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CONSTRUCTION OF FRAGILITY CURVE FOR WATER DISTRIBUTION PIPES BASED ON DAMAGE DATASETS FROM RECENT EARTHQUAKES IN JAPAN

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ABSTRACT

In this study, fragility curves for water distribution pipes are constructed and used to simulate the distribution of water pipe damage from the 2007 Niigata Chuetsu-oki earthquake and from the Tokyo Metropolitan scenario earthquake in Chiba Prefecture. The damage ratio of water distribution pipes is assumed to follow the log-normal distribution, which is evaluated using the weighted least squares method. The results of this study suggest that the relationship, obtained only from the dataset after the Kobe earthquake, between the peak ground velocity and the damage ratio of water distribution pipes can overestimate the damage ratio.

Introduction

To enhance earthquake security, various governmental organizations in Japan make predictions regarding earthquake-induced damages (Murao *et al.* 2000). For some earthquake source faults, the ground motion intensity and the occurrence of liquefaction are estimated for several events, taking into consideration the geological and topographical conditions. The number of collapsed buildings, burned-out houses, casualties, etc. are derived from the estimated ground motions. Also predicted are the loss of lifeline systems (Hoshiya *et al.* 2004), e.g., disrupted water and gas supplies, electricity failure, etc. On the basis of various kinds of impacts due to scenario earthquakes, disaster prevention planning and countermeasures are designed by local governments.

Regarding the water supply infrastructure, we assume that only incidents of damage to buried pipes will disrupt water supply. Isoyama *et al.* (2000) developed the fragility curve of water distribution pipes based on the damage dataset from the 1995 Kobe earthquake in Japan, and this fragility curve was widely used to estimate the number of damage incidents (pipe breaks) after scenario earthquakes. Recently, modifications have been made to estimate damage incidents of water distribution pipes (Kuwata and Takada 2003). Because several events that caused damage to water distribution pipes in Japan have occurred, the fragility curve, which is constructed primarily from the damage dataset of a single event (the Kobe earthquake), can be empirically revised.

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In this study, damage datasets from the 1995 Kobe, 2004 Niigata Chuetsu, 2007 Noto-Peninsula, and 2007 Niigata Chuetsu-oki earthquakes are compiled to construct a fragility curve for water distribution pipes. A scaled log-normal distribution is employed for the fragility function. To judge the accuracy of the estimation, the resulting fragility curve is applied to the area subjected to severe ground motion during the 2007 Niigata Chuetsu-oki earthquake. In addition, the damage ratio of water distribution pipes in Chiba Prefecture, Japan, after the scenario Tokyo Metropolitan earthquake are also illustrated.

Method of Estimating the Damage Ratio of Water Distribution Pipes

To estimate the damage ratio of water distribution pipes (i.e., the number of damage incidents per kilometer of water pipe), Isoyama *et al.* (2000) proposed the following formula:

$$R_m(v) = C_p C_d C_g C_l R(v)\,, \tag{1}$$

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 peak ground velocity (PGV).

$R(v)$ estimates the damage ratio for cast iron pipe (CIP) with a diameter of 100–150 mm and is given as

$$R(v) = c(v - A)^b\,, \tag{2}$$

where b, c, and A are regression coefficients. On the basis of the damage dataset for the 1995 Kobe earthquake, Isoyama *et al*. (2000) obtained the following result for R(v):

$$R(v) = 3.11 \times 10^{-3}(v - 15)^{1.30}\,. \tag{3}$$

In that study, A was assumed to be between 0 and 30 cm/s, and regression analyses were performed by changing A in an interval of 5 cm/s. A was determined to be 15 cm/s because it was for this value that the correlation coefficient between the PGV and damage ratio attained its maximum value.

