# Practical Paper

# Resilient water supply system for earthquake and tsunami

M. Miyajima

## ABSTRACT

This paper focuses on a resilient water supply system for earthquake and tsunami. The 2011 off the Pacific coast of Tohoku earthquake generated not only strong ground vibration but also a tremendous tsunami. Although some of the water supply system suffered damage and water suspension occurred extensively, earthquake-resistant pipes survived and a quick recovery of water delivery was achieved. We must learn many lessons from the earthquake and tsunami disasters and exchange these lessons internationally. In this paper, earthquake performance of the water supply pipeline during the earthquake and tsunami is summarized first. Next, the paper introduces an application of Japan's earthquake-resistant technology in the city of Los Angeles.

**Key words** | earthquake, earthquake-resistant pipe, seismic guideline, tsunami, water supply system

**M. Miyajima**
School of Environmental Design,
Kanazawa University,
Kakuma-machi,
Kanazawa 920-1192,
Japan
E-mail: *miyajima@se.kanazawa-u.ac.jp*

## INTRODUCTION

In Japan, earthquake-resistant technology and seismic design guidelines for drinking water facilities have been advanced and revised based on observed damage in past major earthquakes. Because earthquake-resistant pipes did not suffer damage in recent huge earthquakes such as the 1995 Hyougo-ken Nambu earthquake (Kobe earthquake) and the 2011 off the Pacific coast of Tohoku earthquake (Tohoku earthquake), earthquake resistance of water supply pipelines against earthquake was verified. On the other hand, the 2011 Tohoku earthquake generated a tremendous tsunami and the tsunami hit extensive areas. We must learn new lessons from the tsunami disaster. The present paper summarizes lessons from the recent earthquakes and tsunami. It also discusses a test installation of Japan's earthquake-resistant pipe in the USA to establish resilient water supply systems for earthquake and tsunami.

## DAMAGE TO WATER SUPPLY FACILITIES BY TSUNAMI

### Damage characteristics by tsunami

The 2011 Tohoku earthquake generated a tsunami of unprecedented height and exceptional extent along the northeast coast of Japan. In the majority of flooded areas, residents have not been able to return home after the event because most buildings and houses have been washed away. As a result, there has been no need to distribute water in these areas, and most of the damaged pipelines have been left unrepaired. Thus we have not been able to collect the entire data of damage to water supply pipelines. So far, the following damage has been revealed.

Causes of damage by the tsunami are roughly classified into three categories: inundation, washing away, and scouring of surface ground. Some intake facilities were inundated and have not functioned for a long time because of a high concentration of sodium chloride in groundwater (Figure 1). Figure 2 shows damage to a water pipe bridge, which was completely washed away. It is unknown as yet what caused this kind of damage, water pressure, floating wreckages or both. We need to study the force acting on the water pipe bridge during the tsunami through damage analysis. Figure 3 shows damage to a buried pipeline. The pipe was exposed as the covering soil had been scoured by the tsunami. The mechanism of damage to the pipe, that is, how much force was acting on the pipe in what way, is still unknown and awaits clarification in the future.

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**Figure 1** | Inundated intake facilities (Sukedukuri No. 2).

