually "Image Improvement Competition of Waterworks Construction" is held, which awards imaginative and original activities such as method of waterworks management and construction, consideration for surroundings, and communication with local residents.

Every year several construction works which TSS supervised have been rewarded. Picture-3 shows a scene related to an awarded work; at the playground of an elementary school, where children had rare experiences to look inside or touch distribution main pipes actually to be installed under the ground. Besides, two representative children had another precious experience to try a connecting work of NS pipes which enabled them to understand that, the work is available even for children, while once the connection is done, the function of earthquake-resistance acts, preventing pipes from slipping off.

Picture-3: scene at practical study of earthquake-resistant pipes in an elementary school

In this manner, establishing good communication with local customers makes understandings about waterworks constructions which involves noises and traffic obstacles, and contributes to progress of 10 Year Project.

Promotion of Adjustment Project of Service Pipes under Private Roads

In Tokyo metropolitan area, many of service pipes under private roads which were made of polyvinyl chloride or lead were not shock-proof and could result in leakage until stainless steel was applied to service pipes.

In 23 Ward area, prior to Tama area, Adjustment Project of Service Pipes under Private Roads (hereinafter referred to "Adjustment Project") has contributed to improvement of earthquake-resistance and leakage prevention by newly installing distribution sub-mains and replacing branched service pipes with stainless ones which are excellent in shock- and corrosion-resistance as shown in Figure-5.

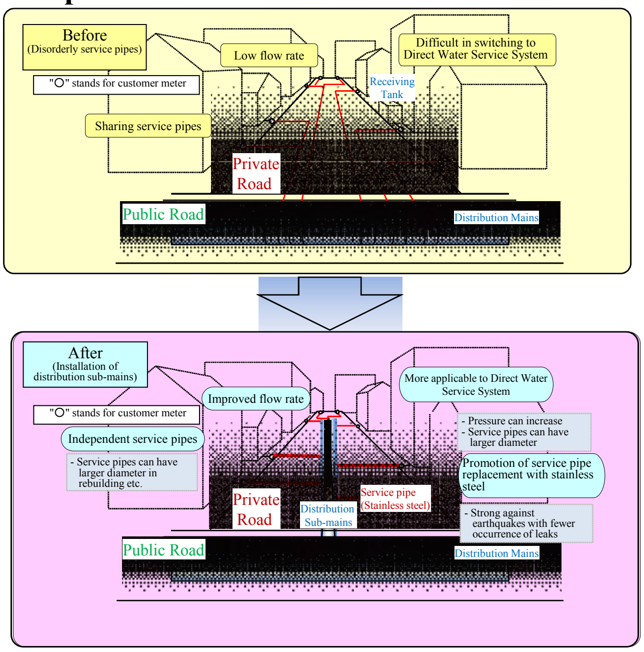

Figure-5: abstract of "Adjustment Project of Service Pipes under Private Roads"

In Tama area, on the other hand, the project began on a large scale around 2011 when entrustment of business affairs to municipalities had been almost resolved.

Adjustment Project, placed as one of the important projects to promote reinforcement of earthquake-resistance of pipelines, is financially wholly under the responsibility of TMWB and its achievement ratio for all the targeted distribution lines in Tokyo metropolitan area is set as 79 % as of the end of 2023 FY. Besides, for further implementation of the project, in 2012 FY the application criteria was revised to be relaxed from the original so that the project can be conducted in case of more than 3 service connections (customer meters). At the end of distribution sub-mains which are installed under private roads, drainage valves with the same structure as hydrants are installed; they are also available for emergency water supply in earthquake disasters or first-aid firefighting.

For implementation of the project, basically a signature and a seal on the "letter of approval for installing distribution sub-mains under private roads" are necessary. Though such approval works in Tama should be conducted by the consulting company as a contractor of designing work for the concerned pipeline, there are some difficult cases to be given approvals because of refusal of construction works, difficulty in contact, or other reasons. In such cases TSS staff who are responsible for designing works work together for approval, but repeated occurrence often results in delay of designing works.

To improve these situations, TSS formed a team to compile business affairs about letter of approval, which consists of part-timers. Consequently the delay of designing work solved and 10 Year Project is smoothly advancing. By the way, part-timers become able to make appropriate explanations about this project through short-term in-house training by understanding the leaflet which is prepared by TSS, even if they have no knowledge about Adjustment Project. Anyway, the project is running more successfully than the initial expectation.

UTILIZATION OF VARIOUS PIPE INSPECTION DATA

Pipeline Diagnosis Work

TSS has been consistently entrusted "Pipeline Diagnosis Work" by TMWB since its establishment in 1987. "Attached facilities of pipeline investigation," which is one of the main businesses in Pipeline Diagnosis Work, becomes the basic materials for the pipeline replacement plan developed by TMWB.

This inspection sets the object that leakage accidents and traffic accidents, which are caused by unevenness of road surface on attached facilities, can be prevented and that the results of investigation can be reflected on sound maintenance of attached facilities by investigation of current situation of maintenance, aging deterioration on attached facilities of pipeline, and function of gate valves. Among them, the inspection of function is utilized as criteria for priority of the maintenance and repairs by ranking its results as shown in Table-2 below.

Table-2：assessment standard table for judgment

Rank	Rank A	Rank B	Rank C
	Failed facilities which are dangerous and necessary to repair immediately	Failed facilities which seem to be necessary to repair and improve	Facilities which have slight failure and seem to be necessary to repair and improve sooner or later
Inspection item	Chamber or its iron cover of valve, hydrant, etc.: paving / capability of opening and closing / rattling / difference in level / error in sign / damage of iron cover / crack of pavement / insufficient drainage of water and mud / damage of chamber / condition of pipeline / leakage / condition of valve / body of vertical shaft and tunnel / pipe in vertical shaft and tunnel / operational problem / water quality problem / crossing pipeline		

Photo-4 shows inspection of difference in level which is 24 mm between road surface and a cover of gate valve. As this facility is “failed facility which is necessary to repair immediately” according to Table-2, it should be carried out repair work immediately by the maintenance department.

Picture-4: condition of difference in level

10 Year Project is promoting reinforcement works of earthquake resistance of pipelines by giving priority to pipelines for evacuation center and major station and so on. While the attached facilities of pipelines that need emergency treatment will be repaired and replaced as soon as possible according to the results of this inspection.

In addition, the abundant information that has been accumulated by the Pipeline Diagnosis Work is not only reflected on maintenance of attached facilities of pipelines, but also used as an effective data for judgment of priorities to develop earthquake-resistant routes and areas.

Mobile Mapping system

Traditionally, Tokyo Waterworks stores its pipeline information in the “Water Mapping System” and it has been useful for specifying position and grasping the attribute information of pipeline in earthquake disasters.

However, speaking about the damage in Great East Japan Earthquake, searching for information was difficult because a fatal situation occurred; for example, collapse of government buildings, disconnection of communication network, and suspension of power supply which was required for operation of communication system. Therefore, serious trouble broke out in understanding of local conditions and subsequent restoration activities. In addition, even in the event of earthquake disasters, currently “paper-based” documents which are output from the mapping system terminals are dealt with. That means, it is impossible to output paper-based data in power failures. As there are problems that it is hard to see at night and it can get wet in the rain, obstacles for recovery efforts have been supposed.

In order to solve these problems, TSS has innovated "Mobile Mapping System" since 2014, to provide rapid and reliable temporary restoration in emergency. This terminal is a tablet type which has cooperative functions with GPS. Staff can receive support for fast recovery response


Figure-6: mobile mapping system terminal


Picture-5: use of terminal

from it by bringing it to site and exactly getting the location and pipeline information in earthquake disasters. Moreover, the terminal is highly waterproof, not influenced by night and weather, easily displays pipeline information, and enables appropriate works on site. At the same time, the terminal enables an office to accurately grasp situations with utilization of functions such as work reports and telephotography for sharing of site conditions with the office.

Mobile Mapping System is in a trial stage in Tama area at this time for its introduction. In the future, investigations for excellent functions towards the full-scale adoption and subsequent consultation with stakeholders should be conducted.

COLLABORATION WITH TMWB IN EARTHQUAKE DISASTERS

Reinforcement of Collaborative System

TMWB decided to work on the basis of "the Tokyo Water Works Bureau Earthquake Disaster Emergency Plan" in the event of earthquake disasters. Therefore, each division of TMWB achieves emergency recovery activities smoothly by developing an action manual.

When disasters occur, not only clear policy of TMWB but also collaborative system among waterworks stakeholders is extremely important. TMWB and TSS concluded "Agreement of Emergency Response Operations against Disasters (31st March, 2009)" to secure collaboration. In addition, for the similar purpose, support system is secured by being specified measures during emergency in the specification of the project which TSS is ordered. Moreover, TMWB concluded agreements with related organizations and secures collaboration by describing contractors' gathering and command system in disasters on the specification.

TSS should quickly deploy specific activities by reflecting this policy in "Earthquake Disaster Emergency Plan" and "Earthquake Disasters Action Manual" established by TSS, because damage investigation, emergency recovery, and emergency water supply are the main activities as the part of TSS in earthquake disasters.

Practice of Training against Earthquake Disasters

In order to practically learn the behavior in earthquake disasters, TSS is periodically conducting training such as "disaster prevention training (emergency recovery training)", "information contact training", and "gathering training" together with TMWB to prepare for activities in case of occurrence of disasters.

Picture 6: information contact training

Picture 7: emergency recovery training

Development of Circumstances Concerning Devices etc. for Earthquake Disasters

When earthquake disasters occur, it is necessary for waterworks stakeholders to conduct recovery activities cooperatively. TSS has experienced communication panic, planned blackouts, fuel shortage, and so on in the Great East Japan Earthquake. So, it is necessary to promote development of circumstances as far as possible for forecasted situations.

Not only stock of disaster prevention equipment but also securing of communication means for contact with TMWB and formation of internal structure is essential. TSS has installed satellite-based mobile phones and non-utility power generation facilities for power failure as well as wireless communication prepared by TMWB.

CONCLUSION

Tokyo Waterworks has set the target to improve the rate of earthquake-resistant joints on pipeline in the whole Tokyo area up to 54% as 10 Years Project until 2022 FY. The achievement of this target depends on if TSS, in charge of pipe network planning / designing, construction site supervision works, and so on, can enough play a role for which Supervised Organization is responsible by fully using extensive knowledge and experience that has been accumulated in waterworks operation.

TSS, as a partner company of TMWB, hopes to contribute to development and optimization of waterworks operation, eagerly tackling reinforcement of earthquake-resistance of waterworks facilities with its rich experience and high technical skills in the future.

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Evaluation of Fire Protection Capacity in Disasters Based on Disaster Resilience Curve

N. Hirayama, T. Yamada, M. Wada, S. Itoh, and C. A. Davis

ABSTRACT

After the 2011 Tohoku disaster, water supply utilities in Japan have encouraged to address issues of disaster prevention and resilience in water system. The purpose of this study is to develop an evaluation method on the fire protection capacity of water distribution system from the viewpoint of business continuity. In this study, an evaluation model based on disaster resilience curve, which could describe disaster mitigation and resilience in water service, was developed. The distribution network analysis including emergence of the fire extinguishing quantity of water was carried out, the number of node available as fire hydrant was calculated in accordance with the requirements of hydraulic pressure at nodes. The fire protection capacity of the water distribution system in the emergency restoration period for the actual distribution network of the Kobe City was evaluated with the numerical evaluation model. Then, an evaluation procedure on the fire protection capacity of water supply distribution system based on disaster resilience curve was proposed. As a result, it was pointed out that more disaster resilient water system would require not only disaster preparedness but also business continuity management system

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INTRODUCTION

After the 2011 Tohoku disaster, water utilities in Japan have been promoting to address issues of disaster prevention and resilience in water system. In Japan, business continuity planning and management is required for public works, and government of Japan has encouraged municipal government to establish business continuity planning. The Business Continuity Guidelines 3rd ed. – Strategies and tactics to overcome any incident – was published by Cabinet office, Government of Japan [1]. Ministry of Economy, Trade and Industry published Guidelines for Business Continuity Plans [2].

Ministry of Health, Labour and Welfare, the Government of Japan published the Guidelines for disaster prevention of earthquake disasters in water supply sectors, and it was pointed out that it is significant to establish the PDCA cycle based on the disaster management cycles [3]. The Handbook for emergency response and operation in water sector was published by Japan Water Works Association [4]. In this guidelines and this handbook, it is indicated that Business Continuity Management (BCM) in water sectors is required for emergency response to the unexpected incidents. Business Continuity Planning for Water Utilities: Guidance Document was published by Water Research Foundation [5]. This technical report indicates that water utilities need a Business Continuity Plan (BCP) and a Business Continuity Plan's and goal is maintaining solid operations – financially, managerially, and functionally, after any incident.

Recently, many researchers and water professionals conduct research projects on establishment of BCM in water sector. However, the evaluation method of business continuity in water service after the disasters has been hardly examined. Actually, BCM would involve the implementation of PCAD cycle of Business Continuity Planning (BCP) and it is required to evaluate the business continuity of water service during the restoration period. Thus, the purpose of this study is to develop an evaluation method on the fire protection capacity of water distribution system from the viewpoint of business continuity with the disaster resilience curves.

METHOD

In this paper, the objective of this study is to evaluate earthquake resilience of water distribution system from the viewpoint of fire protection function. EPANET2 [6] was used for numerical analyses in this study.

Business Continuity and Disaster Resilience Curve

BCM is defined as a compilation of processes that identifies and evaluates potential risks to an organization and develops the organization's resilience by ensuring critical objectives are met the resources necessary to achieve those objectives are available [7]. Water Research Foundation indicated that BCP is an integral part of the emergency management system, which typically includes a suite of plans for a lager utility or one comprehensive plan for a smaller utility [5]. It was pointed out that it is important that business continuity planning be integrated into a utility's culture and, as such, consistent with the utility's mission. In addition, the execution of BCP in water sector is proposed as the following:

1. Define the scope
2. Establish written policy by the water utility Executives
3. Define the incident
4. Provide basic assumptions

5. Integrate with other plans

Figure 1 shows the concept of BCP and disaster resilience curve [1]. Thus far, many water utilities try to carry out the disaster prevention & preparedness, and the risk and crisis management based on the concept of BCP as a critical infrastructure which citizens' lives and the economy rely on. In addition, some activities of water utilities for the establishment of BCP were reported [8]. In the previous recovery & reconstruction planning and BCP in water utilities, water supply ratio or available quantity of water have been used as an evaluation indicator of the restoration curves. Sakaki, *et al.* [9] developed the earthquake disaster risk evaluation modeling of not only water supply ratio and emergency restoration period but also opportunity loss of water, which is defined as the difference between the amount of water available in emergency and normal time. Davis and O'Rourke [10] and Davis [11] introduced and characterized five water service categories that are important for quantifying the total post-earthquake restoration of a water system. These categories are water delivery, quality, quantity, fire protection, and functionality services. In addition, Davis [12] presented a case study on applying these service restorations to the Los Angeles Water System following the 1994 Northridge earthquake. Hirayama and Davis [13] developed the quantitative evaluation model for evaluation of performance of disaster prevention in water sector. With the implementation of BCP and BCM in water sector, it is more indispensable to evaluate on business continuity of water service. Thus, in this study, it is develop the evaluation procedure of water service in the aftermath of earthquake using disaster resilience curves of fire protection.

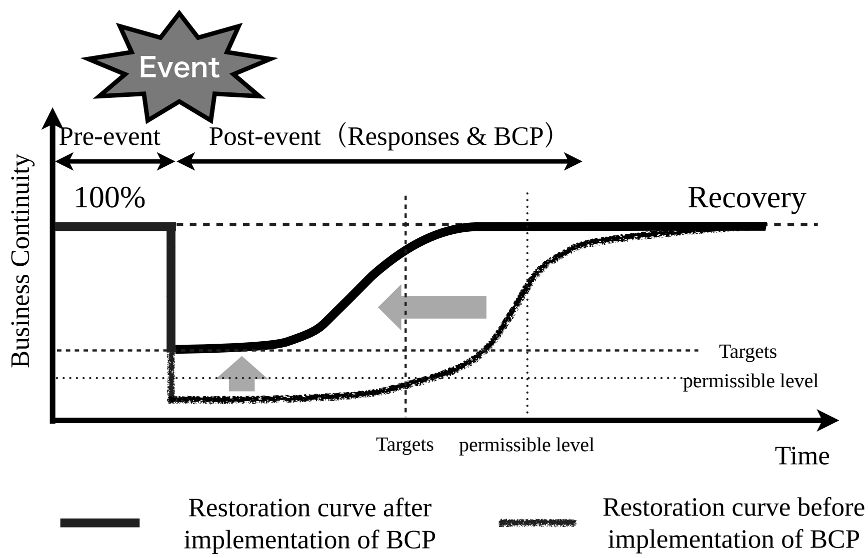

Figure 1. Concept of BCP and disaster resilience curve [1]

Performance indices

Earthquake resilience could be evaluated as opportunity loss of water, water supply ratio, and fire protection capacity in restoration period after earthquake. In calculating of water supply ratio, the conditions of water supply after earthquake are no damage pipe in the route from water reservoir to water demand point and more 10 m water head at the water demand point [14]. Opportunity loss of water is defined as the difference between the amount of water available in emergency and normal times, water which would be available if the disaster does not occur [9].

In general, design for fire hydrants in Japan is according to Japanese standards for water sources necessary for fire defense [15]. In this paper, fire protection is defined as capability of fire fighting at every node in conditions of additionally 3.0 m^3/min water demand for firefighting and positive water pressure at the next nodes, which connect the fire hydrant [16]. In this pipe network analysis, Hazen-Williams Coefficient was used as 110 and time factor in pipe network hydrologic accounting was 1.82 in normal times as observed in evaluation areas and 1.00 in emergency.

Evaluated Areas and Their Characteristics

The evaluation area in this study is Nada Low-layer water distribution area in Kobe City, as shown in **Figure 2**. These water distribution systems are gravity flow system and based on 2013 Kobe Pipeline mapping system (P-DES).

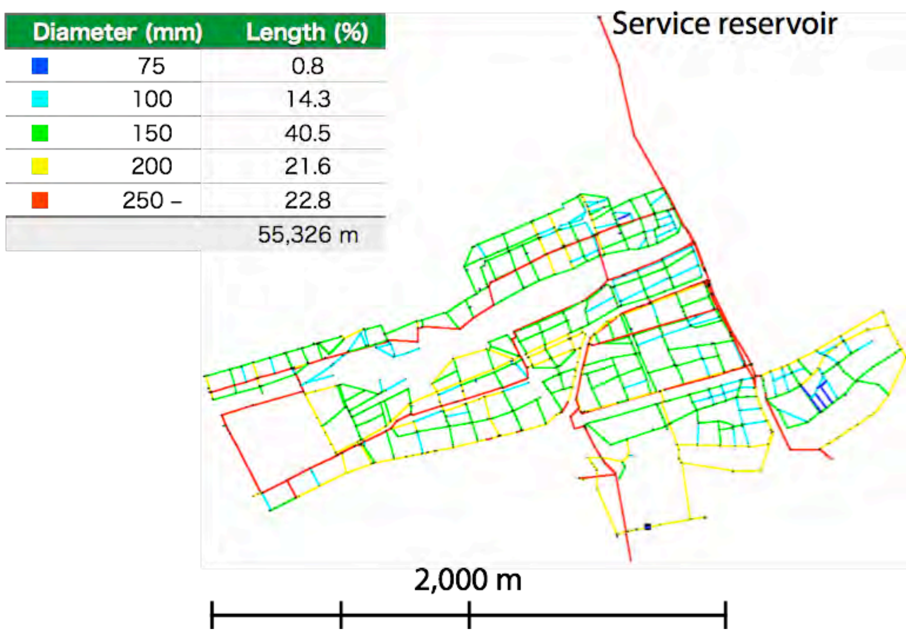

Figure 2. Nada Low-layer water distribution area in Kobe City

Distribution Network Analysis in a Seismic Condition

In this study, when we make a distribution analysis after earthquake, the hazard of earthquake was the same scale of the 1995 Kobe earthquake. The cross-tabulation table related to diameter and peak ground velocity (PGV) is shown in **Table 1**.

Table 1. Pipe length ratio related to diameter and PGV in Nada

Distribution area	Pipe length (m)	Diameter	Peak ground velocity (PGV)				Subtotal (%)
			60 cm/s	100 cm/s	140 cm/s	180 cm/s	
Nada	54,327	– 75 mm	0.6	0.0	0.2	0.0	0.9
		100 mm	4.0	3.4	4.9	2.1	14.5
		150 mm	9.3	7.3	18.9	5.7	41.2
		200 mm, 250 mm	9.0	4.3	7.2	1.5	22.0
		300 mm –	4.3	4.6	9.9	2.7	21.4
		Subtotal (%)	27.9	21.5	39.2	11.5	100.0

The node with negative pressure is considered as no-flow node through which no water can pass or a partial flow node through which water can pass with reduced flow rates compared with those predicted by conventional hydraulic network analysis [17]. In a case that some node has negative pressure in pipe network hydrologic analysis results, pipe network analyses will be conducted after removal of these nodes with negative pressure.

Water supply ratio

Cornell University [17] developed a pipe network analysis tool, which describes a seismic condition in EPANET software. In this study, the ratio of water supply during restoration period after earthquake was evaluated with GIRAFFE.

The calculation process of water supply ratio has five steps. First, damage probability of each pipe is estimated according to the pipe damage estimation procedure and the fragility curves of pipe caused by quake [18]. Pipe material, pipe joint type, diameter, geographical features, and Peak Ground Velocity (PGV) are required for this estimation formula. Then, number of damage position is calculated based on Poisson distribution of damage probability of pipe. Third, condition of damage to pipe is determined with Monte Carlo method. The damage condition has two categories. One category of pipe damage is a detachment of pipe joint, which causes completely pipe break and disconnection of pipes. The other is a pipe leakage. In this paper, pipe leakage type has five levels, defined in GIRAFEE algorithm. Pipe leakage level is determined with Monte Carlo method. Then, pipe mapping data set including damaged pipe caused by quake is laid for pipe network analysis.

Pipe network hydrologic analysis is conducted to the pipe mapping data set with assumed damage on EPANET2. In a case that the calculated pressure of either node is negative, the node with negative pressure is excluded from the pipe mapping date set. After checking the connectivity of the pipe network, pipe network analysis is carried out again. When none of nodes has negative pressure in the calculation result, pipe network hydrologic accounting result is confirmed.

At the last step, the emergency recovery process is examined with the recovery process numerical simulation model. Emergency recovery rate depend upon pipe diameter. The recovery rate for a pipe break on more than or equal to 250 mm dia. pipeline was 0.63 location per day, and that for less than 250 mm dia. pipeline was 2.0 location per day, according to observations in 1995 Kobe earthquake [9]. In this paper, the recovery operation would first be conducted upstream and large pipeline of the water distribution network.

Opportunity loss of water

In the context of this paper, 'Opportunity Loss' of water is defined as the amount of emergency water not provided to citizens for some reason while there was a demand on citizens' side [9]. Thus, an integration value of the quantity of water not provided to citizens during the emergency restoration period was calculated.

Fire protection capacity

In this section, evaluation procedure for fire protection capacity during emergency restoration period after earthquake is described. The leakage caused by pipe breaks depends on condition, location, water pressure of pipe break, and so on. The leakage from damaged pipe is estimated by eqn. (1) as the following

$$Q = C \times P^{\alpha} \qquad \text{eqn. (1)}$$

The leakage volume is designated by Q. C represents Hazen-Williams Coefficient. The pressure of damaged conduit is designated by P and a represents pipe damage mode coefficient. In this paper, we set that the coefficient C is 2.0×103 and the coefficient α is 1.15.

It was pointed out that the leakage from service connections is a reason to decrease water pressure after earthquake disasters [18]. Uno, *et al.* [19] estimated the number of damage service connection as 1861 sites in Nada Low-layer distribution area. Thus, we take the leakage from service line into account in this evaluation process. The leakage from damaged service line is estimated by the same equation (1). The coefficient C for service connection leakage was 3.0×104 and the coefficient α is the same 1.15. In addition, the calculated leakage from service connection was added to water demand in each node.

The ratio of node with fire protection capability was examined with hydraulic accounting on EPANET2. In the emergency restoration period, the repair number of service connection was constant 50 sites per day.

COMPUTATIONAL RESULTS

Evaluation Results of Fire Protection in Normal Condition

The fire protection function of Nada Low-layer Distribution Network in normal was evaluated by the available ratio of fire hydrant. **Figure 3** shows the map of water pressure of Nada distribution network in normal condition.

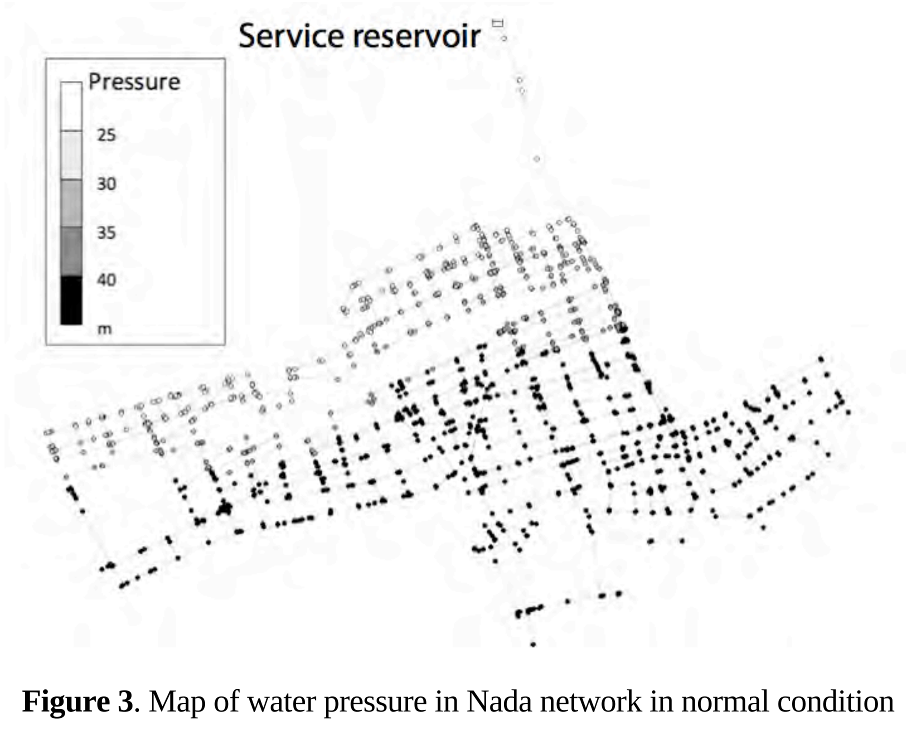

Figure 3. Map of water pressure in Nada network in normal condition

Nada distribution network is gravity flow. This figure indicates that the pressure head of most nodes in the upper stream, which is near to distributing reservoir, becomes the value from 30 m to 35m. The pressure head in the downstream are more than 40 m. The calculated map of nodes with fire protection function in Nada network is shown in **Figure 4**. As a result, the ratio of availability for fire protection was evaluated at 0.99. These nodes, which do not have fire protection function, are connected to 100mm dia. distribution branch and are located in the place of higher altitudes in this distribution area.

Figure 4. Map of nodes with fire protection function in Nada distribution network

Evaluation Results of Fire Protection after Earthquake Disaster

The calculated map of water pressure after earthquake disaster is shown in **Figure 5**, and **Figure 6** illustrates the map of nodes with fire protection function or without in Nada distribution after the event.

Figure 5. Map of water pressure in Nada distribution network after the earthquake disaster

Figure 6. Map of nodes with fire protection function in Nada distribution network after the event

Because of leakage with 62 damage to distributing main and 1861 damage to service pipe, the pressure head of approximately 300 nodes became the negative pressure. Then, it was pointed out that it is hard to be said that sufficient water and the water pressure can be secured in Nada Low-layer distribution area after the earthquake disaster. In addition, the number of node with fire protection function would decrease and the ratio of available node for fire protection was evaluated at 0.75. It may be said that fire protection function of Nada distribution area decreases to approximately three-fourths in the normal. It was pointed out that it is indispensable not only to promote the earthquake resistance of pipeline for mitigation of weakening fire protection function but also to improve the local firefighting capability by the securing of water utilization for fire fighting.

The disaster resilience curves of fire protection capacity, disaster resilience curve of water supply ratio and opportunity loss of water of the present network were calculated. The evaluation result of fire protection capability with disaster resilience curve is shown in **Figure 7**.

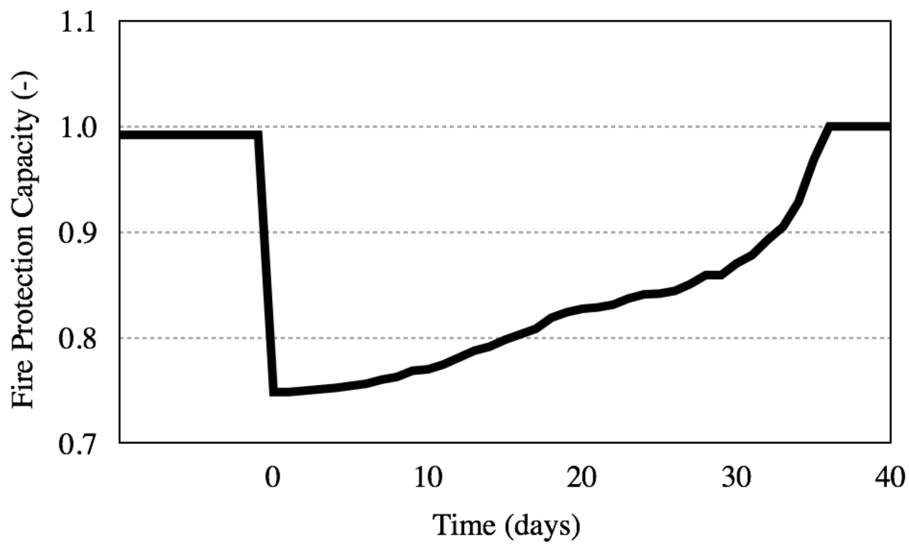

Figure 7. Disaster resilience curve of fire protection capability in Nada distribution network

In the disaster resilience curve of fire protection capability as Figure 7, recovery rate increased after 28th days. In this paper, the priority of the emergency recovery operation does not be considered. This is a reason why a recovery effect of the pressure head in the water distribution network by the pipeline reconditioning on the disaster preliminary period is small. Thus, it was indicated that disaster countermeasure of the water distribution system would require to mitigate the reduction of fire protection function in the initial response period, and to examine a water distribution network restoration strategy to improve the capacity to recover quickly from disasters. Consequently, it was pointed out that it is essential to establish business continuity management system in water utility for the water utility services to customers such as quantity, quality, water accessibility, water delivery, and fire protection function of water in addition to earthquake-resistant technologies.

CONCLUTIONS

In this study, an evaluation model based on disaster resilience curve, which could describe disaster mitigation and resilience in water service, was developed. The distribution network analysis including emergence of the fire extinguishing quantity of water was carried out, the number of node available as fire hydrant was calculated in accordance with the requirements of hydraulic pressure at nodes. The fire protection capacity of the water distribution system in the emergency restoration period for the actual distribution network of the Kobe City was evaluated with the numerical evaluation model. The findings of this study are as follows.

1. An evaluation method on the fire protection capacity of water distribution system from the viewpoint of business continuity with the disaster resilience curves was developed.
2. The fire protection function of Nada Low-layer Distribution Network in restoration period after earthquake disaster was evaluated. As a result, the number of node with fire protection function would decrease and the ratio of available node for fire protection was evaluated at 0.75. It was pointed out that it is indispensable not only to promote the earthquake resistance of pipeline for mitigation of weakening fire protection function but also to improve the local firefighting capability by the securing of water utilization for fire fighting.
3. From the calculated disaster resilience curve of fire protection capability, it was indicated that disaster countermeasure of the water distribution system would require to mitigate the reduction of fire protection function in the initial response period, and to examine a water distribution network restoration strategy to improve the capacity to recover quickly from disasters.
4. Consequently, it was pointed out that it is essential for disaster resilient water system to establish business continuity management system in water utility for the water utility services to customers such as quantity, quality, water accessibility, water delivery, and fire protection function of water in addition to earthquake-resistant technologies.

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Niigata as a temporary water works relay base: support for teams in a major seismic disaster

Etsuro Kawase [1]

Abstract

Water works support in Niigata for the Great East Japan Earthquake in 2011 allowed us to find a new role as a temporary relay base connected water works support teams from areas far from the disaster area. In this study, we report on the role of Niigata as a temporary emergency support relay base for water works bureaus for the Great East Japan Earthquake and discuss its role as an ideal temporary relay base for subsequent disasters.

Following the emergency support for the Southern Hyogo Earthquake in 1995, new emergency rules for emergency water supply and emergency restoration work were put in place to ensure a speedy recovery from major disasters. However, in the Great East Japan Earthquake, because a widespread area was so seriously damaged, these rules were found to be insufficient, resulting in chaos in the primary period after the disaster. As emergency recovery efforts were established, new roles, which had previously not been needed, were determined for Japanese disasters. One of these new roles was the establishment of temporary relay bases for water works support teams that needed to be located between the disaster area and the areas the teams came from. Niigata was chosen to be one of these temporary relay bases because of its location and its convenient transportation system.

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1 THE DISASTER SUPPORT SYSTEM IN JAPAN

1-1 The 1995 Southern Hyogo Earthquake

The largest natural disaster in Japan since World War II, the Southern Hyogo Earthquake, struck in the Hanshin area on 17 January 1995 with a seismic intensity of 7. The earthquake killed more than 6,000 people, destroyed more than 100,000 houses and resulted in a total financial damage of about 10 trillion yen. Lifelines, such as roads, railways, electricity, water works, gas lines and telephone services were cut off by the earthquake. Furthermore, congested roads leading to the disaster area interfered with emergency support and the supply of necessary goods. Water was cut off from 1,270,000 houses, with 4,700 water works emergency support man-days needed to repair the system. Niigata Water Works Bureau also sent water works support teams to Ashiya city. For the emergency water supply and emergency restoration work, the Japanese Water Works Association allocated support areas for the water works support teams throughout Japan. However, it is difficult to judge the efficiency of this support work. The Japanese Water Works Association represents water works bureaus from across Japan and is divided into seven local branch associations, each of which is managed by a prefecture association organised by the prefecture water works bureau. Ideally, when planning for a major seismic disaster, it would be more effective for emergency activities to be organised by a prefecture association unit or a local branch association unit. However, in the initial response to the emergency activity at this time, this rule was not considered.

To take advantage of lessons learned from this major disaster, in 1996, the Japanese Water Works Association published *Reports about emergency correspondence in case of disasters such as earthquakes*, which describes the emergency activity rules for water works bureaus in Japan.

1-2 The 2007 Niigata Prefecture Chuetsu Earthquake

On 23 October 2004, the Niigata Prefecture Chuetsu Earthquake struck with a seismic intensity of 7 and was followed by many aftershocks. Because the epicentre was not downtown, the death and destruction toll was small compared with the Southern Hyogo Earthquake. However, there was serious damage in the mountainous areas such as in Yamakoshi village, which was forced to shelter as a group as all roads to the village had been destroyed by the earthquake. Lifelines, such as electricity, water, gas and telephones, were cut off and the railways and roads were also destroyed. According to the water works bureau, 130,000 houses had no water supply and more than 150 water works bureaus and private companies provided emergency support. The Japanese

Water Works Association and the Chubu local branch association, which represented nine prefecture associations in mid-Japan, coordinated the emergency support and information between the disaster area and the support water works bureaus, meaning that in this case, the emergency water supply and emergency restoration work were effectively completed. Niigata city assigned emergency support water works support teams in Niigata prefecture, in its role as prefecture association chief bureau. Furthermore, emergency support teams were dispatched to Nagaoka city, Odiya city and Kawaguchi town to assist in providing emergency water supplies, emergency restoration work, pipeline surveys and restoration planning.

1-3 The 2007 Niigata Chuetsu-oki Earthquake

On 16 July 2007, the Niigata Chuetsu-oki earthquake of seismic intensity 6 plus, caused the suspension of water to 59,000 houses in seven cities, towns and villages. Most damage was concentrated in the downtown area of Kashiwazaki city, and even though lifelines, such as electricity, water, gas, telephone, cellular phone and internet services, were seriously damaged, the recovery was much faster than in the Southern Hyogo Earthquake because the emergency water supply and emergency restoration work rules functioned well.

The Niigata Prefecture Chuetsu Earthquake, the Japanese Water Works Association and the Chubu local branch association collaboratively worked to ensure the emergency support, resulting in the water suspension being repaired within 15 days. Niigata, in its role as prefecture association chief bureau, assigned emergency support to the water works support teams in Niigata prefecture and assigned other bureau support teams from outside Niigata city in cooperation with Nagoya city, which is the Chubu local association chief bureau. Niigata city also participated in the determination of the emergency water supply plan, the emergency restoration plan and information collection management for the damaged water works facilities. It also assisted in the emergency water supply activities and emergency restoration works for Kashiwazaki city.

In 2008, the emergency support water works rule was reviewed in light of the experiences and lessons learnt from the great disasters in Niigata prefecture. The *Reports about emergency correspondence in case of disasters such as earthquakes* was also revised.

Photo.1-3-1

A crushed house—Niigata Prefecture Chuetsu Earthquake in 2004

Photo.1-3-2

Restoration work—Niigata Chuetsu-oki Earthquake in 2007

2 GREAT EAST JAPAN EARTHQUAKE CHARACTERISTICS

2-1 Earthquake damage characteristics

Due to the subsequent tidal wave caused by the earthquake and the accident at the Fukushima Nuclear Power Plant, the Great East Earthquake (GEE), with a seismic intensity of 7, caused serious damage across east Japan. A characteristic of this earthquake was the broad-based catastrophic damage caused in the areas hit by the earthquake-generated tsunami. The Japanese Water Works Association local branch chief bureau and the prefecture chief bureau, which were responsible for assigning water works support teams, also suffered serious damage, with communication systems such as cellular phones out of order and food and gasoline shortages. Due to this and the never-before-experienced radiation hazards, it was difficult to conduct effective and efficient emergency activities.

