Proceedings of the Tenth Pacific Conference on Earthquake Engineering
Building an Earthquake-Resilient Pacific
6-8 November 2015, Sydney, Australia

Vulnerability analysis of water distribution pipes based on the damage dataset compiled for Sendai City after the 2011 off the Pacific coast of Tohoku earthquake

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ABSTRACT: Water supply was disrupted for approximately 2.2 million households after the 2011 off the Pacific coast of Tohoku earthquake. In Sendai City in the Miyagi Prefecture, which is the most populated city in Tohoku District, 437 pipe breakages were found after the event. This study investigates the seismic vulnerability of water distribution pipelines based on the damage dataset compiled by the Sendai City Waterworks Bureau. The fragility functions of water distribution pipes commonly used in Japan have correction coefficients for the pipe material, diameter, geological condition, and liquefaction occurrence. These coefficients were determined by previous studies primarily after the 1995 Kobe earthquake. This study performs a series of Monte Carlo simulations to evaluate the seismic vulnerability of water distribution pipelines with respect to the pipe material, diameter and geological condition. Poisson-distributed random variables are generated to simulate the number of pipe breakages for each 250 × 250 m^2 grid cell. From the results, the seismic vulnerability of water distribution pipelines is evaluated with respect to pipe material, diameter, and geological condition. This can be helpful in determining strategies of updating buried pipes depending on site conditions and expected ground motion intensities for future earthquakes.

1 INTRODUCTION

Lifeline facilities such as electric power supply, water supply, sewage, city gas supply, and telecommunication systems were severely affected by the 2011 off the Pacific coast of Tohoku earthquake. The water supply was disrupted for approximately 2.2 million households (JWWA, 2011). According to the report by the Japan Water Works Association in 2011, disruption rates of more than 75% were observed for the water-supply areas in Tohoku District. The water supply was restored by the end of September 2011 except for the areas affected by tsunami (JWWA, 2011).

Sendai City in the Miyagi Prefecture, which is the most populated city in Tohoku District, was affected by both an earthquake and a tsunami. The total number of casualties in Sendai City was approximately 900 (as of March 31, 2014), and most were due to the tsunami. There were 5,728 building lots in the hilly areas of the city that were damaged by ground movement (Sendai City, 2014). Incidents of damaged buried pipes were concentrated in the hilly areas in Sendai City as well.

In Japan, different kinds of empirical fragility functions for water distribution pipelines (Isoyama *et al.*, 2000; Takada *et al.*, 2001; Maruyama *et al.*, 2011) are employed to improve earthquake security and establish a disaster mitigation plan. These methods use government estimations of water supply disruption periods. The fragility functions include correction coefficients for pipe material, diameter, geological condition, and liquefaction occurrence in order to determine variations in seismic vulnerability for buried pipes. These coefficients were determined empirically mainly after the 1995 Kobe earthquake. Vulnerability factors for water distribution pipelines, which are estimated from the correction coefficients of the fragility functions, are employed to evaluate nationwide seismic vulnerabilities of the water supply network (Nojima, 2008).

This study evaluates the seismic vulnerability of water distribution pipelines based on the damage dataset compiled by the Sendai City Waterworks Bureau after the 2011 earthquake. The inventory of

Table 1. Summary of damage incidents to water distribution pipes in Sendai City after the 2011 earthquake off the Pacific coast of Tohoku.

Pipe material	Damage to pipe body	Joint loosening	Others	Total	Length (km)
DIP (Ductile cast iron pipe)	27	84	6	117	2723.1
VP (Vinyl pipe)	244	45	8	297	1514.5
GP (Galvanized pipe)	4	1	1	6	4.9
SP (Steel pipe)	1	4	7	12	137.3
Others	3	1	1	5	78.2
Total	279	135	23	437	4458.0