**Figure 2** | Washed-away water pipe bridge.

**Figure 3** | Damage to pipe by tsunami-induced scouring.

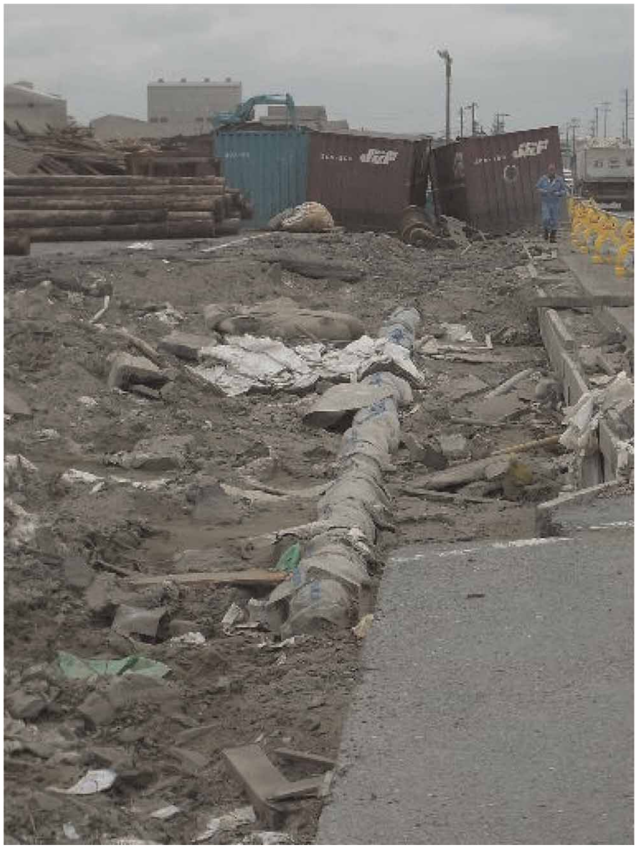

**Figure 4** | ERDIP exposed above ground.

## Field survey of surviving earthquake-resistant pipes from tsunami

The earthquake-resistant joint ductile iron pipes (ERDIP) did not suffer damage at all in the 2011 Tohoku earthquake. A field survey was conducted on surviving ERDIP buried in the tsunami-hit area at Ishinomaki City in Tohoku region. Figure 4 shows an ERDIP exposed above ground surface by scouring caused by the tsunami. The exposed pipelines were covered by debris of crushed wooden houses and a steel container as shown in Figure 5. This pipeline is ERDIP with 300 mm of nominal diameter, installed in 2010. Deformation of pipeline, displacement, and bending angle at each joint were measured for 14 pipes as shown in Figure 6.

**Figure 5** | ERDIP covered by debris.

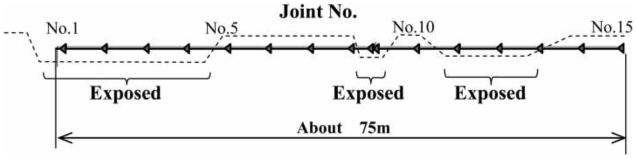

**Figure 6** | Profile of ERDIP with 300 mm diameter. (Dashed line indicates the level of the ground surface after the earthquake.)

Figure 7 illustrates the horizontal distance to a pipeline from the edge of a road before and after the earthquake. Because the road was not dislocated horizontally or deformed by the earthquake and tsunami, this figure indicates that the pipeline moved about 40 cm. Figure 8 shows the bending angles at joints measured in the field. The maximum bending angle is 7.5 degrees at joint No. 11. It appears that the pipeline was exposed above ground by the scouring, hit by a steel container and debris in the undertow of the tsunami, and moved to the coastline. There was, however, no damage to ERDIP and water suspension did not occur.