2-2 Influence on emergency activities

Before the GEE, water works bureaus had carried out emergency water supplies in cooperation with the Self-Defense Forces. However, because the Self-Defense Forces had to deal with the disaster areas near the seashore where the tsunami had destroyed houses and there were missing people, Niigata had to provide the emergency water supplies. In the primary period immediately after the GEE, a shortage of supplies, especially in fuel for generation systems, stopped the water supply in some cases. Therefore, because it had not been decided as to which bureau was in charge of which area, there was significant chaos as many water works bureaus had come to support the disaster water works, but they did not know where they were needed. Because of the

Fukushima Nuclear Power Plant accident, many water works bureaus went to the disaster area via Niigata city, which is on the opposite side of the disaster area. Therefore, it took considerable time for them to reach the disaster area, especially for those bureaus that had come from the western areas of Japan.

3 ACTIVITIES IN THE PRIMARY DISASTER PERIOD

3-1 The initial response in Niigata city

For the prefecture association chief bureau, the most important activity in the primary disaster period was to check the damage in its own water works facilities and to obtain information about the disaster area. In Japan, the water works are run by the public; therefore, emergency support is expected to be provided by the public.

On 11 March 2011, there was a long periodic seismic wave for several minutes in Niigata city. Just after the wave settled, water works facilities damage from the earthquake was checked, and no damage was found in the water filtration plants, distribution plants or pipeline construction fields. Because no information related to the Tohoku area could be obtained, it was assumed that this area had sustained serious damage; thus, the Niigata prefecture water works association emergency response headquarters was established so that information collection could be started and emergency support teams prepared. It was not possible to obtain reliable information; thus, in cooperation with Nagoya city, it was necessary to dispatch an advance emergency support team to collect information. Additionally, based on the mutual support agreement for disaster relief between ordinance-designated cities, Sendai city called for an emergency water supply from Niigata city.

Photo.3-1-1

The departure of Niigata water works advance support team on 11 March 2011

Photo.3-1-2

The damage caused by the tsunami

On 11 March at midnight, the Niigata city advance emergency support team and two water trucks departed for Sendai city. They reached Sendai city the following morning and started collecting information and performing emergency water supply activities.From the report of the advance emergency support team, we found that the water supply was widely cut off in Miyagi prefecture. On 12 March, an advance emergency support team from the Chubu local branch association went to Miyagi prefecture to survey the support needed by the water works bureau in the disaster area.

3-2 Prior arrangements between disaster water works and support teams

In the primary period after an earthquake, it is most important to confirm the water works bureau's damage level in the afflicted areas and assess the scale of support needed as soon as possible. If the damaged area is wide enough, it is necessary to divide the disaster area into several blocks and decide which bureau is in charge of which block.

The Niigata city advance emergency support team installed a booth at the Sendai water works bureau and, after consultation with Sendai city on timing and the support activity priorities, told the Niigata city headquarters the level of support needed for Sendai city. The Chubu local branch association advance emergency support team surveyed the water works facilities damage in Miyagi prefecture and, in cooperation with other advance emergency support teams from local branch association bureaus, decided on what was needed by the water works bureaus. In the Great East Japan Earthquake, the disaster area was so widespread that many water works bureaus sustained serious damage. Therefore, nation-wide support was needed. From the information supplied by the Niigata city and Chubu local branch association advance emergency support teams, the Japanese Water Works Association and the local branch association bureaus decided which local branch association was to be in charge of which prefecture.

4 SUPPORT ACTIVITIES IN THE DIASATER AREA

4-1 The initial response towards the disaster area in the primary period

The two-week period following a disaster is known as the 'primary period'. During this period, disaster water works bureaus require emergency water supplies. After the GEE, many water works bureaus across Japan were engaged in the supply of emergency water, with many going to the disaster area via Niigata prefecture to avoid the effluence from the Fukushima Nuclear Power

Plant accident and the turmoil of the earthquake in the Kanto area. Niigata city was not so far from the disaster area and had not sustained any damage from the earthquake; thus, it was given a new role as a temporary relay base.

In the primary period, water supplies were cut off in a wide area; thus, it was necessary to take water service balloons and temporary water service faucets depending on the disaster water works bureaus' requests. Each balloon has a capacity of 1 m^3 and has an efficient water supply, temporary water service faucets and a frame. At this time, 66 water balloon sets were sent to three water works bureaus, who told us that the balloons were efficiently used. From the Niigata prefecture association booth installed in the Sendai city water works bureau, we collected information about the disaster bureaus in Miyagi prefecture and accepted the water works support teams that had avoided the Fukushima Nuclear Power Plant effluence.

Photo.4-1-1

The headquarters for disaster recovery at Sendai City Water Works Bureau

Photo.4-1-2

Water service balloon with temporary water service faucets

4-2 Activities in the post primary period

Two weeks after 11 March, as the water supply suspension area decreased, the need for emergency water supplies was also decreasing. As the needs of the disaster water works bureaus shifted from emergency water supply to emergency restoration work, the importance of our role as a temporary relay base also disappeared. However, the disaster water works bureaus indicated that there was a significant increase in the need for emergency restoration works, such as repair teams to fix leaking pipes and pipeline field survey teams to check the leak points on damaged pipelines and to confirm whether repairs had been completed.

Photo.4-2-1

Emergency restoration works—finding valves

Photo.4-2-2

Emergency restoration works—confirming pipeline functions after repair work

5 FUNCTION OF TEMPORARY RELAY BASE

There are three main functions of a temporary relay base.

①As a meeting point for water works support teams
➢Temporary waiting space for the teams coming from areas far from the disaster area
➢Temporary parking space for water trucks and other emergency vehicles

②A logistical base for bureaus supporting their teams working in the disaster area
➢A place for supplies, food and equipment

③As an information control base for every bureau conducting emergency recovery
➢Understand the needs of the disaster area and provide information to support teams in the disaster area
➢Management of the scale and content of the support

Niigata city has a convenient transport system, such as an airport in the city, a Shinkansen system and an advanced expressway. A report from the Ministry of Land, Infrastructure and Transport reported that traffic to East Japan going via Niigata prefecture greatly increased in the month following 11 March.The first function of a temporary relay base is as a meeting point for water works support teams, as the base can provide a temporary waiting space for the teams from areas far from the disaster area as they wait to go to the disaster area. At the Sinanogawa water filtration plant, more than 30 water works support teams, who had especially come from the western area of Japan, used our space and prepared themselves before going to the disaster area.

The Sinanogawa water filtration plant was an ideal temporary relay base because it was located within five minutes of the express interchange and had a huge car park. The second function of the temporary relay base was as a logistics base for the bureaus to support their teams. Niigata city is located in a suitable position for the support teams supplying food and essential equipment for the activities in the disaster area. In the primary period of the disaster, it was difficult to purchase food or equipment in the disaster area or in the Kanto area, which also faced a shortage of equipment. Some bureaus that came from the western area of Japan purchased winter tyres for the snow-covered roads, because ordinarily they do not require such tyres. The third function of the temporary relay base was as an information control base for every bureau conducting emergency activities in the disaster area. We collected information from the disaster area, organised the information and then, explained the information to the bureaus conducting emergency recovery away from the disaster area. Because it was difficult for the bureaus away from the disaster area to understand what kind of support was really needed, we arranged emergency activities for the support teams based on the latest information. Simultaneously, we sometimes advised the western bureaus about the equipment needed, such as the clothes or equipment necessary for the winter conditions.

6 PREPARATIONS FOR EFFECTIVE ACTIVITIES AS A TEMPORARY RELAY BASE

The following preparations are necessary for an effective temporary relay base.

①Large carpark
➢Parking space for cars, water trucks and construction vehicles

②Facilities for support teams
➢A lounge, a meeting space and a lodging place

③Ability to obtain necessities in an emergency
➢Foods and fuels, such as gasoline and kerosene

④Manuals for the emergency
➢Places to receive support teams, parking areas, unified chain of command

⑤Simulations about gigantic earthquake for heavily populated areas
➢Specific work/education programs about earthquake preparations and contingencies

Having adequate parking space is the most important of all the preparations mentioned above. It is important to beforehand arrange large car park at areas such as baseball grounds, athletic stadiums, soccer grounds or at the university or college campus. Having earthquake emergency agreements between water works bureaus and private companies such as hotels, restaurants, supermarkets and gas stations enable support teams to be received smoothly. In the primary period of the GEE, significant confusion and a shortage of equipment affected the efficiency and effectiveness of the emergency activities. Therefore, in the future, it is necessary to ensure that adequate preparations for emergencies are made in advance to ensure the provision of necessities in time by arranging agreements with those private companies. Furthermore, manuals need to be prepared that clearly outline the people responsible for the various emergency activities: a 'who must what until when' guideline. In Japan, there is a significant risk of large earthquakes, such as the Tokai Earthquake, the Tonankai Earthquake, the Nankai Earthquake, the Nankai trough Earthquake and the Tokyo inland Earthquake in the future. Therefore, if we wish to act as effective first responders, manuals are vital for effective and efficient operations.Agreements between Niigata city and other bureaus and private companies are shown in the following table.

Table.6-1 Agreements between Niigata City and other bureaus or private companies in case of disaster

Organization name	Agreement contents	date
Okayama City waterworks bureau	Mutual cooperation for emergency fuel	Jan. 2015
Kobe City waterworks bureau	Mutual cooperation for emergency fuel	Mar. 2014
Shizuoka City waterworks and sewage bureau	Mutual cooperation for emergency fuel	Feb. 2014
Yokohama City waterworks bureau	Mutual cooperation for emergency fuel	Aug. 2013
Sendai City water works bureau	Mutual support at the disaster	Nov. 2012
Niigata water service foundation	Emergency restoration work	Aug. 2014
Niigata City plumbing business cooperative	Emergency restoration work	Sep. 1997
Gosen City	Mutual water supply at the disaster area	Jan. 2000
Sanjo City	Mutual water supply at the disaster area	Mar. 2013
Gas stations in Niigata City	Emergency fueling agreement	Oct. 2013
Kirinzan Shuzo Co. Ltd	Emergency water supply at the disaster area	Mar. 2007
Kondo Sangyo Co. Ltd	Emergency water supply at the disaster area	2007

7 CONCLUSIONS

The Niigata city local resilience plan in 2015 has two key policies: 'emphasizing the reinforcement of relief and a substitution function'. This is a resilience plan, which aims to contribute to national resilience. Our city's location and the results from our support during the Great East Japan Earthquake has shown that Niigata can be an essential coordination centre for devastating earthquakes on the Pacific Ocean side of Japan. In this local resilience plan, five areas need to be highlighted: wide-area traffic infrastructures, an accumulation of industrial functions, energy bases, food bases and cooperation between areas. The provision of water during such emergencies should be a high priority in this plan, the contingencies for which should be prepared in advance so that if such earthquakes occur again, there is a plan of action in Niigata prefecture.

In retrospect, the initial response in the primary period at the essential activities in the past earthquakes is the most important. In other words, the initial actions are directly connected to the success or failure of the emergency support. Moreover, when a major disaster occurs, with the support of the prefecture association unit or the local branch association unit, we can efficiently support the emergency activities as a relay centre. First, we need to collect information about the kind of support the water works bureaus in our prefecture can offer. Then, we need to give and discuss this information with the bureaus in the prefecture association or the local branch associations so that we can achieve an efficient initial response in the future devastating earthquakes.

Development of New Disaster Information System

H.Nishikawa*,H.Sano*,Y.Hunahashi*

ABSTRACT
Waterworks are a critical lifeline that supports both civilian lives and urban activities. Because they are so critical, they necessitate the establishment of a reliable water supply system and the strengthening of existing crisis management systems. For this reason, the Osaka Municipal Waterworks Bureau is structuring a disaster information system. This disaster information system centralizes management and shares disaster-related information such as damage information, restoration activity information, and emergency water supply information during times of disaster such as earthquakes. By utilizing this system, quick and accurate situational analysis can be conducted, and countermeasures can be decided upon. This paper reports upon the functions and characteristics of disaster information systems, the thinking behind the final decisions regarding the functions of the system, and expected practical uses for the system during times of disaster.

PREFACE

Waterworks are a critical lifeline that supports prosperity of civilian life and advanced urban activities, and providing a stable water supply is their main objective. By engaging in various earthquake provisions such as earthquake-proofing its distribution pipes/purification facilities and constructing distribution reservoirs, the Osaka Municipal Waterworks Bureau has strived towards the establishment of a highly reliable water supply system and a strengthened crisis management system in order to provide secure water supply in both normal and disaster conditions such as earthquakes. On January 17th, 1995, the Great Hanshin and Awaji earthquake caused tremendous damage to a great majority of lifelines that city functions were built upon. The resulting prolonged water outage from damaged waterworks was an especially devastating blow to civilian lives, which necessitated further strengthening of crisis management systems by waterworks services. Since then, the Osaka Municipal Waterworks Bureau has worked to structure a disaster information system as a part of its efforts to strengthen reliability of its information communication system during times of disaster. Operation of this system has commenced in December of 2003.

It has been approximate 12 years since the current disaster information system was put into place. During that time, the Bureau has drawn up the "Osaka Municipal Waterworks Bureau's Business Continuity Plan (BCP)", which indicates actions plans during times of disaster. Furthermore, the Bureau's work environment has undergone change during this time. Such changes include the introduction of other works systems, such as attendance management systems and finance and procurement management systems. By updating the disaster information system, coordinating data with other work systems, and creating BCP-relevant forms, the Bureau has reconstructed the system with a focus on improving usability and operability. It is planning to start operations for this system as a newly updated version, starting November of 2015.

CURRENT WATERWORKS SERVICES IN THE CITY OF OSAKA

The Osaka Municipal Waterworks Bureau has been supplying water to Osaka city area since its establishment in 1895. It has developed its facilities and pipelines since then, and its current status is shown (Table 1 and Figure 1).

Table 1: Current waterworks services in the City of Osaka

Commencement of Operation	Nov. 13th, 1895	Daily Water Supply Capacity	2,430,000m^3
Population Served	2,690,214	Maximum Daily Supply(2014.4–2015.3)	1,286,700m^3
Number of Households Served	1,536,275	Average Daily Supply(2014.4–2015.3)	1,168,309m^3
Number of Employees	1,557	Total Length of Water Conduits and Distribution Pips	5,223km

(All numbers as of the end of March, 2015)

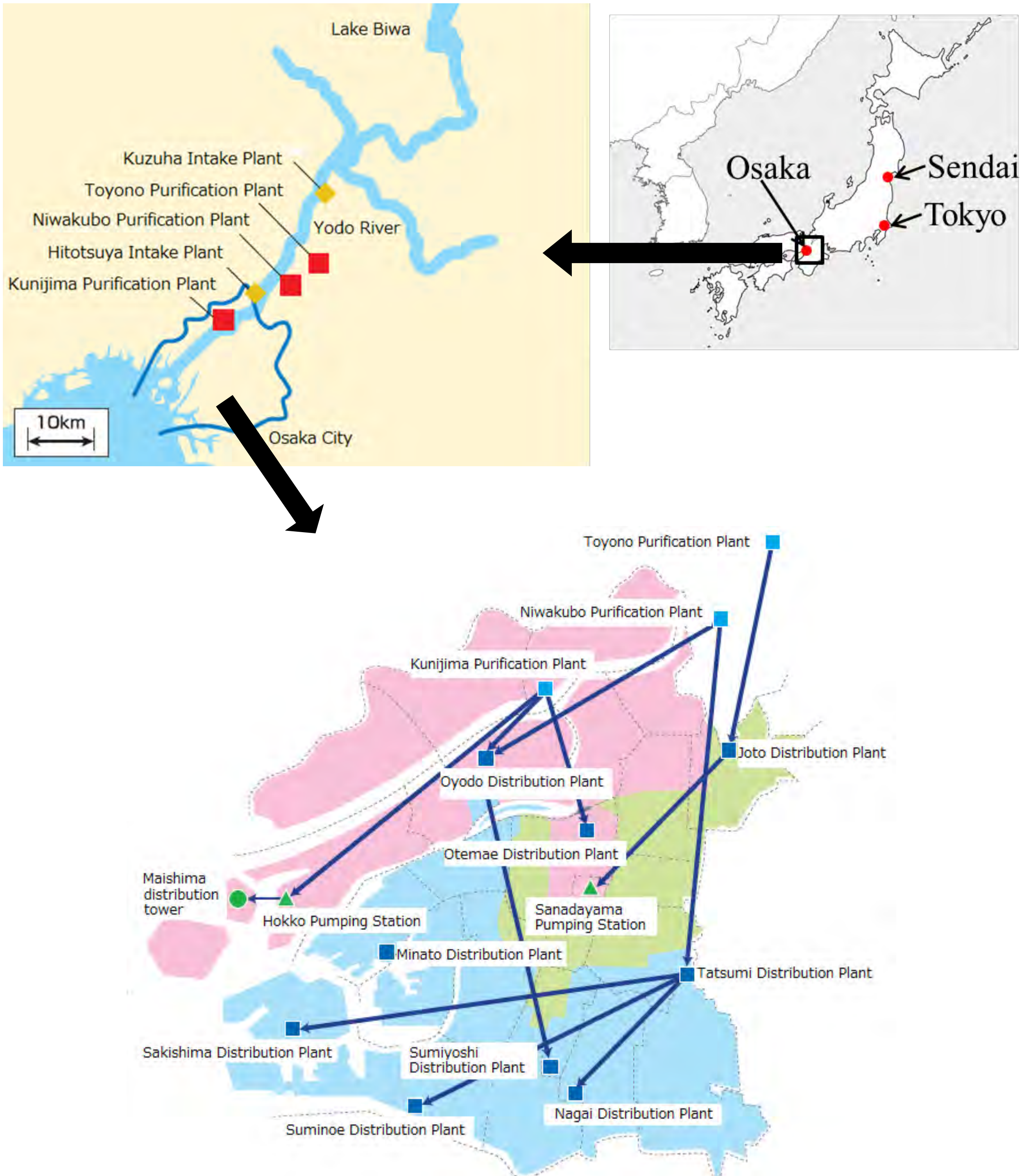
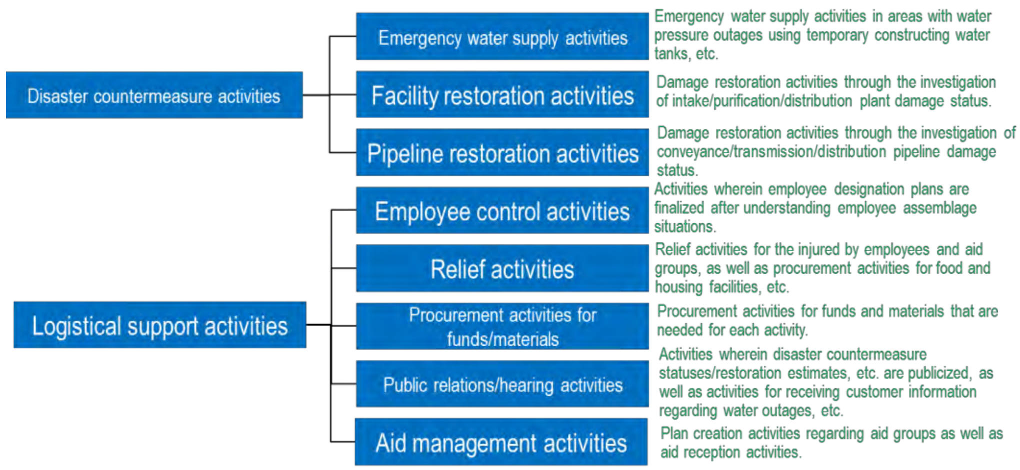


Figure 1: Locations of purification plants and water distribution reservoirs in the City of Osaka

OSAKA MUNICIPAL WATERWORKS BUREAU'S DISASTER COUNTERMEASURES

The BCP drawn up by the Osaka Municipal Water works Bureau in March of 2010 details action plans for a system that makes early recovery of waterworks services or continued waterworks services possible, even during times of disaster. The BCP states that during times of disaster, waterworks units should be established as lesser organizations belonging to the Osaka Disaster Countermeasures Headquarters, and details the actions that each waterworks units should take, such as emergency water supply activities, facility restoration activities, pipeline restoration activities, etc. (Table 2).

Table 2: Main activity details for each waterworks unit



CHARACTERRISTICS OF THE NEW SYSTEM

The disaster information system aims to support activity implementation, which includes the establishment of an organized immediate-response system, quick and accurate situational analysis, and counter-method decision-making, through the realization of centralized management and sharing of disaster-related information such as damage information, restoration activity information, and emergency water supply information during times disaster.

As a characteristic of the new system, the server equipment is installed in a remote data center so that the system will still be operational even during times of disaster.

The current disaster information system operates using a designated device that is installed per organization. Now, to account for disaster-time situations where a high volume of information must be entered by a limited number of devices, the new system will be operable on devices that each employee uses in his or her daily work routine, with the expectation that these employees will be familiar with how to operate their routinely-used devices, making disaster-time use of the system go smoothly.

Furthermore, the Osaka Municipal Waterworks Bureau has introduced work systems apart from the disaster information system, which include pipeline information management system which manages pipeline information by utilizing computer mapping systems and water distribution information management systems that collect real-time information regarding water pressure, flow levels, water quality data, etc. from telemeters installed in purification plants/water distribution reservoirs and city-wide pipelines. It has also introduced the attendance management system, which manages when employees clock in and out, etc., and the finance and procurement management system, which manages delivery and reception of goods, etc. To lessen the need for workers to register the same data to multiple systems during disasters, information entered into these work systems is also sent to the disaster information system, and is also displayed in the disaster information system.

The new system is functionally structured to fit the needs of the newly-formulated BCP, and has also been given additional functions that enable the creation of fixed reports and forms, etc. needed to report and collect information during disasters when it is necessary to do so swiftly.

BASIC STRUCTURE OF THE NEW SYSTEM

As functions for supporting activities during times of disaster, the new system contains disaster situation comprehension functions, pipeline restoration information management functions, emergency water supply information management functions, facility restoration information management functions, and logistical support activity management functions. The outline of these functions is detailed in Table 3, as follows.

Table 3: Outline of system functions

Disaster situation comprehension function	A function that centralizes and manages information regarding damage status and restoration activities of waterworks facilities during times of disaster, and aids in swift and decisive decision-making.
Facility restoration information management function	A function that allows for the understanding of damage/restoration statuses of water intake/purification/distribution plants, the water storage level and quality of purification/distribution reservoirs, etc., and supports restoration activities for facilities.
Emergency water supply information management function	A function that allows for the understanding of emergency water supply activities in areas with water outages, and supports the implementation of emergency water supply activities.
Pipeline restoration information management function	A function that, by inputting data such as the seismic intensity scale into the disaster information system, allows for the understanding of the scale of damage estimated right after the onset of disaster, and supports damage investigations of conveyance/transmission/distribution piping and implementation of piping restoration.
Logistical support activity management function	A function that supports the implementation of miscellaneous activities that will arise in conjunction with emergency countermeasure activities, such as understanding employee attendance statuses, managing goods/materials, public relations functions, managing aid groups from other cities, etc.

In during times of disaster, the system will be utilized to organize and share information such as damage and activity statuses through the registration of information by each waterworks unit, using the system's pipeline restoration information management functions and emergency water supply information management functions. Furthermore, the disaster information system has a function that creates reports based on entered information. Items that should be detailed in the reports are organized beforehand so that information necessary by Headquarters to make decisions can be collected. Headquarters must comprehend the entirety of the damage and activity status information pertaining to the disaster that has been reported to them via each unit and the disaster situation comprehension function, and will give instructions to each unit regarding courses of actions to take, along with information disclosure to outside parties in the form of press conferences etc. (Figure 2).

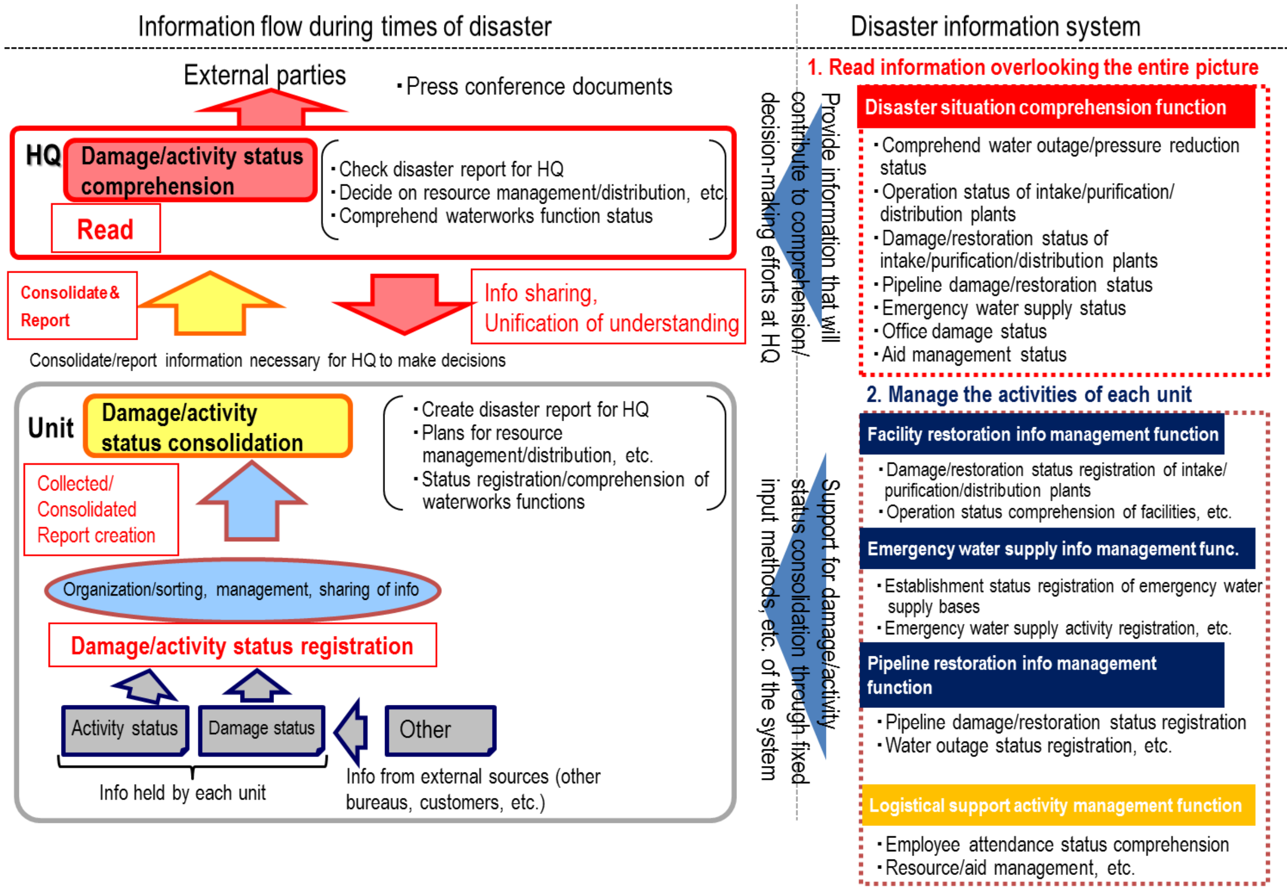


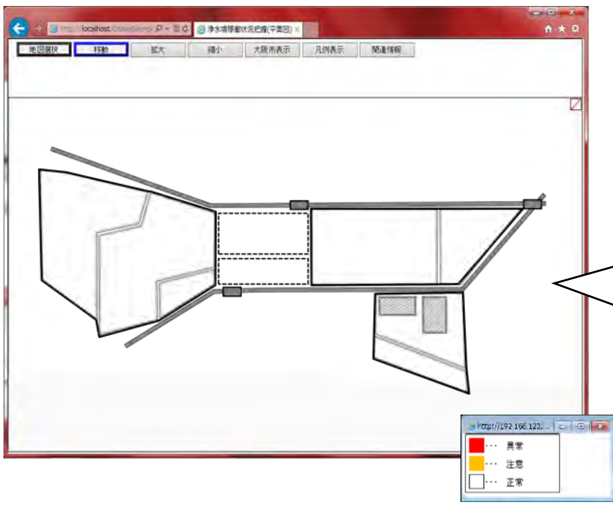
Figure 2: Utilization methods for the disaster information system in times of disaster

FUNCTIONS OF THE SYSTEM

Facility restoration information management function

This function registers and manages damage restoration statuses of water intake/purification/distribution plants via site floor plans and water purification processing flow charts (Figure 3). It also allows for registration/management of results from emergency water quality tests conducted by the water quality unit. Using the system makes it possible to know whether water intake/purification/distribution plants are operating normally or if they are damaged.

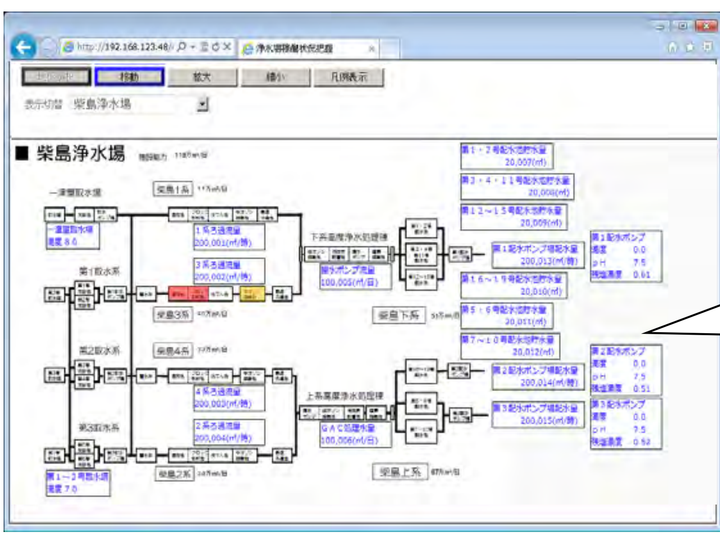
Furthermore, this function is able to coordinate data with the water distribution information management system, and can collect real-time information regarding the amount of water being processed in purification plants, along with water quality, amount of water stored in purification/water distribution reservoirs, distribution amounts, etc. (Figure 4).



By selecting individual facilities from the purification plant's, etc. floor plan and entering damage statuses, the damaged facility is highlighted and displayed in color.
Furthermore, selecting the facility highlighted in color allows users to check registered damage details.

- Stopped facility: Red
- Abnormal functions: Yellow
- No abnormalities: White

Figure 3: Damage restoration information of water intake/purification/distribution plants



Facility operation statuses (flow amount, turbidity, pH, residual chlorine concentration, etc.) during each step of the water purification process is displayed.

Figure 4: Operation status information of purification/distribution plants

Emergency water supply information management function

In the event that a water outage occurs during times of disasters, Osaka Municipal Waterworks Bureau will conduct emergency water supply through two methods: the first, which is the "base water supply method," where water is supplied at a central base by establishing temporary constructing water tanks and temporary constructing water supply valves in large-scale evacuation areas and evacuation shelters (schools, etc.).The second is the "delivery water supply method", where water supply trucks deliver water to tanks of key facilities such as medical facilities.

This function registers and manages establishment statuses of emergency water supply bases and installation statuses, etc. of temporary constructing water tanks and temporary constructing water supply valves for relevant facilities involved in base water supply and delivery water supply (Figure 5). This allows for efficient comprehension of the emergency water supply activity status in areas with water outages.

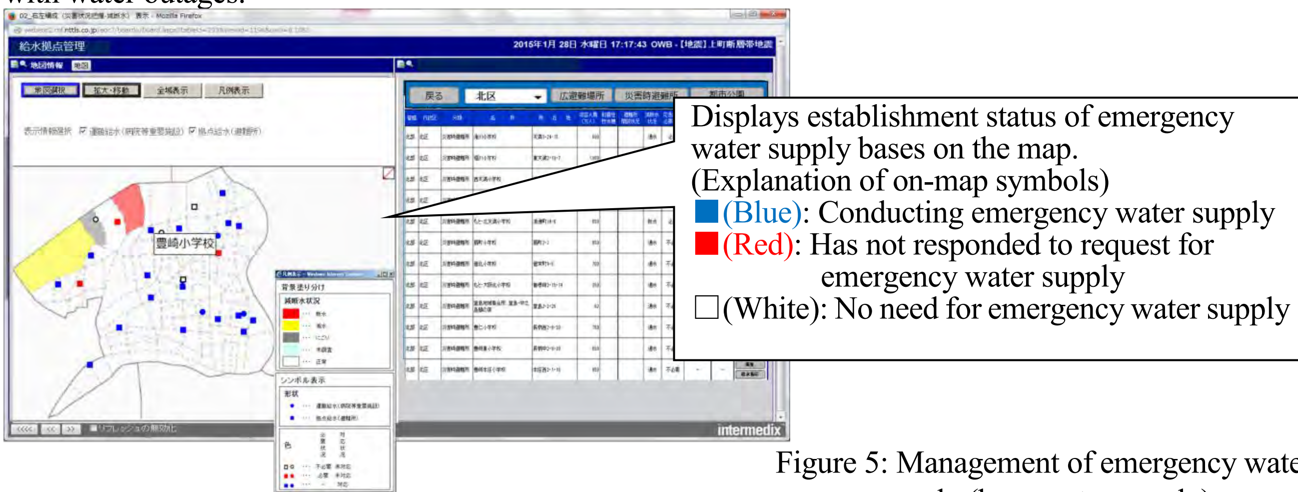


Figure 5: Management of emergency water supply (base water supply)

Pipeline restoration information management function

(1) Damage prediction function

During times of informational blanks and confusion directly after the outbreak of a large-scale earthquake, this function supports the establishment of swift initial onset structures such as requests for aid to other cities, through predictions of damage levels depending on the hypocenter and seismic intensity scale and comprehension of the breadth of pipeline damage.

Furthermore, the system includes a function that displays, on a map, regions that are predicted to undergo water outages (water pressure reduction) based on water pressure information that has been relayed from distribution telemeters installed in municipal areas. These predictions are to be used in on-site damage status investigations (Figure 6). It also contains a function where information reported, etc. by civilians regarding water outages can be recorded as references for on-site investigations.

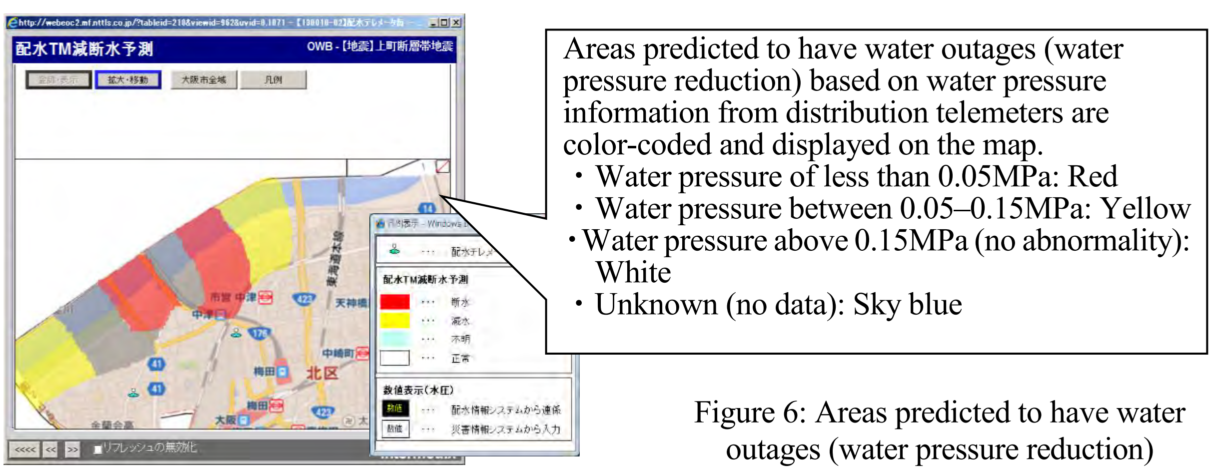
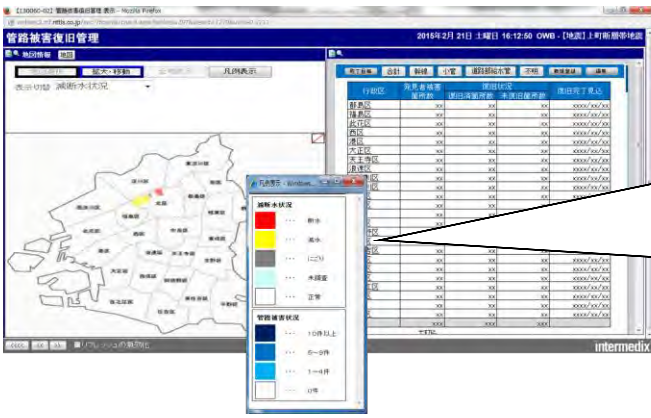


Figure 6: Areas predicted to have water outages (water pressure reduction)

(2) Water outage (water pressure reduction) status comprehension, pipeline damage restoration management
This function registers/manages, on a map, pipeline damage information, restoration activity information, and water pressure decrease statuses based on damage investigation results gathered by pipeline restoration units (Figure 7). Furthermore, regarding pipeline damage information, by taking the information that has been registered into the pipeline information management system and coordinating that data, they can be processed, and displayed on the disaster information system. This allows for precise comprehension of the damage situation of city-wide pipelines, which contributes to the drawing up of emergency water supply plans or emergency restoration plans.



Areas with pipeline damage based on information entered into the pipeline information management system are color-coded and displayed on the map.

- 10 or more instances of pipeline damage: Dark blue
- 5 to 9 instances of pipeline damage: Blue
- 1 to 4 instances of pipeline damage: Light Blue
- No instances of pipeline damage: White

Figure 7: Pipeline damage restoration management

Logistical support activity management function
(1) Management function for goods/equipment
This function manages the amount of goods and equipment necessary for actions during times of disaster, which include piping material, emergency water supply equipment for temporary constructing water tanks and temporary constructing water supply valves, etc., vehicles such as water supply trucks, and food. This function allows for easy understanding of which goods/equipment are in shortage, making procurement/aid requests run more smoothly. The amount of piping material that is on the possession of the Bureau is displayed in the disaster information system, and data is received from the finance and procurement management system.

(2) Employee assemblage status comprehension function
This function allows for easy understanding of the attendance status of Osaka Municipal Waterworks Bureau employees during disasters. By receiving data from the attendance management system, the number of employees in attendance can be displayed on the disaster information system. (Figure 8). This allows for human resources to be tracked, and contributes to the establishment of employee designation plans for disaster countermeasure activities.

(3) Report creation function
This function creates fixed reports and forms (disaster reports) in accordance with the BCP through the automatic processing of water outage statuses, emergency water supply and damage restoration information for waterworks facilities, etc. that has been registered by each waterworks unit. Disaster reports created by this function are used in countermeasure meetings held at the Bureau’s headquarters, as well as for public information to be released to customers, as press conference material, or information to be posted on the Bureau’s online homepage.