The constant A gives the minimum PGV that causes damages to water distribution pipes. Thus, the results of Isoyama *et al*. (2000) given in Eq. (3) indicate that water distribution pipes fail for PGVs greater than 15 cm/s. The constant A obtained from analyzing damage datasets of other earthquake events is sometimes different. For example, the following formula is used to simulate the number of damage incidents for water pipes in the Metropolis of Tokyo (2006):

$$R(v) = 2.24 \times 10^{-3}(v - 20)^{1.51}\,. \tag{4}$$

Fragility Curve for Water Distribution Pipes Considering Recent Damage Datasets

Damage Dataset from Recent Earthquakes

The damage datasets from the 2004 Niigata Chuetsu, 2007 Noto-Peninsula, and 2007

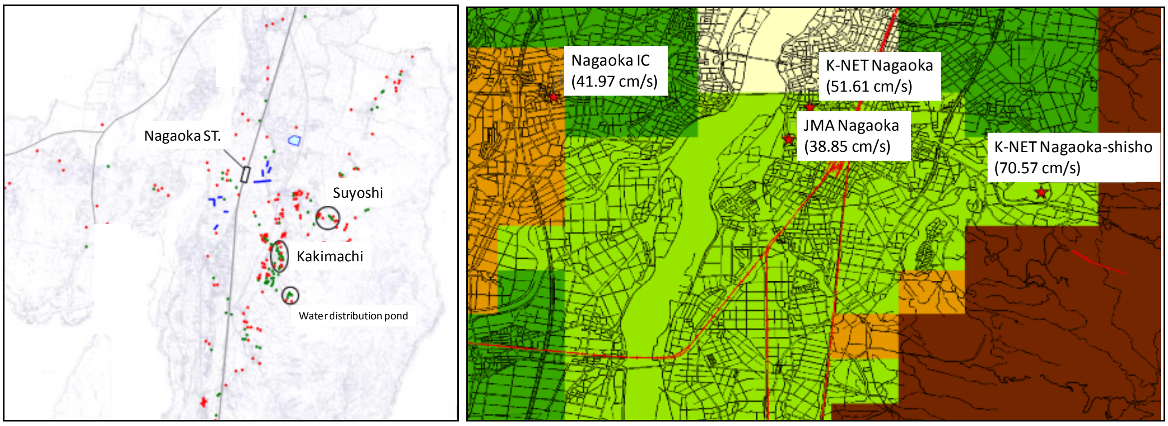


Figure 1. Location of damaged water distribution pipe in Nagaoka city after the 2004 Niigata Chuetsu earthquake (left) and for seismic observation stations (right).

Niigata Chuetsu-oki earthquakes are also considered in the current study. The damage dataset from the Kobe earthquake gives the damage ratio of water distribution pipe in a 2 km^2 area centered on a seismic observation station. Although there are 27 seismic observation stations in the dataset, the 8 damage ratios associated with seismic motion affected by liquefaction and structural responses were excluded from the dataset.

Regarding the three recent earthquakes, detailed damage datasets such as that of the Kobe earthquake are not available. The Health, Labor, and Welfare Ministry of Japan (2004) and the Japan Water Works Association (JWWA 2007) reported the number of damage incidents to the water pipes in every municipality. Because the intensity of ground motion depends on the local topography and the subsurface geological conditions, it is desirable to use a detailed damage dataset such as that of the Kobe earthquake. On the other hand, more damage datasets are expected to be used as long as the fragility curve is empirically obtained. This study includes the damage datasets from three recent earthquakes to investigate differences in ground motion characteristics among earthquake events. In this study, we also compiled the damage ratios from 2 municipalities (Ojiya and Nagaoka) in the 2004 Niigata Chuetsu earthquake, from 5 municipalities (Monzen, Shika, Anamizu, Wajima, and Nanao) in the 2007 Noto-Peninsula earthquake, and from 5 municipalities (Kashiwazaki, Izumozaki, Nagaoka, Joetsu, and Kariwa) in the 2007 Niigata Chuetsu-oki earthquake to construct the fragility curve.

We determine the reference PGV from the ground motion recorded in every municipality. If multiple accelerometers were installed in a municipality, the PGV observed in an area from where more damage incidents were reported is defined as the reference PGV. Figure 1 shows an example of choosing the reference PGV from multiple ground motion records in a municipality. In the 2004 Niigata Chuetsu earthquake, 4 seismic motion records were available in Nagaoka city. Considering the distribution of damaged water pipe reported by the Health, Labor, and Welfare Ministry of Japan, we selected the PGV at K-NET Nagaoka-shisho (NIED 2009) as the reference value (70.57 cm/s). Table 1 shows the damage dataset for water distribution pipe after the three recent earthquakes. The reference PGVs were mainly selected from the seismometers deployed by the National Research Institute for Earth Science and Disaster Prevention (NIED) and the Japan Meteorological Agency (JMA). The damage ratios of water distribution pipes were correlated with the PVG values for different pipe materials, which include cast iron pipe (CIP), ductile cast iron pipe (DIP), and vinyl pipe (VP).