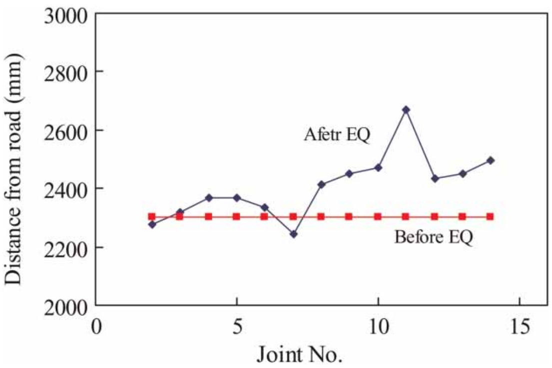

**Figure 7** | Distance to the pipeline from a road edge before and after the earthquake.

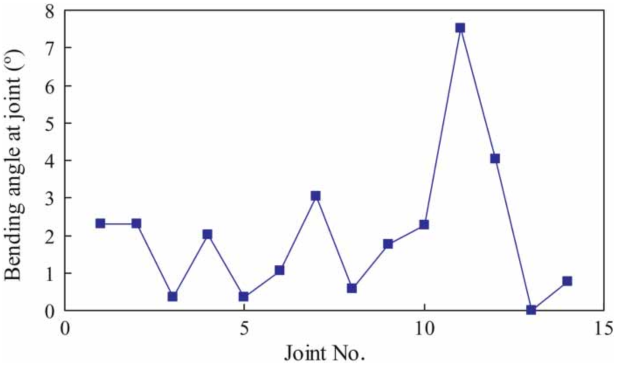

**Figure 8** | Bending angle at joint measured at the field.

## DAMAGE TO WATER SUPPLY PIPELINE IN STRONG GROUND MOTION AREA

The maximum JMA (Japan Meteorological Agency) seismic intensity of this earthquake was 7, which was recorded in Kurihara City, Miyagi prefecture. 7 is also the maximum grade of JMA scale. The JMA seismic intensity in the surrounding Osaki City, Tome City, and Wakuya Town was 6 + . The damage to buried pipeline in those municipalities, including Kurihara City, is discussed here. Figure 9 illustrates the distribution of JMA seismic intensity estimated by QuakeMap (National Institute of Advanced Industrial Science and Technology) and sites of damaged water supply pipeline in the four municipalities. JMA seismic intensity estimated by QuakeMap is given in each 250 m cell. Table 1 lists the number of cells by each level of JMA seismic intensity. According to QuakeMap, 7.6, 33.6, and 23.8% of the total area marks the JMA seismic intensity of 7, 6 + , and 6 – , respectively.

The main types of buried water pipes in Japan are ductile cast iron pipes (DIP), gray cast iron pipes (CIP), steel pipes (SP), polyethylene pipes (PE), polyvinyl chloride pipes, and asbestos cement pipes (ACP). Figure 10 illustrates an accumulated damage rate of each pipe type. This figure indicates that the damage to pipelines starts to occur at 5+ of JMA seismic intensity and the damage rapidly increases at 6 + .

A microtopography classification map of surface ground by J-SHIS (National Research Institute for Earth