(4) Aid management function
This function records number of aid members and equipment in their possession, as well as implementation statuses of aid activities that are performed by aid groups from third party water suppliers, etc. The function allows for easy understanding of capabilities and activity statuses of aid groups, as well as for appropriate activity requests to be sent to said aid groups that are within their abilities.

Employee attendance statuses are processed and displayed by organization based on the information received by the attendance management system (a system that manages attendance, etc. of employees).
[Display details (Example)]
○○ Division
Total # of employees: ○, ○ employees in attendance, ○ employees in attendance in other offices

Figure 8: Employee assemblage status indication function

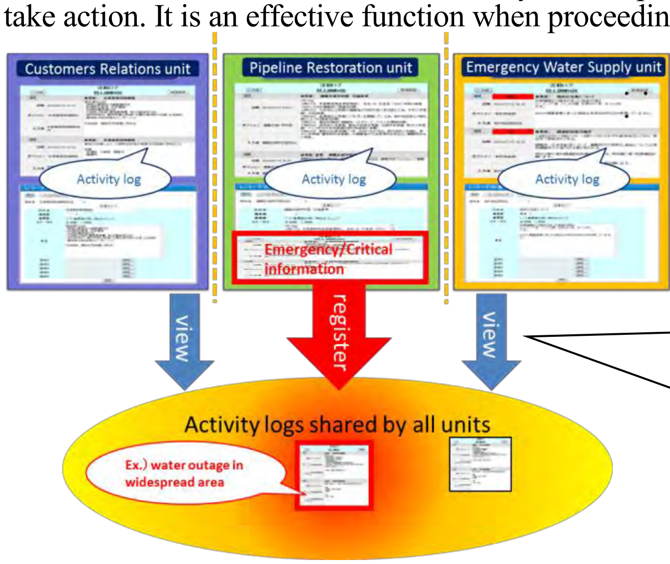
Other functions

(1) Activity logging

In times of disaster, many pieces of information are bound to get muddled, and information that does not fit the fixed reporting patterns of the functions outlined above is expected to appear. This type of information is usually the kind that is written up on whiteboards, etc., such as instructions/orders, response records, handover information, know-how, and directives, and can be valuable information when managing disaster-time activities. Therefore it becomes necessary to have a function to record these types of information as category-free comments. The function allows for free input of information such as activity statuses, tasks, and directives conducted by relevant waterworks units, and makes handover of tasks and information sharing go more smoothly (Figure 9). Furthermore, if organization-wide sharing of critical or emergency information becomes necessary, it is possible to conduct universal information sharing by changing the settings.

(2) Communications processing form

When taking action during times of disaster, there are bound to be many instances of additional instructions from headquarters, as well as work and adjustments requested from related organizations. This function registers/processes these communication items for smoother implementation of requests and orders that are exchanged between waterworks units (Figure 10). Because this function records communications items into the system, it prevents the forgetting of requests and failure to take action. It is an effective function when proceeding with disaster-time activities.



Countermeasures against disasters are recorded by organization, allowing information to be shared/viewed within the organization.
Furthermore, critical/emergency information can be shared/viewed regardless of organizations.

Figure 9: Activity logging

Figure 10: Communications processing form

CONCLUSION

As stated throughout this report, the disaster information system is a system that consolidates the Osaka Municipal Waterworks Bureau's activity and damage statuses in times of disasters. Because information that needs to be input in a fixed procedure is being organized preemptively, as well as the forms and papers that are used to input this information, employees are encouraged to record information that will be necessary in times of disaster, which allows for secure accumulation of data even during states of confusion during disasters. Furthermore, by utilizing the system, executive employees who give instructions and perform adjustments for disaster countermeasures can accurately comprehend the ever-changing state of affairs, and can draw up plans/make decisions swiftly and carefully for disaster countermeasure plans, etc.

However, because the disaster information system is not one that is used for usual operations, the main task of the Bureau is to find a way to improve the Bureau's employees' proficiency in the system. By taking advantage of integrating the new system into the in-office devices that are used for normal operations, the Bureau will create a system structure wherein each employee can practice utilizing the system during their daily operations. The Bureau also aims to improve proficiency in system operations by introducing robust training and induction courses that utilizes the system.

When managing disaster countermeasures, it is also important to conduct inspections and make revisions when necessary. The Osaka Municipal Waterworks Bureau conducts continuous improvements on the BCP and the functions of this system through PDCA cycles, and aims for the improvement of business sustainability by performing corrections of functions as necessary.

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Damage of water works facilities caused by the Great East Japan Earthquake and future problems for reconstruction in Otsuchi Town

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INTRODUCTION

The Great East Japan Earthquake caused a major disaster due to the tsunami and aftershocks, which were associated with the Tohoku Earthquake off the Pacific coast that occurred on March 11, 2011. The hypocenter of the Sanriku Coast on the Pacific Ocean was one of the largest observed in Japan with a magnitude of 9.0. Table 1 overviews the earthquake. Figure 1 shows Epicenter Map in the Off-Sanriku Region. The tsunami resulting from this earthquake caused major damage. In addition, liquefaction, ground subsidence, and collapse of buildings resulted in severe damage. According to the summary of damages[1], the death toll (human damage) was 15,892 and 2,573 were missing as of August 10, 2015, but the numbers are still rising even four years later. This paper discusses the damage to water works facilities, current reconstruction efforts, and the future challenges in Otsuchi Town.

Table 1 Overview of the 2011 Tohoku Earthquake off the Pacific Coast

Description	The 2011 Tohoku Earthquake
Date and time	March 11, 2011, 14:46:18.1
Coordinate and depth	North latitude 38°06.2' East longitude 142°51.6' 24 km
Magnitude	9.0 (moment magnitude) (the largest observed in Japan)

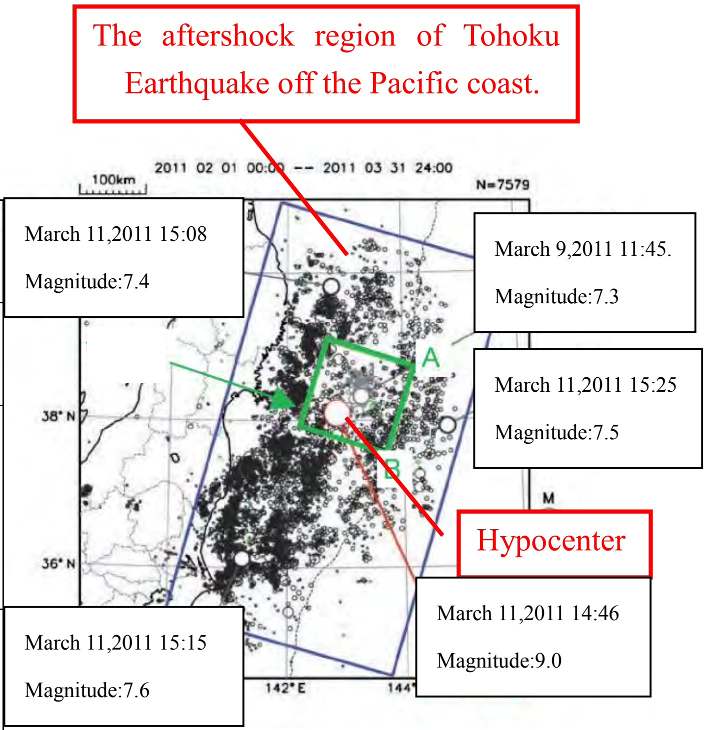

Figure 1 Epicenter Map in the Off-Sanriku Region[2]

DAMAGE BY THE DISASTER

Damage in Otsuchi Town

Otsuchi Town in the Iwate Prefecture, which is located north of Kamaishi City on the Pacific Ocean, was one of afflicted areas by the Great East Japan Earthquake (Figure 2). Prior to the earthquake, it had a population of 15,276. The local water utility served 13,961 residents and two small water utilities with a total average daily supply of 6,973 m^3 of water.

The Great East Japan Earthquake devastated coastal cities due to the associated tsunami, including a long-term disruption to the water supply. The majority of Otsuchi Town residents lived along the coast. The toll included 809 dead, 423 missing, (as of June 1, 2015)[4)], and 4,167 houses destroyed (as of May 31, 2011). The earthquake itself caused little damage compared to the accompanying tsunami, which caused massive flooding that was responsible for most of the damage.

Table 2 overviews the seismic ground motion due to the 2011 Tohoku Earthquake measured at Kamaishi City[5)]. (Note that the data from Kamaishi City is shown because the observation data from Otsuchi Town is not available.) Figure 3 shows photographs of the damage in Otsuchi Town.

Table 2 Overview of the seismic ground motion at Kamaishi City

Instrumental seismic	5.74
Maximum acceleration (gal)	741.56
Maximum velocity (kine)	29.09

(Measured on March 11, 2011 at 14:46)

Figure 2 Location of OtsuchiTown[3)].

Figure 3 Aerial view of the center of Otsuchi Town(left) before and (right) after The Great East Japan Earthquake.

Damage to the Water Works Facilities

Figure 4 shows damage to the water works facilities. Figure 5 shows damage to the main pipelines. The water works facilities in Otsuchi Town sustained the following damage:

- Household effect: 5,605 households experienced an interruption with their water supply[6)]
- Water purification plant: The tsunami hit the water source (well) for the Ogakuchi pumping station within the water purification plant, raising its water level. Although tsunami damage was not inflicted, if the water level had risen another 40 cm, the water purification plant would have been completely shut down. The non-utility generation facility was also spared damage. These facts made the water purification plant the center for water supply activities after the earthquake.
- Pumping station damage : Three booster pumping stations were completely shut down.
- Distribution pipes damage: 58 km of 107 km of water transmission (delivery) pipes were nonoperational.
- Population served: The number of people served by the water supply was reduced from 13,961 to 9,418. (Note that currently 9,676 residents are being served and the number is gradually increasing.)

Figure 4 Damage to (left) the water purification plant and (right) the Namiita pumping station .

Figure 5 Damage to the pipelines. (left) Broken main pipelines near the coast was washed away and (right) a damaged stop valve with water flowing out.

Emergency water supply

The emergency water supply activities for Otsuchi Town can be summarized as follows:

- Start date of emergency water supply: March 17, 2011
- Number of days that emergency water was supplied: 90
- Number of emergency water supply locations: 17, including a water utility plant as the main location
- Total number of water supply tank vehicles: 425
- Water supplied: 2,305 m^3
- Supplying agency: The emergency water supply was provided primarily by the 48 water utilities belonging to the Japan Water Works Association (43 utilities belonging to the Kansai branch and 5 utilities belonging to the Tohoku branch).

Because emergency water supply personnel could not find accommodations within Otsuchi Town, they were based in Morioka City, which is more than 100 km away, and commuted daily.

RECONSTRUCTION PLAN

Designing the Reconstruction Plan

Developing a reconstruction activity was a time-consuming endeavor due to the tsunami-induced damage to the booster pump stations and main pipelines. The Master Plan for Water Works Facilities Reconstruction was formulated in September 2012 using the guiding concept "to prepare for an unexpected disaster and develop sustainable water works facilities" in response to the experiences of the Tohoku Earthquake. Staff from the City of Kobe involved in the disaster and reconstruction activities after the Great Hanshin/Awaji Earthquake in 1995 helped draft the Master Plan. The initial plan has been modified twice to align the reconstruction of the water works facilities with the overall reconstruction plan for Otsuchi Town. Table 3 shows the overall reconstruction plan for Otsuchi Town.

Table 3 Overall reconstruction plan for Otsuchi Town

Item		Guiding principle
Tsunami damage prevention	Facilities	Build tsunami barriers, evacuation routes, and evacuation centers.
	Operation	Conduct disaster prevention education and strengthen disaster prevention system.
Land use		Basic principle is to move to higher ground. A maximum height of 20 m of soil is to be laid on areas that were hit by the tsunami in 2011.
Transportation system		Secure alternate routes if major roads are damaged.

Initial Plan

(1) Fundamental Concept in Building Water Works Facilities in Otsuchi Town

- Main pipelines are not to be built in designated flood-prone areas in the new tsunami barrier plan.
- Elevated water reservoirs and existing pumping stations are to be eliminated in tsunami-inundated areas. A gravity flow system that does not rely on an electrical power supply is to be used.
- An emergency water supply is to be secured by providing non-utility generation facility, emergency stop valves, earthquake-proofing pipes connecting to schools, etc.

(2) Examples of the Initial Plans

i. Move important water works facilities out of designated flood-prone areas or consolidate and discontinue these facilities.

- Example (Figure 7 A): Three afflicted pumping stations will be decommissioned to reduce the operating budget and maintenance costs. New reservoirs are to be built on elevated grounds.

ii. Build a system that will maintain its water supply capability even against a giant tsunami

- Example (Figure 7 B): Construction of main pipelines systems along National Route 45, Prefectural Route Kirikiri Kamaishi, and Town Route Kirikiri Namiita.

Although water supply pipes are not typically built along National Routes and other major roads, this Master Plan, which was devised in close cooperation with the authorities for national and other routes, enables main pipelines to be built alongside major roads (National Routes) outside flood-prone areas. As seen in this example, this Master Plan follows an unconventional and rational approach to prepare for disasters.

iii. Eliminate areas where water pressure is insufficient or water cannot be supplied due to the way water supply lines and facilities are built in high-altitude areas where people have relocated.

iv. Build emergency water supply centers.

- Example (Figure 7 C): Schools for grades 1 to 9, Ando pumping station, Akahama new r eservoir, etc.

Revised Plan

The estimated budget for the water works facility reconstruction (the amount from the design consultation in fiscal year 2013) was 3,012,000,000 yen. A 2013 review revised the reconstruction plan for the water works facilities to align the plan with the overall reconstruction plan for all of Otsuchi. The current plan is to be completed in 2018. Table 4 shows the changes to the reconstruction plan.

Table 4 Changes to the reconstruction plan

	Changes to the plan for Otsuchi Town	Changes to the plan for the water utility
(i)	Set up efficient and strategic management and operation of facilities and infrastructure considering future maintainability to realize a sustainable and compact community. The altitude of elevated land is also to be reviewed.	Terminate the plan to build reservoirs in elevated areas, and alter the plan to distribute water from the water sources owned by the water utility.
(ii)	Build a disaster-proof community while considering the traditional ways of Otsuchi Town.	The water source for Otsuchi Town exists only in the Machikata district. Emergency preparedness is strengthened by constructing bypass pipes in the Kirikiri district and Namiita district to form a loop.

In formulating this plan, the residents' opinions were incorporated and the reconstruction plan for the water works facilities was reviewed in light of changes in the overall reconstruction plan for Otsuchi Town. Revisions include building looping water supply pipe systems instead of reservoirs on elevated land. This flexibility in the plan is one of the characteristics of the Otsuchi Town reconstruction projects.

Figure 6 shows designed cutaway drawing in Otsuchi town. Figure 7 shows the revised plan for the Otsuchi Town water supply system. There are two major changes:

i. Terminate the plan to build reservoirs on elevated land. Instead water is to be directly supplied from the existing water source (Figure 7 D)
ii. Construct bypass pipes in the Kirikiri District (Figure 7 E)

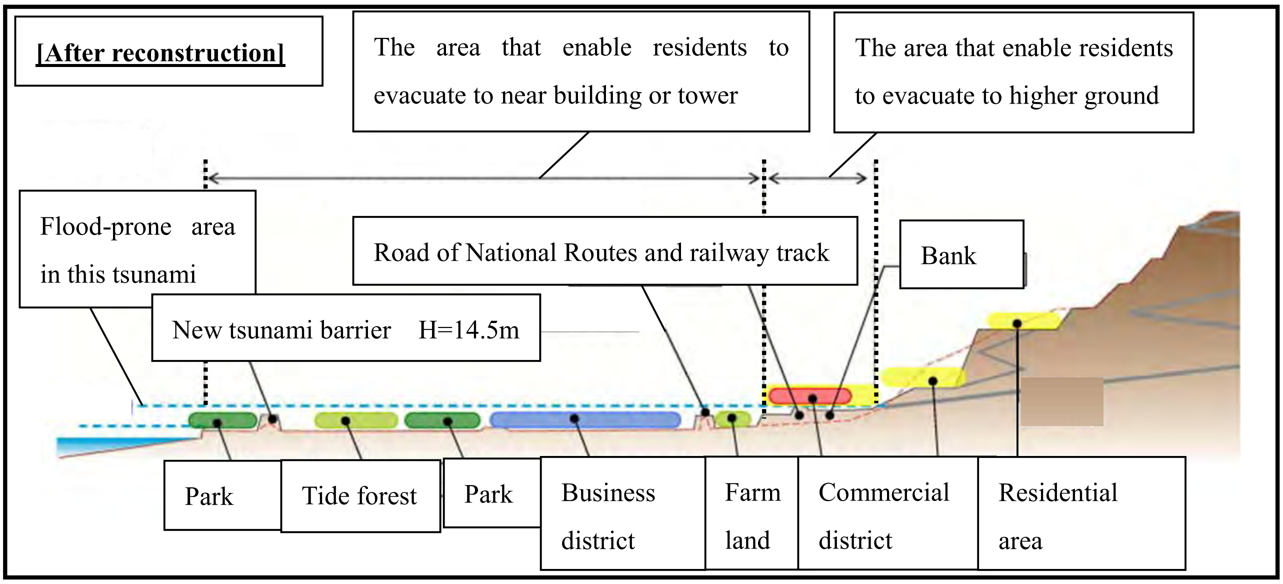

Figure 6 Designed cutaway drawing in Otsuchi town.

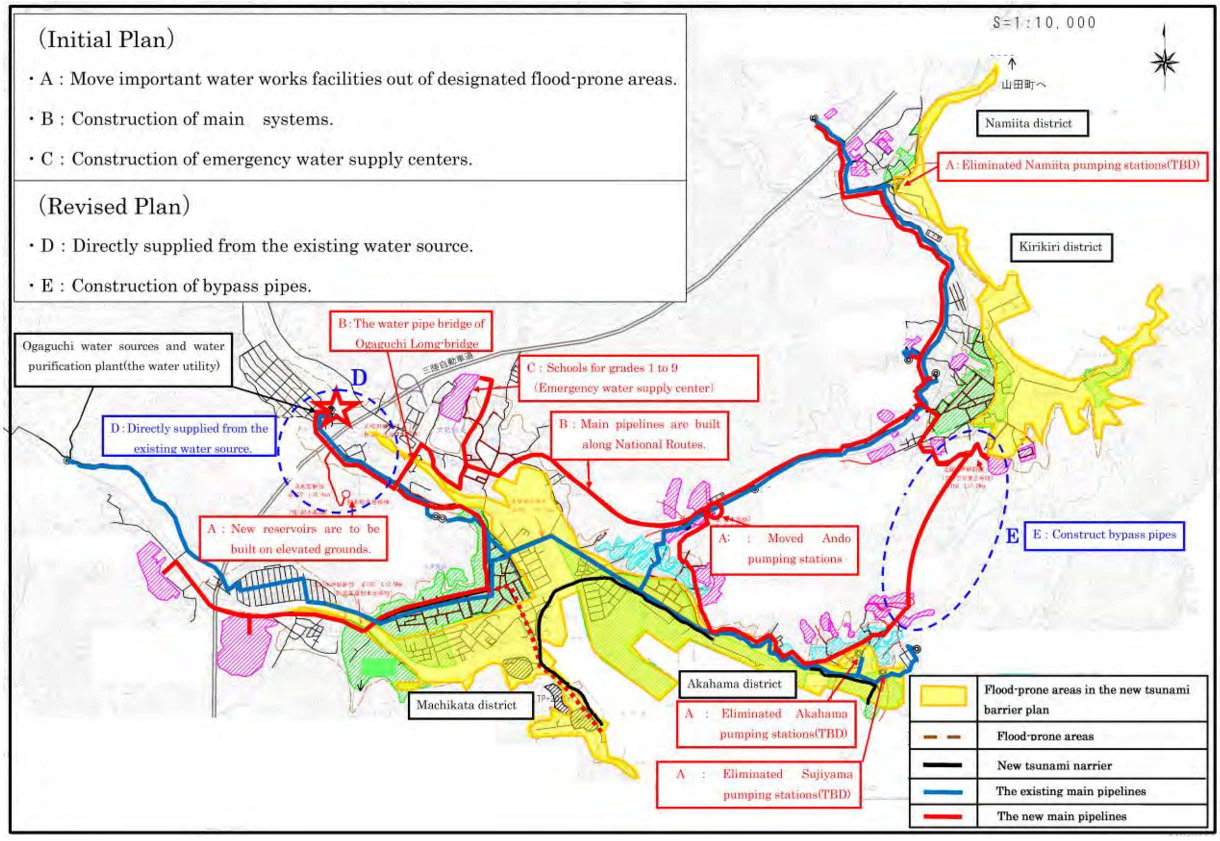

Figure 7 Revised plan for the Otsuchi Town water supply system.

CURRENT STATUS OF THE RECONSTRUCTION PROJECTS, CHALLENGES, AND COUNTERMEASURES

Current Status of the Reconstruction Projects

(1) Coordination with Other Construction Projects

Reconstruction projects are ongoing. The peak activity is in a three-year period from 2015 to 2017, in which many redevelopment and mass-relocation projects will commence. These activities must be coordinated with other reconstruction projects by national, prefectural, and municipal governments as well as those of the Japan Railway.

(2) Increased Activities after the Earthquake

- Field responses for the reconstruction projects (including CMR, meetings with contractors, and operation of valves)
- Changes to the overall plan for special evaluation, release of suspension, various applications, etc.
- Evaluation and inspection associated with the applications to construct water supply equipment

(3) Staffing

Various staffing issues have emerged. Table 5 shows the number of water utility staff. While the number of dispatched and temporary staff for the entire town has increased drastically after the earthquake, only one full-time engineer has been added to the staff. Due to this shortage of engineers, Otsuchi Town has been unable to assign its own staff to lead the water works facilities reconstruction projects. Additionally, only about one week of overlap is allocated between old and newly dispatched staff. The lack of a proper turnover results in newly dispatched staff members with insufficient knowledge of the activities under the previously dispatched staff.

Table 5 Number of water utility staff

	Number of staff (engineers)	Town employees	Temporary employees	Dispatched employees	Remarks Entire town
Before the Earthquake	7 (2)	7	0	0	136
After the Earthquake	9 (3)	5	2	2	276

Problems in the Reconstruction Projects

Otsuchi Town is facing three major problems:

(1) Shortage of staff

The number of staff members has increased by three after the earthquake by receiving dispatched staff members from other organizations, including the City of Sakai. However, there is a still a shortage of staffing in light of the amount of work to be done such as construction management for the reconstruction projects, coordination with other reconstruction projects, and coordination with CMR, etc.

(2) Building facilities

Vast financial and human resources are currently being spent on reconstruction projects of facilities. Consequently, updating and expanding the capacity of existing aging facilities (such as reservoirs and pipelines), earthquake proofing, and building of small water supply systems are currently left undone.

(3) Population decline

The decreasing population is a cause for concern over the reduction in the staffing level for the water utility as well as the decline in the service level. The declining population has resulted in a reduced demand for the water supply. In fact, the amount of water supplied in Otsuchi Town has decreased significantly since the earthquake.

Table 6 shows the forecasted water supply revenue in relation to the population decrease.

Table 6 Forecasted water supply revenue in relation to the population decline

	2009	2013	Percentage	Forecast for 2035
Registered population	16,171	12,673	78%	8,916
Households supplied water	5,969	4,549 Note	76%	3,436
Water supply revenue	231 million yen	160 million yen	69%	133 million yen
Large consumers	45	23	51%	No data

Note: The number of Households supplied in the year 2013 include accommodations for 150 reconstruction workers, volunteers, and dispatch staff members. After the reconstruction project is complete, this number is expected to be nil.

Other problems include:

- Operation of the water utility is becoming financially difficult due to the decreased revenue associated with the significant decline in demand for water as well as increased depreciation costs. Actually, average daily supply in Otsuchi town was decreased more than half in two years from 2011.
- The population may not recover according to the plan after the reconstruction projects are complete, further reducing the demand for water.
- The significant decrease in the demand for water may mean that the capacity of the water supply facilities will be too large in the future.

Challenges to problems

This section describes the responses to the three problems.

(1) Shortage of staff

- Accelerate hiring and promotion of staff members, including dispatched workers from the private sector.
- Provide a sufficient turnover between old and new staff members.

(2) Building of facilities

- Selectively choose projects other than reconstruction projects. Implement higher priority projects first and update existing facilities in order to utilize limited financial resources.
- Future projects should be leveling and facilities built for a long operational life to reduce human and financial resources.

(3) Population decline

- Try to bring in and retain large consumers such as marine product processors.
- Incorporate downsizing into future facility updates to reduce cost and improve efficiency.
- To overcome potential financial difficulties with the water supply operations due to the population decline, implement a water rate increase.

CONCLUSIONS

(1) Lessons Learned

- The impact of Great East Japan Earthquake was greater than anticipated, and Otsuchi Town was not properly prepared. To minimize damage, the worst-case scenario must be considered when planning facilities and operations.
- A rational and robust reconstruction plan was drawn against future disasters due to the support and guidance from people with disaster relief experience.
- It is important to review reconstruction plans in coordination with residents' opinions and overall plans.

(2) Remaining Challenges

- Full-fledged recovery of the water supply facilities is lagging compared to the restoration of other earthquake damage due to the delay in developing an overall reconstruction plan for the entire town. Early planning of basic reconstruction principles is desirable in response to a major disaster.
- While the entire nation is experiencing a low birth rate and aging of its population, the population decline may be further accelerated due to a disaster in regions like Otsuchi Town where the total population is small, exacerbating the population decline issue. Hence, after the reconstruction projects are complete, securing human and financial resources will be difficult.

ACKNOWLEDGMENTS

We appreciate the staff who works in water supply utility in Otsuchi town for providing significant information.

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Non-linear Pushover Analysis of Water Pipelines under Soil Liquefaction

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ABSTRACT

Soil liquefaction may be induced during earthquake. In this situation, bearing capacity of soil under water pipelines will be reduced or vanished. If the joint or the pipe itself is not strong to withstand the gravity load of the pipes and water inside, the pipeline will be damaged or disengaged and water supply is affected. In this paper, the behavior of pipeline under soil liquefaction is investigated. Parameters of plastic hinges are adopted from previous study and they are allocated on the pipes and at the joints. It is assumed that the bearing capacity of soil in the liquefaction area vanishes. Pushover analysis is conducted such that the uniform distributed load on the pipeline is increased gradually. If the capacity of the pipelines is larger than the demand (weights of pipes and water), the water pipeline are safe. Otherwise, damage or disengagement may happen. The process of pushover analysis of water pipelined under liquefaction is illustrated by ductile iron pipes with K-type joints. The behavior of pipelines highly depends on the extent of soil liquefaction. If the area of liquefaction is limited to 16 m along the pipelines, the pipelines will not damage.

Keywords: water pipeline, soil liquefaction, pushover analysis

1. INTRODUCTION

Taiwan is located in seismically active area and disastrous earthquake may happen in every 10 years so people in Taiwan have to live with earthquakes. Water pipeline may be ruptured during earthquakes and water supply may be disrupted. However, water is very important for human beings and water system is an important lifeline. Therefore, seismic performance of water pipeline is very crucial. Earthquake may be followed by soil liquefaction. Under soil liquefaction, bearing capacity of soil is greatly reduced and underground water pipeline may be settled and failure occurs.

Nonlinear behavior of underground structures such as pile has been studied by nonlinear pushover analysis. The pile is modeled by beam element and its nonlinear properties are represented by plastic hinges. Soil is modeled by spring with perfectly elastic plastic properties. Displacement and force relationship of ductile iron pipes was developed from experimental and numerical studies [1]. According to the experimental and numerical results, axial (including tension and compression) and bending nonlinear plastic hinges were established. In addition, since the K-type joint is highly nonlinear, the axial (including tension and compression) and bending plastic hinges were solely derived from laboratory tests

[2]. In this paper, the behavior of underground water pipeline under soil liquefaction is investigated. In the region where liquefaction occurs, the bearing capacity is assumed to vanish and in the region where no liquefaction, the soil is modeled by nonlinear spring. The extent of liquefaction is assigned and the loading pattern is uniformly distributed load to simulate the weight of pipe filled with water. The displacement of pipeline increases gradually and the corresponding load is acquired. From the relationship between uniformly distributed load and displacement, the maximum one is the capacity of the pipe. If the capacity is larger than the demand, the pipeline survives. The critical situation can be obtained by varying the extent of soil liquefaction.

2. PUSHOVER ANALYSIS

In this paper, ductile iron pipes with K-type joints are investigated. The diameter D is 407 mm and the thickness t is 7 mm. The pipes buried under the ground are simulated by beam elements. It is assumed that the bearing capacity of soil completely vanishes during soil liquefaction. Therefore, the weight of the pipes with water becomes the external force of the structural system. The sketch of the analysis model for the system is shown in Figure 1 where L is length of soil liquefaction region along the pipeline and l is the length of beam element of the pipes. It is found that analysis results are accurate enough if the size of beam element is as small as 0.2 times the pipe diameter, that is, $l = 0.2D$. At the nodes of the beam element, nonlinear axial (including tension and compression) and moment plastic hinges for the pipes are assigned. Since the ductile iron pipes are fabricated in segments with length 6 m, there is a joint at every 6 m of the pipeline. Nonlinear axial (including tension and compression) and moment plastic hinges are also assigned at the joints.

The region of soil liquefaction is unknown in advance so that the distribution of joints with respect to the liquefaction region is arbitrary. Therefore, two types of joint distribution pattern are considered. In joint distribution type a (Figure 2), a joint is located at the center of the liquefaction region. In joint distribution type b (Figure 3), the midpoint of a pipe segment is located at the center of liquefaction region. In the region of soil liquefaction, soil springs are removed and the pipes are not supported (Figure 1). Beyond the region of soil liquefaction, the pipes are supported by soil springs in the longitudinal and lateral directions. It is found that analysis results are accurate enough as long as the length of the model is 3 times the length of liquefaction ($3L$). In this situation, the reactions (shear forces, axial forces and bending moments) at the two far ends of the model are small enough to be neglected.

The external force for pushover analysis is uniformly distributed load, simulating the weight of pipe with water. The center of liquefaction region is assigned as the control point. The displacement of the control point increases by one step and the uniformly distributed load is adjusted such that the displacement can be achieved. The above-mentioned process repeats again and again until the displacement cannot be increased any more. The pushover curve for case with the length of liquefaction L equal to 20 m is shown in Figure 4. The uniformly distributed load increases linearly when the displacement is small and becomes nonlinear when the displacement is large enough. After reached the maximum point, the uniformly distributed load attenuates. The maximum uniformly distributed load is different for different joint distribution types. Between joint distribution types a and b, type a has lower maximum uniformly distributed load, $w_{max} = 1.288\,\text{kN/m}$ which is the capacity of the pipe under soil liquefaction with region $L = 20\,\text{m}$. The weight of the pipe with water per unit length is $w_t = 1.8716\,\mathrm{kN/m}$, which is the demand of the pipe. Since the capacity is less than the demand, the pipes fail under this situation.

The procedures mentioned above are repeated for other cases (length of liquefaction region L equal to 12, 14, 16, 18, 20, 21, 22, 23, 24, 26, 28 and 30 m). Joint distribution types a and b are considered. The maximum uniformly distributed loads $w_{\max}$ are plotted against the lengths of liquefaction region L as shown in Figure 5. The capacity (maximum uniformly distributed load $w_{\max}$) decreases as the length of liquefaction region L increases. When the region of liquefaction exceeds 16 m, the lower of the maximum loads of joint distribution types a and b becomes less than the unit weight $w_t = 1.8716\,\mathrm{kN/m}$.

Joint distribution type b can be considered as type a shifted by 3 m. Since the capacity of the pipe under soil liquefaction is highly dependent on the way the joints are distributed in the liquefaction region, three more joint distribution types c, d and e are taken into account. Types c, d and e are type a displaced by 0.75, 1.5 and 2.25 m, respectively. Since the length of pipe segment is 6 m, all the joint distributions are varied from type a by shifting no more than 3 m. Figure 6 shows the pushover curves of pipeline with joint distribution types a, b, c, d and e under liquefaction length of 17 m. The maximum uniformly distributed loads of types b and e are less than $w_t = 1.8716\,\mathrm{kN/m}$. Therefore, the pipeline fails under soil liquefaction of length $L = 17\,\mathrm{m}$. Similarly, 5 pushover curves can be constructed for $L = 16\,\mathrm{m}$. All the five maximum uniformly distributed loads exceed the demand w_t. In a word, the pipeline can sustain soil liquefaction of length L not greater than 16 m.

3. CONCLUSIONS

In this paper, a method is developed to investigate the behavior of water pipeline under soil liquefaction. It is assumed that bearing capacity of soil completely vanishes within the region of liquefaction. The weight of pipe with water is simulated by uniformly distributed load which is the load pattern for pushover analysis. The nonlinear characteristics of pipe and its joint are represented by plastic hinges. Maximum uniformly distributed load are obtained from pushover analysis. If the capacity (maximum uniformly distributed load) is higher than the demand (weight of pipe with water), the pipeline survives. Otherwise, the pipeline fails. The process repeats for various extents of liquefaction so that the critical situation can be found.

The method is illustrated by an example of ductile iron pipe with nominal diameter 400 mm and thickness 7 mm. It is found that the performance of pipeline under soil liquefaction depends on the distribution of joints relative to the center of liquefaction region. After considering all joint distributions, the pipeline can survive if the length of pipeline in the liquefaction is no more than 16 m. The proposed method can be readily extended to other cases once the nonlinear properties of pipe section, pipe joint and soil.

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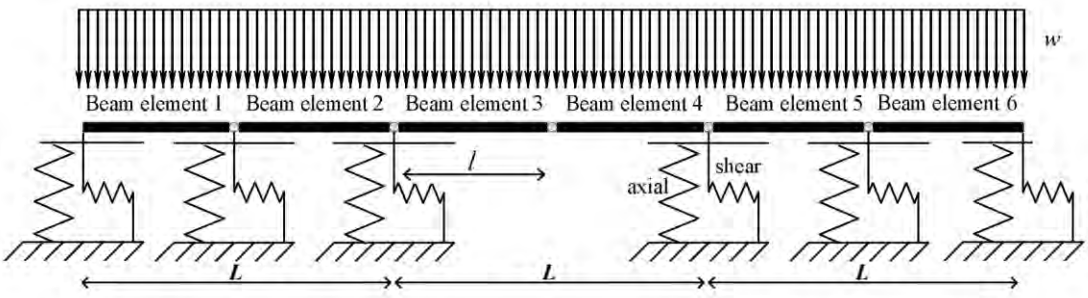

Figure 1 Pushover analysis model of pipelines under soil liquefaction

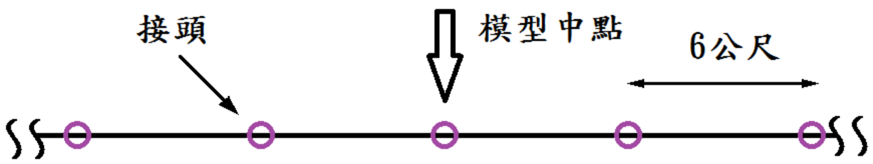

Figure 2 Joint distribution type a (joint located at center)

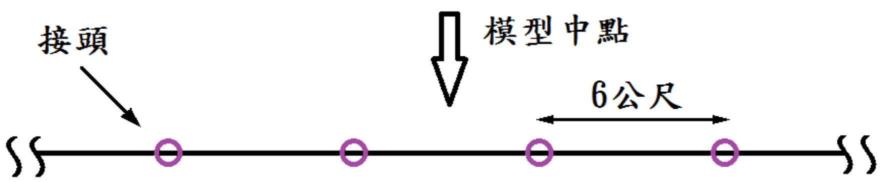

Figure 3 Joint distribution type b (pipe midpoint located at center)

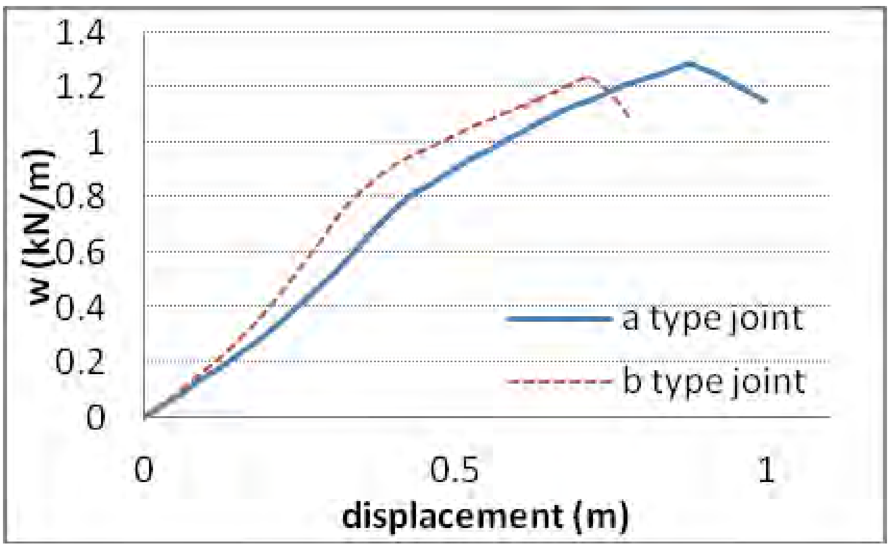

Figure 4 Pushover curve of pipeline under soil liquefaction ($L = 20$ m)

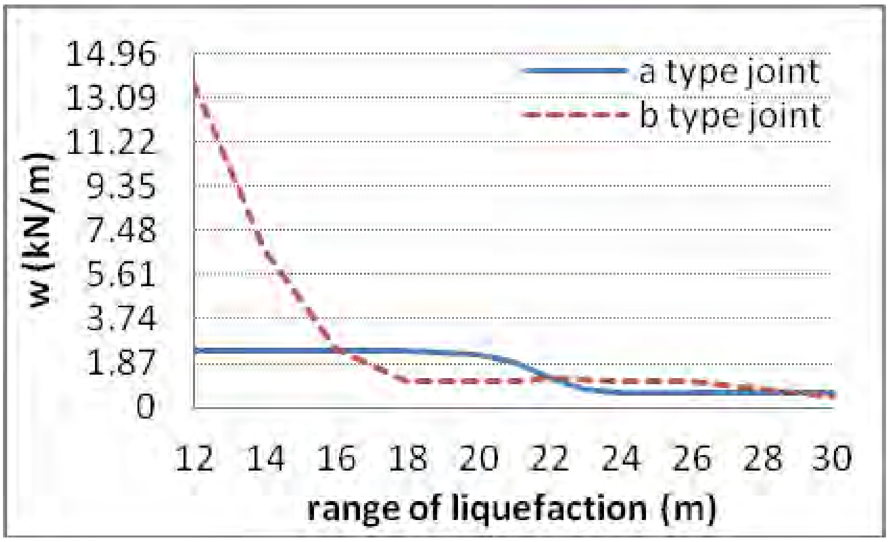

Figure 5 Maximum uniformly distributed load and length of liquefaction

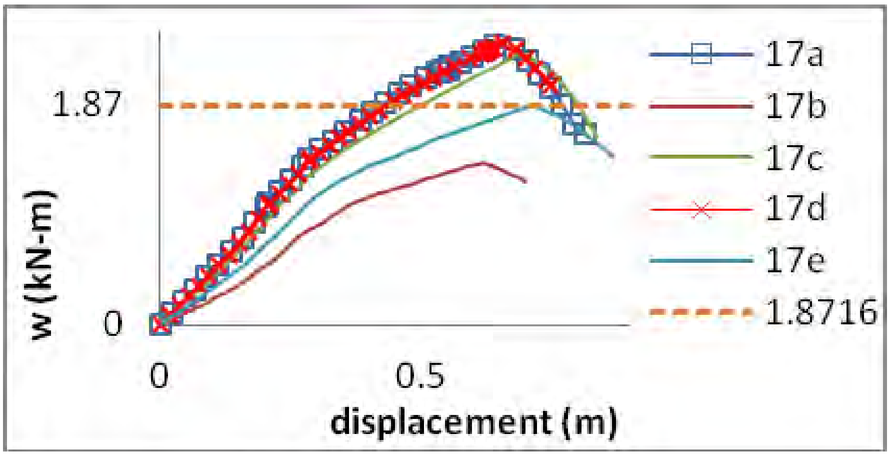

Figure 6 Pushover curve of pipeline with 5 joint distributions under soil liquefaction ($L = 17$ m)

New Study on Soil Liquefaction Susceptibility Categories

Chin-Hsun Yeh[1], Gee-Yu Liu[1] and Lee-Hui Huang[1]

Abstract

Soil liquefaction is one of the major geo-hazards caused by large earthquakes. Some of buildings, bridges and buried pipelines in the severe liquefied regions may damage or loss of functions. In order to identify the probable liquefied regions and to assess the amount of settlement and the degree of influence on various kinds of civil infra-structures, it is necessary to have a feasible and effective method to assess the soil liquefaction probability and the associated settlement in wide area due to scenario earthquakes. A methodology of earthquake scenario simulation and risk assessment, that is, Taiwan Earthquake Loss Estimation System (TELES) has been developed by the National Center for Research on Earthquake Engineering (NCREE) in Taiwan. Integrating the concept of soil liquefaction susceptibility categories in HAZUS and the engineering borehole data from the Central Geological Survey Bureau of Taiwan, a set of empirical formulas for each soil liquefaction susceptibility category was proposed in TELES to assess soil liquefaction potential index and the associated settlement. The peak ground acceleration (A), earthquake magnitude (M) and ground-water depth (D) were taken into account in deriving the empirical formulas. Besides reviewing the existing analysis model and empirical formula, this paper intends to reinvestigate the classification scheme of soil liquefaction susceptibility categories, to propose a new functional form for empirical formula, and to modify the interpretation of liquefaction potential index. A soil liquefaction susceptibility category map of Taiwan will also be updated by using additional borehole and geologic data. The scenario simulation results and the probable applications will be discussed.