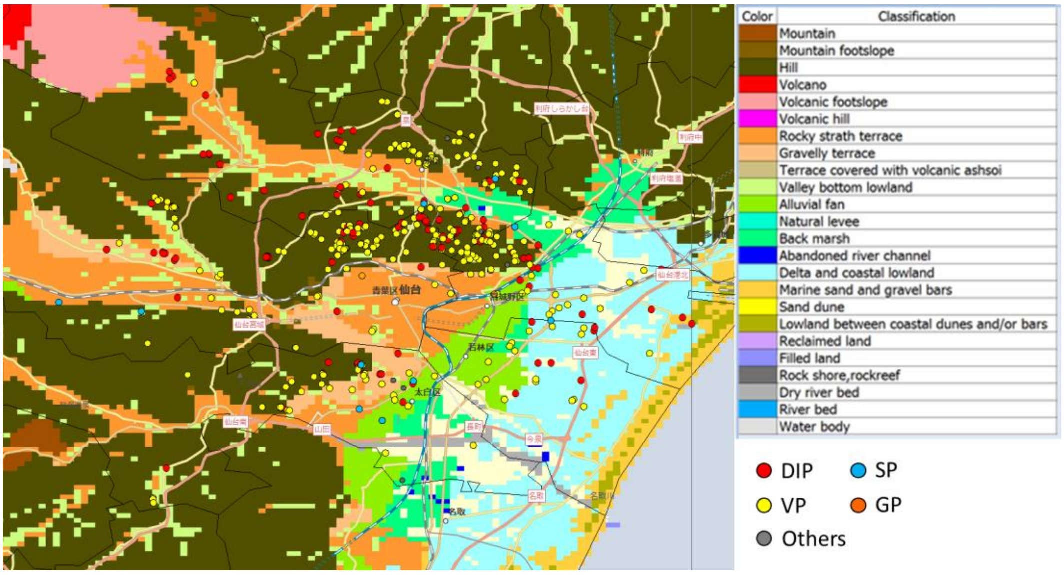

Figure 1. Locations of damage incidents to water distribution pipes in Sendai City after the 2011 off the Pacific coast of Tohoku Earthquake.

the buried pipes, which can be projected onto a geographic information system (GIS), is also employed in this study. A series of Monte Carlo simulations is performed by generating Poisson-distributed random variables to re-create the number and the locations of damage incidents for the distribution pipes. The mean of the random variables is assumed to follow the empirical fragility curve, which is a function of the peak ground velocity (PGV) of ground motion. A random variable is assigned for each 250 × 250 m grid cell in the water-supply area. The seismic vulnerability of the distribution pipelines is evaluated with respect to pipe material, diameter, and geological condition.

2 DAMAGE TO WATER DISTRIBUTION PIPELINE IN SENDAI CITY, MIYAGI PREFECTURE

The water supply system was interrupted for approximately 230 thousand households in Sendai City, which corresponds to a disruption rate of 50%. In total, 437 pipe breakages in the distribution pipelines were found to have been caused by this earthquake (Sendai City Waterworks Bureau, 2012). Table 1 summarizes the damage incidents to the distribution pipes in Sendai City. Ductile cast iron pipes (DIP) and polyvinyl chloride pipes (VP) were mainly installed in the water-supply area. Approximately 95% of the damage incidents were for these two kinds of pipes. It should be noted that there were no pipe breakages for DIPs that had earthquake resistant joints.

Figure 1 shows the locations of the damage incidents to the distribution pipes in Sendai City. In the figure, the Japan Engineering Geomorphologic Classification Map (JEGM) (Wakamatsu and Matsuoka, 2013), which consists of 250 × 250 m grid cells, is also shown. Damage to the distribution pipes is observed in areas such as alluvial fan, delta and coastal lowlands. Additionally, incidents are especially concentrated in areas classified as hilly.

A previous study by the authors (Maruyama *et al.*, 2014) detected hilly areas, which were developed by cutting and leveling the hills and filling the valleys for residential use, using the land utilization segmented mesh data provided by the National Land Numerical Information (MLIT, 2015) and by JEGM. The concentration of damage incidents for distribution pipes in the developed hilly areas was evaluated. The results show that the damage ratio of water distribution pipelines, which is defined as the number of damage incidents per kilometer, was 0.23 for the developed hilly areas while that for the entire of the city was 0.1.