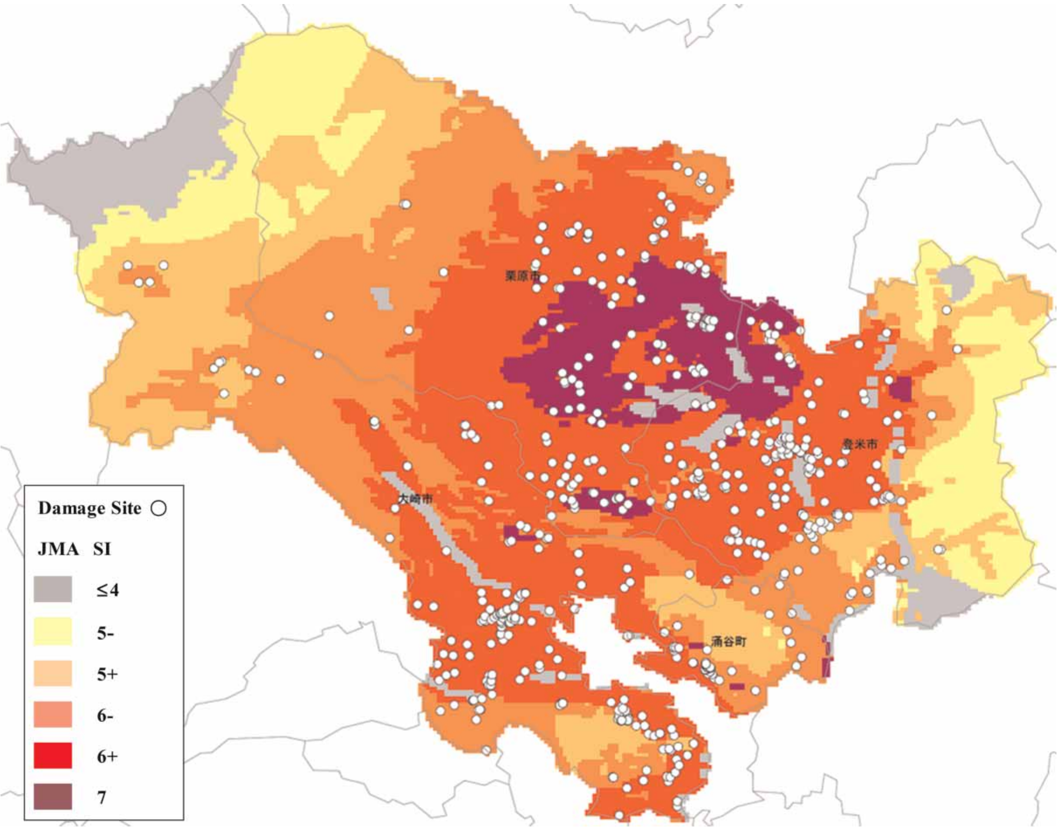

**Figure 9** | Distribution of JMA seismic intensity and sites of damage.

**Table 1** | Number of cells in each level of JMA seismic intensity

| JMA SI | Kurihara city | Osaki city | Tome city | Wakuya town | Sum | Percentage (%) |
|---|---|---|---|---|---|---|
| Others | 156 | 297 | 543 | 35 | 1,031 | 2.8 |
| ≤4 | 80 | 1,403 | 294 | | 1,777 | 4.8 |
| 5 – | 1,448 | 855 | 1,902 | 12 | 4,217 | 11.4 |
| 5 + | 1,647 | 2,486 | 1,292 | 465 | 5,890 | 16.0 |
| 6 – | 3,452 | 3,456 | 1,209 | 672 | 8,789 | 23.8 |
| 6 + | 4,315 | 4,814 | 3,026 | 243 | 12,398 | 33.6 |
| 7 | 2,137 | 29 | 622 | | 2,788 | 7.6 |
| Sum | 13,235 | 13,340 | 8,888 | 1,427 | 36,890 | 100.0 |

Science and Disaster Prevention) is used here. These data are also organized in 250 m cells. Microtopography classification can be divided into two categories: Bad (soft ground in which pipe is susceptible to earthquake damage) and Good (ground type other than Bad), as shown in Table 2. Figure 11 illustrates the distribution of ground categories, JMA seismic intensity, and the sites of damage. Much damage occurred at the boundary between Bad of more than 5+ and Others. Figure 12 illustrates a comparison of damage rate by pipe type in the two

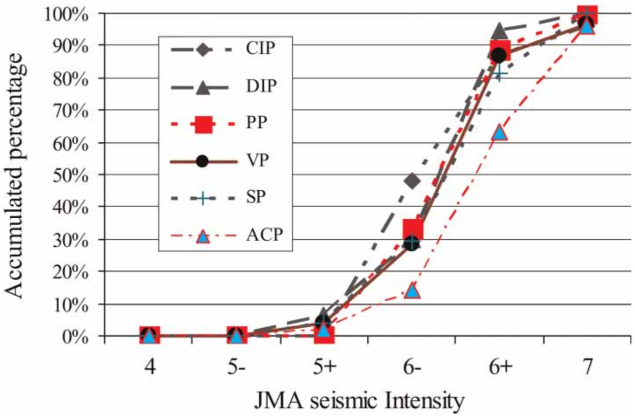

**Figure 10** | Accumulated damage rate of each pipe type.

**Table 2** | Microtopography classification and its categories

| No | Microtopography | Category |
|---|---|---|
| 1 | Mountains | Good |
| 2 | Piedmont areas | |
| 3 | Hill | |
| 4 | Volcanic areas | |
| 5 | Volcanic piedmont areas | |
| 6 | Volcanic hills | |
| 7 | Mesa | |
| 8 | Quality gravel plateau | |
| 9 | Loam plateau | |
| 10 | Lowland valley | Bad |
| 11 | Alluvial fan | |
| 12 | Natural levee | |
| 13 | Backswamp | |
| 14 | Old River Road | |
| 15 | Delta and coastal lowland | |
| 16 | Reef and in gravel | |
| 17 | Dune | |
| 18 | Reef and between the lowland dunes | |
| 19 | Reclaimed land | |
| 20 | Filled land | |
| 21 | Rocky and reef | |
| 22 | Riverside | |
| 23 | River channel | |
| 24 | Lake | |

microtopography classification categories. This figure suggests that the damage rates in Bad are much greater than those in Good.