Table 1. Damage dataset for water distribution pipes after the recent earthquakes.

Municipality (Seismic observation station)	PGV (cm/s)	Upper: No. of damage incidents Lower: Length (km)		
		DIP	CIP	VP
2004 Niigata Chuetsu EQ.				
Nagaoka (K-NET Nagaoka-shisho)	70.57	84 777.6	-	154 227.5
Ojiya (JMA Ojiya)	93.5	39 234.4	-	20 29.9
2007 Noto-hanto EQ.				
Monzen (Monzen town office)	110.4[*1]	15 70.5	-	25 94.2
Wajima (K-NET Wajima)	43.9	1 52.9	3 4.9	8 132.9
Shika (JMA Shika)	55.18	6 198.2	-	13 191.9
Anamizu (K-NET Anamizu)	103.4	7 57.7	0 4	0 26.2
Nanao (K-NET Nanao)	34.79	12 280.8	2 11.5	26 172.4
2007 Niigata Chuetsu-oki EQ.				
Kashiwazaki (Kagami-machi gas holder)	113.7	218 539	13 3.4	249 299.1
Kariwa (Kariwa village office)	156.2	72 52.484	-	17 16.01
Teradomari and Yoita (Nakanoshima city office)	35.5	3 105.2	3 5.7	12 210.1
Kakizaki (Kakizaki ward office)	93.9	7 21.39	-	12 63.3
Izumozaki (JMA Izumozaki)	55.4	0 3.8	-	6 82.2

[*1] Estimated value from the peak ground acceleration and JMA seismic intensity

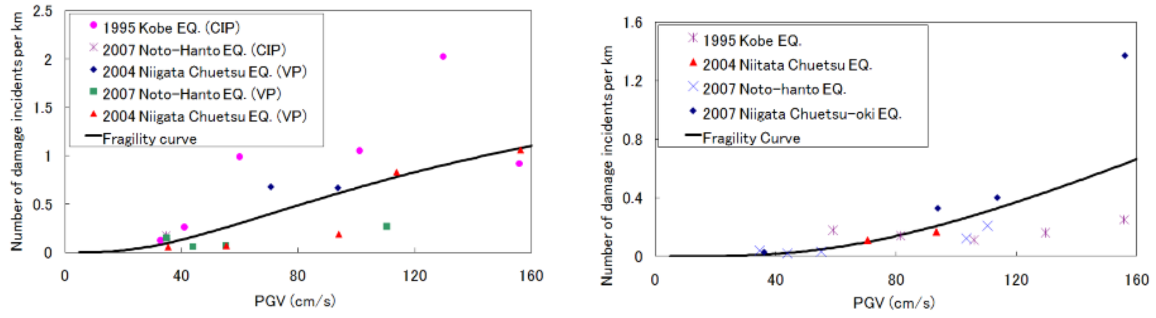
Nonlinear Regression Analysis

As shown in Eq. (2), we use a power-law function to estimate the damage ratio of water distribution pipe. If the damage ratio is assumed to follow a power-law function, the number of damage incidents becomes extremely large under severe ground motion. Hence, the upper limit for the damage ratio of buried pipe is sometimes assigned (Toprak and Taskin 2007). In addition, the lower limit of the PGV [i.e., the constant A in Eq. (2)], which affects the damage ratio, is set according to a series of parameter studies, and is not obtained directly from a regression analysis.

To use the fewest parameters in determining the lowest PGV that cause damage to water distribution pipe and the largest damage ratio, we choose the scaled log-normal distribution (Maruyama *et al.* 2008). Explicitly,

Table 2. Fragility curve parameters determined by nonlinear regression analysis.

Material of pipe	ζ	λ	C
CIP and VP	0.860	5.00	2.06
DIP	0.864	6.04	4.99



(a) (b)

Figure 2. Fragility curves for water distribution pipe for (a) CIP and VP and (b) DIP.

$$R(v) = C\Phi\left(\left(\ln v - \lambda\right)/\zeta\right), \tag{5}$$

where $\Phi(x)$ is the cumulative distribution function of the standard normal distribution, and λ, ζ, and C are constants determined by a regression analysis. With this formula, only three parameters need to be determined to resolve the lowest PGV that causes damage and the largest damage ratio.