Keywords: soil liquefaction susceptibility category, liquefaction potential index, settlement

Review of Existing Soil Liquefaction Assessment Model

When saturated loose soil is subjected to cyclic loadings, and if the vibration is large enough and lasts for a long time, the soil particles will tend to rearrange their relative positions, the volume tends to shrink due to gravity, the pore-water pressure increases rapidly, and soil liquefaction phenomenon will occur. Generally speaking, the ground shaking intensity, duration and ground-water depth are three major factors that will influence soil liquefaction potential and the associated severity of settlement or lateral spreading. To simplify liquefaction assessment model, the peak ground acceleration and the earthquake magnitude are commonly used to indicate the excitation intensity and the duration of excitation, respectively.

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Liquefaction Susceptibility Categories

According to the earthquake loss estimation methodology of HAZUS (RMS, 1997), the soil liquefaction susceptibility at a site was classified into six categories, that is, "very high", "high", "moderate", "low", "very low" and "none" susceptibility. The empirical formulas for each category to estimate the liquefaction probability and the induced permanent ground deformation were also provided in the technical manual. However, the classification scheme proposed in HAZUS for soil liquefaction susceptibility was not based on operational definitions or quantitative descriptions. To overcome the shortcomings, a modified classification scheme for soil liquefaction susceptibility was proposed by Yeh, et al (2002) and had been used in TELES. The modified classification scheme was based on layer properties, such as SPTN and fine content, of engineering borehole data.

In Yeh, et al. (2002), a soil liquefaction potential index (P_L) proposed by Iwasaki, et al. (1982) was used to estimate the liquefaction potential and severity at the site subjected to any combination of peak ground acceleration, earthquake magnitude and ground-water depth. Comparing many liquefied and non-liquefied cases after strong earthquakes, Iwasaki, et al. (1982) found that in case $P_L \geq 15$, the liquefaction probability is high and the sites may be severely liquefied; on the other hand, if $P_L \leq 5$, the liquefaction probability is low and the sites may not be liquefied at all. In the classification scheme, according to Yeh, et al. (2002), the earthquake magnitude and the ground-water depth are assumed to be constant (7.5 and 1.5 meters, respectively) but the level of ground shaking in terms of peak ground acceleration (PGA) was gradually increased to determine the threshold when $P_L \geq 15$. The boreholes with $P_L \geq 15$, when PGA were 0.15g, 0.2g, 0.25g, 0.35g and 0.45g, belong to "very high", "high", "moderate", "low" and "very low" susceptibility categories, respectively. All the other boreholes with $P_L < 15$, when PGA is 0.45g, were classified as "none" sensitive to soil liquefaction.

Empirical Formulas for Estimating Liquefaction Potential

From figures of P_L versus PGA for different susceptibility categories and under various earthquake magnitude and ground-water depth, it is noted that the relationships between P_L and PGA are almost linear within the range $5 \leq P_L \leq 20$. Thus, for simplicity and suggested in HAZUS, the empirical formulas of liquefaction potential index for different susceptibility category i were expressed as follows in Yeh, et al (2002) study:

$$P_{L,i} = \alpha_i \cdot f(M) \cdot g(D) \cdot A + \beta_i \tag{1}$$

Where A was the peak ground acceleration at the site; subscript i indicates susceptibility category; α_i and β_i were constants and listed in Table 1. The modification functions due to earthquake magnitude (M) and ground-water depth (D) were not sensitive among different liquefaction susceptibility categories and can be expressed as follows:

$$f(M) = 0.0353M^2 - 0.1855M + 0.4069 \tag{2}$$

$$g(D) = 0.0002D^4 - 0.0051D^3 + 0.0535D^2 - 0.2758D + 1.3105 \tag{3}$$

Table 1 Values of α_i and β_i in Eq. (1).

Category	α_i	β_i
Very High	227.52	-13.63
High	188.30	-18.45
Moderate	157.35	-20.51
Low	103.02	-14.95
Very Low	66.95	-10.64

Empirical Formulas for Estimating Settlement

Ishihara (1993) proposed a method to estimate settlement due to soil liquefaction. Ge (1997) made some assumptions and used a nonlinear regression method to analyze the Ishihara's data and proposed analytic formulas to estimate liquefaction settlement. From figures showing relationship of settlement versus PGA for different combinations of earthquake magnitude and ground-water depth, it can be seen that the amount of settlement approaches a limiting value when PGA becomes larger; and the limiting value depends only on the susceptibility category. Since the relationship of settlement versus PGA was similar to a log-normal distribution function, only two parameters, that is, median and log-standard deviation were required to describe the relationship.

In Yeh, et al (2002) study, the relationship of liquefaction settlement (S) versus peak ground acceleration (A) were expressed as

$$S = \bar{S}_i \cdot \Phi\left[\frac{\ln(A/m_i)}{\sigma_i}\right] \tag{4}$$

where $\bar{S}_i$ is the limiting value for susceptibility category i; $\Phi(\cdot)$ is the standard normal distribution function; and m_i and σ_i are the median and the log-standard deviation of the log-normal distribution function, respectively. It is noted that m_i and σ_i are functions of earthquake magnitude and ground-water depth; but the modification functions due to earthquake magnitude ($\bar{f}(M)$) and ground-water depth ($\bar{g}(D)$ and $\bar{h}(D)$) were not sensitive to liquefaction susceptibility category. Thus, m_i and σ_i were expressed as follows:

$$m_i = \mu_i \cdot \bar{f}(M) \cdot \bar{g}(D) \tag{5}$$

$$\sigma_i = \lambda_i \cdot \bar{h}(D) \tag{6}$$

$$\bar{f}(M) = 0.1231M^2 - 2.2052M + 10.5954 \tag{7}$$

$$\bar{g}(D) = -0.007188D^2 + 0.145195D + 0.7919 \tag{8}$$

$$\bar{h}(D) = 0.003208D^2 - 0.042231D + 1.0611 \tag{9}$$

where μ_i and λ_i were constants and listed in Table 2.

Table 2 Values of $\bar{S}_i$, μ_i and λ_i in Eq. (4).

Category	$\bar{S}_i$ (cm)	μ_i (g)	λ_i
Very High	47.43	0.0872	0.4522
High	50.22	0.1292	0.3657
Moderate	46.21	0.1613	0.3433
Low	35.89	0.1875	0.3430
Very Low	25.66	0.2104	0.3764

Updated Soil Liquefaction Assessment Model

Although the previous observations and empirical formulas for soil liquefaction potential and settlement have been proved to be useful, it needs improvement. For example, use of a linear form in Eq. (1) could not distinguish effectively the relative potential at two different sites where P_L were both greater than 20. In addition, as shown in Figure 1, the liquefaction potential index should have an upper limit and is seldom larger than 70. However, the predicated P_L does not saturate when PGA is large by using Eq. (1).

Classification Scheme of Soil Liquefaction Susceptibility

To increase resolution of soil liquefaction susceptibility for different soil conditions using borehole data, the soil liquefaction susceptibility was classified into ten categories. They are designated from category 9 to category 0. The category 9 corresponds to the most sensitive soil site, while category 0 correspond to none sensitive soil or rock sites. Similar to the approach in Yeh, et al (2002), under constant earthquake magnitude ($M_w = 7.5$) and ground-water depth (1.5 m), the PGA threshold of $P_L \geq 15$ for various kinds of liquefaction susceptibility categories fall within the ranges divided by 0.15g, 0.2g, 0.25g, 0.3g, 0.35g, 0.4g, 0.45g, 0.5g, 0.6g, respectively. For example, $P_L \geq 15$ when PGA is less than 0.15g at the most sensitive sites (category 9); $P_L \geq 15$ when PGA is greater than 0.15g but less than 0.2g at the second sensitive sites (category 8), and so on.

Comparing with the existing classification scheme for soil susceptibility categories, the categories 9, 8 and 7 correspond to categories "very high", "high" and "moderate" susceptibility, respectively. The original "low", "very low" and "none" susceptibility categories are partitioned into seven sub-categories to increase recognition of different soil conditions.

Empirical Formula for Soil Liquefaction Potential Index

Figure 1 shows a plot of soil liquefaction potential index (P_L) versus peak ground acceleration (PGA) for category 9 with different ground-water depth and subjected to the same earthquake magnitude (7.5). As shown in the figure, the P_L approaches to a limiting value when PGA becomes larger and larger. Furthermore, through nonlinear regression, it can be shown that the limiting values of P_L depend on the earthquake magnitude and the ground-water depth, as shown in Figure 2. To assess P_L more accurately, a log-normal distribution function, instead of a linear function in Eq. (1), was used to describe the nonlinear relationship between P_L and PGA subjected to different combinations of earthquake magnitude and ground-water depth. In other words, the estimated P_L can be expressed as:

$$P_{L,i} = u_{i,PL} \cdot \Phi\left[\frac{\ln(A/m_{i,PL})}{\beta_{i,PL}}\right] \tag{10}$$

where subscript i indicates susceptibility category; $u_{i,PL}$, $m_{i,PL}$ and $\beta_{i,PL}$ are upper-limit of P_L, median value of PGA and log-standard deviation of the log-normal distribution function, respectively. The $u_{i,PL}$, $m_{i,PL}$ and $\beta_{i,PL}$ are functions of earthquake magnitude and ground-water depth, and can be expressed as follows:

$$\begin{aligned} u_{i,PL} = K_{u,i} \cdot (-0.01729M^2 + 0.3072M - 0.331) \\ \cdot(0.000916D^2 - 0.01578D + 1) \end{aligned} \tag{11}$$

$$\begin{aligned} m_{i,PL} = K_{m,i} \cdot (-0.03907M^3 + 0.9699M^2 - 8.236M + 24.7) \\ \cdot(0.001021\,D^3 - 0.02482D^2 + 0.234D + 1) \end{aligned} \tag{12}$$

$$\begin{aligned} \beta_{i,PL} = K_{\beta,i} \cdot (-0.00739M^3 + 0.1404M^2 - 0.726M + 1.665) \\ \cdot(-0.0000871\,D^3 + 0.004257D^2 - 0.05307D + 1) \end{aligned} \tag{13}$$

where $K_{u,i}$, $K_{m,i}$ and $K_{\beta,i}$ are constants and listed in Table 3. As shown above, the variations of $u_{i,PL}$, $m_{i,PL}$ and $\beta_{i,PL}$ with respect to earthquake magnitude and ground-water depth for different susceptibility categories are almost the same and can be approximated by the same functions. The anchor-point in evaluation of $K_{u,i}$, $K_{m,i}$ and $K_{\beta,i}$ is earthquake magnitude 7.5 and ground-water depth 0 meter.

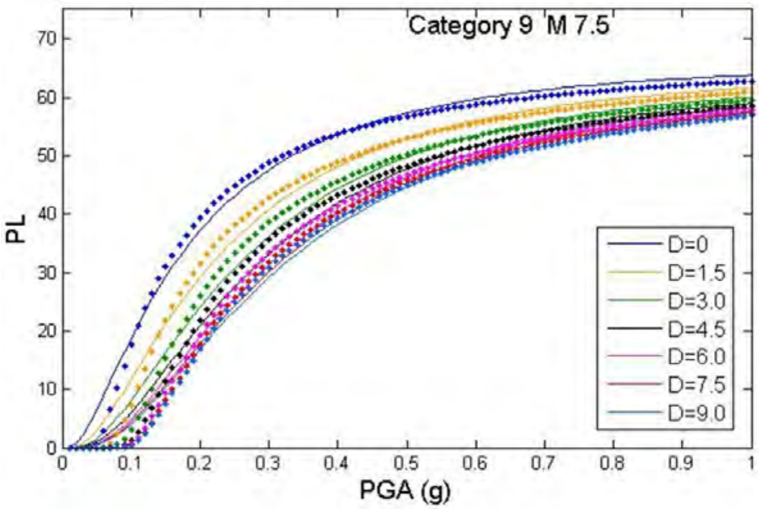

Fig. 1 Plot of P_L versus PGA for category 9 with different ground-water depth and subjected to earthquakes with magnitude 7.5.

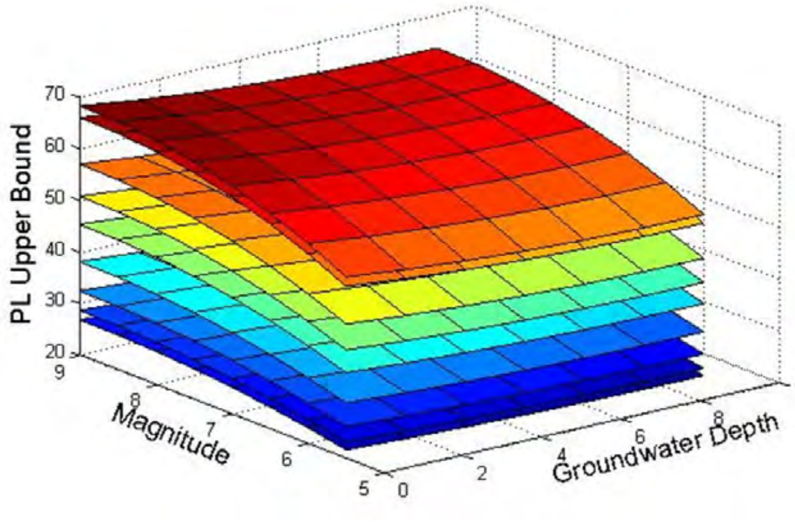

Fig. 2 Upper bounds for plot of P_L versus PGA under different combinations of earthquake magnitude and ground-water depth.

Table 3 Values of $K_{u,i}$, $K_{m,i}$ and $K_{\beta,i}$ in Eq. (11), (12) and (13), respectively.

Susceptibility Category	$K_{u,i}$	$K_{m,i}$	$K_{\beta,i}$
Category 9	65.86	0.1712	0.9540
Category 8	63.69	0.2280	0.8275
Category 7	54.97	0.2630	0.7646
Category 6	48.98	0.2949	0.7234
Category 5	43.72	0.3213	0.6963
Category 4	36.71	0.3354	0.6840
Category 3	31.22	0.3354	0.7013
Category 2	27.60	0.3394	0.7095
Category 1	25.83	0.3557	0.6871

Empirical Formula for Settlement due to Soil Liquefaction

Applying a similar procedure on the analysis of settlement due to soil liquefaction, Figure 3 shows a plot of settlement versus peak ground acceleration (PGA) for category 9 with different ground-water depth and subjected to the same earthquake magnitude (7.5). As shown in the figure, the amount of settlement due to liquefaction approaches to a limiting value when PGA becomes larger and larger. Secondly, the limiting value does not change with different ground-water depth. If the nonlinear relationship of settlement and PGA was described by a log-normal distribution function, which was obtained by nonlinear regression technology, can be expressed as follows:

$$S_i = u_{i,S} \cdot \Phi\left[\frac{\ln(A / m_{i,S})}{\beta_{i,S}}\right] \tag{14}$$

where subscript i indicates susceptibility category; $u_{i,S}$, $m_{i,S}$ and $\beta_{i,S}$ are upper-limit of settlement, median value of PGA and log-standard deviation of the log-normal distribution function, respectively. As can be seen from the results of nonlinear regression, the upper-limit and the log-standard deviation of the log-normal distribution function, that is, $u_{i,S}$ and $\beta_{i,S}$ almost keep constant for the same soil liquefaction susceptibility category. However, the median value ($m_{i,S}$) of log-normal distribution function does vary with respect to earthquake magnitude and ground-water depth. In summary, the $u_{i,S}$, $m_{i,S}$ and $\beta_{i,S}$ can be expressed as follows:

$$u_{i,S} = S_{u,i} \tag{15}$$

$$\beta_{i,S} = S_{\beta,i} \tag{16}$$

$$\begin{aligned} m_{i,S} = S_{m,i} \cdot (-0.05693M^3 + 1.4192M^2 - 12.0101M + 35.263) \\ \cdot(0.000483\,D^3 - 0.01458D^2 + 0.1897D + 1) \end{aligned} \tag{17}$$

where $S_{u,i}$, $S_{m,i}$ and $S_{\beta,i}$ are constants and listed in Table 4. As is implied in Eq. (17), the variation of $m_{i,S}$ with respect to earthquake magnitude (M) and ground-water depth (D) is almost the same for different susceptibility categories and can be approximated by the same functions. The anchor-point in evaluation of $S_{m,i}$ is earthquake magnitude 7.5 and ground-water depth 0 meter.

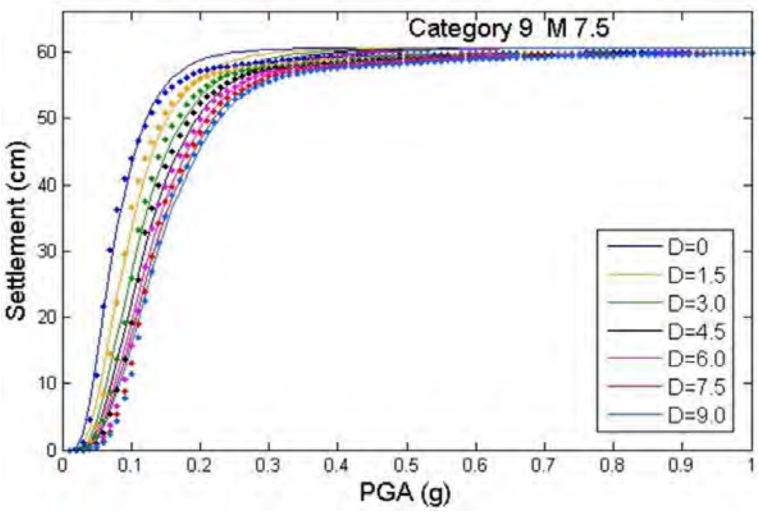

Fig. 3 Plot of settlement versus PGA for category 9 with different ground-water depth and subjected to earthquakes with magnitude 7.5.

Table 4 Values of $S_{u,i}$, $S_{m,i}$ and $S_{\beta,i}$ in Eq. (15), (16) and (17), respectively.

Susceptibility Category	$S_{u,i}$	$S_{m,i}$	$S_{\beta,i}$
Category 9	60.64	0.0746	0.5276
Category 8	52.09	0.1052	0.5318
Category 7	42.36	0.1276	0.5572
Category 6	34.99	0.1452	0.6065
Category 5	30.69	0.1643	0.6583
Category 4	25.69	0.1697	0.6687
Category 3	20.30	0.1683	0.6951
Category 2	18.25	0.1651	0.6908
Category 1	15.78	0.1742	0.7169

Discussion

A liquefaction potential index proposed by Iwasaki, et al. (1982) has been commonly used in engineering society to indicate the liquefaction potential and severity at the sites during strong earthquakes. Using the updated classification scheme for soil liquefaction susceptibility, it is possible to distinguish liquefaction potential in the original "low", "very low" and "none" susceptibility sites. Use of log-normal distribution function in the empirical formulas may improve accuracy in estimating liquefaction potential index; it also provides a natural way to assign liquefaction probability at the sites in scenario earthquakes. Liquefaction susceptibility category map of Taiwan will be updated later and applications to probabilistic seismic hazard analysis will be studied, too.

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Design and Seismic Prevention of Water Main crossing Faults Cases in Taiwan

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Keywords：Shan-Yi active fault, water main, shield tunnel

Abstract

Design of underground pipeline should consider the geology, environment and influence of active fault. Two cases of water mains seismic strategy passing through active faults will be discussed. First is TWC water main project, its alignment is close and almost parallel to the Shan-Yi active fault in Miao-Li. The pipeline will cause severer damage than the situation just cross the fault, such as the Taipei Dadu water main project (alignment is cross Shan-chiao active fault). Meanwhile, the seismic design strategy and analysis is totally different. This paper will demonstrates the TWC project feasible engineering judgments, design with BIM techniques and the shield tunneling consideration in hard gravel formation as reference.

一、Foreword

For water supply in urban area, some pipeline being parallel or crossing active fault should be considered. TWC water main project alignment is parallel with San-Yi active fault, maintenance walkway space is kept within shield tunnel. The main design task is to analyze influence of earthquake waves. Taipei Dadu water main project alignment is cross Shan-chiao active fault, the main design task is to analyze displacement of fault moving. Owing to complicated pipeline layout, these two cases consider 3-D numerical analysis model instead of conventional plane strain method.

二、Dynamic analysis method of water main tunnel

Influence of earthquake induced by active faults moving can be classified into two types. Type I consider influence of water main structure from fault moving wave, ex. TWC project. TypeII consider influence of water main structure from fault moving displacement, ex. Dadu project.

2.1 Influence of water main structure from fault moving wave analysis

2.1.1 Racking method

Analysis of underground structure such as water main is different from general structure. Racking method is adopted usually, where the racking angle is given to simulate stratum deformation. The racking angle is seldom less than 0.5%, and is related to stratum SPT-N value.

The racking deformation induced by earthquake force within free domain is calculated as follow equation.

$$R = I \times \frac{V_{\max}}{C_{se}}$$

Where I=1.2 is importance coefficient, V_{max} is largest velocity of ground movement, and Cse is stratum shear velocity, which can be estimated as follow equations if no measured value.

$C_{Se} = 100N^{\frac{1}{3}}$ (Cohesive soil)

$C_{Se} = 80N^{\frac{1}{3}}$ (Cohesionless soil)

The TWC project consider joint between launching shaft and shield tunnel by racking method, where stress concentration occurs as Fig.1a and 1b. To analyze soil structure interaction(SSI) effect, numerical analysis must involve structure and surrounding soil, which will take more time to calculate.

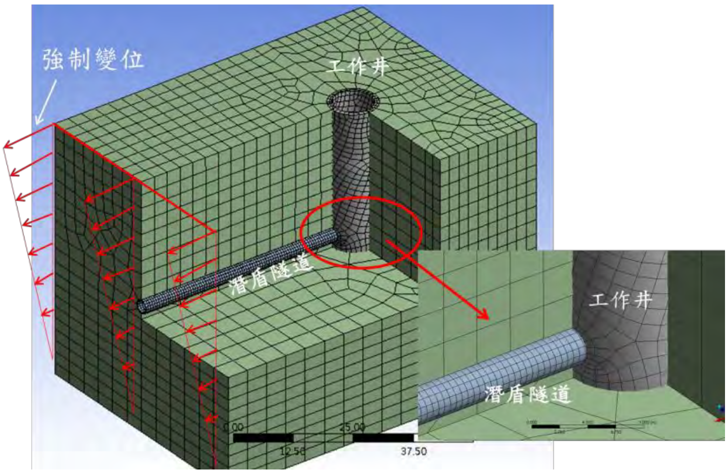


Fig.1a Analysis Mesh of launching shaft and shield tunnel

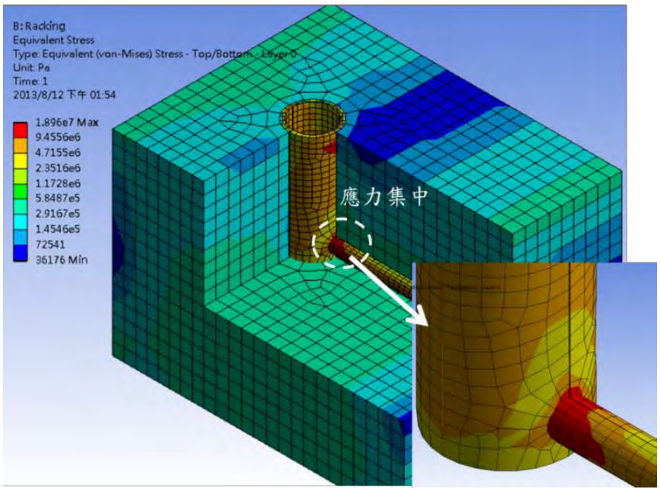


Fig.1b Stress increasing contour of racking method

2.1.2 Response Spectrum Analysis

The TWC project in shield tunnel with maintenance walkway space, which is surrounded by air instead of soil, thus racking method is not available.

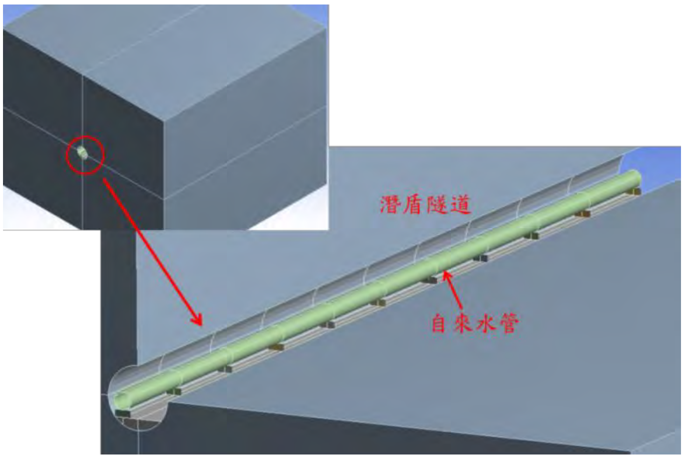
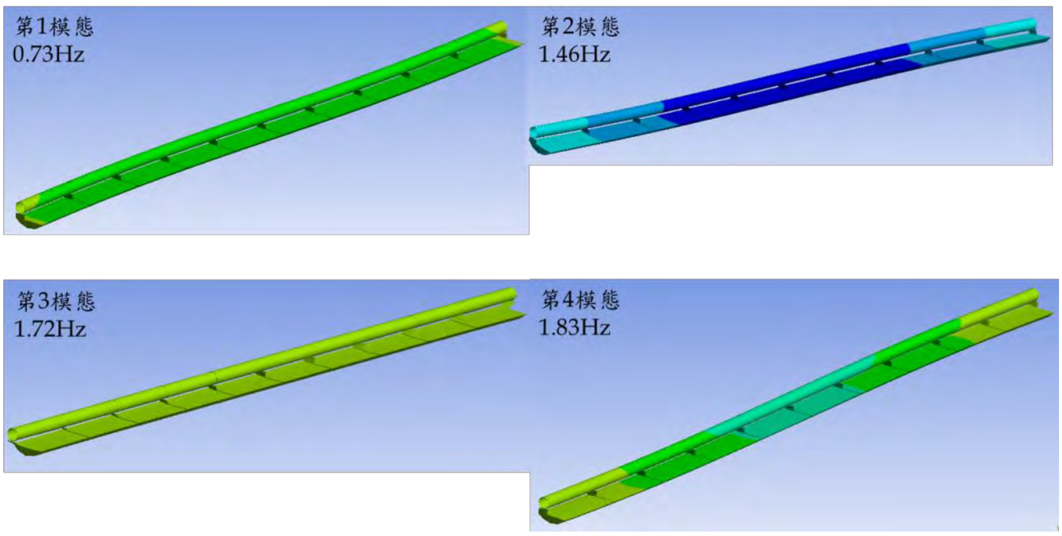


Fig.2 3-D layout of TWC project water main

Response spectrum analysis is more usually adopted than time domain analysis due to calculation time is less, especially for the complicated degrees of freedom.

Usually we take basic mode instead of high frequency mode to simulate dynamic analysis, so 10 modes is progressed of TWC project as Fig3. The 10 modes earthquake response of TWC project can be got after calculation of both modes frequency and acceleration spectrum from NCREE, where the 1st mode(0.73Hz) and 4th mode(1.83Hz) contribute 70% and 16% of earthquake response. Thus the dynamic behavior is composed of 1st mode and 4th mode.



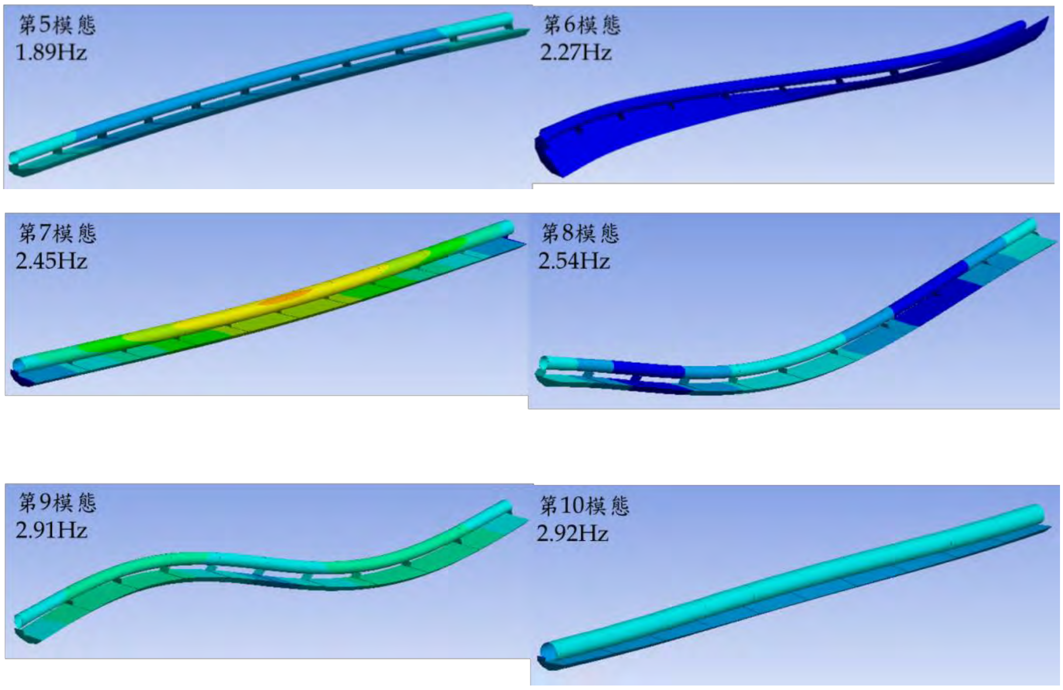


Fig.3 Related frequency of 10 modes frequency of TWC project

三、Introduction of TWC water main project

The TWC project locates on Sanyi Township, Miaoli County. Where φ 1000mm water main is 1416 meters long within shield tunnel, and connected with φ 1000mm pipe lines at both ends to supply water for neighbourhood area. The project location is shown of Fig.5

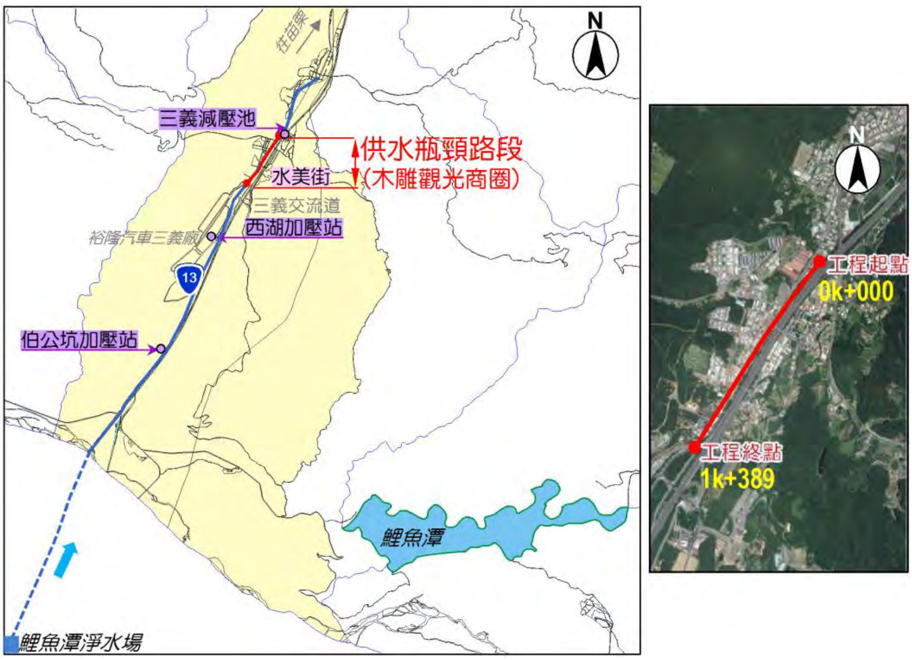


Fig.5 Location of TWC project

3.1 Location

The TWC project is located under No.13 provincial road within a tourist spots, as shown of Fig.6.

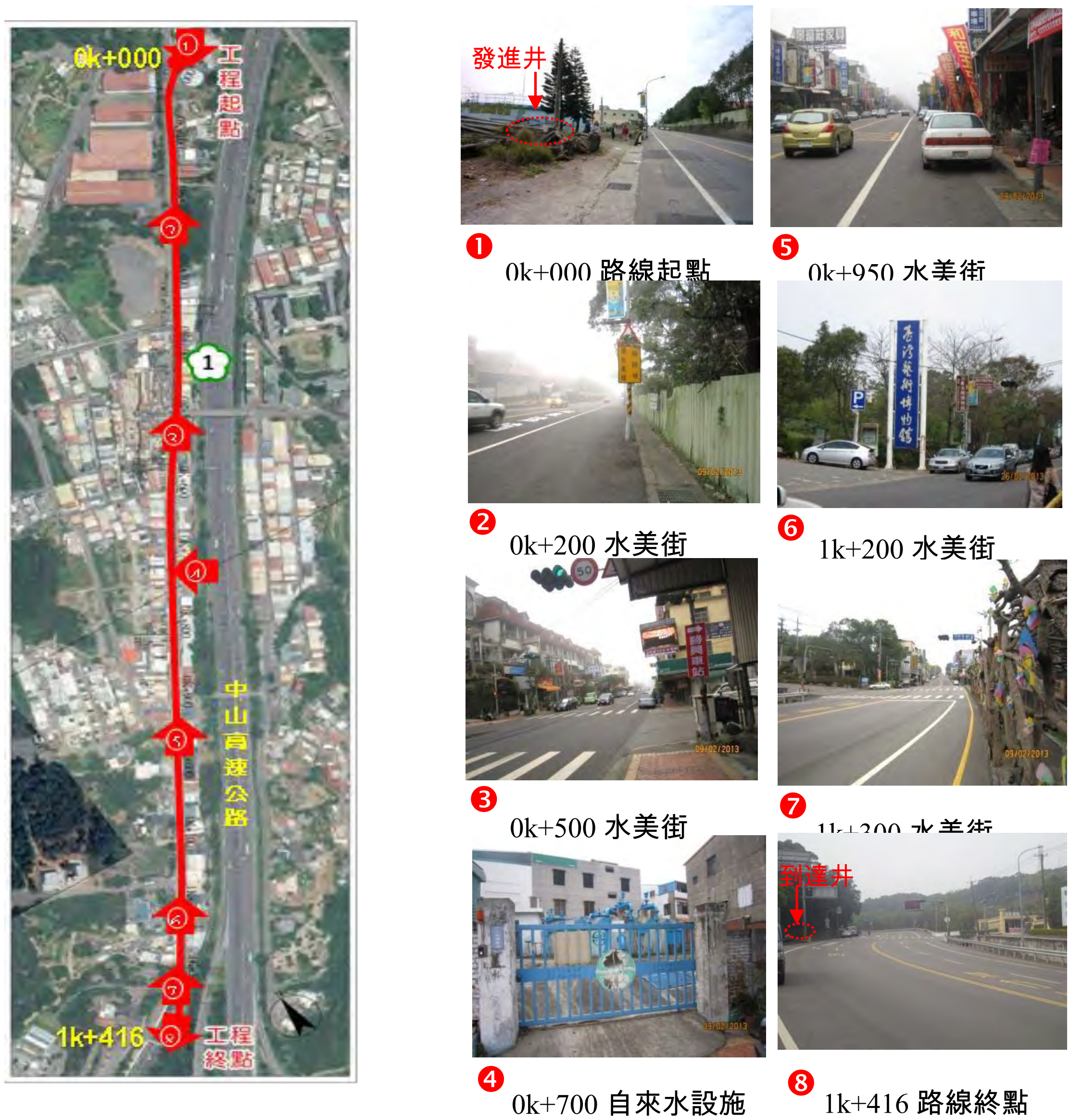


Fig.6 Photos of TWC project

3.2 Topography, Geology and Groundwater

3.2.1 Topography and Geology

The site elevation is 310~365 meters at hill area with gravel formation, where gravel diameter is 0.2~1.0 meters.