Table 3 lists a piping length in each level of JMA seismic intensity, categories of microtopography classification, and pipe type. There was no damage to ERDIP and fusion-bonded polyethylene pipe in this earthquake. According to Table 3, about 45 km of ERDIP and about 15 km of fusion-bonded PE survived in the strong ground motion area where JMA seismic intensity was more than 6− and the microtopography classification category was Bad.

## EARTHQUAKE-RESISTANT DESIGN AND TECHNOLOGY

Seismic design guidelines for drinking water facilities have been revised several times based on lessons learned from past major earthquakes. The 1995 Kobe earthquake had a significant impact on earthquake-related policies in Japan because it was the first earthquake in Japan's history to directly hit a modern large city, Kobe. Promptly after the event, in 1997, major revisions were made to the seismic design guidelines with the concepts of Level 1 and Level 2 earthquake ground motion and Rank A and Rank B facility importance ratings newly introduced. As a result, the earthquake-resistant performance was regulated as listed in Table 4 (Japan Water Works Association 1997).

Experiences of hazardous earthquakes have also advanced earthquake-resistant technology for water pipelines. DIP accounts for 60% of all the buried pipes. Since earthquake damage to these pipes primarily consists of pull-out at joint, joint structures have been improved following major earthquakes. DIP joints are mainly divided into Types A, T, K, S, S-II, NS, and GX (Table 5). Older joints of Types A, T, and K do not have a joint disengagement prevention mechanism. On the other hand, Types S and S-II, developed more recently in 1982 (Figure 13) are seismic joints with high earthquake resistance, bending and expanding substantially to accommodate differential settlement of soft ground and large ground deformation induced by liquefaction, keeping pipes from being pulled