3 COMPARISON BETWEEN THE DAMAGE RATIOS AND EMPIRICAL FRAGILITY FUNCTION

3.1 Fragility function of water distribution pipe

One of the most important lessons learned after the recent earthquakes is the need to develop a restoration strategy for various lifeline facilities. In order to achieve this, an estimation of damages that can occur in the event of an earthquake is required. Physical loss estimations are also helpful in controlling supplies and for a rapid response immediately following an earthquake. In the Hazus Earthquake Model, which is a nationally applicable standardized methodology for estimating potential losses from earthquakes (FEMA, 2015) damage functions for buried pipelines are defined with respect to ground motion intensity.

To estimate the damage ratios of water pipes, the following formula is commonly used in Japan (Isoyama *et al.*, 2000). The damage ratios are calculated considering different types of material, ranges of diameter, geological conditions, and extent of liquefaction.

$$R_m(v) = C_p C_d C_g C_l R(v) \qquad (1)$$

where R_m is the damage ratio, C_p, C_d, C_g, and C_l are correction coefficients for the pipe material, diameter, geological condition, and liquefaction occurrence, respectively, and v is the PGV of ground motion. $R(v)$ is the estimate for the damage ratio of cast iron pipe (CIP) with a diameter in the range of 100–150 mm. Using the damage dataset for the 1995 Kobe earthquake, Isoyama *et al.* (2000) obtained the following result for $R(v)$. Similar functions are also proposed in other studies (Takada et al., 2001 and Maruyama et al., 2011).

$$R(v) = 3.11 \times 10^{-3} (v - 15)^{1.30} \qquad (2)$$

Table 2 shows an example of the correction coefficients, which were originally proposed by Isoyama *et al.* (2000) and revised by the Japan Water Research Center after the 2011 Tohoku earthquake (JWRC, 2013).

3.2 Relationship between damage ratio and peak ground velocity

The ground motion records in Sendai City during the 2011 Tohoku earthquake were compiled in a previous study (Maruyama *et al.*, 2014). Figure 2 shows the locations of seismic observation stations colored with respect to the PGV. The previous study defined the area associated with each seismic observation station, where the equivalent PGV was expected considering topographical conditions.

The damage ratios of the water distribution pipelines were calculated with respect to the PGV. The range of the PGV was set to be approximately 10 cm/s, and the damage ratios were obtained for DIP and VP while taking into account the range of diameter following the definition of the correction coefficients in Table 2. Table 3 shows the number of damage incidents, pipe lengths, and damage ratios with diameters in the range of 100–150 mm for PGV. The damage ratios for VP were defined taking into account the different types of joints; taper socket (TS) and rubber ring (RR) joints. The results are shown with respect to the zones defined in Table 2. No areas were classified as Zone 5 in Sendai City. Only the damage ratios in the developed hilly areas for residential use (Maruyama *et al.*, 2014) were calculated for Zone 1, because all the damage incidents in Zone 1 were found to be in the developed hilly areas.

Table 2. Examples of correction coefficients for the fragility function of water distribution pipeline.

Pipe material	Correction coefficient (C_p)
DIP	0.3
VP	1.0
CIP	1.0
SP	0.3
ACP (asbestos cement pipe)	1.2

Diameter (mm)	Correction coefficient (C_d)
50-80	2.0
100-150	1.0
200-250	0.4
300-450	0.2
500-900	0.1

Liquefaction	Correction coefficient (C_l)
None liquefaction	1.0
Partial liquefaction	2.0
Total liquefaction	2.4

Zone	Japan engineering geomorphologic classification	Correction coefficient (C_g)
1	Mountain, Mountain footslope, Hill, Volcano, Volcano footslope, and Volcanic hill	0.4
2	Gravelly terrace, and Terrace covered with volcanic ashsoil	0.8
3	Valley bottom lowland, Alluvial fan, Back marsh, and Delta and coastal lowland	1.0
4	Natural levee, Abandoned river channel, Marine sand and gravel bars, and Sand dune	2.5
5	Filled land, Reclaimed land, and Water body	5.0