The geological structures at site neighborhood are syncline and San-Yi active fault. Where San-Yi active fault locates 170~230 meters from site with apparent influence of TWC project. The site geological map is shown as Fig.7

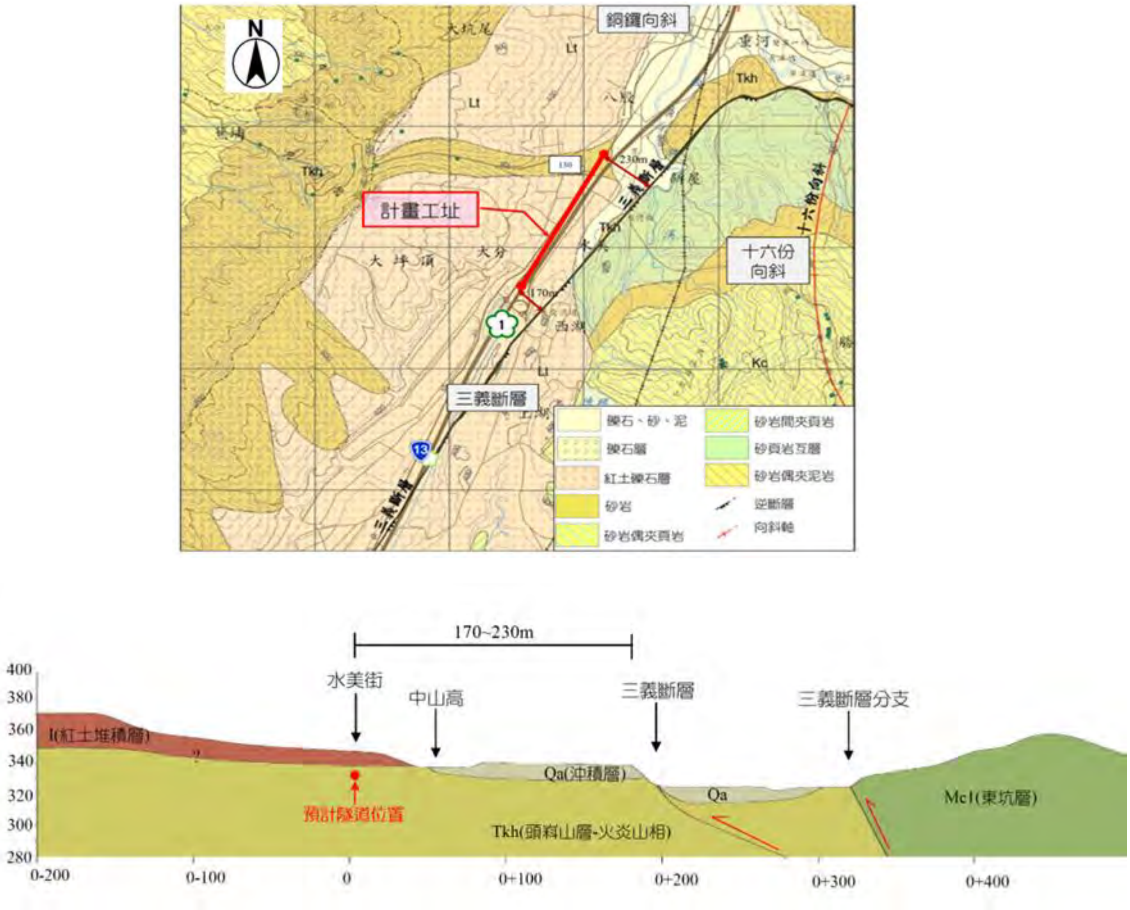


Fig.7 Geological map and profile of TWC project

3.2.2 Groundwater

Most of the project alignment is above groundwater level after boring observation as shown of Fig.8. Groundwater level near launching shaft is about -5.7~-12.6 meters, and about -40.0m of arrival shaft.

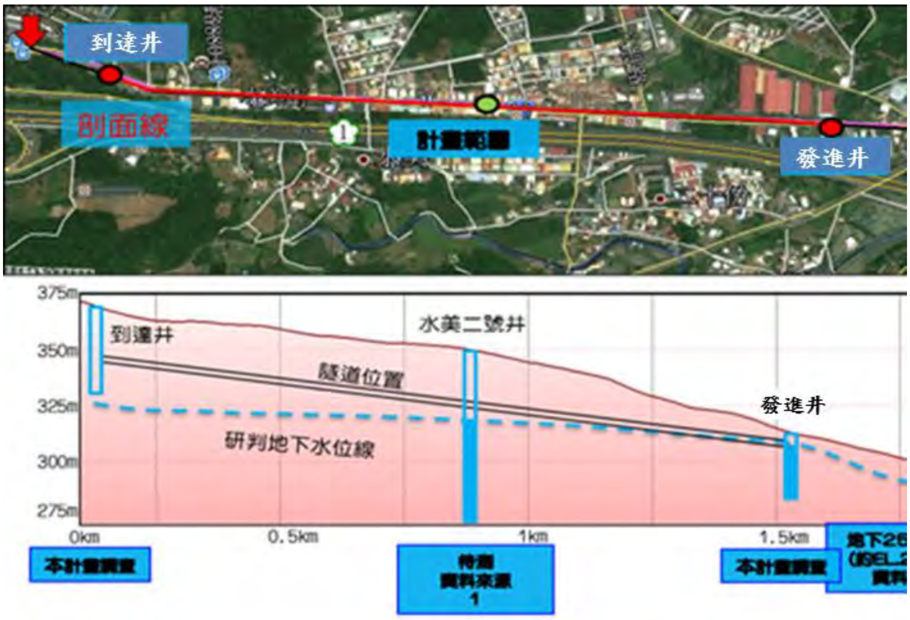


Fig.8 Groundwater condition

3.2.3 Engineer Geology

The site formation include overlay, sandy silt and gravel. The gravel uniaxial compression strength is between 735~1475 kgf/cm2. The simplified stratum parameters is shown as Table 1.

Table 1 Simplified stratum parameters

layer	Stratum	Depth (m)	SPT-N value	γ_t (t/m^3)	c (t/m^2)	ϕ (deg.)
1	Overlay	1.2	-	1.80	0	29
2	Sandy silt	3.2	9	1.91	0	31
3	Gravel	40	50	2.10	0	35

3.3 Shield Tunnel Design

3.3.1 Tunnel alignment

The TWC project should consider shield tunnel construction and pipe installation. Especially the tunnel overburden depth, alignment slope and smallest drainage slope in tunnel.

3.3.2 Tunnel profile

1. The φ 1000mm water main must consider maintenance walkway and pipe reinstallation space.
2. The ventilation of restricted space must be considered for maintenance safety.
3. The tunnel inner diameter is 3200mm, and segment thickness is 200mm. Where the profile is shown as Fig.9

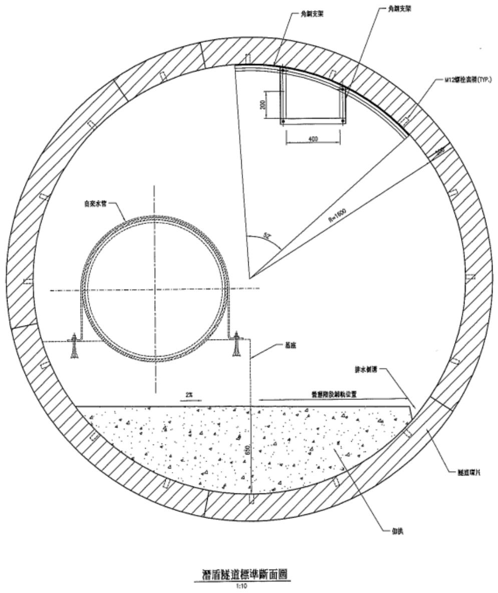


Fig.9 Tunnel profile

3.3.3 Segment Design

The tunnel segments are composed of three type A, one type B2, one type B1 and one type K (longitudinal installation) parts. The segment width is 1.0m, and thickness is 200mm.

3.4 Launching and Arriving shaft

1. The shaft diameter is 8 to 10 meters for shield construction and pipe installation needs.
2. Launching shaft caisson depth is 12 meters with press-in assistant method. The layout is shown as Fig.10 and Fig.11.

Fig.10 Location of Launching shaft

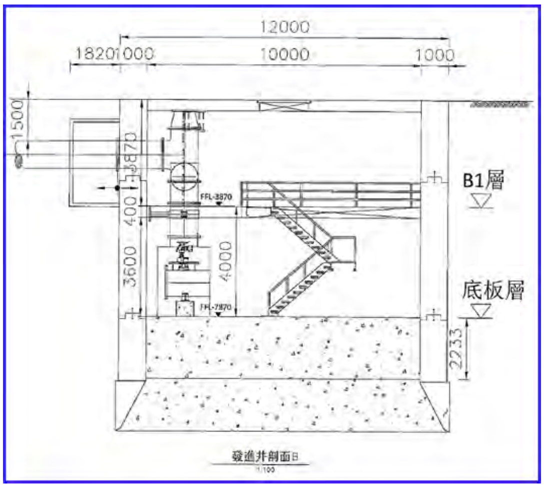


Fig.11 A-A profile of launching shaft

3. Arrival shaft depth is 29 meters, which is constructed by Liner plate method. The layout is shown as Fig.12 and Fig.13.

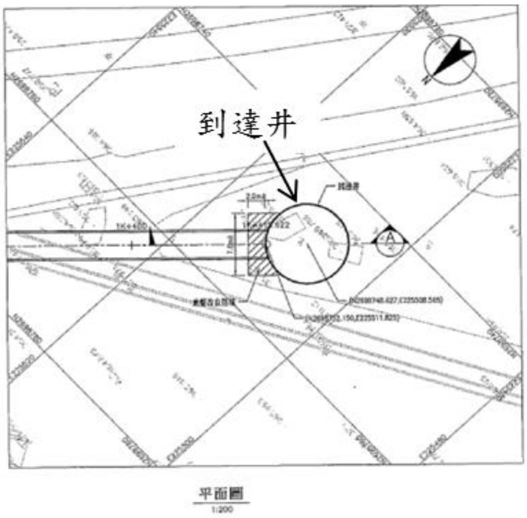


Fig.12 Location of Arrival shaft

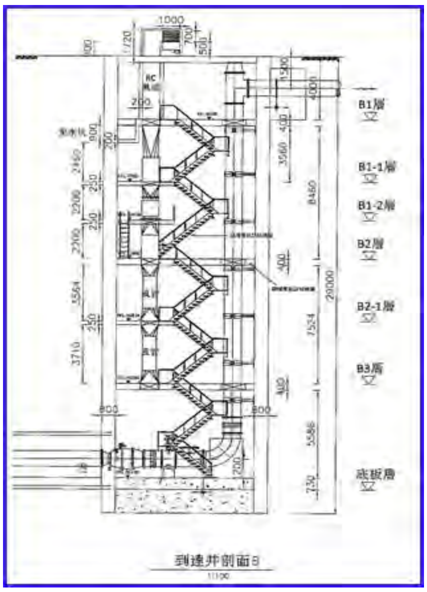
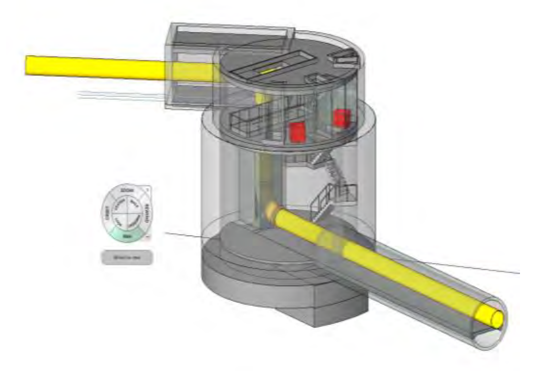
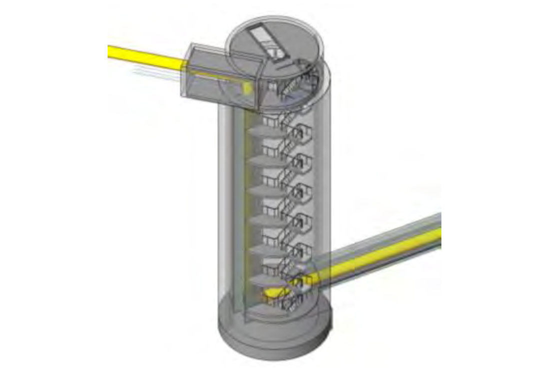


Fig.13 A-A profile of Arrival shaft

3.6 BIM Appalication

Building Information Modeling (BIM) is used to confirm the maintenance space of tunnel and shafts, which can be as reference of construction and maintenance period for life cycle.

	
BIM model of Launching shaft	BIM model of Arrival shaft

3.7 Construction of Gravel Formation

The main tasks of shield progress in gravel formation includes gravel hardness (highest qu is 2000kgf/cm2), cutter wear from matrix blocking, low progress rate, shield shale deformation induced by gravel compression…etc. Consider the TWC project alignment is above groundwater level, semi-mechanical open type shield is adopted for benefits of cutter wear, progress rate and more economic.

四、conclusion

1. The water main design of crossing fault condition should consider both earthquake wave and fault moving tasks.
2. Composite analysis of both soil and pipeline is suggested to avoid soil and structure interaction (SSI).
3. Shield tunnel with maintenance walkway space should consider ventilation for safety.
4. BIM is available for design, construction and maintenance.

Seismic Enhancement Framework and Screening of Critical Water Mains – A Proposal

Gee-Yu Liu[1]

ABSTRACT

Water supply systems may lose serviceability after disastrous earthquakes. One of the major causes is the damage in water mains due to severe seismic hazards including ground shaking, fault rupture, liquefaction, slope failure, etc. As a result, the systems may fail in raw water conveyance and treated water transmission. In this study, a framework is proposed to accommodate the procedure for performing seismic upgrading of water mains as well as the essential information, data and factors. In this procedure, there are two stages of seismic screening. The preliminary screening is to identify the exposure of water mains to high seismic hazards. The secondary screening is to narrow down the exposure to limited ones being most critical and vulnerable. The result can be employed to develop a seismic mitigation program of water pipelines which may be more effective and finically feasible. The seismic hazards and inventory of water mains in Taiwan are overviewed. A pilot project using slip-out resistant ductile iron water pipes in a liquefaction susceptible site in New Taipei City is introduced.

Keywords: water pipes, seismic enhancement, seismic screening

INTRODUCTION

Taiwan is located on the circum-Pacific seismic belt. It is one of the most earthquake-prone countries in the world. In the 1999 Chi-Chi earthquake, the largest event in recent decades in Taiwan, a widespread damage in water supply systems was observed (Chen and Wang, 2003). According to Taiwan Water Corporation's report, as many as 3,826 damages in utility-owned pipeline were recorded, among which 351 occurred in pipes with diameters between 300 and 2,600mm (TWC, 2000). The most significant single damage occurred near the Feng-Yuan First Water Filtration Plant, as depicted in Figure 1. It is a ϕ2,000mm steel pipe served solely as a common outlet of Feng-Yuan First and Second Water Filtration Plants, which provide 70% of water demand from 740 thousand customers in the Taichung metropolitan area before event. It was bent 90 degree and buckled by the offset of Chelungpu fault rupture. It is now kept at the Water Park in Taipei for permanent exhibition.

As upgrading of water pipes against earthquake hazards is an urgent need in Taiwan, a procedure for performing seismic upgrading of water mains is conceptually proposed in this study. The process of seismic screening of water mains is discussed. The seismic hazards and inventory of water mains in Taiwan are overviewed.

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Figure 1 A ϕ2,000mm steel pipe bent and damaged at Chelungpu fault crossing near the Feng-Yuan First Water Filtration Plant in Chi-Chi earthquake (courtesy Taiwan Water Corp.)

SEISMIC UPGRADING OF WATER MAINS THROUGH SCREENING

The water supply systems may be damaged when a major earthquake occurs. Buried water pipes may be damaged due to various factors. According to "Seismic Fragility Formulations for Water Systems" (ASCE, 2001), these factors consist of ground shaking, landslides, liquefaction, settlement, and fault crossings. In addition, pipe properties also contribute to the fragility. For example, each of continuous pipeline, segmented pipeline, appurtenances and branches, and age and corrosion of pipes has its own characteristics of fragility.

A solution that can help enhance the seismic safety of water pipeline infrastructures should be both effective and finically feasible. It can be achieved by seismic screening, as it can narrow down all water mains into a manageable scope of pipes being most critical and vulnerable. A framework is proposed to accommodate the procedure for performing seismic upgrading of water mains as well as the essential information, data and factors, as depicted in Figure 2. The procedure consists of four steps: (1) preliminary screening, (2) secondary screening, (3) prioritization, and (4) implementation of seismic enhancement.

There are two stages of seismic screening. The preliminary screening requires both the knowledge of known seismic hazards and the database of water pipes. The former, termed as seismic hazard maps, includes the information of active fault traces, liquefiable areas, unstable slopes, and so forth. The later, termed as inventory of pipes, includes basic properties and service capacity of the pipes. They can be over layered to identify the exposure of water mains to high seismic hazards.

The secondary screening required further knowledge of the known seismic hazards and detailed data of water pipes. The former, termed as seismic hazard models, includes methods and information for quantifying the seismic hazards. The later, termed as the pipe vulnerability models, takes into account pipe properties that affect a pipe's seismic vulnerability. They can be compiled to achieve a group of water mains which need being enhanced most.

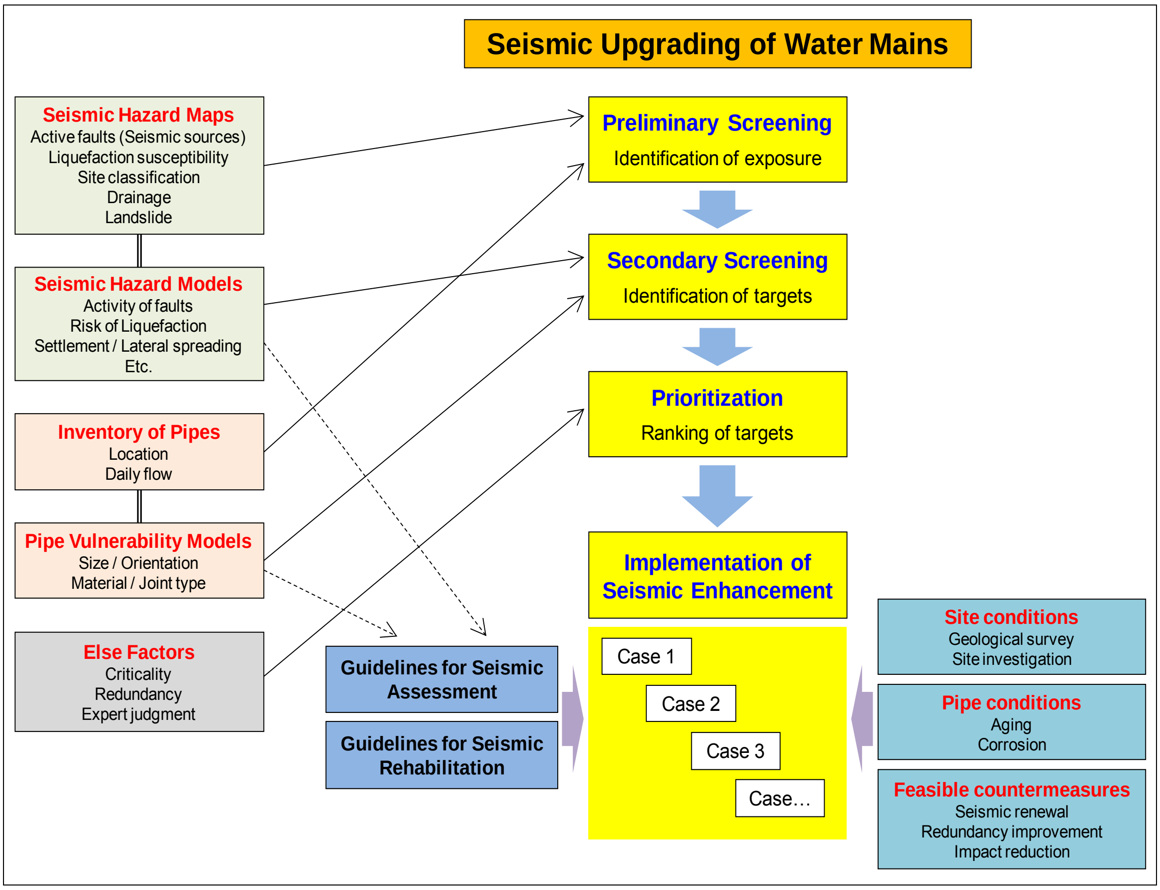
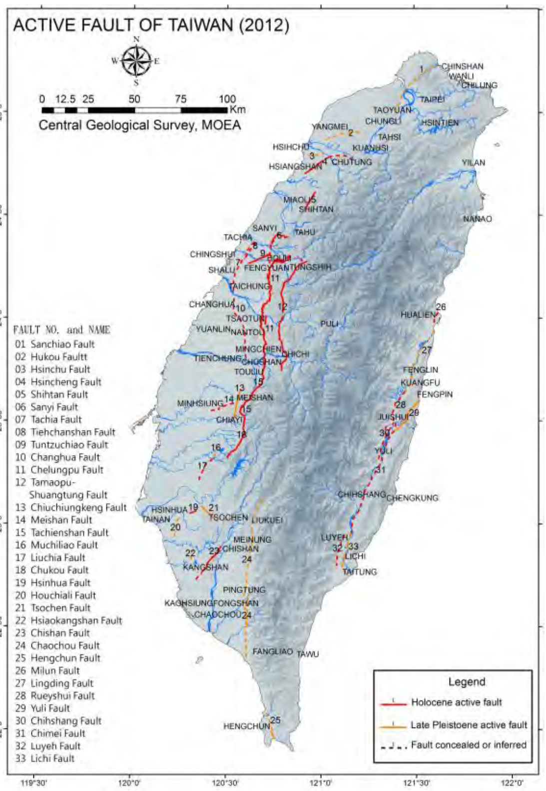


Figure 2 The proposed framework for performing seismic upgrading of water mains and the required models and data of hazards and pipe inventory

SEISMIC HAZARDS IN TAIWAN AND THEIR EFFECTS ON BURIED WATER PIPES

The tectonic setting and interaction of the Eurasian and Philippine Sea Plates are the major triggering mechanism of seismic activities in vicinity of Taiwan. Recently, Central Geological Survey (CGS), MOEA released an active fault map of Taiwan, as depicted in the left of Figure 3. There are 33 active faults on the island, 20 of which belonging to the Category I and the rest Category II. The former refers to faults that activate within past 10,000 years and are considered more active, while the later activate within past 100,000 years and less active (CGS website). Currently, only the active faults of Category I are considered in “Taiwan Building Seismic Design Code (2011)” to account for the effects of fault crossing and near-fault ground shaking. Based on CGS research reports, Wen et al. have summarized some of the properties of major active faults, listed in Table 1, for engineering applications (2005). There exist other active fault maps of Taiwan based on various studies. The right of Figure 3 depicts the map by Institute of Applied Geology, NCU, Taiwan, which lists a total of 50 active faults.

According to “Seismic Fragility Formulations for Water Systems” (ASCE, 2001), fault offset movement will heavily damage segmented pipes. Continuous butt-welded steel pipes are less prone to damage if they are oriented such that tensile strains result. Pipelines in compression may buckle as a beam or it may deform by local warping and wrinkling of its wall.



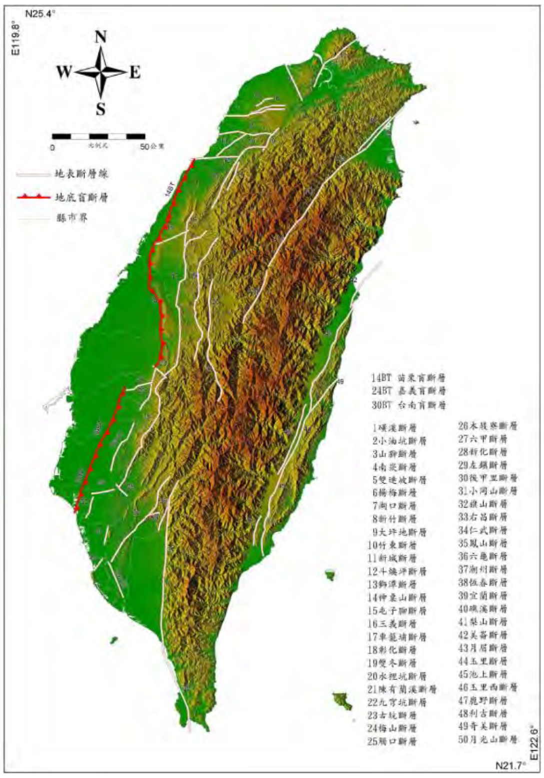


Figure 3 Maps of active faults in Taiwan by Central Geological Survey, MOEA (left, Ver. 2012) and Institute of Applied Geology, NCU, Taiwan (right, courtesy Prof. Lee, Chyi-Tyi)

Table 1 Properties of major active faults in Taiwan (Wen et al., 2005)

Name	Length (km)	Type	Max. Offset (m)		Return Period (yr.)	Upper Bound of Magnitude (M_L)	Last Event (yr.)
			Hor.	Ver.			
Shintan	12	reverse	-	3	-	6.8	1935
Shenchoshan	5	reverse	-	0.6	-	6.8	1935
Tuntzuchiao	14	reverse	1.5	-	-	6.8	1935
Meishan	13	oblique reverse	2.4	1.8	114	7.1	1906
Hsinhua	6~12	oblique reverse	2	0.76	210	6.1	1946
Milun	7~25	oblique reverse	2	1.2	600~700	7.0	1951
Chimei	18	reverse	-	1~2	-	7.3	1951
Yuli	43	oblique reverse	-	1.63	< 250	7.3	1951
Chihshang	47	oblique reverse	-	< 0.5	-	7.3	1951
Hsincheng	15~28	reverse	-	1.3~1.85	2000	> 7.0	-
Chelungpu	-	reverse	-	-	400~1000	7.3	1999
Tachienshan	25	reverse	3.94	-	-	-	-
Chukou	40	reverse	-	-	-	-	-

The factors affecting soil liquefaction occurrence include the seismic intensity and duration of ground motions, and the ground water depth. Usually, the peak ground acceleration (PGA) is used for the seismic intensity, while the earthquake magnitude is employed to stand for the duration of ground motions. Following the methodology of HAZUS (RMS, 1997), the soil liquefaction susceptibility is classified into six categories, that is, “very high”, “high”, “moderate”, “low”, “very low” and “none”. Yeh et al. (2002) has analyzed more than 11,000 sets of borehole data in Taiwan, and then proposed a classification scheme to identify the liquefaction susceptibility category of each borehole. Based on the specified liquefaction susceptibility of each borehole as well as geological maps, the liquefaction susceptibility map of Taiwan has been developed. As an example, Figure 4 shows the boreholes and soil liquefaction susceptibility map in Taipei city.

Liquefaction may result in local ground settlement as well as lateral spreading. According to “Seismic Fragility Formulations for Water Systems” (ASCE, 2001), pipe breaks occur due to vertical settlement at transition zones, and in areas of young alluvial soils prone to localized liquefaction. Heavy concentrations of pipe breaks will occur in areas of lateral spreading.

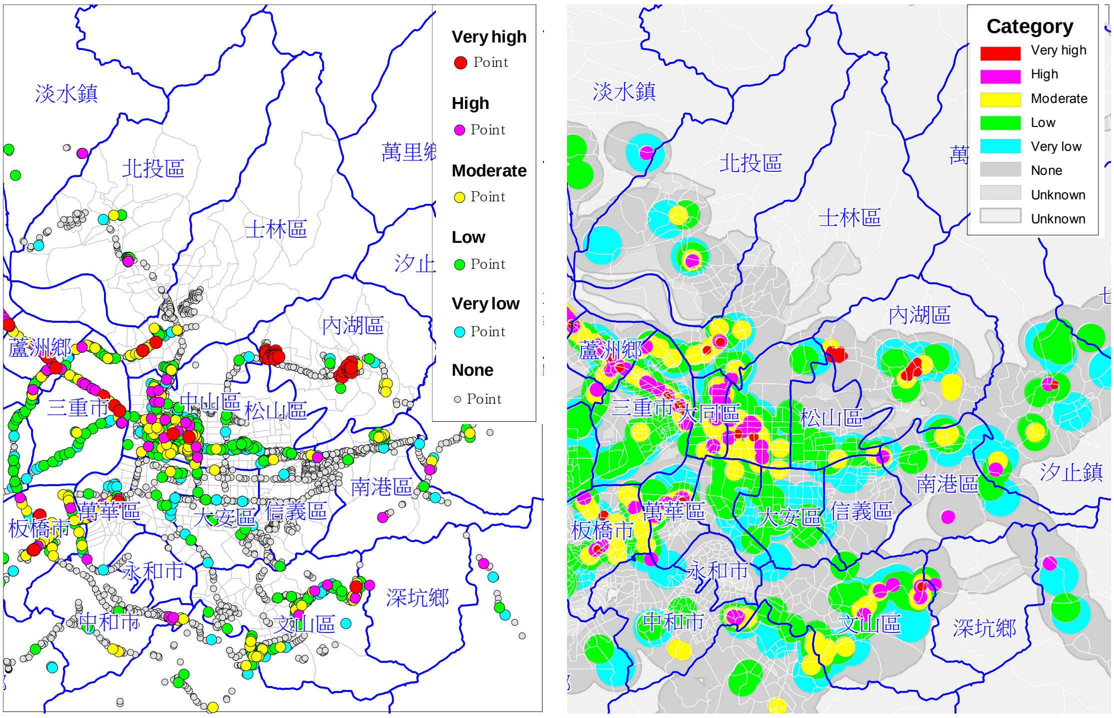


Figure 4 Maps of boreholes and their liquefaction susceptibility category (left) and soil liquefaction susceptibility (right) of Taipei city (Yeh et al., 2002)

INVENTORY OF WATER MAINS IN TAIWAN AND THEIR VULNERABILITY

Figure 5 depicts two percentage charts of pipe materials of Taiwan Water Corporation’s water mains (WRA, 2014). The left one is for pipes with diameters between 800 and 1,500mm, and the right one is for pipes greater than 1,500mm. It indicates that, for very large water mains (greater than 1,500mm), the majority are PCCPs (pre-stressed concrete cylinder pipes, 30%), PSCPs (pre-stressed concrete pipes, 23%) or SPs (welded steel pipes, 23%). While for smaller water mains (between 800 and 1,500mm), the majority are DIP_Ks (ductile cast iron pipes of K-type joint, 30%), PSCPs (28%) or DIP_As (ductile cast iron pipes of A-type joint, 19%). All of these, except SPs, are segmented pipelines.

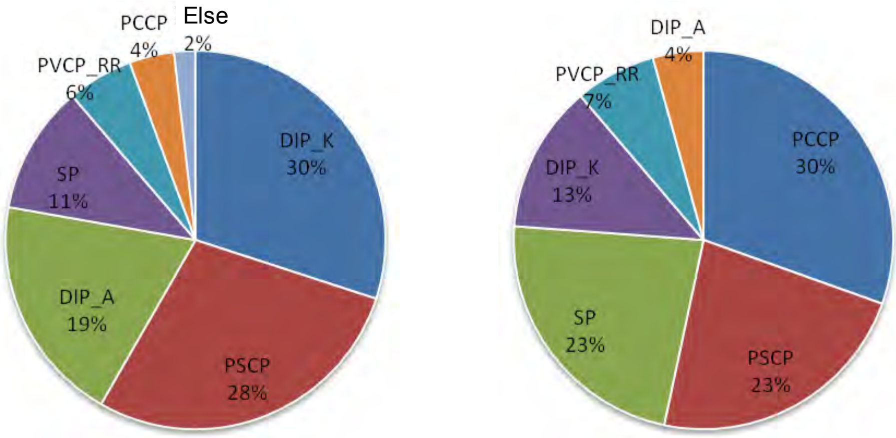


Figure 5 Percentages of pipe materials of TWC's water mains with diameters between 800 and 1,500mm (left), and above 1,500mm (right) based on preliminary statistics (WRA, 2014)

PCCP and PSCP are, while being designed to take optimum advantage of the tensile strength of steel and corrosion inhibiting properties of concrete, considered a brittle pipe material and very vulnerable to ground deformations. DIP_A is an old version of ductile cast iron pipe. With insufficient length of socket, it is also very vulnerable to ground deformations, too. DIP_K, a modification from DIP_A, has a longer socket and improved rubber gasket. It is arguably of good seismic capacity against ground shaking, especially in area of stiff site condition.

Therefore, the majority of water mains do not have enough seismic capacity to withstand devastating seismic actions. There is an urgent need to carry out an earthquake hazard mitigation plan to water pipeline infrastructures in Taiwan to confront major earthquakes in the future.

PRIORTIZATION AND IMPLEMENTATION OF PIPE ENHANCEMENT

After the secondary screening, a group of most critical and vulnerable water mains can be marked. A prioritized scheme should be developed and applied to this group of water mains. In addition to the severity of seismic hazards and the seismic vulnerability of the pipes themselves, else factors should be included to decide the ranking of the pipes, as depicted in Figure 2. Factors affecting the ranking of a pipe may be: (1) its criticality to the serviceability of the entire water system, (2) the numbers of customers related, (3) the importance of the area served, (4) its redundancy, (5) emergency facilities (i.e. large hospitals, shelters) served, and finally (6) others by expert judgment.

As suggested in Figure 2, when it comes to action to enhance any of the leading pipes, the kind of hazard and pipe failure mode should be identified, and the actual sites conditions and pipe conditions should be investigated. Engineering or non-engineering solution (improved emergency response, for example) should be developed according to the situation. It is highly desired to have prescribed guidelines for pipe seismic assessment and rehabilitation. They may be derived from the seismic hazard models and pipe vulnerability models presented in Figure 2. They will guarantee that the implementation of pipe seismic enhancement will be conducted in a more practical and uniform way.

In 2014, Taipei Water Department (TWD) carried out a first ever project using slip-out resistant pipes in Taiwan (Wu, 2014). As depicted in Figure 6, the site locates in the Erchong Floodway Redevelopment Zone, Sanchong, New Taipei city. It is of alluvial soil, topographically flat and liquefaction susceptible. The employed ϕ150mm and ϕ200mm pipes, K-bar DIPs, add bar-like me
locally. Bef
Engineering
ISO 16134

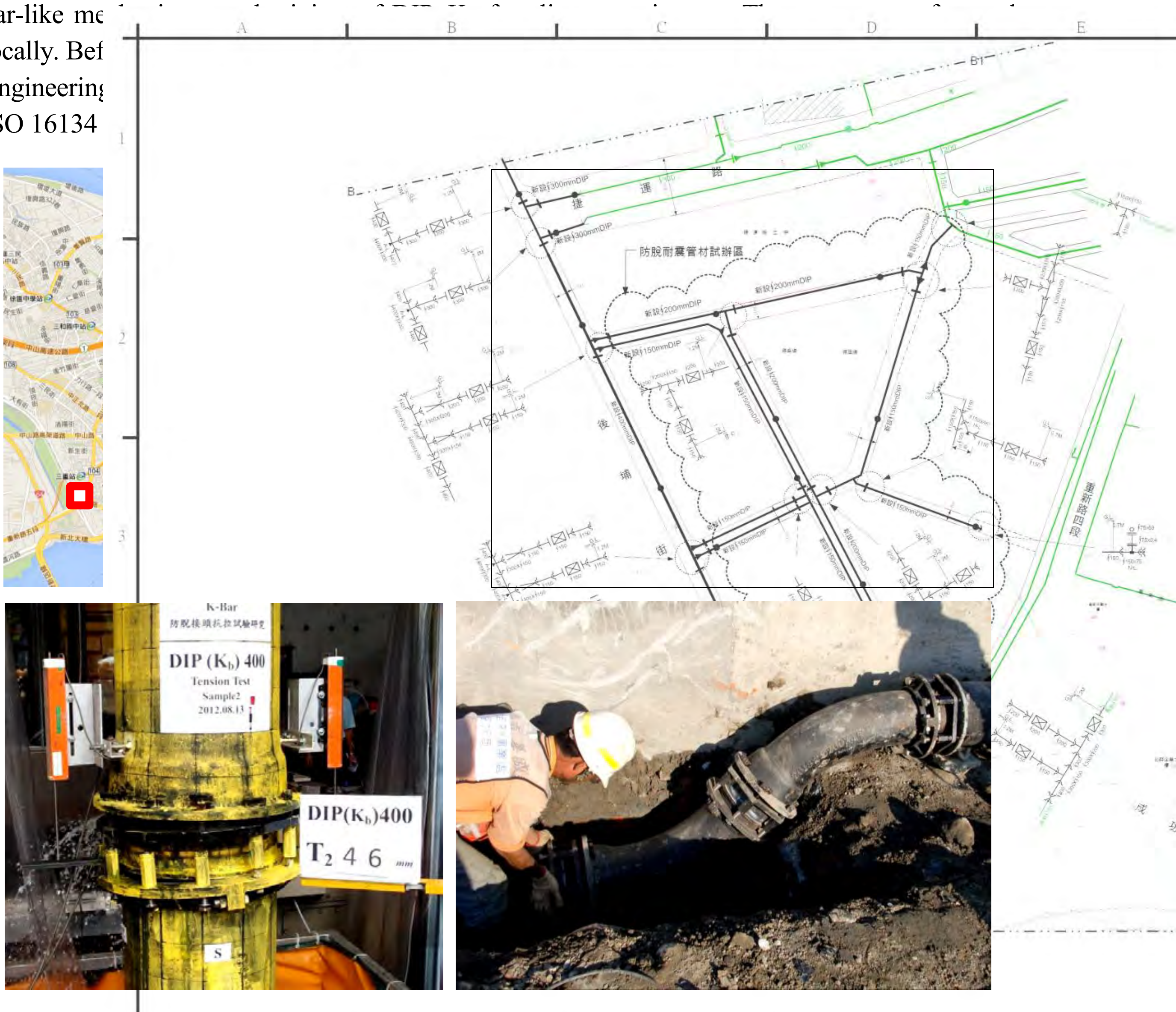


Figure 6 A pilot project using K-bar slip-out resistant ductile iron water pipes in Erchong Floodway Redevelopment Zone, Sanchong, New Taipei city (Wu 2014; courtesy TWD)

CONCLUDING REMARKS

In this study, a framework prescribing how to perform seismic upgrading of water mains has been proposed. There are four steps involved: (1) preliminary screening, (2) secondary screening, (3) prioritization, and (4) implementation of seismic enhancement. A two-stage seismic screening is adopted in the framework for achieving a group of water mains which need being enhanced most. The seismic hazards and inventory of water mains in Taiwan have been overviewed. It is shown that there is an urgent need to carry out earthquake hazard mitigation plans to water pipeline infrastructures to confront future big earthquakes. A TWD pilot project using slip-out resistant ductile iron water pipes in a liquefaction susceptible site is introduced. Hopefully, this pilot project could shed light on the development and employment of water pipes of better seismic performance in Taiwan in the future.