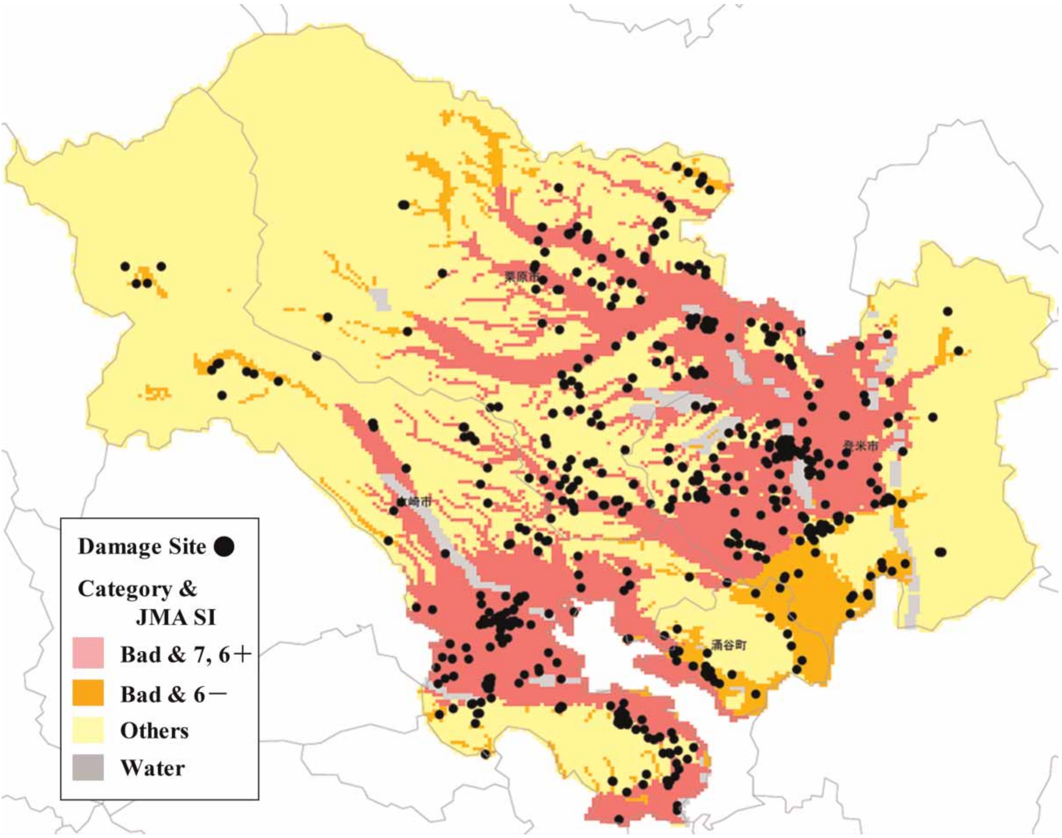

**Figure 11** | Distribution of ground categories, JMA seismic intensity, and the sites of damage.

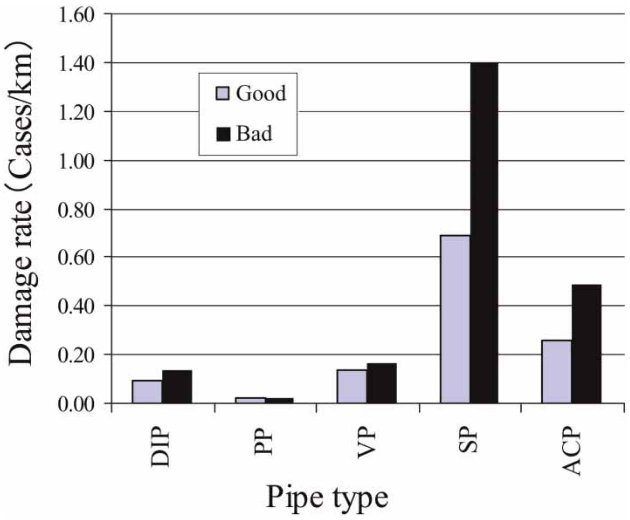

**Figure 12** | Comparison of damage rate of each pipe type in microtopography classification category.

out of the joint. In the wake of the 1995 Kobe earthquake, an easy-to-install Type NS joint was developed to promote widespread use of seismic pipes. In the Kobe earthquake and the 2011 Tohoku earthquake, no damage was caused to these three seismic pipes, demonstrating their high earthquake resistance. The most recent development of seismic DIP joint is Type GX.

## APPLICATION OF EARTHQUAKE-RESISTANT TECHNOLOGY IN LOS ANGELES

ERDIP is available and used only in Japan. A Japanese pipe manufacturing company and the Los Angeles Department of Water and Power (LADWP) have, however,

**Table 3** | Piping length in each level of JMA seismic intensity, categories of microtopography classification, and pipe types

| Category | JMA SI | CIP | DIP (ERJ) | DIP | PE (Fusion) | PP | VP | SP | SUS | ACP | Others | Sum |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Good | <4 | | 1,499 | 1,232 | 12 | 4,860 | 10,915 | 180 | 75 | 52 | 0 | 18,825 |
| | 4 | | | | | 435 | 445 | 0 | | | 0 | 881 |
| | 5 − | | 1,076 | 10,020 | 409 | 4,949 | 17,681 | 892 | 34 | 35 | 0 | 35,095 |
| | 5 + | 627 | 4,767 | 45,326 | 9,500 | 23,730 | 115,270 | 3,116 | 132 | 4,726 | 41 | 207,235 |
| | 6 − | 404 | 14,017 | 90,504 | 9,083 | 63,873 | 265,575 | 5,561 | 306 | 10,929 | 1,118 | 461,380 |
| | 6 + | 930 | 11,337 | 82,438 | 5,687 | 57,004 | 357,647 | 2,667 | 92 | 14,935 | 275 | 533,009 |
| | 7 | | 900 | 21,545 | 613 | 10,029 | 79,164 | 682 | | 15,743 | 53 | 128,730 |
| Sum of Good | | 1,961 | 33,596 | 251,064 | 25,304 | 164,880 | 846,696 | 13,098 | 639 | 46,420 | 1,487 | 1,385,154 |
| Bad | ≤4 | 536 | 842 | 17,739 | 1,572 | 13,663 | 54,481 | 2,831 | 560 | 3,985 | 14 | 96,223 |
| | 5 − | | | 113 | | 200 | 587 | 30 | 10 | | 0 | 940 |
| | 5 + | | 1,905 | 14,022 | 2,576 | 16,908 | 42,309 | 1,255 | 331 | 562 | 101 | 79,967 |
| | 6 − | 4,344 | 20,551 | 87,439 | 16,536 | 68,613 | 288,032 | 7,157 | 778 | 10,648 | 176 | 504,358 |
| | 6 + | 15,863 | 44,501 | 329,648 | 13,155 | 142,744 | 839,706 | 15,029 | 1,545 | 34,686 | 592 | 1,437,468 |
| | 7 | 4,499 | 1,974 | 38,234 | 1,614 | 28,999 | 154,013 | 1,582 | 140 | 23,753 | 333 | 255,139 |
| Sum of Bad | | 25,241 | 69,773 | 487,195 | 35,453 | 271,127 | 1,379,127 | 27,884 | 3,364 | 73,632 | 1,215 | 2,374,096 |
| Sum | | 27,202 | 103,369 | 738,259 | 60,757 | 436,007 | 2,225,824 | 40,982 | 4,004 | 120,052 | 2,702 | 3,759,250 |