We thus performed a nonlinear regression analysis to determine the three parameters in Eq. (5). The error term ε, shown in Eq. (6), was minimized using the quasi-Newton method.

$$\varepsilon = \sum (P_R - R(v))^2 w \tag{6}$$

In this equation, P_R and w represent the actual damage ratio and the length of the water distribution pipe, respectively.

Fragility Curve for Water Distribution Pipe

The fragility curve for water distribution pipe is constructed on the basis of the damage ratio of CIP in the 1995 Kobe earthquake. Regarding the damage datasets for the three recent earthquakes, CIPs were not widely used as water distribution pipe in the affected areas. Therefore, it is difficult to perform a regression analysis using the damage datasets including the recent earthquakes for CIPs. Conversely, DIPs and VPs were the primary types of pipes used in the areas concerned by the three recent earthquakes. The correction coefficient C_p for the pipe material in Eq. (1) is defined to be 1.0 for VPs on the basis of the damage dataset obtained after the 1995 Kobe earthquake.

On the basis of the correction coefficient C_p and the damage datasets for the recent earthquakes, the fragility curves for water distribution pipe were constructed to estimate the

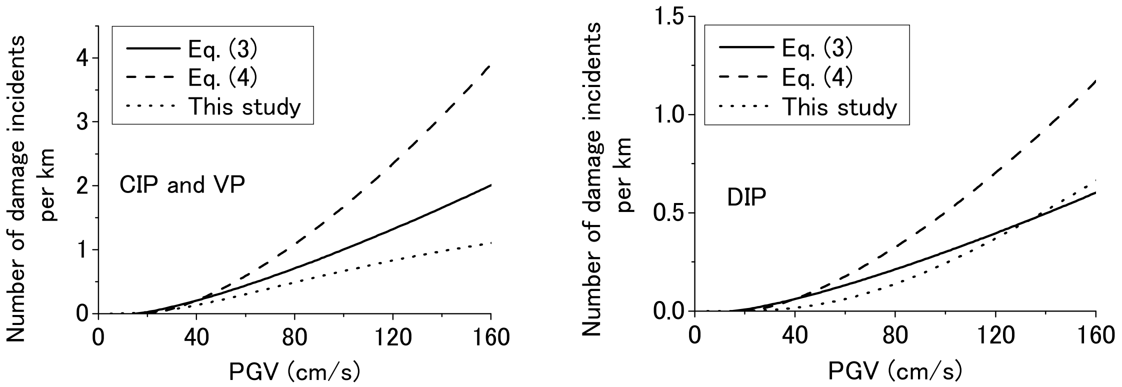


Figure 3. Comparison of the fragility curves for the water distribution pipes.

damage ratio of CIPs, VPs, and DIPs. According to statistical data compiled by the JWWA (Nojima 2008), over 50% of water distribution pipes are DIPs. Based on the fact, we also construct the fragility curve for DIPs, which we expect to use in a future research as a standard function for damage estimation.

Table 2 lists the parameters of the obtained fragility curves, which are shown in Fig. 2. Figure 3 compares the fragility curves constructed in the current study with those from Eqs. (3) and (4). The damage ratios for DIP are estimated from Eqs. (3) and (4) by multiplying by C_p, which is set to be 0.3 in the previous study. According to the fragility curves obtained in the current study, the lowest PGV that causes damage to CIPs and VPs is about 20 cm/s, whereas the lowest PGV that causes damage to DIPs is approximately 30 cm/s. Overall, the result of the current study allows one to estimate the minimum number of damage incidents to water distribution pipe.

Numerical Simulation for the Damage Distribution of Water Pipes

Damage Distribution in Kashiwazaki City after the 2007 Niigata Chuetsu-oki Earthquake

The damage distribution for water pipe is estimated using the fragility curves for CIP, VP and DIP in Kashiwazaki City, which was subjected to severe ground motion in the 2007 Niigata Chuetsu-oki earthquake. To perform the numerical simulation, the water pipe information is compiled using the geographic information system (GIS). The actual damage ratios of water pipe were obtained in 250 × 250 m^2 grid cells, which were compared with the estimated results.