ACKNOWLEDGMENTS

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__Cover page__

Title: **Introduction to the Earthquake Resistance Capacity Assessment and Reinforcement of Taipei Water Department Office Building.**

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Introduction to the Earthquake Resistance Capacity Assessment and Reinforcement of Taipei Water Department Office Building

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ABSTRACT

Taiwan is located along the Circum-Pacific seismic zone where the earthquake happens frequently. The evaluation of seismic force has been adopted in the Building Code and Regulations since 1974. Along with the updated technical rules, the government authorities have gradually realized whether the old public facilities are able to meet the seismic capacity provided by the existing code. Therefore, the government regulated that, the seismic capacity of all the public buildings established before 1997 should be assessed. The case introduced Shui Yuan Market Building, established in 1980, which is a RC building with two underground floors and ten floors on the ground. Its exterior wall was designed by an Israeli artist, Yaacov Agam, using a variety of color into the first giant wall of public art in the world. Prior to a detailed assessment of seismic capacity in 2011, because of they did not meet the statutory standards by existing code, it is necessary to reinforce the building. But the proposed of reinforcement design at that time had seriously affecting the traditional market on 1st and 2nd floor and the circulation of other floors of office space. It had to postpone due to the residents' opposition. Therefore, we decide to change from the seismic reinforcement design of strengthening the internal structures of buildings to external structural reinforcement in this case so that it reduces the impact of the use of interior space. It will supplement by the internal reinforcement if the seismic strength is still not raised to the statutory standard. In summary, the requirements of the existing market and user should be considered into the program design of seismic capacity evaluation and retrofitting. In addition, the limitation of public artistic work modification will also affect the program design. Therefore, setting 4 steel structural frames per floor into the interior of 1st and 2nd floors and the constructed 25cm shear walls will be used in the four exterior corners from 1st to 3rd floors that has been proposed. The original seismic capacity is expected to be increased from 0.186G to 0.242G in x direction and 0.210G to 0.279G in y direction. The estimated amount of total expense is about 1 million US dollars and the project is under progress from 2014 to 2016.

Keywords: Earth Quake, Water Supply Facility, Seismic Resistance Capacity, Assessment

FOREWORDS

Taiwan is located along the Circum-Pacific Seismic Zone and occurrence of earthquake is very frequent. The requirements on considering of seismic force in the building design were begun only from 1974. With the frequent update of Building Code and Regulations, confirming existing buildings' seismic capacity in satisfying the present statutory required seismic capacity become an important works of the government in promoting earthquake disaster preventing services, especially after earthquake occur, public-owned buildings need to maintain normal functioning and be a shelter for victims.(eg. train stations, power plants, water utilities, schools, gym, medical facilities, police station, firework station and government institutions.) In view of this, as from 2000, government agencies in Taiwan started to promote "Seismic Resistance Capacity Reinforcement Programs for Building" and established that public buildings built before 1997 must be included in the scope of seismic resistance capacity assessment and reinforcement. According to statistics, total 26,399 public buildings in Taiwan shall be assessed and among them 25,536 building has completed preliminary. After the assessment, 7,397 needs be worked to reinforce and 1094 shall be demolished and rebuild. The portion needs be reinforced or demolished accounts for 33% of the number completed assessment.

The Shui Yuan building as presented in this case is located in Zhongzheng Dist., Taipei City. The Building was completed in 1980 and is therefore 35 years old. In 2010, the exterior wall was renovated by Mr. Yaacov Agam, an Israeli master in kinetic arts to be a giant compound drawing, a public art. The building has 2 levels underground and 10 levels above ground, an RC structure building. The basement is for parking and 1st and 2nd floor above ground are for conventional market and 3rd through 9th floors are offices for government agencies and the 10th floor is a theater. In 2009, Shui Yuan Building was determined as with doubt of insufficient capacity in seismic resistance in the preliminary assessment of seismic resistance capacity. In Exhaustive assessment of 2011, it is determined as failed the statutory standard and must undergo reinforcement work. At that time, the proposed reinforcement design program affects the space, circulation of conventional market at 1st and 2nd floors and the offices of other floors seriously and was objected by most of the tenants and the proposed reinforcement design program was unable to carry out. Therefore, the design program changed from reinforcing interior than reinforcing exterior, so as to reduce the impact on usable space inside, and when the seismic resistance capacity is still less than statutory standard, there will be internal reinforcement, so that the required capacity will be attained and the impact on the tenants will be minimized and the reinforcement work can be carrying on smoothly.

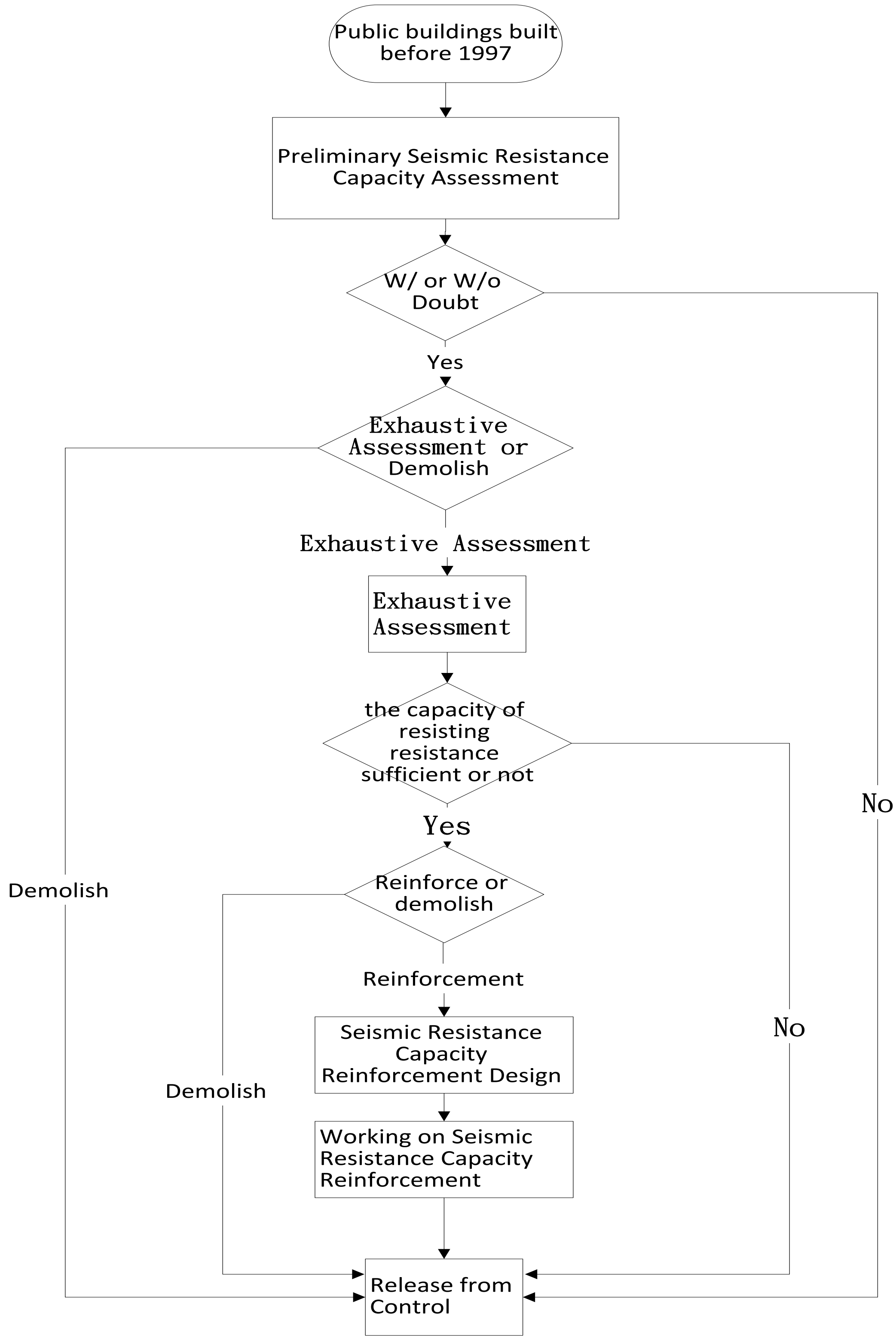
Public buildings built before 1997
Preliminary Seismic Resistance Capacity Assessment
W/ or W/o Doubt
Yes
No
Exhaustive Assessment or Demolish
Exhaustive Assessment
Demolish
Exhaustive Assessment
the capacity of resisting resistance sufficient or not
Yes
No
Reinforce or demolish
Reinforcement
Demolish
Seismic Resistance Capacity Reinforcement Design
Working on Seismic Resistance Capacity Reinforcement
Release from Control

Fig 1- Operation Flow of Building Seismic Resistance Capacity Assessment and Reinforcement for Buildings in Taiwan

Table 1- Overview of Seismic Resistance Assessment and Reinforcement for Public Buildings in Taiwan

Preliminary Assessment		Exhaustive Assessment		Reinforcement Work		Demolish	
No. under control	No. & Percent of completion	No. under control	No. & Percent of completion	No. under control	No. & Percent of completion	No. under control	No. & Percent of completion
26,339	25,536 (97.0%)	13,359	10,429 (78.1%)	7,397	3,344 (45.2%)	1,094	583 (53.3%)

Fig.2 Appearance of Shui Yuan Building

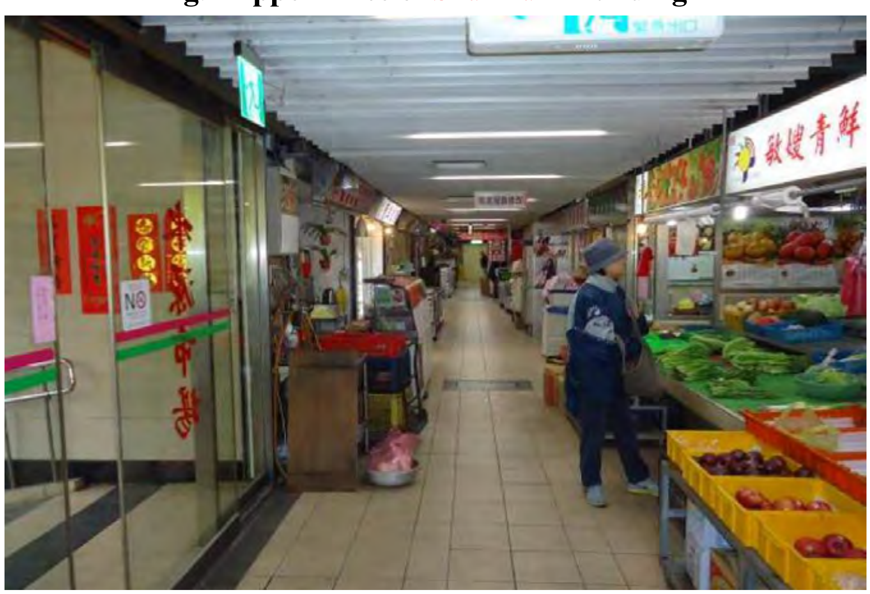

Fig. 3-Inside of Shui Yuan Building (Market)

BRIEF OF THE CASE

1. Basic information of Shui Yuan Building

The structure is a ten floors RC building with two underground floors. The plot plan of structure is rectangular, approximately 55.2m in length and 45.5m in width.

Underground area of the building is used as emergency bunker and parking space, 1st to 2nd floor as Market area, 3rd to 9th floor as office space, and 10th floor is used as theater. The description of the building is as follows:

Table 2- Basic information of Shui Yuan Building

Building name	Shui Yuan **Building**
Number of floors	Ten floors on the ground and two underground floors
The total height of the floor	33m
Year built	Established in 1977, completed in 1980
Area	26723.04m^2
Structural materials and systems	Reinforced concrete / Mat Foundation
Layout and shape	It is a beam-column rectangular system and the four corners of stairs are made of shear wall.
Status of investigation	(1) Its exterior wall was designed by Yaacov Agam in 2010, creating a 4-d art wall. (2) Internal rate of usage achieve to 100%. (3) All of floors are used as public agencies office space except 1st and 2nd floor.
Status purpose	Underground area is used as emergency bunker and parking space, 1st to 2nd floor is used as Market area, 3rd to 9th floor are all office space, and 10th floor is used as Theatre.

2. Reinforced Project Evaluation and Options

The primary purpose of Reinforce Method options is to be able to make the seismic capacity of buildings to meet the existing code, and then take into consideration the status of use, lighting, ventilation and circulation.

Table 3- The main topics anf solutions of Shui Yuan Building

No	Topics	Solutions
1	Discussion the reason of original structure with lack seismic capacity. (1) Concrete with insufficient comprehensive strength (2) No toughness design requirements in early days.	The building that is lack of seismic capacity can be considered reinforcing budget, economic efficiency and the usage status of subject matter, therefore using the reinforcing method such as exterior Adding shear wall and the internal steel bracing system.
2	To consider the Reinforce Method by the tenants side	The factors to be considered when making decision of seismic method of reinforcement is as follows: (1) Whether the position of reinforcement would affect the feature of usage status, lighting and reduce the hinder of moving line to a minimum. (2) Whether the position of reinforcement would affect the escape routes (3) Due to the migration issues of Hydropower pipeline by reinforcing positions, resulting in the extension of duration
3	During construction of reinforcement may affect the market operations and the use of office functions	Construction scheme of the staging and partition can be taken, such as the regional construction. Reducing the impact of the period of use, it may also adopted the staging and partition construction during reinforcement
4	It should be match with the environment after reinforcing	The position of reinforcement in the future should take into consideration the original form of structure. To avoid the material of reinforcement interference with the original one, using the similar material to the original decoration.
5	Cost-saving design program	According to the subject matter that need to improve earthquake-resistant capacities, in compliance with existing code under the seismic capacity of reinforcement, it is the first priority in order not to waste the funds. (1) Select the method to minimize recovery problem after the demolition of Hydropower pipeline. (2) Select the method to minimize the original decoration materials of knockouts and recovery in order to reduce expenditure

3. Reinforcement Program

(1).After consideration the status, the principles of structural reinforcement position are as follow：

A.Set of symmetric reinforcement component in order to conform to rules of structural system.

B. It would reduce the impact of interior usage by considering the interior line.

C. Steel metal frame set-up needs to consider the impact or damage to the surrounding structural environment. Spacing between metal frame and surrounding structures need to be at least 15cm apart, and adding shear studs on the iron frame. With rebar-planting around the existing RC beams and columns, dispose spiral stirrups that touch the surrounding beams and columns closely in the middle in case that the deformation of the steel frame may cause damage directly to the surrounding structure.

(2). Recommended reinforcing method：

Shear wall and steel frame bracing(Shear wall for surrounding and steel frame inside of building)

The way of reinforcement：

Adding shear wall： four places of each floor from 1st to 3nd floor in x and y direction

Steel frame bracing： two places of each floor from 1st to 3nd floor in x and y direction

The material of reinforcement：

Concrete fc'=280kgf/cm2

Reinforce fy=2800 kgf/cm2（#5 or less）、4200 kgf/cm2（#6 above）

Steel CNS SN400B，Fy=2400 kgf/cm2

The plans of reinforcing components are as follows：

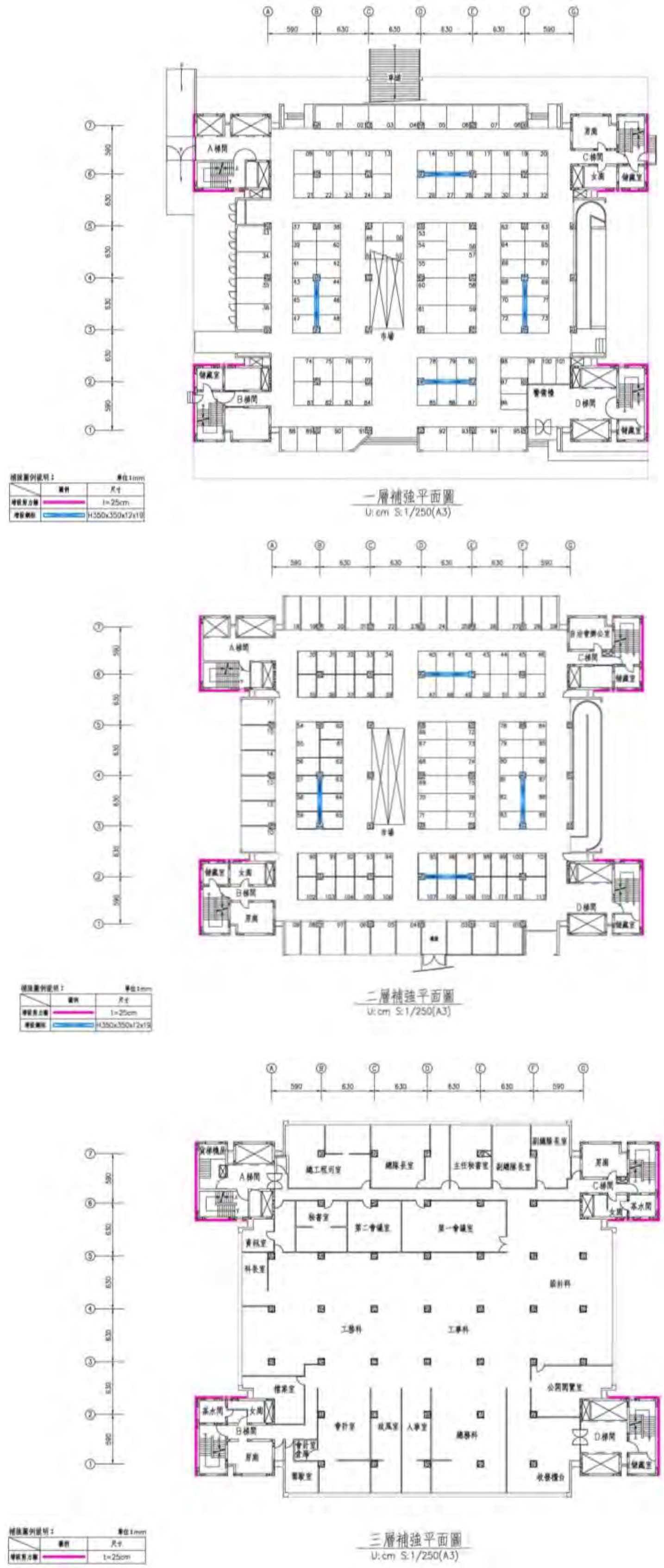

Fig. 4-The plans of reinforcing components

4. Promoting Process

While this program is mainly of external reinforcement and assisted with internal reinforcement, but in the process of promotion, there are still many difficulties need to be overcome. For example the Art Work of Yaacov Agam, the Israel kinetic art master. The work used a variety of color and combined with aluminum and plastic compound board. It is an artistic highly valued by Taipei City Government and place under control. Basis considerations of seismic resistance and disaster prevention and respect the art works of Yaacov Agam, we have explained the importance of seismic resistance and reinforcement, and simulating drawings to show the minimal change of the overall visual scene to his work and we assured him that the work will be reinstated in original color and original form. We have received his consent on Oct. 31, 2014. In the part of internal reinforcement, since it will affect the vendors business, many presentations had been held (Jan. 26, 2015, Mar. 16, 2015 and June 15, 2015) and presented them with the purpose and design concept of the reinforcement work as well as clarify their doubt and understand their needs. The approaches taken are: 1. Providing temporary business premises for the vendors affected by the work; 2. Interior steel structure frame will be worked in phases and maximum 2 frames are allowed to work at the same time, so as to avoid affecting vendors due to working in large scale; 3. Suspend the work during the boom time of business, such as Chinese New Year period, total 1.5 months before and after, to minimize the impact of the reinforcement work on vendors. With such effort in communication and in coordination, the reinforcement work has design completed on May 27, 2015 and works has been contacted out on Aug. 7 and Commencement is expected in October and completion is scheduled in June 2016.

CONCLUSION AND SUGGESTION

In order to ensure that the public building will maintain its function after earthquake, Taiwan has implemented “Seismic Resistance Capacity Assessment and Reinforcement Program for Buildings” in 2008 and all public buildings built before 1997 shall be included in the assessment and reinforcement. Shui Yuan Building of TWD Engineering Division is one of them. Since the floors in the building has different use of space (including market, office, theater) and are controlled by different agencies, and there are many interfaces. So the key points of this case are to integrate needs of all the tenants, adopting the reinforcement program with minimum impact so that the work may be performed smoothly and successfully.

In the selection of reinforcement manner, in addition to consider the statutory standards of seismic resistance capacity needs be reached, the tenant’s needs shall also be satisfied. In this case, the usual internal reinforcement approached is not based but change to external structure reinforcement basis earthquake destruction simulation results. If the new approach cannot reach the target, the internal reinforcement will be performed to assist. So as to reduce the needs of installing shear wall inside building, or steel frame of expanding column, and all of them will have impact on internal space and movement line, and this has won support from the market vendors and tenants.

Due to scarcity in land for public work, the public buildings are mostly designed for multipurpose and / or for joint use of multiple agencies. In this case, the External Reinforcement based and Internal Reinforcement as support mode for building reinforcement to provide for reference in reinforcement in seismic resistance, so that the target of promoting seismic resistance capacity will be attained and the inconvenience to the tenants will be minimized.

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The earthquake damage and reinforced method of combined water tank

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ABSTRACT

Because Taiwan is located in between the Eurasian Plate and the Philippine Sea Plate, there are 33 fault zones existing in the island of Taiwan. The high frequency of earthquake activity, such as the famous 921 Jiji Earthquake, has been causing different extent of damages of running water tanks. This makes the concern of insufficient earthquake resistance ability more outstanding.

Because the design code in early years didn't attach the importance of earthquake resistance ability. That caused the inexact contents of code or requirements of the detail of construction which was more inexact than nowadays. The running water facilities designed in early years was damaged during the serious earthquake. Especially the structure of combined water tanks is easier to occur such as the sort of structure damage such like cracking, even dislocation, of the bottom board or the wall of water tank. That would really affect the steady water supplying.

The research principally analyses the damage of combined water tank caused by earthquake, and try to propose a method to reinforce the earthquake resistance ability. Then, according to the "The Guide of Seismic Design of Water-Supplying Facility", we try to estimate the earthquake resistance ability after reinforced whether to be enough. Eventually, make sure the steady water-supplying ability after earthquake.

1. Introduction

Combined pools are common in T.W.C. earlier reservoirs, and the key feature is to combine several individual pools with expansion joints. Although each pool has the independent structure system and is able to bear the dead load of stored water, this design has not considered the frequency of earthquake in Taiwan, which probably leads to the distortion between each subarea and the damage of expansion joints (as shown in Fig. 1). The research will investigate the damage to combined pools, then propose the method of repairing storage function and reinforcing the earthquake resistance ability

Figure 1 The roof of water tank – the failure of extension joint by expansion

2. Analysis of the damage of combined pools

At present, the reservoir is located nearby the forth public cemetery and Providence University in Shalu Dist., Taichung City. It is away from the Tuntzuchio fault approximately 2.623 KM, which was constructed in 1990 (The project of water distribution center in the specific district of Taichung Harbor). The overall sizes are 108M of length, 64M of width, 6.4M of height, about 0.8M of foundation depth, and the storage capacity is about 40,000 tons. The structure got slightly deformation and leakage, showing as figure 2.

Figure 2 the nearby of water tank

The water tank is reinforced concrete structure. There are several part divided by extension joint, showing as figure 1. Each part of tank is an independent structure, bearing self-weight and external forces by itself. And then all independent water tank combined to one complete large water tank, connecting by extensive for preventing leakage.

2.1 impairment of storing function

The common usage impairment is the crack of walls and plate that is caused by interactional collision, or tear impairment of extension joint caused by large displacement, showing by figure 3, figure 4 and figure 5. Moreover the combined water tank was built in early years. And the early building code which is lenient on the capacity of earthquake resistance, the joints of beam and column usually got cracking after the earthquake, showing by figure 6.

Figure 3 The crack caused by interactional bump of base plate of water tank

Figure 4 The expansion of the extension joint

Figure 5 the crack of wall

Figure 6 the crack of the joint of beam and column

2.2 Lack of capability of earthquake resistance of whole water tank

The water tank was built in 1990, the water tank combined by 16 rectangular water tank and 4 irregular water tank. Each water tank was connected by extension joint. There is a similar water tank which is located at Taichung. The water tank had got extremely severe damaged by the over expansion of extension joints in earthquake duration. It caused the fundamental losing and storage function losing, showing by figure 7. Therefore this tank we discuss here didn't apply connection of improving earthquake capability. It may also face the same situation which the large expansion displacement causes the storage capability losing after a massive earthquake.

Figure 7 The severe expansion of extension joint

3. The program of improve and repair

3.1 Repair of the storage function

Because of the combined feature of these combined water tank, every independent structure system of unit water tank will vibrate separately during the earthquake. The corner, side and internal part was damaged by strike of the interactional displacement. That causes the severe damage of extension joints.

The damaged extension joints can be dealt by removing the exterior of 60 cm, re-placing the waterproof material, re-smearing silicon that is elastic and waterproof, placing three layers of glass fabrics, smearing silicon again, placing the rubber mat, placing stainless steel plate and then fixing the stainless steel plates with expansion screws.

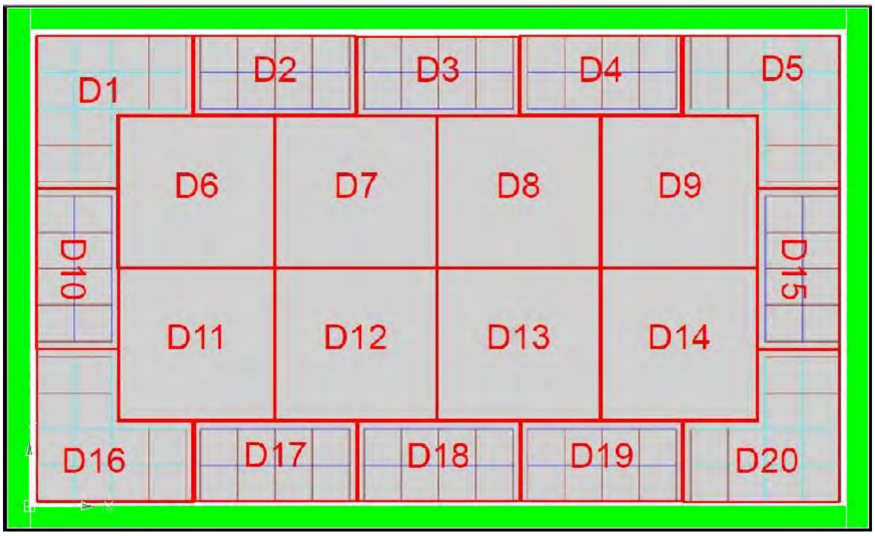
About the respect of corrosion of concrete reinforcing bars, after cleaning up the damaged part of concrete and corrosion of concrete reinforcing bars, the concrete cover repairing method is smear Anti rust ester and Epoxy resin interface, and then smear epoxy resin. But the repairing way can only prevent the corrosion going on, not recover the capability of earthquake resistance. If another earthquake strike, the damaged part will get more severe damaged, and the lower capability of earthquake resistance will cause more numbers and damaged degree of extension joints.

3.2 The improve method for earthquake resistance

Reinforcing program will forcing on the horizontal stiffness, avoiding the large interactional displacement of each separate water tank during massive earthquake. Using the proper internal or external space builds new wall to undertake the earthquake affect and reduce the interactional displacement between each separate unit water tank.

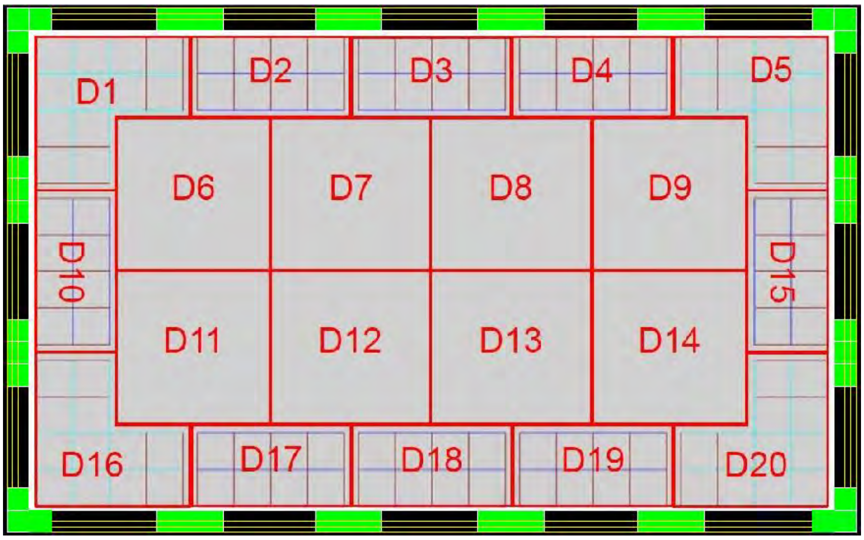
Program1:

Considering the water tank is still using, for maintaining the water supply, applying the external space to build new walls. The horizontal stiffness and confining effect are provided by the new wall to confine the internal displacement.



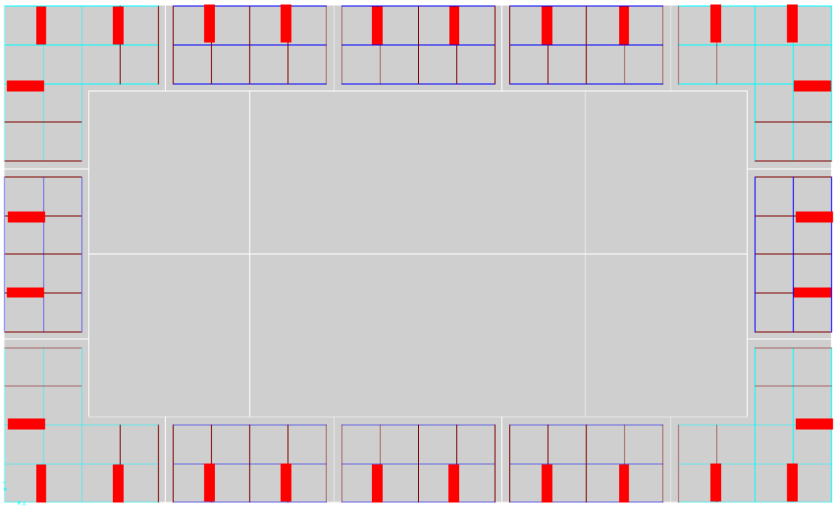
Program2

Installing prestressed steel strand, using the external force confines water tanks. Besides providing the resistance of horizontal earthquake force, it also can confine the displacement during earthquake. Otherwise this program can maintain steady water supply because of building outside of water tank.



Program3

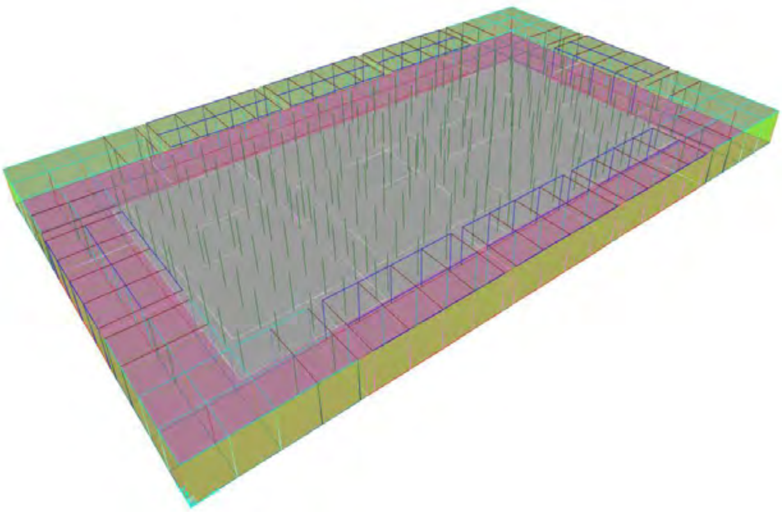
This program has built some walls inside of the water tank. The horizontal and vertical reinforcing bars connect with original bean and column by planting. On the length side, we plan to build 8 walls totally, 4 walls at each side, distributing evenly. On the width side, the program is to build 20 walls totally, 10 walls at each side, distributing evenly.



4. The structure analysis and the estimate of earthquake resistance

4.1 The structure analysis

Using SAP2000 analysis software analyzes the whole building model, including beam, column and plate...etc. all structure element and span base on the real size or distance for simulating as the real situation. Each plate and wall is divided by extended joint as well. Every divided part would not interact by each other. The vibration barycenter will depend on the setting of combined water tank. Totally 20 pieces of vibration barycenter was set. The earthquake forces applied on water tank calculate and applied separately, according to the real weight of structure.



3D analysis model

According to the degree of importance and waterproofness of this water tank, it should take the first rank of earthquake resistance and RANK A1. And the design should take the second rank of earthquake force to ensure the stress would not surpass the limitation of elasticity.

4.1.1 The calculation of site class

There is no drilling report to represent the site class data. So it introduces the drilling Reports “Engineering drilling report of land NO.741, Shalu Dist., Taichung City 433”. That site is in the distance of 1.7Km. The calculation of site natural vibration period is as fallow.

H	N	Vs	H/Vs
2	10	99.65	0.0201
4.5	39	132.79	0.0339
10	50	235.14	0.0425

※Vs suggests of $61.8\times N^{(-0.211)}$

After calculation, T_G is 0.4976. The site class is the second kind.

4.1.2 Calculation of dynamic water pressure

Because the water tank includes overflow pile, the water in tank is of the property of free water surface. So according to the design code, the dynamic water pressure applying on the wall in X and Y direction is as follow:

$$P(Z) = \beta \times \frac{7}{8} \times \gamma_0 \times K_h \times \sqrt{h \times z}$$

$$= 1 \times \frac{7}{8} \times 0.3048 \times 0.52 \times \sqrt{z}$$

In which β is the modified coefficient is the ratio of B and H. The ratio is bigger than 4 regardless of the X and Y direction of the tank. Conservatively, we take 1.0 for it. According to the formula, it is associated with Z which is height.

4.2 The estimate of capacity of earthquake resistance

In general, the estimate of capacity of earthquake resistance is divided into three stages, which is preliminary estimate, detailed estimate and then the final stage of improving design. The method of estimating earthquake resistance capacity which is accepted by the administration of Taiwan is TS-RC, SERCB (Seismic Evaluation of RC Building) and TEASPA (Taiwan Earthquake Assessment for Structures by Pushover Analysis). And TS-RC belong elastic analysis. Using the estimate ductility as the capacity of earthquake resistance might not response the real capacity. The outcome is too conservative and then causes the higher improvement budget. It is not commonly used. While the pushover analysis is the non-linear statics analysis method, the estimate result is more close to the real action. It also is common method to analyze.

So far, this tank is still at preliminary estimate stage. We would like to use the normal non-linear business software, like ETABS, SAP2000 etc. Though they can run the analysis of Pushover Analysis, they still can not provide the non-linear joint on the shell element, and the earthquake resistance capacity most is provided by the shell element. Therefore this paper still needs further detailed estimate of earthquake resistance capacity.

5. Conclusion

Tap water is the necessity of life, even the most important goods during the severe disaster. Therefore the water supply system needs the serious earthquake resistant design, avoiding the shutdown. Although, the earthquake resistant capacity of this water tank is not sufficient, but the economic benefit that repair the tank is still considerable. So it suit to do further detailed improve analysis of earthquake resistance, or it should be rebuilt. In addition, if water tank is the important facility for modification, and the improve design should enhance the capacity by applying several equipment of earthquake resistance and damping.

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Cover page

Title: **Seismic Assessment of Steel Chemical Storage Tanks.**

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Seismic Assessment of Steel Chemical Storage Tanks.

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ABSTRACT

Water supply is one the crucial lifeline systems. The seismic safety of critical water facilities is a pivotal issue in urban earthquake hazard mitigation. This project conducts the seismic assessment of two typical steel chemical storage tanks (one in Zhitan and one in Changxing water purification plants) of Taipei Water Department. The assessment criteria follow Taiwan Building Seismic Design Code (2011; design response spectra), JWWA Guideline to and Explanation of Seismic Construction Method of Water Supply Facilities (2009; water pipe bridges) and API 650 Welded Steel Tanks for Oil Storage (11th ed., 2012, Appendix E: Seismic Design of Storage Tanks; steel tanks). Major findings include: Tank No. 2 of Zhitan and Tank No. 6 of Changxing do not have sufficient anchorage; also, the later doesn't have enough freeboard while at its highest content level. Accordingly, measures to enhance their seismic integrity or secure their seismic safety have been advised.