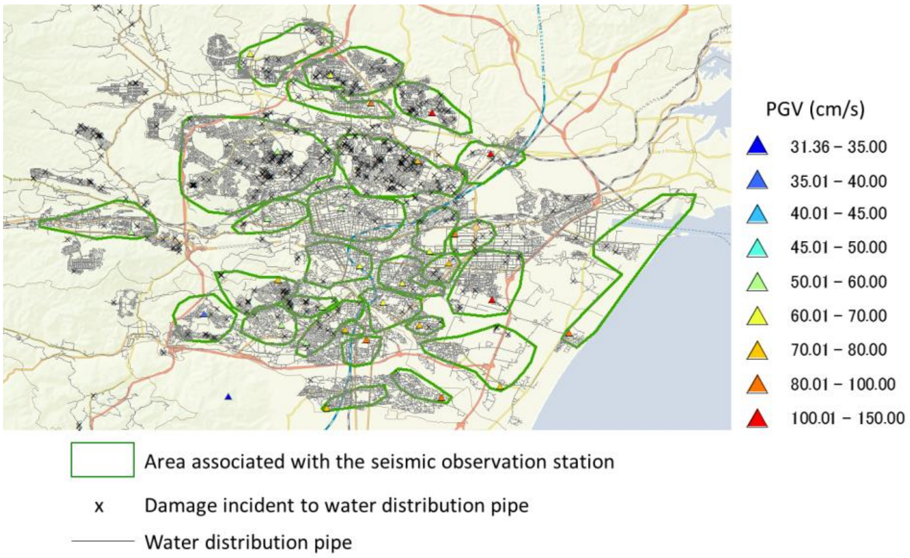

Figure 2. Locations of seismic observation stations in Sendai City and their peak ground velocities during the 2011 off the Pacific coast of Tohoku earthquake.

In Figure 3, the damage ratios of pipes with diameters in the range of 100–150 mm in Sendai City are compared with the empirical fragility function developed by Isoyama *et al.* (2000). The fragility functions are used for different C_g's with C_d set to 0.3 for DIP and 1.0 for VP. Some of the ratios may not be statistically significant to represent the seismic performance because the lengths are not long enough. To draw a solid conclusion, the ratios should be screened properly. The damage ratios in the developed hilly areas, which are classified as hills in JEGM, are larger than those for other zones despite using the correction coefficient value of 0.4 for geological condition. Because less damage incidents for buried pipes are expected in firm grounds, the smallest value of C_g is assigned for Zone 1, which includes developed hilly areas. However, more damage incidents were observed in Sendai City due to the landslide of building lots and collapses of embankment. As a whole, no significant differences were observed among the damage ratios in Zones 2-4. The damage ratios in these zones were generally smaller than those estimated by the fragility function.

4 EVALUATION OF SEISMIC VULNERABILITY OF WATER DISRTIBUTION PIPELINE

According to the results in the previous section, the damage ratios in the developed hilly areas are not associated with the smallest correction coefficient for the geological condition. A discrepancy among

Table 3. Number of damage incidents, pipe lengths, and damage ratios with pipe diameters in the range of 100-150 mm with respect to the PGV.

		Developed hilly areas			Zone 2			Zone 3			Zone 4		
PGV (cm/s)	Mean of PGV (cm/s)	DIP	VP (TS)	VP (RR)	DIP	VP (TS)	VP (RR)	DIP	VP (TS)	VP (RR)	DIP	VP (TS)	VP (RR)
< 60	55.6	10 125.0 0.08	9 36.7 0.25	2 27.0 0.07	5 97.1 0.05	4 23.5 0.17	0 23.0 0.00	3 26.5 0.11	3 16.7 0.18	0 4.7 0.0	0 0.0 -	0 0.1 0.0	0 0.0 -
60-70	64.0	4 57.8 0.07	1 3.9 0.26	0 1.6 0.00	1 27.3 0.04	0 3.8 0.00	0 3.3 0.00	0 30.4 0.00	4 14.5 0.28	0 11.9 0.0	0 4.0 0.0	0 0.7 0.0	0 0.9 0.0
70-80	76.2	20 67.3 0.30	10 17.7 0.57	7 17.7 0.40	1 5.3 0.19	3 0.8 3.93	1 0.6 1.77	0 29.0 0.00	2 18.0 0.11	0 7.7 0.0	0 6.9 0.0	0 5.0 0.0	0 3.3 0.0
80-90	83.2	0 0.0 -	0 0.0 -	0 0.0 -	0 16.0 0.00	0 1.4 0.00	0 1.3 0.00	0 12.2 0.00	3 6.6 0.45	0 2.5 0.0	2 23.9 0.08	0 11.0 0.0	0 6.8 0.0
90-100	-	-	-	-	-	-	-	-	-	-	-	-	-
> 100	135.0	2 23.3 0.09	2 0.3 5.95	1 1.4 0.73	0 0.0 -	0 0.0 -	0 0.0 -	3 35.3 0.09	2 16.3 0.12	2 15.1 0.13	1 13.7 0.07	2 2.3 0.87	0 4.7 0.0