First, the distribution of the PGV in the 2007 Niigata Chuetsu-oki earthquake (Fig. 4) was estimated following our previous study (Maruyama *et al.* 2008), which employed simple Kriging interpolation considering the local site and subsurface geological conditions to draw the distribution of the PGV. Sixty-one (61) seismic motion records were used to perform simple Kriging interpolation.

Figure 5 shows a comparison between the actual and estimated damage ratios of water distribution pipe (CIP, VP, and DIP) in Kashiwazaki City after the 2007 Niigata Chuetsu-oki earthquake. The estimated damage ratio shown in Fig. 5 corresponds to $R(v)$ in Eq. (1). In other words, no correction coefficients for diameter, geological condition, and liquefaction were considered. Hence, the actual damage ratio of water distribution pipe is greater than 2.0 in some

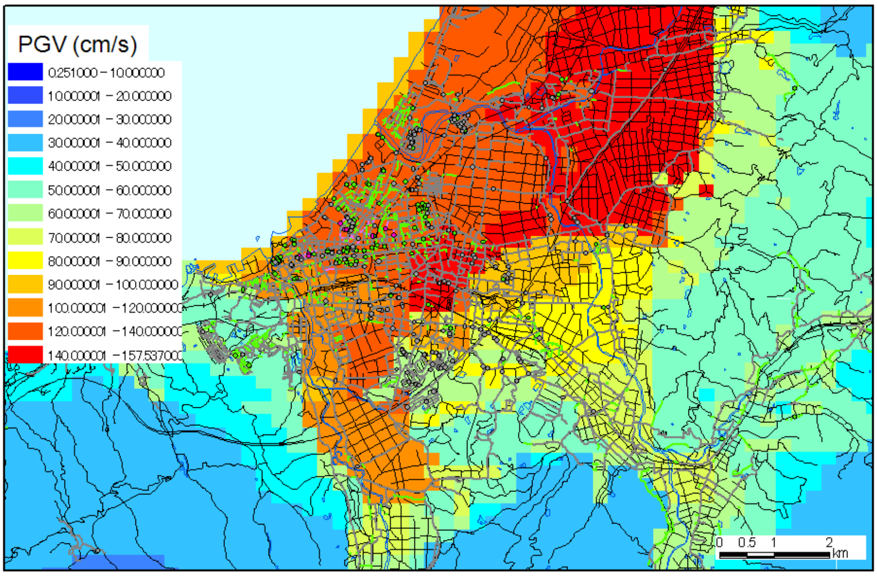


Figure 4. Estimated distribution of the PGV in Kashiwazaki during the 2007 Niigata Chuetsu-oki earthquake.

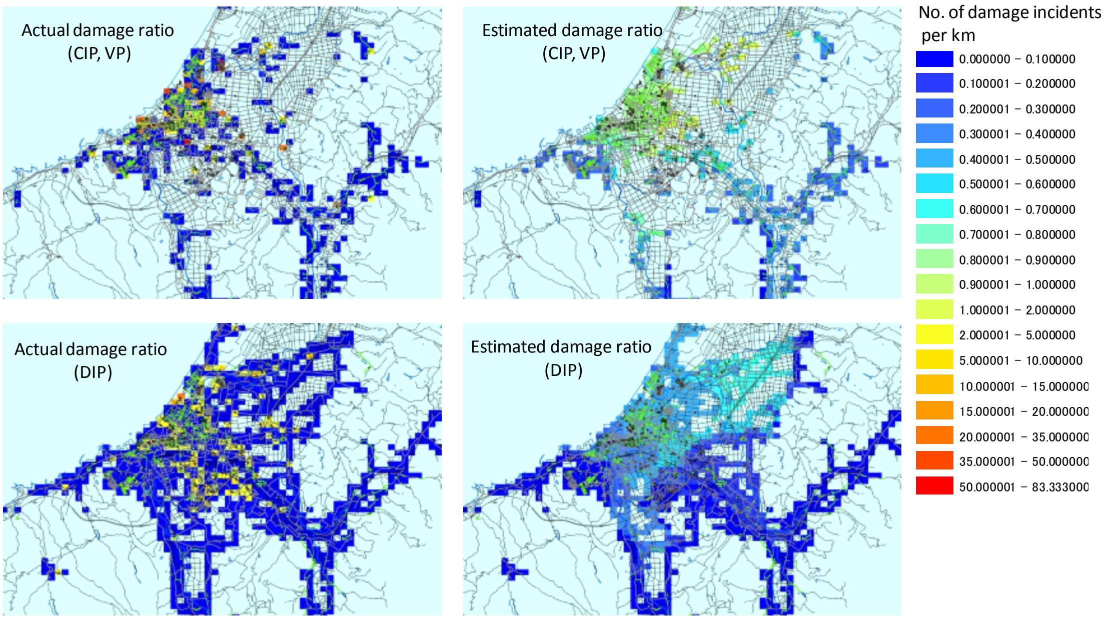


Figure 5. Comparisons between the actual and estimated damage ratios for water distribution pipe in Kashiwazaki after the 2007 Niigata Chuetsu-oki earthquake.