Keywords: Water facilities, Seismic assessment, Steel chemical storage tanks, API 650

INTRODUCTION

The steel chemical storage tanks selected for study under this project are No. 2 tank of Zhitan and No. 6 tank of Changxing water purification plant. They are the largest tanks of respective plant with capacity of 300 Tons and the heights are 7.7 meters and 9.2 meters and for accommodating PAC and NaOH respectively. The chemicals (liquid) posed remarkable weight, and any damage of the tanks could result detrimental effects to the purification quality. A rational approach to assess the seismic safety of such tanks is greatly needed..

SEISMIC ASSESSMENT PROCEDURE OF STEEL CHEMICAL STORAGE TANKS

For the design of these hazardous liquid storage tanks, "Appendix E: Seismic Design of Storage Tanks" in API 650 Welded Steel Tanks for Oil Storage (API, 2007) is most applied. Theoretically, it considers two response modes of a tank and its contents: impulsive and convective (Housner, 1963). This procedure applies to anchored steel tanks, which are the most commonly used variety, and is of high seismic concern in Taiwan. It is also incorporated with the ground motion specified in Taiwan Building Seismic Design Code (Construction and Planning Agency Ministry of the Interior,R.O.C., 2011).

API 650 classifies tanks into three Seismic User Groups (SUGs). **SUG III** tanks are those that provide service to facilities essential to the life and health of the public, or those that contain hazardous substances, to which it is greatly important to prevent public exposure. **SUG II** tanks are those that provide direct services to major facilities, or which store materials that may pose a public hazard and lack secondary controls. The rest belong to **SUG I** tanks.

In this study, a seismic assessment procedure for steel liquid storage tanks is given, as depicted in **Fig. 1**.

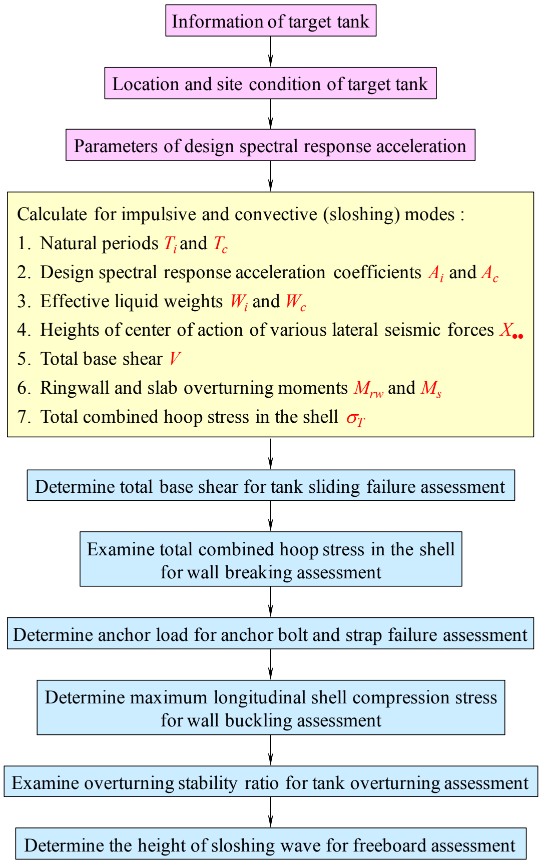
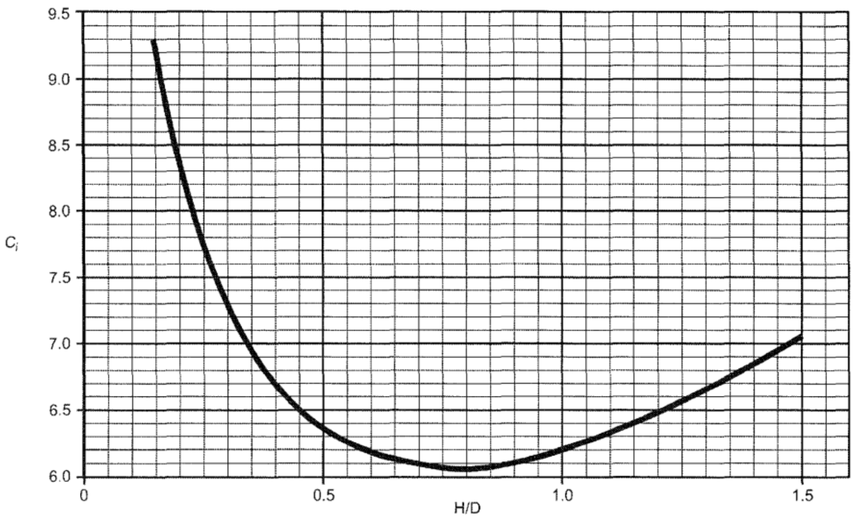


Fig. 1 Seismic assessment procedure for steel liquid storage tanks following API 650, App. E requirements.

1. Determine T_i (s) and T_c (s), the natural periods of vibration for impulsive and convective (sloshing) modes of behavior of the liquid.

$$T_i = \frac{1}{\sqrt{2000}} \cdot \left(\frac{C_i H}{\sqrt{\frac{t_u}{D}}} \right) \cdot \sqrt{\frac{\rho}{E}} \qquad T_c = 2\pi \cdot \sqrt{\frac{D}{3.68 g \cdot \tanh\left(\frac{3.68 H}{D} \right)}}$$

where the coefficient C_i is a function of H / D depicted in the following chart.



2. Determine A_i (g) and A_c (g), the impulsive and convective design spectral response acceleration coefficients.

$$A_i = \left(\frac{I}{R_{wi}}\right)\cdot S_{aD}(T_i) \qquad A_c = K\cdot\left(\frac{I}{R_{wc}}\right)\cdot S_{aD}(T_c)$$

where I is set by Seismic User Group (SUG), and $K = 1.5$ unless otherwise specified. The values of force reduction coefficients R_{wi} and R_{wc} for the impulsive and convective modes using allowable stress design methods are 4 and 2, respectively, for mechanically-anchored tanks.

3. Determine V (N), the total base shear, from W_i (N) and W_c (N), the effective impulsive and convective portions of the liquid weight, respectively. Examine the possibility of tank sliding.

$$V = \sqrt{V_i^2 + V_c^2}$$

where

$$\begin{cases} V_i = A_i(W_s + W_r + W_f + W_i) \\ V_c = A_c W_c \end{cases} \quad W_i = \begin{cases} \dfrac{\tanh\left(0.866\dfrac{D}{H}\right)}{0.866\dfrac{D}{H}}\cdot W_p & D/H \ge 1.333 \\ \left(1.0 - 0.218\dfrac{D}{H}\right)\cdot W_p & D/H < 1.333 \end{cases} \quad W_c = 0.230\frac{D}{H}\cdot\tanh\left(\frac{3.67H}{D}\right)\cdot W_p$$

The calculated value of V should not exceed the sliding resistance V_s (N) calculated by:

$$V_s = \mu(W_s + W_r + W_f + W_p)(1.0 - 0.4A_v)$$

4. Determine the ringwall overturning moment M_{rw} (N-m) acting at the base of tank shell perimeter and the slab overturning moment M_s (N-m) used for slab and pile cap design.

$$M_{rw} = \sqrt{\left[A_i(W_i X_i + W_s X_s + W_r X_r)\right]^2 + \left[A_c(W_c X_c)\right]^2}$$

$$M_s = \sqrt{\left[A_i(W_i X_{is} + W_s X_s + W_r X_r)\right]^2 + \left[A_c(W_c X_{cs})\right]^2}$$

where $X_{\bullet}$ and $X_{\bullet\bullet}$ refer to the height from the bottom of the tank shell to the center of action of various lateral seismic forces from liquid, tank shell and roof.

$$X_i = \begin{cases} 0.375H & D/H \geq 1.333 \\ \left(0.5 - 0.094\dfrac{D}{H}\right)H & D/H < 1.333 \end{cases} \quad X_c = \left[1.0 - \frac{\cosh\left(\dfrac{3.67H}{D}\right) - 1}{\dfrac{3.67H}{D} \cdot \sinh\left(\dfrac{3.67H}{D}\right)}\right]H$$

$$X_{is} = \begin{cases} 0.375\left[1.0 + 1.333\left(\dfrac{0.866\dfrac{D}{H}}{\tanh\left(0.866\dfrac{D}{H}\right)} - 1.0\right)\right]H & D/H \geq 1.333 \\ \left(0.5 + 0.060\dfrac{D}{H}\right)H & D/H < 1.333 \end{cases} \quad X_{cs} = \left[1.0 - \frac{\cosh\left(\dfrac{3.67H}{D}\right) - 1.937}{\dfrac{3.67H}{D} \cdot \sinh\left(\dfrac{3.67H}{D}\right)}\right]H$$

5. Determine σ_T, the total combined hoop stress in the shell (MPa).

$$\sigma_T(\pm) = \frac{N_h \pm \sqrt{N_i^{\,2} + N_c^{\,2} + (A_v N_h)^2}}{t}$$

where the product hydrostatic membrane force N_h (N/mm), and the impulsive and convective hoop membrane forces N_i (N/mm) and N_c (N/mm) in tank shell, respectively, are calculated by:

$$N_h = \frac{9.81 \cdot GDY}{2}$$

$$N_i = \begin{cases} 8.48A_i GDH\left[\dfrac{Y}{H} - 0.5 \cdot \left(\dfrac{Y}{H}\right)^2\right] \cdot \tanh\left(0.866\dfrac{D}{H}\right) & D/H \geq 1.333 \\ 5.22A_i GD^2\left[\dfrac{Y}{0.75D} - 0.5 \cdot \left(\dfrac{Y}{0.75D}\right)^2\right] & D/H < 1.333 \quad \text{and} \quad Y < 0.75D \\ 2.6A_i GD^2 & D/H < 1.333 \quad \text{and} \quad Y \geq 0.75D \end{cases}$$

$$N_c = \frac{1.85A_c GD^2 \cdot \cosh\left[\dfrac{3.68(H-Y)}{D}\right]}{\cosh\left(\dfrac{3.68H}{D}\right)}$$

6. Examine P_{AB}, the anchor load (N).

$$P_{AB} = \left(\frac{1.273M_{rw}}{D^2} - w_t(1 - 0.4A_v)\right) \cdot \left(\frac{\pi D}{n_A}\right)$$

The calculated value of P_{AB} should not exceed 80% of the yield strength of anchor bolts.

7. Examine σ_c, the maximum longitudinal shell compression stress (MPa).

$$\sigma_c = \left(w_t(1 + 0.4A_v) + \frac{1.273M_{rw}}{D^2}\right) \cdot \frac{1}{1000t_s}$$

The calculated value of σ_c should not exceed the allowable longitudinal shell-membrane compression stress F_C (MPa) calculated by:

$$F_C = \begin{cases} 83 \cdot t_s / D & GHD^2/t^2 \geq 44 \\ 83 \cdot t_s/(2.5D) + 7.5\sqrt{GH} < F_{ty} & GHD^2/t^2 < 44 \end{cases}$$

8. Examine that the overturning stability ratio is 2.0 or greater.

$$\frac{0.5D \cdot (W_p + W_f + W_T + W_{fd} + W_g)}{M_s} \geq 2.0$$

9. Determine δ_s, the height (mm) of sloshing wave above the product design height. Examine the sufficiency of tank freeboard to accommodate the calculated value of δ_s.

$$\delta_s = 0.5DA_f$$

where

$$A_f = \begin{cases} KS_{D1}I \cdot \left(\dfrac{1}{T_c}\right) & T_c \leq 4 \\ KS_{D1}I \cdot \left(\dfrac{4}{T_c^{\,2}}\right) & T_c > 4 \end{cases} \qquad A_f = \begin{cases} KS_{D1} \cdot \left(\dfrac{1}{T_c}\right) & T_c \leq T_L \\ KS_{D1} \cdot \left(\dfrac{T_L}{T_c^{\,2}}\right) & T_c > T_L \end{cases}$$

Nomenclatures	
A_v : vertical earthquake acceleration coefficient (g), taken as $0.14S_{DS}$ or greater for the ASCE 7 method D : nominal tank diameter (m) E : elastic modulus of tank material (MPa) F_{ty} : yield strength of shell (MPa) G : product specific gravity g : acceleration due to gravity (m/sec^2) H : maximum design product level (m) I : importance factor coefficient; I = 1.0, 1.25 and 1.5 for SUG I, II and III, respectively K : coefficient for adjusting spectral acceleration (from 5 to 0.5% damping) n_A : number of anchors around the tank circumference $S_{aD}(T)$: design earthquake spectral response acceleration coefficient for structural period T S_{D1} : design (5% damped) spectral response acceleration parameter at one second S_{DS} : design (5% damped) spectral response acceleration parameter at short periods (0.2s)	T_L : regional-dependent transition period for longer period ground motion (s) t : thickness of shell ring under consideration (mm) t_s : thickness of bottom shell (mm) t_u : equivalent uniform thickness of tank shell (mm) W_f : weight of the tank bottom (N) W_{fd} : total weight of tank foundation (N) W_g : weight of soil over tank foundation footing (N) W_p : total weight of the tank contents (N) W_r : total weight of fixed tank roof (N) W_s : total weight of tank shell and appurtenances (N) W_T : total weight of tank shell, roof, framing, knuckles, product, bottom, attachments and appurtenances (N) w_t : tank and roof weight acting at base of shell (N/m) Y : distance from liquid surface to any point (positive down (m) μ : friction coefficient for tank sliding (max. 0.4) ρ : density of fluid (kg/m^3)

SEISMIC ASSESSMENT OF STEEL CHEMICAL STORAGE TANKS

●Seismic Assessment Database of Tanks

The seismic assessment database of No. 2 Tank in Zhitan and No. 6 Tank in Changxing purification plant are given below as **Table 1**:

Table 1 –Seismic Assessment Database of Tanks

N0. of Tank	Zhitan Purification Plant No. 2 Storage Tank	Changxing Purification Plant No. 6 Storage Tank
Address.	No. 2, Zhitan Road, Xindian Dist. New Taipei City	No. 131, Changxing Street, Daan Dist. Taipei City
Coordinates	N 24.941647 E 11.529174	N 25.014429 E 121.549655
Type of Chemical	NaOH solution, concentration 45%, Sp.G: 1.48	Poly Aluminum Chloride solution, Sp.G 1.15
Shape and dimensions of tank body	■Cylinder □Rectangular OD： 7.6 m Height ： 7.665 m Effluent height： 6.735 m(from bottom up) Shell thickness： 6 mm Bottom plate thicknes： 6 mm Capacity ： 300 MT	■Cylinder □Rectangular OD： 6.8 m Height： 9.16 m Effluent height： 8.66 m Effluent height: 8.66 M(from bottom up) Shell thickness： 4.5-6 mm Bottom plate thicknes： 6 mm Capacity ： 300 MT
Building material of tank	■Steel ■W/inner lining：yes (FRP)	■Steel ■W/ Inner Lining：yes (FRP)
Placing Manner	■Elevated Height of bottom plate：2.80 m RC Base：yes Foundation pile: nil Anchored with bolts：yes Numbers of Anchoring Bolt: 18 Spec. of bolt: M20	■Ground RC Base：yes Foundation pile: yes Anchored with bolts：yes Numbers of Anchoring Bolt:：16 Spec. of bolt: M25
Location placed	■Outdoor ■W/O effluent pond/ channel	■Outdoor ■W/O effluent pond
Year completed	2013 ■No seismic resistance reinforcement	2007 ■No seismic resistance reinforcement

<table>
<tr><td>Seismic Assessment Database</td><td>$S_S^D = 0.6$ 、 $S_1^D = 0.35$ ；
$N_a^{(D)}$=1.0、$N_v^{(D)}$=1.0；
Type 2 Crust，$F_a^{(D)} = 1.1$ 、
$F_v^{(D)} = 1.4$ ；
$S_{DS} = 0.66$ 、 $S_{D1} = 0.49$ ；
$A_v = 0.14S_{DS} = 0.0924$ ；
$T_0^D = S_{D1} / S_{DS} = 0.74$ ；
Steel elasticity modal $E = 207{,}000$ MPa；
$g = 9.81\text{m/s}^2$ ；
$H / D = 0.887$ ，$C_i = 6.1$ ；
$T_i = 0.0874\text{s}$ 、 $T_c = 2.887\text{s}$
(procedure 1)；
$I = 1.5$ ；
K=1.5
R_{wi}=4(mechanically-anchored)
R_{wc}=2(mechanically-anchored)
Ai=0.187、Ac=0.297(procedure 2);
ρ_s=7850Kg/m^3
$W_s=8.46\times10^4$N ; $W_r=2.24\times10^4$N
$W_f=2.1\times10^4$N ; $W_p=4.43\times10^6$N
$W_i=3.34\times10^6$N ; $W_c=6.48\times10^5$N
(procedure 3) ;
$M_{rw}=2.62\times10^6$N-m;$M_s=3.01\times10^6$N-m
(procedure 4) ;</td><td>$S_{DS} = 0.6$ 、 $S_{D1} = S_{DS} \cdot T_0^D = 0.78$ ；
$A_v = 0.14S_{DS} = 0.084$ ；
$T_0^D = 1.30\text{s}$ ；
$S_{aD} = 0.6$ ；
Steel elasticity modal $E = 207{,}000$ MPa；
$g = 9.81\text{m/s}^2$ ；
$H / D = 1.27$ ，$C_i = 6.6$ ；
$T_i = 0.117\text{s}$、$T_c = 2.727\text{s}$ ；
(procedure 1)；
$I = 1.5$ ；
K=1.5
R_{wi}=4(mechanically-anchored)
R_{wc}=2(mechanically-anchored)
Ai=0.225、Ac=0.675(procedure 2);
ρ_s=7850Kg/m^3
$W_s=7.91\times10^4$N ; $W_r=1.35\times10^4$N
$W_f=1.68\times10^4$N ; $W_p=3.59\times10^6$N
$W_i=2.98\times10^6$N ; $W_c=6.48\times10^5$N
(procedure 3) ;
$M_{rw}=3.95\times10^6$N-m;$M_s=4.46\times10^6$N-m
(procedure 4) ;</td></tr>
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●**Results of Detail Seismic Resistance Assessment**

Concluding the above database and analysis, the of No. 2 Tank in Zhitan and No. 6 Tank in Changxing purification plant seismic assessment results are shown in **Table 2** and **Table 3**.

Table 2 –Results of Detail Seismic Resistance Assessment- No. 2 Tank in Zhitan Purification Plant

Item	Results of Detail Seismic Resistance Assessment
The possibility of tank sliding	The total base shear for tank sliding $V=7.34\times10^5$N The sliding resistance $V_S=1.76\times10^6$N $V_S > V$ ……OK. (**procedure 3**)
The total combined hoop stress in the shell	$\sigma_T(+)$=70.84MPa(tension,at the bottom of the tank) $\sigma_T(-)$=-7.807MPa(compression,at the liquid surface) SUS304 stainless steel fy=206 Mpa > $\sigma_T(+)$ or $\sigma_T(-)$……OK. (**procedure 5**)
The anchor load	$w_t=4.48\times10^3$N/m $P_{AB}=7.09\times10^4$N 80% of the yield strength of anchor bolts=80%×6.47×10^4N=5.18×10^4N< P_{AB}……NG(**procedure 6**) Anchor bolts do not have sufficient anchorage
The maximum longitudinal shell compression stress	The maximum longitudinal shell compression stress σ_c=10.4 Mpa The allowable longitudinal shell-membrane compression stress F_C=49.87 Mpa $F_C > \sigma_c$ ……OK. (**procedure 7**)
The stability against overturning	The overturning stability ratio is 5.75 > 2.0……OK. (**procedure 8**).
The height of sloshing wave	The height of sloshing wave δ_S=0.97m The tank freeboard=7.665-6.735=0.93m≒ δ_S……OK. (**procedure 9**). The height of sloshing wave δ_S is slightly higher than the tank freeboard, but is determined as acceptable.

Table 3 –Results of Detail Seismic Resistance Assessment- No. 6 Tank in Changxing Purification Plant

Item	Results of Detail Seismic Resistance Assessment
The possibility of tank sliding	The total base shear for tank sliding $V=8.21\times10^5$N The sliding resistance $V_S=1.43\times10^6$N $V_S > V$ ……OK. (**procedure 3**)
The total combined hoop stress in the shell	$\sigma_T(+)$=62.33MPa(tension,at the bottom of the tank) $\sigma_T(-)$=-14.72MPa(compression,at the liquid surface) SUS304 stainless steel fy=206 Mpa > $\sigma_T(+)$ or $\sigma_T(-)$……OK. (**procedure 5**)

The anchor load	w_t=4.33×10^3N/m P_{AB}=1.4×10^5N 80% of the yield strength of anchor bolts=80%×1.01×10^5N=0.81×10^5N< P_{AB}……NG(**procedure 6**) Anchor bolts do not have sufficient anchorage
The maximum longitudinal shell compression stress	The maximum longitudinal shell compression stress σ_c=18.87 Mpa The allowable longitudinal shell-membrane compression stress F_C=52.96 Mpa $F_C > \sigma_c$ ……OK. (**procedure 7**)
The stability against overturning	The overturning stability ratio is 3.64 > 2.0……OK. (**procedure 8**).
The height of sloshing wave	The height of sloshing wave δ_S=1.46m The tank freeboard=9.16-8.66=0.5m< δ_S……NG. (**procedure 9**). The height of sloshing wave δ_S is higher than the tank freeboard.

CONCLUSION AND SUGGESTION

Basis "API650 ,Appendix E(API, 2007) " and the basic data as well as site survey of the two steel chemical storage tanks in water treatment, the resistance against anchor load of Zhitan No. 2 Tank and Changxing No. 6 Tank is shown as insufficient. Under design seismic conditions, damage to anchoring position may be resulted. Taipei Water Department has established plan to reinforce anchoring bolts, either to increase or to replace so that the anchoring force will be meeting the need of design seismic resistance. Besides, the height of sloshing wave is higher than the freeboard of Changxing No. 6 Tank about 1 meter. This may lead damage to the top plate due to sloshing wave of fluid during earthquake. New requirement has been set that the liquid level operation height must be 1 meter or more lower than the sufficiency of tank freeboard.

The existing large capacity steel chemical storage tanks similar to Zhitan No. 2 Tank or Changxing No. 6 Tank ,may be existed with insufficient anchoring capacity and insufficient freeboard. This is probably a systematic issue and shall be inspected totally to avoid occurrence of any unnecessary damage.

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The Estimated losses and Preparedness Strategy for Emergency Water Supply of Fire Fighting and Life Supporting in a Rupture Scenario of the Shanchiao Fault.

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ABSTRACT

Taiwan is located on the Circum-Pacific Seismic Zone. Devastating earthquakes occurred frequently. Taiwan's Central Geological Survey announced that there exists 33 active faults in this island. Among them, the Shanchiao Fault stretching along the edge of Taipei basin is the most imperil to Taiwan since Taipei is the political, economic and cultural center. Therefore, a comprehensive preparedness strategy for catastrophic earthquakes caused by the Shanchiao Fault is very important.

This paper first presents the estimated loss of water pipes for the rupture scenario of the Shanchiao Fault by Taiwan Earthquake Loss estimation System developed by The Taiwan's National Center for Research on Earthquake Engineering. Needed water supply for firefighting and life supporting including drinking water and for daily use is focused and taken into concern by days after the scenario event. Short amount of life supporting water supply can be calculated by the population, restoring rate and emergency storage capacity. This deficiency can be made up by neighboring county's supporting. However, a pre-disaster planning and contract should be made before a major earthquake. The results of this study can provide a sufficient advice to the government.

Keywords: Earthquake Scenario, Damage of Water Pipes, Water Supply, Firefighting

Introduction

Water supply system is an indispensable infrastructure to the public. Any long term interruption of water supply will jeopardize a city's life function. Fires after shock are hardly extinguished not only because the rescue capability might be impaired but also due to lack of water. Taiwan is located on the Circum-Pacific Seismic Zone. Devastating earthquakes occurred frequently. Since Taipei is the capital of political, economic, and socio-cultural matters in Taiwan, whether or not it can sustain a major earthquake striking becomes an important issue to the whole country. Currently, water supply in Taipei area is managed by Taipei Water Department of Taipei city government with a consumer population of 3.85 million [1].

According to Taiwan's Central Geological Survey, there exists 33 active faults in Taiwan (Figure 1). Among them, the Shanchiao Fault stretching along the edge of Taipei basin is the most imperil to Taipei. A comprehensive preparedness strategy for catastrophic earthquakes caused by the Shanchiao Fault is very important. We investigated the estimated damage of water pipes for the scenario of the rupture of the Shanchiao Fault by Taiwan Earthquake Loss Estimation System (TELES)[2,3] developed by Taiwan's National Center for Research on Earthquake Engineering (NCREE)[4]. Then, we focus on needed water supply for life supporting including drinking water and daily use and also take into concern the recovery by days after the scenario event. Short amount for life supporting can be calculated by the population, restoring rate and the regulated requirement for emergency supply. We also estimate number of urban fires and need firefighting water and dispatch teams. The deficiency can be made up by neighboring county's supporting. However, a pre-disaster planning and contract should be made before a major earthquake. The results of this study can provide a sufficient advice to the government.

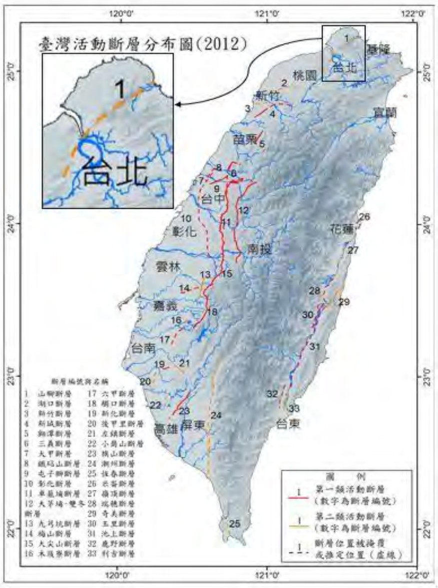


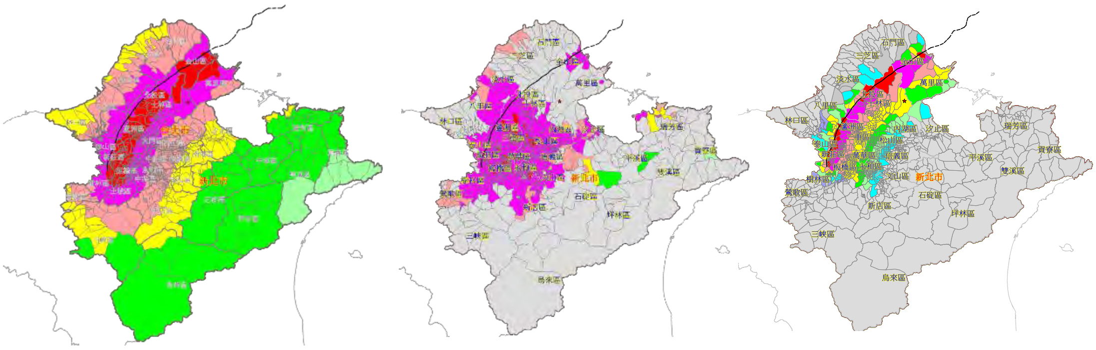
Figure 1 Active Faults in Taiwan

Table1 Seismic Parameters of the Scenario Event

Richter Magnitude (M_L)		6.9
Focal Depth		8 km
Epicenter Longitude		121.589
Epicenter Latitude		25.139
Rupture of the Fault	Dip Angle	50 degree
	Length	56 km
	Width	20 km

Research Methods

The seismic parameters of the scenario event are listed in Table 1. Although, it is considered too conservative by Taiwan's Central Weather Bureau, there are still many researchers regard it as proper. Especially, after the Great 2011 East-Japan Earthquake disaster prevention planners are prone to consider the event beyond expected. We can obtain *PGA, PGD*, liquefaction, and land off-set (Figure 2) form TELES outputs.



PGA Soil Settlement due to Liquefaction PGD

Figure 2 PGA, PGD, Soil Settlement due to Liquefaction of the Scenario Event by TELES

The damage ratio (*DR*) of water pipes are then calculated by the following equations [5].

$$DR = C \times DR_0$$

in with

$$DR_0 = Max\left(DR_{PGA}, DR_{PGD(Fault)}\right) + DR_{PGD(Liquefaction)} \times p_{Liquefaction}$$

$$C = Correction\ factor$$

$$DR_{PGA} = 4.501 \times (PGA - 0.1)^{1.97} \quad (PGA\ in\ g)$$

$$DR_{PGD} = 0.04511 \times PGD^{0.728} \quad (PGD\ in\ cm)$$

$$DR_{PGD} = 0, if\ PGA < 0.1g$$

$$p_{Liquefaction} = Probability\ of\ Soil\ Liquefaction$$

The outbreak of fire after a major earthquake can be estimated by following equations [6].

1. Outbreak Ratio of Fires: $F = 0.3131 \times PGA(g) + 0.03 \times PGD(cm)$
2. Number of Fires: Area (Million m^2) $\times$ Outbreak Ratio of Fires
3. Required Firefighting Dispatch Team：
   (1)Population Above 150 thousand: Number of Fires × 1.7
   (2) Population 100~150 thousand: Number of Fires × 1.4
   (3) Population under 100 thousand: Number of Fires × 1.0
4. Water Needed for Fire Fighting (ton): Firefighting Dispatch Team× 40

Research Outcomes

I. Water for Life-Supporting

The inventory of transmission, distribution and feed water pipes of Taipei Water Department is listed in Table 2 and shown in Figure 3. By bringing these data and TELES outputs into the above equations, we can obtain the damage number of water pipes as shown in Table 3 and Figure 4.

Table 2 Pipe Length of Various Diameters of Taipei Water Department

Pipe Diameter (mm)					Total Length (m)
S1	S2	S3	S4	S5	
10-80	100-250	300-450	500-900	Above 900	
2,844,978 m	2,730,607 m	664,108 m	286,380 m	201,373 m	6,727,446 m

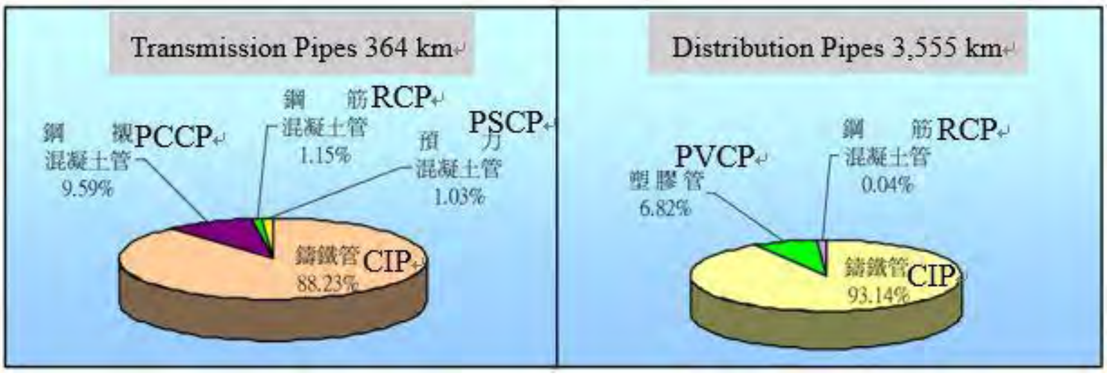


Figure 3 Length Ratio of Various Materials of Transmission and Distribution Pipes [7]

Table 3 Damage of Water Pipes in the Scenario Event [8]

Pipes	**Damage Number**
Transmission Pipes	57
Distribution Pipes	1,309
Feed Pipes	3,685

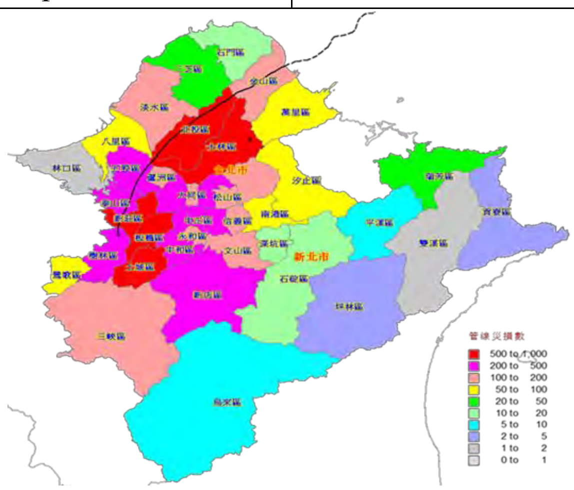


Figure 4 Damage Distribution of Water Pipes in Administrative Regions [8]

Based on the past experience, estimated repair team-hour are listed in Table 4. Taipei Water Department can summon 40 repair teams in ordinary days, but in case of emergency, up to 80 teams can be called, however this cannot last too long. We suggest the repair strategy could be arranged in three stages, first stage ($0\text{-}4^{th}$ day): only for critical facilities and transmission mains; second stage (5^{th} -11^{th} day): only for facilities transmission and distribution mains; third stage (12^{th} -last day): for distribution and feed pipes. Then, we can make a progress list for repairing on the basis of each day.

Table 4 Estimated Repair Team-Hours for Pipe Damages [9]

		Pipe Diameter (mm)				
		S1	S2	S3	S4	S5
		10-80	100-250	300-450	500-900	Above 900
Team-Hours	Replacing of Breaking Pipes	7	11	19	27	42
	Leakage Fixing	3.5	5.5	9.5	13.5	21

As days go by, the number of damages and its corresponding DR will descend. By applying Kawakami's empirical equation for failure ratio of water supply to pipe damage ratio $failure\ ratio\ of\ water\ supply = 1/(1 + 0.0473 \times DR^{-1.61})$ [10], we can calculate the recovery ratio of water supply by days after the scenario event. The result is shown in Figure 5.

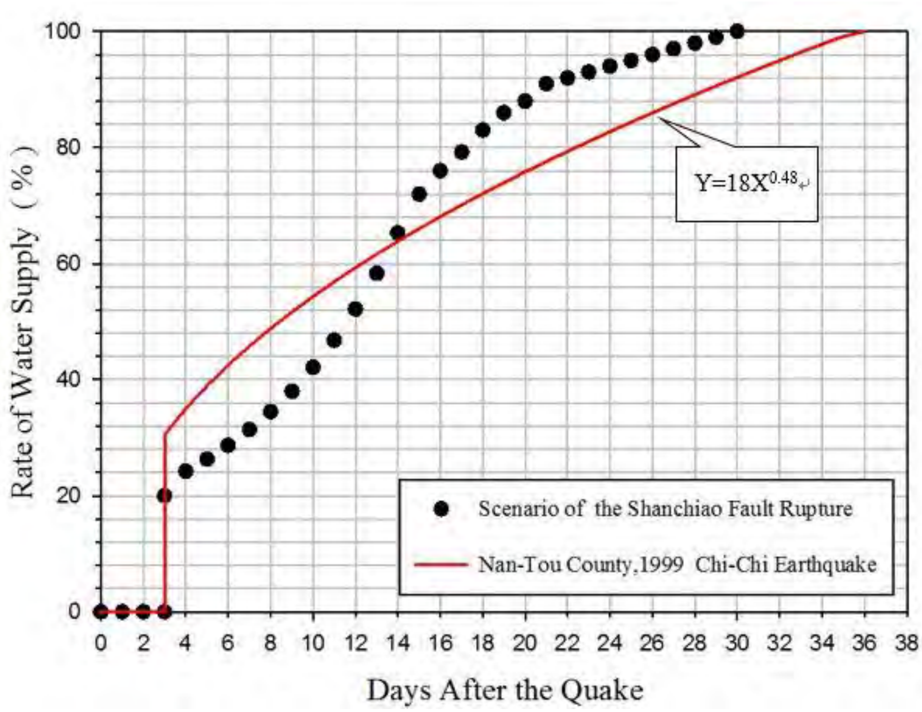


Figure 5 Recovery Ratio of Water Supply by Days

Figure 5 shows that in the first 3 days. Taipei Water Department hardly provides any supply of tap water in Taipei metropolitan. However, after one, two and three weeks of the event, there will have 32, 65 and 92 % of customers resume their water supply, respectively. The restoration is quite fast compared to the 1999 Chi-Chi earthquake.

Short amount for life supporting water can be calculated by the population, recovery ratio and the regulated requirement for emergency supply. We suggest that at least 3 liters for drinking water per person for the first 3 days and 20 liters per person for daily use in the following days should be provided. Therefore, a pre-disaster planning and contracts can be made before a major earthquake.

II. Outbreaks of Fire and Firefighting

On the general spec, one tank truck can carry at least 3 tons of water for firefighting, while 12 tons for a reservoir truck. After a major earthquake, water is not possible to come out from any fire hydrant because severe damage to pipes and facilities. Intakes of firefighting water were already arranged from rivers, ponds, pools and reservoirs.by city governments [11, 12]. On average, one ton of water can be pumped form water source to fire trucks in one minute, and water trucks can shuttle back and forth form fire site to water intakes within one hour. Moreover, It is regulated by governments that fires after quake should be extinguished at the first 12 hours [11, 12]. Therefore, it is adequate to assume that one water truck can shuttle 12 times. In this study, we can estimate the needed amount of firefighting water as well as the supply capacity of fire departments by their existing tank/reservoir trucks. Therefore, lack of water or water trucks can also be estimated. The result of estimated outbreak of fire, needed amount and lack of firefighting dispatch team and water is shown in Table 5. Since this deficit of water trucks should be compensated from other counties outside of the disaster area, to reach a mutual supporting agreement between county governments becomes important.

Table 5 Result of Estimated Fire, Firefighting Water and Dispatch Team

Area	Number of Fires	Needed Firefighting Dispatch Teams	Currently Firefighting Dispatch Teams[13,14]	Lack of team	Needed Amount of Firefighting Water (ton)	Water Tank Trucks in First 12 Hours[13,14]	Lack of Water (ton)
Taipei City	204	343	246	-97	13,649	8,676	-4973
New Taipei City	369	578	904	+326	23,140	10,800	-12,340

Discussion and Conclusion

As shown in Table 6, the damage ratio of transmission and distribution pipes in the 1999 Chi-Chi Earthquake was 0.15, while, 0.35 in this scenario study. It seems reasonable because Taipei is a high-density populated city, and very close to the Shanchiao Fault. However, the damage ratio of feed pipes in the 1999 Chi-Chi Earthquake was 6.58, while, 1.31 in this scenario study. Although, the seismic capability of feed pipes should be much weaker than that of transmission and distribution mains because of material and diameter, the times of damage ratio seems unrelated. This needs more investigation to reach an adequate result.