Top: No. of damage incidents, Middle: Length (km), Bottom: Damage ratio

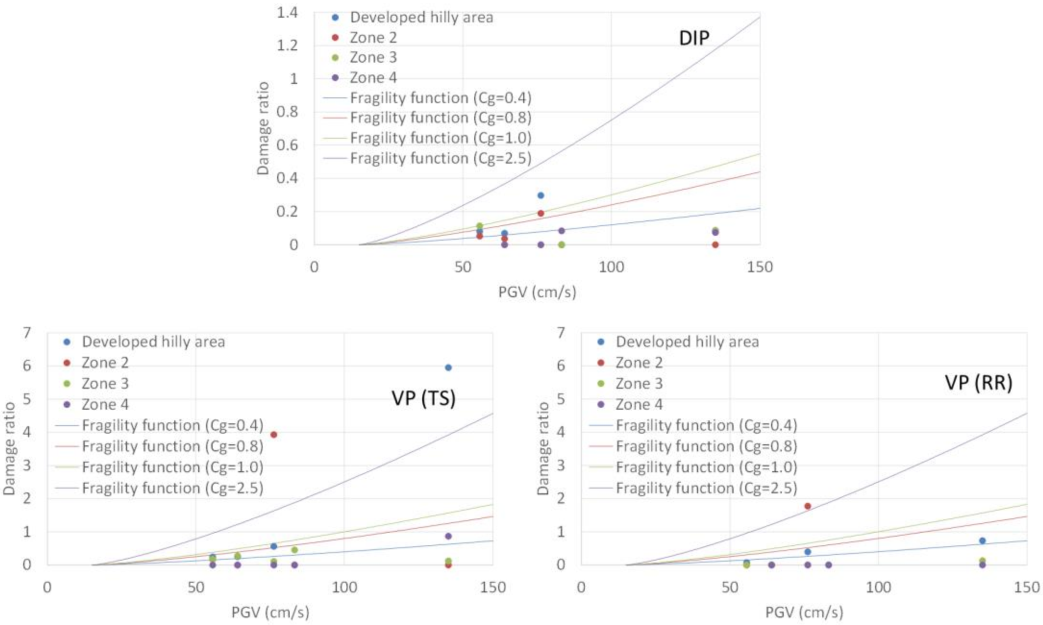

Figure 3. Comparisons of the damage ratios of water distribution pipes with diameters in the range of 100–150 mm to the empirical fragility functions.

the magnitudes of damage ratios for different zones and the values of correction coefficients of the fragility function for water distribution pipeline was observed in some cases. These coefficients were mainly determined after the 1995 Kobe earthquake; revisions based on data from recent earthquakes may be required. Hence, the authors performed a series of Monte Carlo simulations to evaluate the seismic vulnerability of water distribution pipelines.