250 × 250 m^2 grid cells; however, the grid cells with an estimated damage ratio between 0.4 and 0.7 are widely spread in Kashiwazaki City. The spread of the grid cells with higher actual damage ratios seems to correspond to that of grid cells with estimated damage ratios of DIP over 0.2. Although the correction coefficients need to be revised considering the damage datasets from recent earthquakes in a future study, the fragility curves constructed in this study could provide reasonable estimations to evaluate the total number of damage incidents to water pipe in

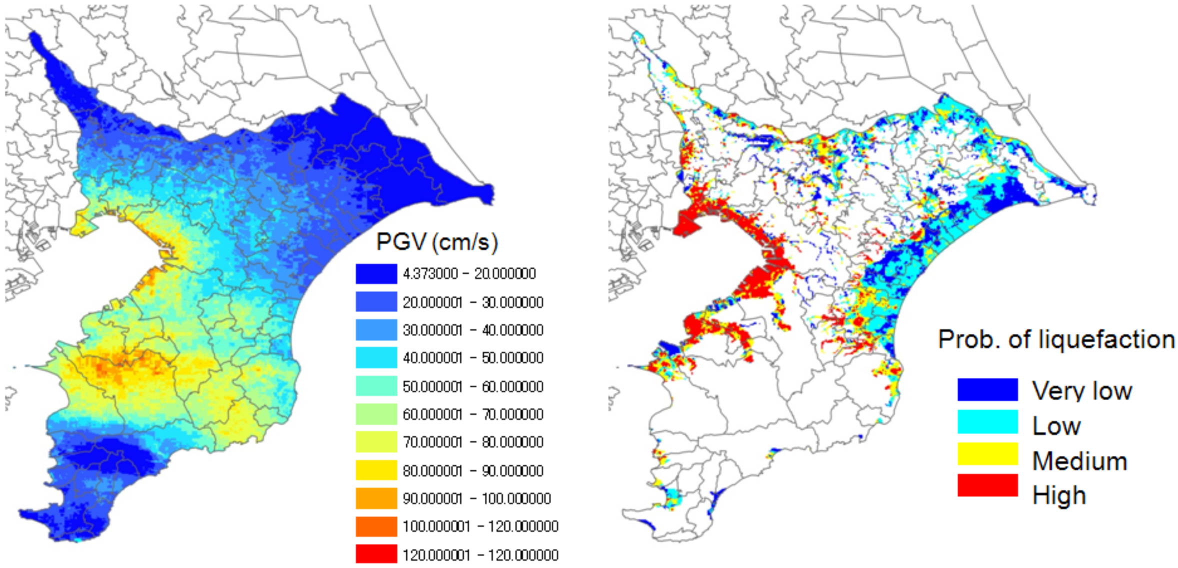


Figure 6. Simulated distribution of the PGV and the probability of liquefaction during the scenario Tokyo Metropolis earthquake.

municipalities. To obtain detailed damage estimations, the correction coefficients in Eq. (1) must be considered.

Estimation of damage distribution in Chiba Prefecture during the Scenario Tokyo Metropolis Earthquake

To promote earthquake security, local governments in Japan make public predictions of the damages and impacts expected from future earthquakes. Chiba Prefecture estimates the damages of future earthquakes almost every decade, and in the latest damage estimation (Chiba Prefecture 2008), they constructed an earthquake scenario assuming that the epicenter was in the Tokyo Metropolis (M_{JMA} = 7.3). Figure 6 shows the expected PGV and the probability of liquefaction occurrence in different zones of Chiba Prefecture.