Table 6 Comparison of Damage Ratio (DR) of Water Pipes

Event	**DR** of Transmission and Distribution Pipes (number/km)	**DR** of Feed Pipes (number/km)
Nan-Tou County,1999 Chi-Chi Earthquake[15]	0.15	6.58
Scenario of Shanchiao Fault Rupture	0.35	1.31

Regarding to the recovery rate of tap water, as shown in Table 7, this scenario event is worse than the Chi-Chi Earthquake at the first week because damage is also more serious. However, the disaster area of the Chi-Chi Earthquake was in countryside, and some villages were even far remote, as well as the restoration capability of Taipei is stronger, the restoration rate of this study catches up very quickly and even exceeds. At last, tt was estimated to need 30 days for a full recovery of water supply in this study.

Table 7 Recovery Rate of Water Supply

Days after Quake	Nan-Tou County,1999 Chi-Chi Earthquake[15]	Scenario of Shanchiao Fault Rupture
7^{th} Day	54.5 %	31.4 %
13^{th} Day	61.8 %	58.3 %
24^{st} Day	85.5 %	94.0 %
30^{th} Day	92.0 %	100.00 %
37^{th} Day	99.0 %	

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The Damaged Water Supply Facility for Repair or Reconstruction Evaluation Program – A Case Study of Nao-Guan Service Reservoir at Taichung, Taiwan

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Abstract

Many water facilities in Taiwan suffered from structural damages during the strong earthquake striking Nantou Jiji on 21/09/1999, causing facility structures leaking or failure in storage function. However, water facilities require more water impermeability than constructions of other function facility. To avoid more damages, it is very important to decide whether to repair, reinforce, rebuild, or find new sites for the damaged water facilities.

For example, Nao-Guan storage tank (Taiwan Water Corporation's property), located in Taiping, Taichung, near Chelongpu Fault, was seriously damaged during the 21/9/1999 Jiji-earthquake. We have evaluated different projects to decide whether to repair, reinforce, rebuild on the same site, or find new sites. Our project evaluations aimed at several aspects of water facilities, such as structural safety, operations, geological features, regulation limits, and the future development. We will choose the most appropriate projects after full assessment.

Introduction

Taiwan is located in the hub of mutual collision between Eurasia continent plate and Philippines ocean plate. There are approximately 15,000 - 18,000 earthquakes of all sizes happened every year.

Many water facilities suffered from major damage during the strong earthquake striking Taiwan on 21/09/1999. For instance, Fongyuan water treatment plant and Nao-Guan storage tank in Taichung were seriously damaged due to their locations in the vicinity of Che-long-pu Fault. For these water facilities which were damaged, whether to repair, reinforce, rebuild on the same site, or find a new site, it is necessary to proceed a detail evaluation procedure and choose the most appropriate projects.

Assessment items and methods

Our evaluations aimed mainly at three aspects of water facilities, structure safe, usability and restoration. Structure seismic-resistance evaluation guideline was applied as our blueprint. Following tasks were sequencing proceeded：

1. Collection of Basic architecture data

   Architecture design figures, structure design figures, calculation sheets of structure, material specifications and design methods of original water facility were collected and interpreted.
2. Structure condition and architecture damage investigation

   Tasks focus on major damage and secondary damage patterns, damage location and extent. Such as crack width and distribution of reservoir, damage situation of top slab, the damage condition of beam and column joint, water seepage, concrete swelling, rust and corrosion of steel reinforcement and investigation of steel reinforcement allocation.
3. Material testing

   Material testing include concrete strength test, neutralization test and chloride test of concrete.
4. Analysis of structure basic data

   To check whether the seismic-resistance design specification which used at that time is a new one from structure design drawing and calculation sheet, and compare it with current specification.
5. Seismic-resistance evaluation and analysis

   3D-model is established by using structure analysis software and then to analyze x、y、z three dimensions seismic resistance capability with 3D-model. 3D-model is also used to calculate axis-force, shear force, moment, displacement, the relationship of function target and requirement of seismic-resistance (A_p/A_T).
6. The choice of seismic-resistance reinforcing plan

   There are three categories for structure reinforce and of repair: strength reinforcement、toughness reinforcement and combined method. Several structure reinforcement and repair methods are now used. Displacement method, thickness increasing method, lining method, truss increasing method, supporting method, steel plate sticking method, FRP sticking method, rolling steel plate cover method, pre-stress method, method of water proof material pouring into crake, seismic-resistance RC shear wall increasing method. Lining method, steel plate sticking method and method of water proof material pouring into crake are frequently used in water facilities structure depending on their structure type.

7. Engineering cost estimation of repair and reinforcement

   Engineering cost was estimated according to the selected repair method and area of repair. Investment benefit also must be carefully considered.

8. Relative ordinance

   Relative ordinance must be carefully evaluated to realize their effects on repair or reconstruction plan. Such as soil conservation law, environmental impact assessment law, building law, Geology law and ban on building.

9. The requirement of operation

   Inlet and outlet pipeline condition, space for pipe installation, space for construction, operation base size and hydraulic analysis are all needed be carefully considered.

10. Engineering geology evaluation

    To justify the property of stratum in planning site, the relative distance between active geological fault and planning site and the susceptive area of active geological fault, then the suitable area to be built water facilities can be scoped.

    After aforementioned information are collected and surveyed, and then taking account of regulation, structure safety, operation requirement and investment benefit. Finally a most appropriate program can be determined.

Case study：The renovation proposal of Nao-Guan storage tank.

1. Basic data collection

   Nao-Guan storage tank is located in Taichung, Taiwan. It is a 10,000 m^3 RC tank with beam-column system and single footing foundation, and built in 1987. It was seriously damaged during the 21/9/1999 Jiji big earthquake and completely lost the function of service take due to its location near che-long-pu fault.

2. Structure current situation and building damage investigation

   The main damage patterns of Nao-Guan reservoir are relative displacement damage produced from expansion joint and stress damage of beam-column joint, as shown picture 1-4. It can be seen that there is an obvious crack and disturbance near ground. This is because reservoir is located near geological fault zone. The maximum crack width from basin wall relative displacement is around 1 m, it can be passed through by one man. Many foundations displacement happened and then resulted in base slab rupture when there is an earthquake due to the single footing foundation was used in the tank structure. The service tank was seriously damaged and completely lost it function.

3. Material testing

   Because the service reservoir was seriously damaged and can't be repaired, the material tests didn't be run.

4. Structure basic data analysis

   Nao-Guan storage tank was constructed in 1987. After 9/21/1999 strong earthquake, the seismic-resistance design rules has been revised three times in 1999, 2005 and 2011. Thus the original design seismic-resistance capability of the tank can't comply with the current rules.

5. Seismic-resistance evaluation and analysis

   Because the service reservoir was seriously damaged, three dimension seismic-resistance capability analyses using 3D model was not carried out.

6. Choice of seismic-resistance reinforcement plan

   Beam-column system structure of reservoir were partly damaged due to extra shear force and moment produced by foundation displacement. To remove and reconstruct a new reservoir is more possible choice because the structure was seriously damaged and the function was completely lost.

7. Cost for reservoir repair and reinforcement

   The capacity of Nao-Guan storage tank is 10,000 m^3. NTD100,000,000 was estimated for rebuild, not including the cost of land which has already been obtained.

8. Relative ordinance

   - Soil conservation

Nao-Guan storage tank is located in Nei-Hu section, Tai-Ping district, Taichung. It belongs to the scope of soil conservation limitation after mapping the extent of hillside issued by Committee of Agriculture, and a soil conservation plan should be provided if the area is exploited.

- Environmental impact assessment

  No matter repair or reconstruction plan be proposed. It is not necessary to execute environmental impact assessment according to the law of environmental impact assessment.

- Building law

  This service reservoir is not a structure for person or public use. So it doesn't belong to the building defined by building law. In this case, it is not necessary to apply for a building permit.

- Geological law

  According to geological law, a site geological investigation and safety evaluation should be executed before land exploitation if the site is totally or partly located in a geological sensitive area.

  The site of Nao-Guan storage tank is located in the susceptive area of active geological fault after mapping the latest active geological fault data. Site geological investigation and geological safety evaluation should be executed.

- Regulation about banning of building

  According to the No.762 meeting record of urban planning committee, both sides within a 15 m limit Che-Long-Pu geological fault line is banned for building.

  The distance after mapping is only 10 m between Nao-Guan storage tank site and Che-Long-Pu geological fault limit region. as shown in figure 5.

To summarize the results of evaluation, if choose to rebuild Nao-Guan reservoir at original site, it is needed to propose soil conservation plan and execute site geological investigation and safety evaluation, although environmental impact assessment is not necessary to implement. On the other hand, it is only 15 m distance between Nao-Guan reservoir and Che-Long-Pu geological fault limit region, although not within the limit region.

According to building technique rule, both sides within 100 m limit of geological fault region, it is not suitable to have any exploitation. So it is also not suitable to construct water facilities near geological fault region.

Again, from picture 6 and 7, it is shown that there is an obvious exposed stratum and ground rupture in the surrounding surface of reservoir. It can be forecasted that if reconstruct reservoir at the original site, it is very possible to have a serious damage when there is an another earthquake happened.

9. Operation requirement

   - Current pipeline situation

     The network hydraulic analysis of average daily demand in Tai-Ping in 2021 is shown in Figure 8, hydraulic analysis of Nao-Guan reservoir is shown in Figure 9. Nao-Guan reservoir elevation is 128 m, the high water level and low water level of design is 129 m and 122.5 m respectively. There is a 1000 mm distribution pipe between pressure-reducing value and this service reservoir, and its distance is 250 m long. The operation head is 140 m before pressure-reducing value, and the operation head is 139.7 m in reservoir inlet.

10. Geology evaluation

    Nao-Guan reservoir is located at hillside, its elevation is 128 m. There is a 3 m pebble and gravel lay on the top of soil (Figure 10), rock characteristic is siltstone intersperse with thin shale strata (Figure 11). This rock stratum is mild to middle weathering, and stratification of stratum is still clear to be identified. The relative position of Che-Long-Pu geological fault and Nao-Guan reservoir is shown in Figure 7. From the point of geological condition view, the site of original Nao-Guan reservoir is located in active geological fault susceptible region, and it is not suitable to reconstruct reservoir in the original site.

Conclusion

It has been almost 27 years since Nao-Guan reservoir completed in 1987. During this period of time, it encountered 21/09/1999 strong earthquake, and it is one of few water facilities that haven’t been repaired after 21/9/1999 earthquake. The reason is that Nao-Guan reservoir was seriously damaged at that time. Several alternatives are proposed including repair, reconstructing at the same place and finding a new site to construct new reservoir, and many aspects must be considered including location, structure safety, future operation requirement, geological feature, regulation limits and economics. After detail evaluation, repairing the damaged reservoir or reconstructing reservoir at the original site is not suitable. Finding a site to construct a new reservoir is a better proposal.

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Figure 1 Split of top slab from expansion joint

Figure 2 Break in the joint of beam-column joint

Figure 3 Split of basin from expansion joint

Figure 4 split of bottom slab

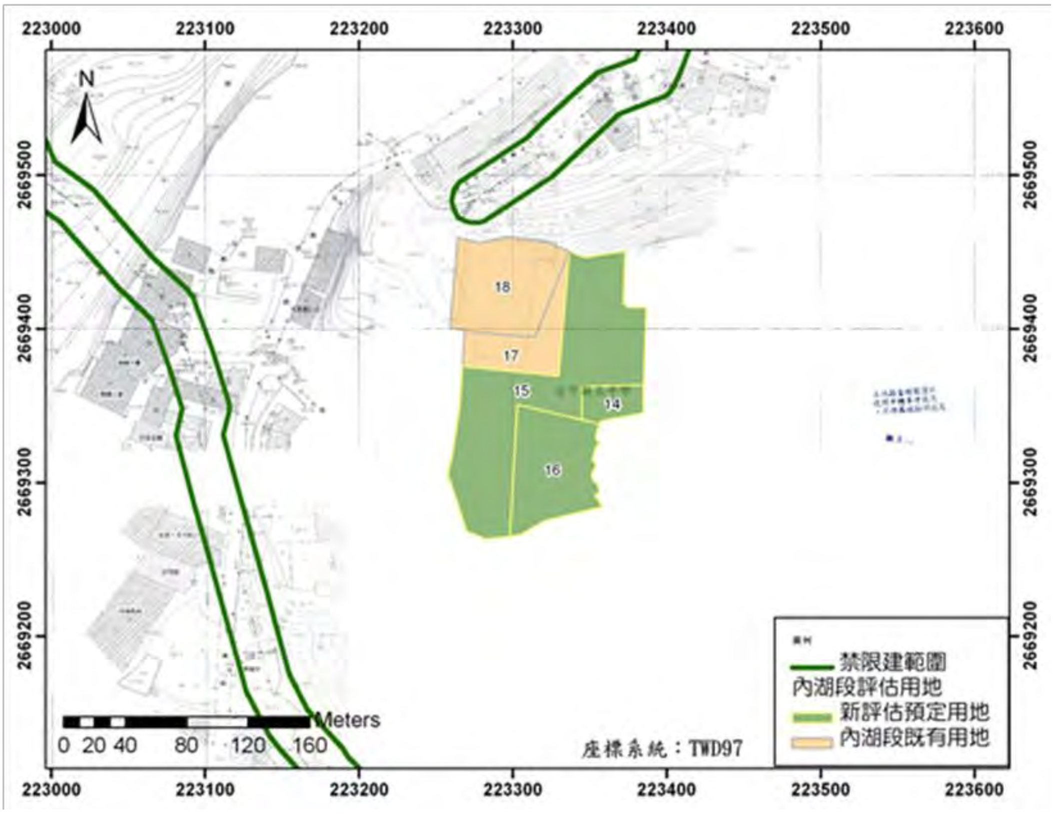

Figure 5 Relative location of reservoir site and region of Chelongpu fault

Figure 6 Rupture of ground in the surrounding surface of reservoir.

Figure 7 Obvious exposed stratum in the surrounding surface of reservoir.

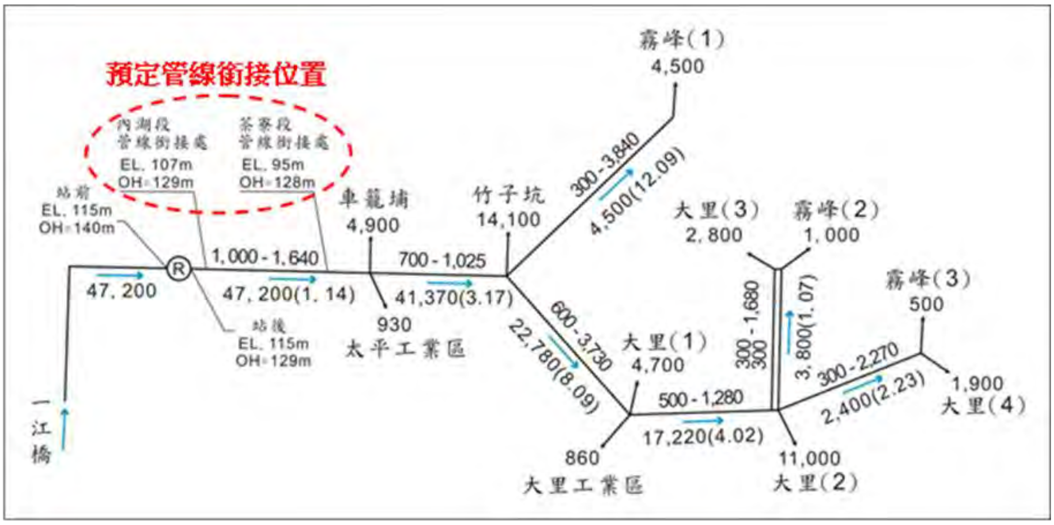

Figure 8 Network hydraulic analysis of average daily demand in Tai-Ping in 2021

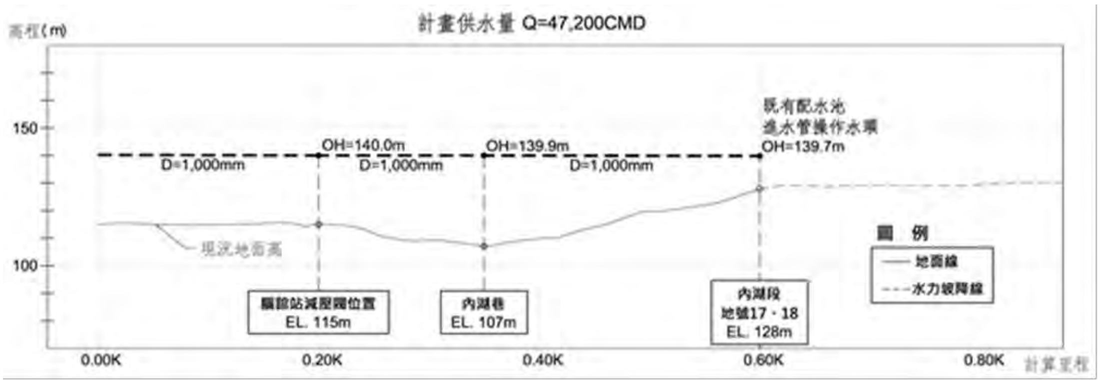

Figure 9 Hydraulic analysis of Nao-Guan reservoir

Figure 10 A 3 m pebble and gravel lay on the top of soil

Figure 11 Siltstone intersperse with thin shale strata in the vicinity of reservoir

The Application of Taiwan Earthquake Impact Research and Information Application Platform for Lifeline Systems

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ABSTRACT

In last decade, several large-scale earthquakes have struck major population areas and caused heavy casualties and losses in many countries. Therefore, to understand the impact and disaster scenarios of assumed large-scale earthquakes to urban areas becomes an urgent and crucial task to the central and local governments of Taiwan. The purpose of this research is to develop an integrated research and application platform, Taiwan Earthquake Impact Research and Information Application (TERIA), which is established to evaluate the impact scenario of earthquakes to the metropolitans in Taiwan. Using TERIA platform in this study, the post-earthquake scenario analysis focused on power and water system as examples. Incorporated with geographic information system (GIS) analysis in 500m×500m grids, the characters of ground shaking and liquefaction for whole area are provided. To conclude with it, the objective of this unique platform is to furnish a comprehensive impact and damage scenario to fulfill the necessary data for planning disaster mitigation strategies and preparedness actions that make the cities in Taiwan more resilient to earthquakes.

Keywords：Earthquake, Impact Scenario, Lifelines, Seismic Response

INTRODUCTION

In last decade, several large-scale earthquakes have struck major population areas and caused heavy casualties and losses in many countries. These natural disasters also revealed the vulnerability of communities, buildings, lifelines, communication and other critical infrastructures, which induced cascading impact and catastrophe unexpectedly. As lessons learnt from these great calamities, to have efficient mitigation strategies and action plans in advance is very important. Therefore, to understand the impact and disaster scenarios of assumed large-scale earthquakes to urban areas becomes an urgent and crucial task to the central and local governments of Taiwan.

Figure 1. TERIA platform (Taiwan Earthquake Impact Research and Information Application)

As an independent administrative institution assigned to bridge research techniques and government information for disaster risk management, National Science and Technology Center for Disaster Reduction (NCDR) has established an integrated framework for earthquake impact scenario assessment and application, named TERIA (Taiwan Earthquake Impact Research and Information Application) platform as shown in Figure 1. A demonstrative exercise via TERIA platform was conducted to assess the impact scenarios of a presumed earthquake M7.0 in Hualien city induced by Milun Fault, which is the drill scenario for National Disaster Prevention Day of Taiwan in 2014. Incorporated with geographic information system (GIS) analysis in 500m×500m grids, the characters of ground shaking and liquefaction for whole urban area were illustrated. The post-quake scenario analysis included building damage, causalities, bridges, roadway system, lifelines, and the emergency relief and response systems…etc. Additionally, the established database and comprehensive assessment scenario can be adopted as a reference for future compound-disaster studies, strategy making, and government policy enactment.

DISASTER RISK MANAGEMENT PROCESS OF EARTHQUAKE

At the boundary of active convergence between the Eurasian and Philippine Sea plates, Taiwan is under intensive threats from earthquakes. Research results have shown the probability of large scale earthquakes in the next fifty years are very high [1]. In 1999, the M7.3 Chi-Chi earthquake occurred at central Taiwan and took away 2,415 lives. More than 11,000 people were wounded, and over 100,000 buildings were completely destroyed or severely damaged. Due to serious damages of infrastructure and lifelines, the performance of emergency response, rescue and relief actions was significantly obstructed. On the other hand, the electronic power system was interrupted, and it caused alternative power outage for more than two weeks in most northern region of Taiwan. The fails of power supply initiated huge business impact to many industries, including the world's largest electronic OEM companies in Hsinchu Science Park and other industrial zones. The direct economic loss due to power outage is about 2 billion USD [2], and the total economic loss caused by this earthquake is 12 billion NTD [3]. As lessons learnt from Chi-Chi earthquake, governmental agencies have supported numerous research work and implemented several important strategies on disaster prevention of urban earthquake.

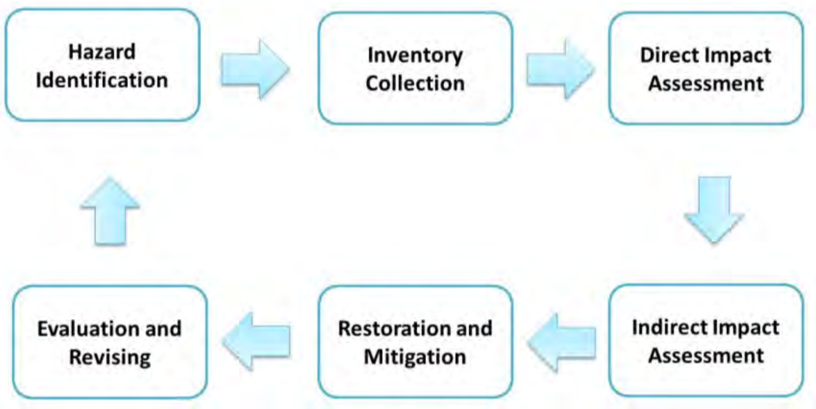


Figure 2. Risk management process on earthquake impact [4]

The process of risk management on earthquake impact is typically expressed into few steps: hazard identification, inventory collection, direct and indirect impact assessment, restoration and mitigation, and evaluation and revising (Figure 2). To implement the process needs interdisciplinary cooperation from geology, earth science and earthquake engineering to identify the probability of earthquake hazard; an comprehensive inventory data collected from governmental and private sectors;

impartial models to assess the direct and indirect impact scenarios; and the implementation of mitigation strategies supported by governments and communities. According to the result of comprehensive scenario investigations and assessments on the assumed large-scale earthquake, the countermeasures and acts on disaster risk reduction are then effectively legislated. In Japan, several disaster-prevention countermeasures have been enacted: the Large-Scale Earthquake Countermeasures Act (LECA), The Earthquake Countermeasures for the East (Japan) Sea, Southern East Japan Sea, and South Japan Sea, and the Earthquake Countermeasures in the Capital Regions [5]. The United States has also promoted the Public Building Safety Act and California Earthquake Hazard Reduction Program [6].

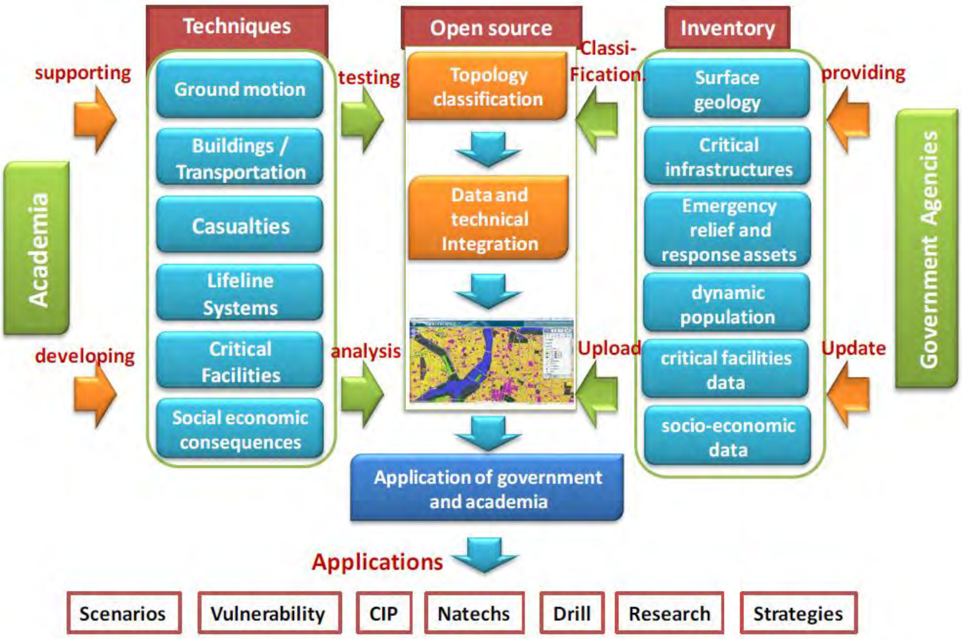


Figure 3. The framework of TERIA platform.

As an independent administrative institution supervised under Ministry of Science and Technology (MOST), NCDR is assigned to integrate scientific knowledge and techniques with government resources, and provides the results to assist strategy and policy making. To aim to this objective, NCDR establishes a platform "TERIA" to incorporate diverse techniques and data for earthquake impact research, and apply the results and information for disaster mitigation and prevention. The stakeholders of TERIA platform include research institutes, private sectors, local government and central government. The development of TERIA platform is purpose-driven, and it is prepared for the national-level drill and preparedness. Its main applications are to support academic research, to enhance assessment models, to study and review the comprehensive earthquake impact scenario, and to apply integrated information and data for the tasks on disaster mitigation and prevention. Figure 3 illustrates the framework of TERIA platform and its applications. As an open-source interface, all the inventory data are protected and expressed in 500m × 500m geospatial grids.

SEISMIC SCENARIOS – SITE SPECIFIC

To demonstrate the operation mechanism of TERIA platform in an early stage, the direct impact scenarios of a presumed M7.0 earthquake in the Hualien city induced by Milun Fault are evaluated. In each 500m × 500m geospatial grid, the distributions of peak ground acceleration, peak ground velocity, and permanent displacement are simulated. The earthquake hazard scenario has included site specific analysis of ground motion. The result of the seismic hazard analysis is graphically shown in Figure 4.

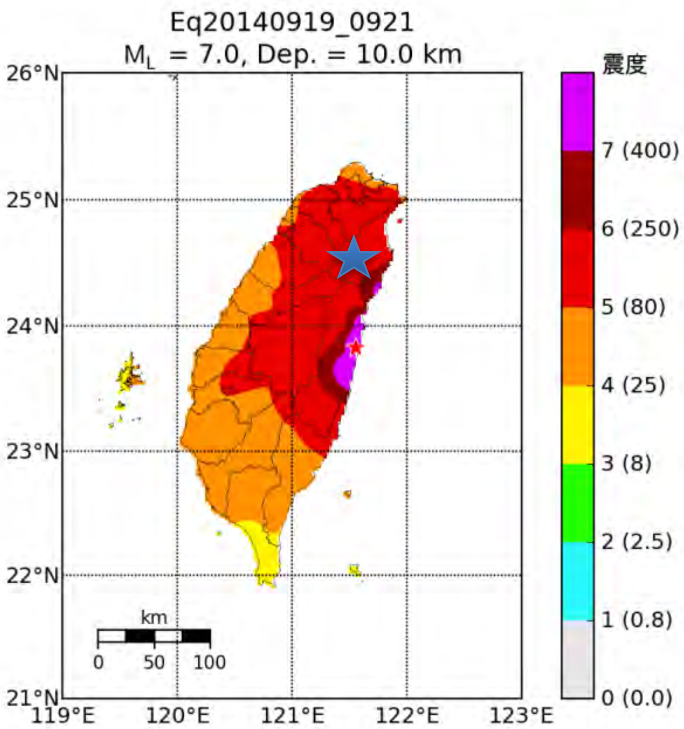


Figure 4. Seismic hazard map: Spatial distribution of PGA.

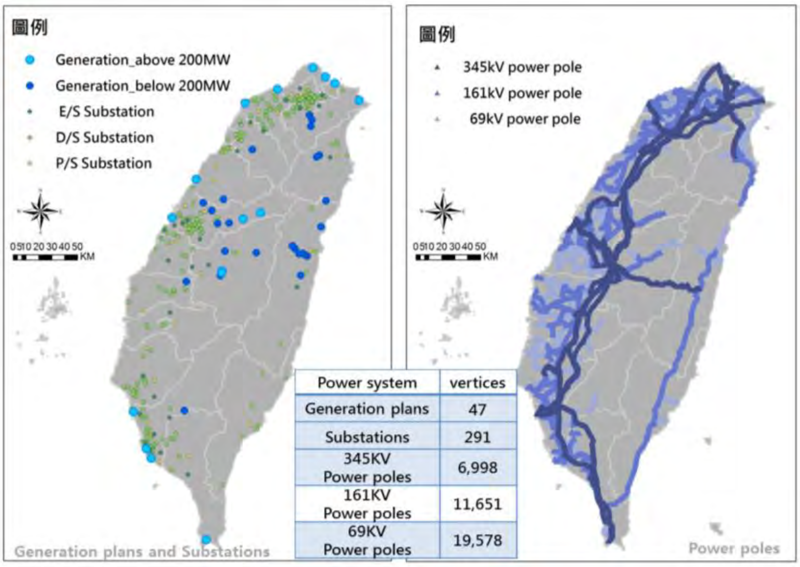
VULNERABILITY ASSESSMENT AND IMPACT SCENARIOS

TERIA is able to analyze and illustrate the direct impact scenarios of buildings, population, bridges, roads, and other infrastructures. The paper focuses on the results about power and water systems.

1. Inventory of lifeline systems in Taiwan

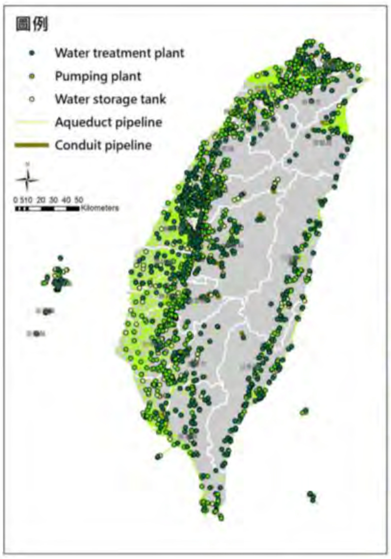
A key component of this study is the inventory data of the Taiwan water and power systems. The source data are gathered from the Taiwan Water Corporation and Taiwan

Power Company. The inventory data present here is the result of processing excel files into GIS data.   The power system data consists of generation plants, substations, power poles, and distribution circuits. On the other hand, the water system data consists of water treatment plants, pumping plants, water storage tanks, and distribution pipes.



Power system	vertices
Generation plans	47
Substations	291
345KV Power poles	6,998
161KV Power poles	11,651
69KV Power poles	19,578

Figure 5. The GIS data sets of Taiwan power system.



Water system	vertices
Water treatment plants	547
Pumping plants	827
Water storage tanks	1,546
Aqueduct Pipelines	33,032
Conduit Pipelines	843

Figure 6. The GIS data sets of Taiwan water system.

2. Application for drill scenario

The areas for the drill scenario of National Disaster Prevention Day of Taiwan in 2014 included Yilan County, Hualien County, Taitung County. Hualien County is classified as a high-risk region where severe impact occured in the scenario simulation.

3. Fragility of lifeline components

The seismic assessment of lifelines systems is to quantify the direct damages related to the seismic hazard intensity. The vulnerability function in this study is probabilistic relationships based on the fragility curves provided in HAZUS-MH MR5(2010), SYNER-G(2011), and TELES(2012) [7,8,9], according the input earthquake hazard scenario [10].

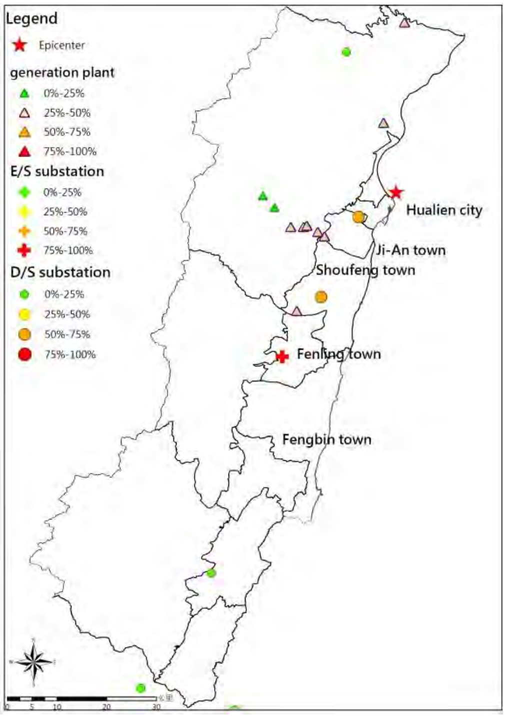


Figure 7. Distribution of expected damages to power system of Hualien county for the seismic scenario.

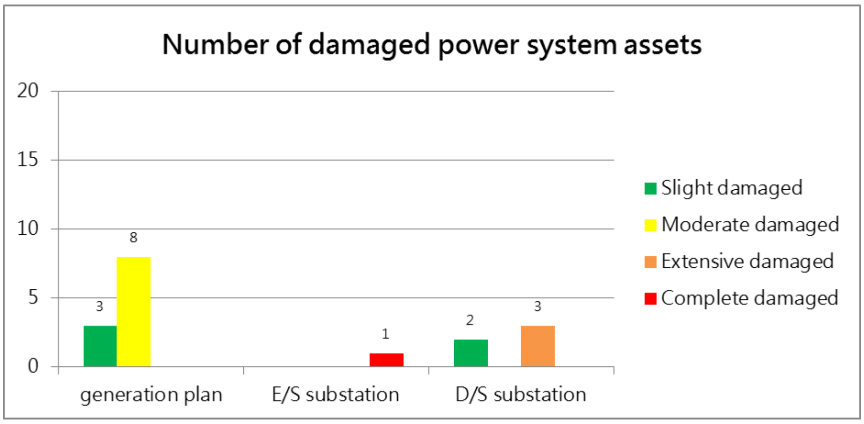


Figure 8. Number of damaged power system assets for the seismic scenario

Most power generation plants and substations response are undamaged. However, few substations are expected to sustain a serious damage under this seismic hazard scenario. This is due to the high values of the peak ground acceleration. According to the damage state of the distribution circuits, it is able to compute how many people are affected. Power outage affected zone such as: Hualien city, Ji-An town, Shoufeng town, Fenling town, and Fengbin town, which are the most affected zones. Further, Fenling E/S, Shoufeng D/S, Sheng-An D/S, and Hualien P/S substations are severely damaged.. The estimated damage status for the power system is shown in Figure 7. The number of damaged power system assets is shown in Figure 8.

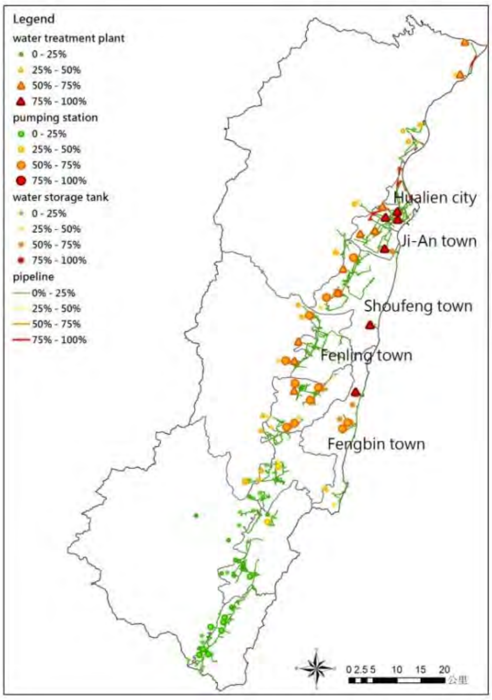


Figure 9. Distribution of expected damages to water system of Hualien county for the seismic scenario.

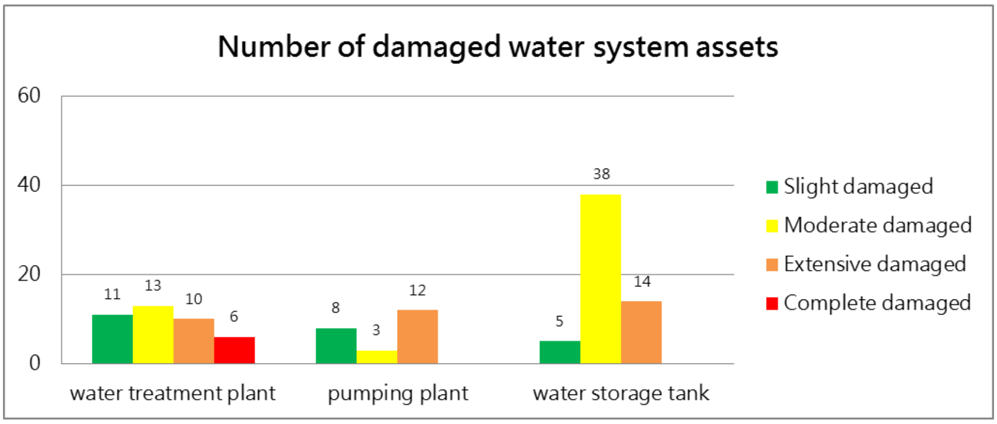


Figure 10. Number of damaged water system assets for the seismic scenario

The majority of water treatment plants, pumping plants, and storage tanks response are undamaged. However, few water treatment plants and pumping plants are expected to sustain serious damage under this seismic hazard scenario. This is due to the high values of the peak ground acceleration. According to the damage state of the distribution pipelines, number of people affected could be computed. Water shortage affected zone such as: Hualien city, Ji-An town, Shoufeng town, Fenling town, and Fengbin town, are the most affected zones. Further, Shanji, Meiluen, Kuangwha water treatment plants are severely damaged.. The estimated damage status for water system is shown in Figure 9. The number of damaged water system assets is shown in Figure 10. The details of the scenario assessments have been documented in the research reports [11,12].

CONCLUSIONS

The task of earthquake impact scenario assessment is crucial and complex. This study introduces a GIS-based earthquake scenario assessment platform which aims to play a collaborated interface between the stakeholders of techniques and data collection. The objective of this unique platform is to furnish a comprehensive impact and damage scenario to fulfill the necessary data for planning disaster mitigation strategies and preparedness actions that make the cities in Taiwan more resilient to earthquakes.

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