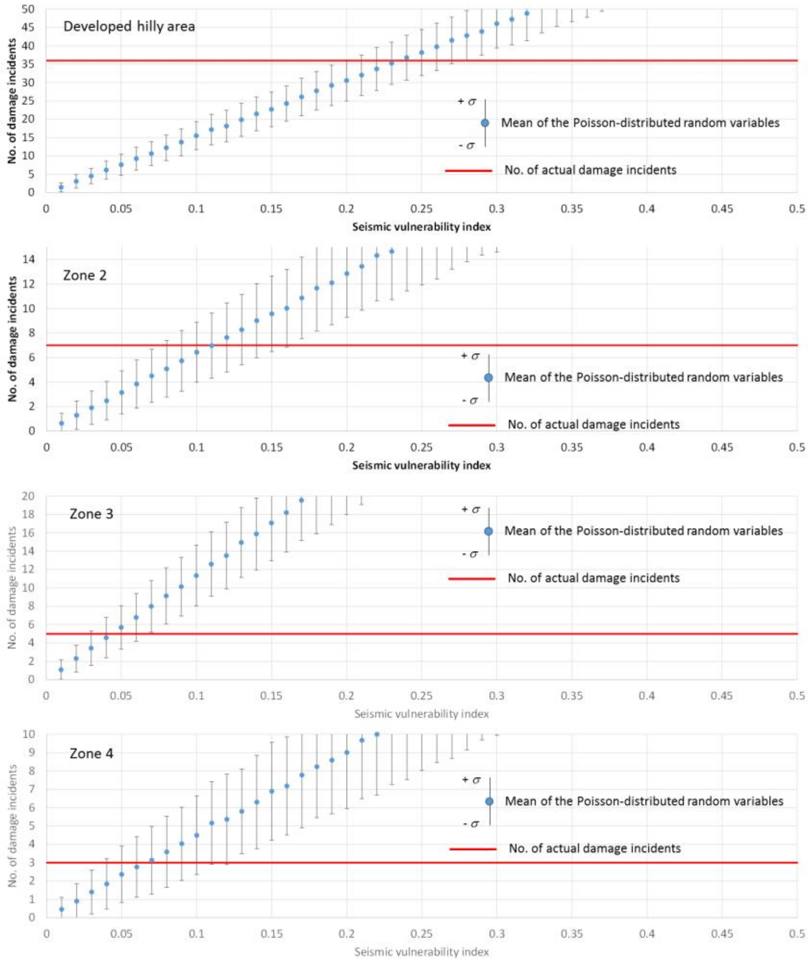

Figure 4. Evaluation of seismic vulnerability of DIP with diameters of 100–150 mm based on Monte Carlo simulations.

Poisson-distributed random variables are generated (Press *et al.*, 1992) to simulate the number of pipe breakages for each 250 × 250 m grid cell. The PGV and the length of the pipe for each grid cell are employed to assign the mean of the Poisson-distributed random variables as follows:

$$\lambda = CR(v)l \qquad (3)$$

where l is the length of pipe of a particular material and with a particular range of diameter, following the definitions given in Table 2. The mean value of random numbers λ was changed in accordance with C. A total of 1,000 sets of Poisson-distributed random variables were generated for each grid cell for a specific value of C. The summation of the generated variables was calculated for each set, and the standard deviation of the sums was also obtained for each specific value of C. These two values were compared with the actual number of damage incidents to find a suitable value of C to simulate the number of damage incidents of pipes with a particular material and diameter. Based on Eqs. (1) and (2), C is equivalent to the product of the correction coefficients, which can be interpreted as an index for indicating seismic vulnerability of water distribution pipelines depending on material, diameter, and geological condition.

Figure 4 shows the results of the evaluation of seismic vulnerability index C for DIPs with diameters of 100–150 mm. The seismic vulnerability indices were evaluated with respect to zones similarly classified in Fig. 3. The vertical axis shows the number of damage incidents to the pipes. In developed hilly areas, 36 damage incidents to DIPs with diameters of 100–150 mm were found in Sendai City. The 1,000 sets of Poisson-distributed random variables were generated for every grid cell with a particular value of C as shown in the horizontal axis, and the sum of each set as well as the standard deviation σ of the sums

Figure 5. Range of seismic vulnerability index for DIPs and VPs with diameters of 100–150 mm.