For local-government estimates of the damage to water distribution pipe, either Eq. (3) or Eq. (4) is used for the fragility curve. The water-disrupted area, which can be estimated from the spatial density of damage incidents to water distribution pipe, often becomes much larger than the gas-disrupted area. According to the latest estimation by the Tokyo Metropolitan Government (2006), more than 40% of the houses in some eastern districts are assumed to be unable to use water even though the gas supply continues as normal. To close the gap between the water and gas cutoff rates, we first revise the fragility curve of water distribution pipe.

Figure 7 compares the estimated damage ratios of water distribution pipe calculated using Eqs. (3) and (4), and the fragility curve constructed in this study. Both Eqs. (3) and (4) predicted higher damage ratios than the curve from this study did in the Tokyo-Bay areas. Especially, Eq (4) predicts higher damage ratios for the entire area.

The results obtained from Eq. (3) and from this study show similar tendencies, although some grid cells have damage ratios higher than 2.0 /km when calculated using Eq. (3).

The predicted damage ratios for Chiba Prefecture were derived from numerical simulations and are therefore not definitive. As long as the fragility curves are constructed

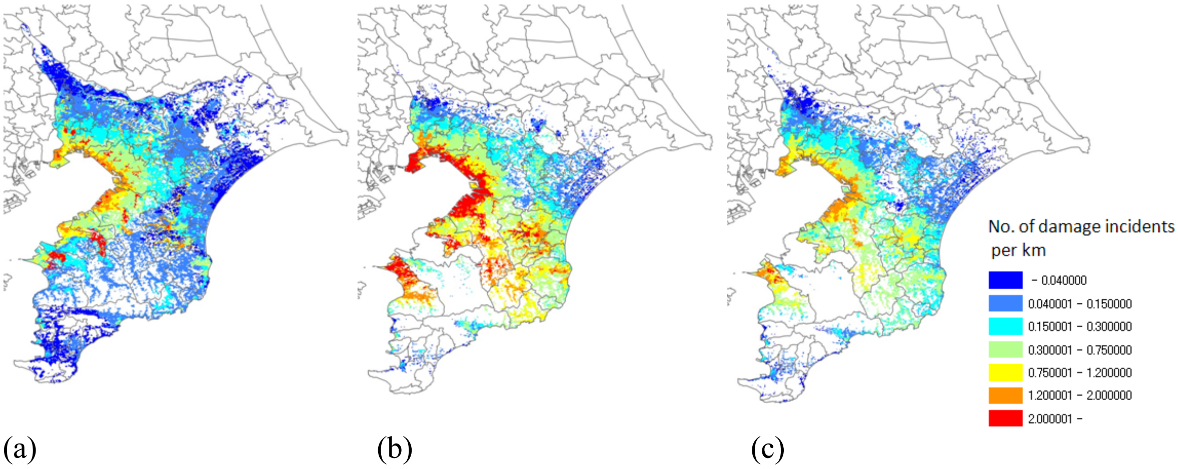


Figure 7. Comparison of the estimated damage ratios of water distribution pipe in Chiba Prefecture calculated using (a) Eq. 3, (b) Eq. 4, and (c) the fragility curve proposed in this study.

empirically, the damage datasets after multiple earthquake events are expected to be considered. In addition, the fragility curves constructed in this study give lower estimations than the previous fragility curves. The gap between the disrupted rates of water and gas can be closed to some extent by using the fragility curves for water pipe proposed herein.

Conclusion

We constructed fragility curves for water distribution pipe considering the damage datasets from three recent earthquakes: the 2004 Niigata Chuetsu, 2007 Noto-Peninsula, and 2007 Niigata Chuetsu-oki earthquakes, and from the 1995 Kobe earthquake. We adopted a scaled log-normal distribution to construct the fragility curves. The lowest PGV for which damage occurs and the largest damage ratio (the number of pipe breaks per kilometer) can be estimated using this fragility.

Compared with previous studies, the fragility curves constructed in the current study lead to lower estimates for the damage ratios of water distribution pipe. Provided the fragility curves are obtained empirically, the curves obtained in this study are preferable because the damage datasets from multiple earthquake events were considered. In some scenario earthquakes, the area where the gas supply is expected to be cut off is much smaller than the area where the water supply is expected to be disrupted. The fragility curves obtained in this study can close the gap between these predictions.

In a future study, the correction coefficients heretofore determined only from the Kobe earthquake dataset will be revised to include the effects of recent earthquakes.

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