**Table 4** | Level of required earthquake-resistant performance

| Degree of importance | Earthquake level<br>Level 1 | Level 2 |
|---|---|---|
| Rank A | Operational capacity is not affected. | Seismic damage is minor and does not severely affect operational capacity. Restoration requires minimum effort. |
| Rank B | Seismic damage is minor and does not severely affect operational capacity. Restoration requires minimum effort. | Seismic damage is minor and does not severely affect operational capacity, but restoration is necessary. |

Level 1: The maximum level of earthquake which may occur during the service period of the facility

Level 2: The maximum level of earthquake which may occur at the site of the facility in the future. Generally, level 2 ≥ level 1.

Rank A: High-priority facilities (such as intake stations, purification plants, and trunk pipelines)

Rank B: Other facilities.

**Table 5** | Characteristics of different joint types

| Joint type | Characteristics |
|---|---|
| A | A rectangular rubber gasket is placed around the socket and the joint bolts are tightened with a gland. |
| T | A rubber gasket is placed around the socket and the spigot is inserted into the socket. |
| K | A modified version of Type A. This has only a rubber gasket in which a rectangular and a round one are combined. |
| S, S-II | A rubber gasket and a lock ring are placed around the socket and the spigot is inserted into the socket. The joint has good earthquake resistance with high elasticity and flexibility and a disengagement prevention mechanism. |
| NS | The same level of earthquake resistance as Type S but is easier to install. |
| GX | Even easier to install than Type NS and has a longer service life. |

collaborated on a proposal to implement a pilot project to install ERDIP in Los Angeles. LADWP would be the first to use ERDIP in the USA. The purpose of the pilot project is to allow the LADWP to become acquainted with the ERDIP, to obtain direct observations and experience of the design and installation procedures, to compare the