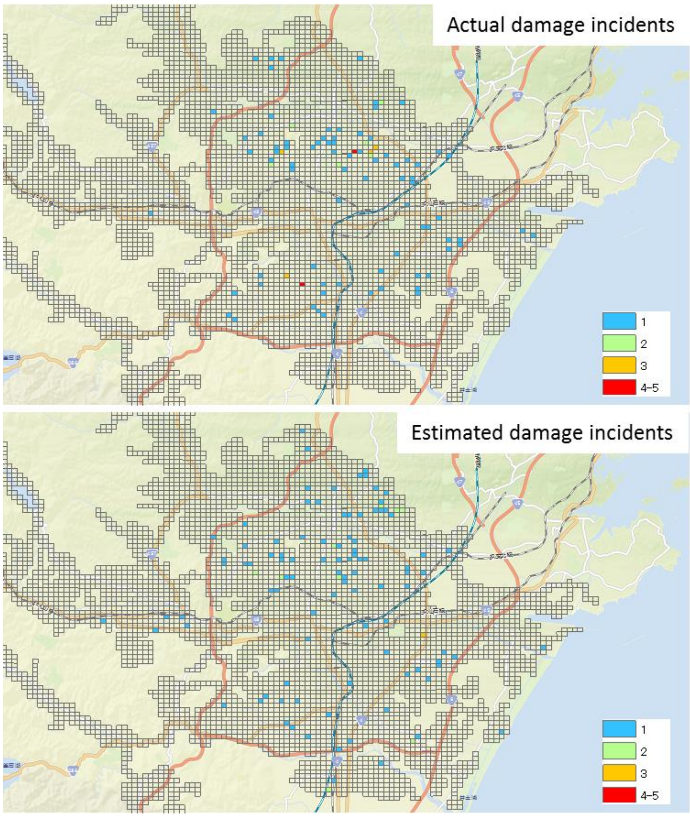

Figure 6. Comparison of the locations and numbers of damage incidents for DIPs and VPs with diameters of 100–150 mm to actual damage data and those from estimations.

were obtained. If C was set to a value in the range of 0.2–0.28, the numerical simulation could estimate the number of damage incidents to the pipes. The suitable ranges of C were similarly determined to be 0.08–0.16, 0.03–0.06, and 0.04–0.12 for Zones 2, 3, and 4, respectively.

Figure 5 summarizes the seismic vulnerability indices for the water distribution pipeline estimated by a series of Monte Carlo simulations. The ranges of seismic vulnerability index C are illustrated for DIPs and VPs with diameters of 100–150 mm with respect to the zones. The VPs with TS joints are associated with larger seismic vulnerability indices while the DIPs are associated with smaller ones. The seismic vulnerability index for developed hilly areas is relatively greater than those for the other zones, with no significant differences among the indices observed for Zones 2–4.

From the results of the seismic vulnerability index C, the location and the number of damage incidents to the pipes were estimated. Poisson-distributed random variables with the mean of λ in Eq. (3) were generated for each grid cell to simulate the damage incidents to the pipes. C for a particular pipe material in a specific zone was set to be the median of the range shown in Fig. 5. Figure 6 compares the locations and numbers of damage incidents to the pipes with diameters of 100–150 mm to actual damage data and those from estimations. A total of 111 actual damage incidents were identified, and 117 damage incidents to the pipes were estimated taking into account seismic vulnerabilities of the pipe material, diameter and geological condition. Hence, the seismic vulnerability indices obtained in this study are reasonable for re-creating the damage situations and effective for improving the accuracy of damage estimations.

5 CONCLUSIONS

This study evaluated the seismic vulnerabilities of water distribution pipelines with respect to pipe material, diameter, and geological condition based on the damage dataset obtained for Sendai City in the Miyagi Prefecture after the 2011 off the Pacific coast of Tohoku earthquake. Poisson-distributed random variables with the mean value estimated from the empirical fragility function were generated for each 250 × 250 m grid cell to simulate the number of damage incidents to the distribution pipes.

From the comparison between the damage ratios and the empirical fragility function, it can be seen that the damage ratios in Sendai City were generally smaller than those estimated by the fragility function. Because the correction coefficients for the fragility function were defined primarily after the 1995 Kobe earthquake, these coefficients are required to be reevaluated to include the data from recent earthquakes. This study proposes a way to determine the seismic vulnerability index of distribution pipelines through a series of Monte Carlo simulations.

According to the results, the seismic vulnerability indices for developed hilly areas were larger than those for other zones. The indices associated with ductile cast iron pipes were smaller than those associated with polyvinyl chloride pipes. Taking into account the seismic vulnerabilities with respect to the pipe material and geological condition evaluated by this study, the number of damage incidents to the water distribution pipeline was estimated. The result has good accuracy, and the seismic vulnerability of water distribution pipelines is properly evaluated. For future studies, damage datasets for other recent earthquakes can be employed to evaluate the seismic vulnerability of water distribution pipelines.

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