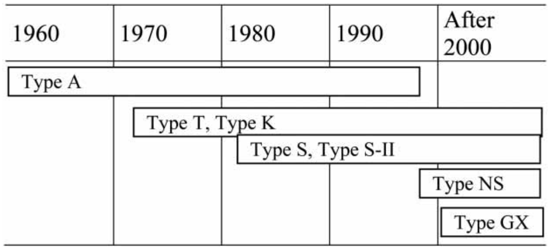

**Figure 13** | History of DIP joints.

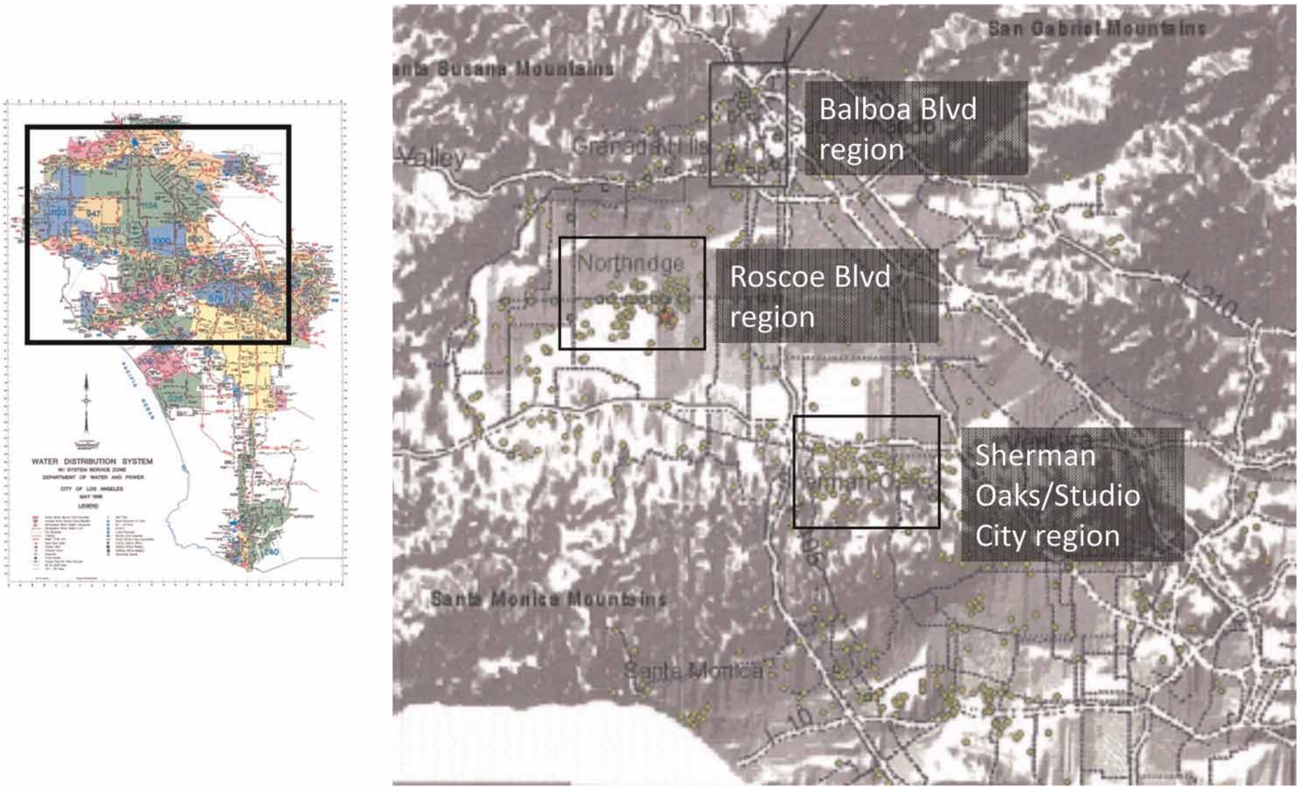

**Figure 14** | Locations of pilot projects in Los Angeles.

design and installation of ERDIP with pipes normally installed by LADWP, and to make their own assessment on suitability for using the ERDIP to improve network reliability.

The pilot project first started to identify areas damaged by ground failure during the 1994 Northridge earthquake, such as Balboa Blvd region, Roscoe Blvd region and Studio City/Sherman Oaks region as shown in Figure 14 (Davis 2012). Then, two pilot areas were determined: relatively level ground in San Fernando Valley (Roscoe or Balboa Blvd) and sloped and curving roads in Studio City/Sherman Oaks area.

The pilot project in Roscoe Blvd and Reseda Blvd aims at direct comparison of installing standard US manufactured push-on DIP with Japanese ERDIP in the same street with the same diameter pipe with the same crews and improving the seismic performance of an area previously damaged from permanent ground deformations. The proposed main replacement in Contour Drive is not completely consistent with the proposed long-term seismic improvement program, but is consistent with the pilot project for benchmarking pipe installation in a hillside area while meeting current pipe replacement needs.

## CONCLUSIONS

In the past 20 years, the water supply system in Japan has experienced huge earthquakes such as the 1995 Kobe earthquake and the 2011 Tohoku earthquake, which was followed by a tsunami. We have learned many lessons from the disasters and the damage analysis is still being conducted. Challenges posed by earthquake and tsunami are not specific to Japan but are faced by many other countries around the Pacific Ocean, such as New Zealand, the USA (California), China, Taiwan, etc. Therefore, we must continuously exchange lessons learned from these damaging events and collaborate to establish resilient water supply systems for earthquake and tsunami.

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