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DAMAGE ASSESSMENT OF BURIED PIPES DUE TO THE 2007 NIIGATA CHUETSU-OKI EARTHQUAKE IN JAPAN

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This study investigated the damage distribution of buried pipes due to the 2007 Niigata Chuetsu-Oki earthquake in Japan. Various damage datasets — e.g. water pipes, low-pressure gas pipes, mid-pressure gas pipes, sewage lines, collapsed houses, and liquefaction occurrences — were integrated into a geographic information system. Using the datasets, the spatial distribution of damage was investigated with respect to geomorphological land classification and altitude. The minimum distances between the damaged locations were measured, and the spatial correlations of damage incidents to lifeline systems were evaluated. In addition, the damage ratios of water distribution pipes were compared with different fragility curves constructed from the damage datasets for the 1995 Kobe earthquake and other recent earthquakes in Japan.

Keywords: Chuetsu-Oki Earthquake; buried pipes damage.

1. Introduction

In Japan, various governmental organizations predict earthquake-induced damage to enhance earthquake security [Murao *et al.*, 2000]. For some earthquake source faults, the ground motion intensity and occurrence of liquefaction are estimated for several events by 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. The loss of lifeline systems are also predicted [Hoshiya *et al.*, 2004], e.g. disrupted water and gas supplies, electricity failure, etc. Local governments design disaster prevention plans and countermeasures based on the various kinds of predicted impacts due to earthquake scenarios.

The probability that an M7-level earthquake occurs in the Tokyo metropolitan area within the next 30 years is estimated to be about 70% [Headquarters for Earthquake Research Promotion, 2009]. The Central Disaster Prevention Council [2005] has estimated huge economic losses (approximately 112 trillion yen) if the Tokyo metropolitan earthquake scenario occurs. The damage to lifeline systems alone is estimated to be approximately 11.4 trillion yen. Tokyo Metropolis is the most important social, political, economic, and financial center of Japan. This role would be disrupted for a long time after the Tokyo metropolitan earthquake scenario.

Local governments also predict seismic-induced damages for various earthquake scenarios to establish proper restoration plans. Fragility curves, which are used to estimate the number of seismic-induced damage incidents, have been primarily constructed from the damage dataset of the 1995 Kobe earthquake. As long as fragility curves are constructed empirically, several earthquake events are needed to reveal the characteristics of damage incidents to different structures, lifeline systems, etc.

This study investigates the damage distribution characteristics after the 2007 Niigata Chuetsu-Oki earthquake in Japan combined with various nationwide spatial datasets. The distribution of damage incidents to buried pipes is evaluated in terms of simultaneous occurrences in space. The damage ratios of water distribution pipes due to the event are compared through the different fragility curves.

2. Integration of Various Datasets on GIS

Geographic information systems (GISs) are often used to analyze the damage to lifeline systems during earthquakes [Jeon and O'Rourke, 2005; Kuwata *et al.*, 2008]. This study used GIS to investigate the damage datasets for the 2007 Niigata Chuetsu-Oki earthquake.

Various kinds of damage datasets, e.g. water pipes, low-pressure gas pipes, mid-pressure gas pipes, sewage lines, collapsed houses, liquefaction occurrences, etc., were collected and integrated on ArcGIS 9 software. The datasets include information on buried pipes — location, material, diameter, etc. — in Kashiwazaki city and Kariwa Town in Niigata Prefecture, which were subjected to severe seismic motion during the earthquake, and they were mapped in a GIS environment.

The damage datasets for lifeline systems used in this study are shown in Table 1. The datasets include the locations of breaks/leaks in water, gas, and sewage lines. The 56 collapsed houses were detected through visual damage inspection using aerial images from the Geographical Survey Institute of Japan. Liquefaction occurrences were also detected by visual inspection by Pasco Co., Ltd. Inventory data of

Table 1. Damage datasets for lifeline systems of the 2007 Niigata Chuetsu-Oki earthquake used in this study.

Lifeline system	Number of damage incidents	Length of pipes (km)
Water pipe	524	852.6
Low-pressure gas pipe	158	653.2
Mid-pressure gas pipe	26	135.3
Sewage line	1,885 sections (65.1 km)	710

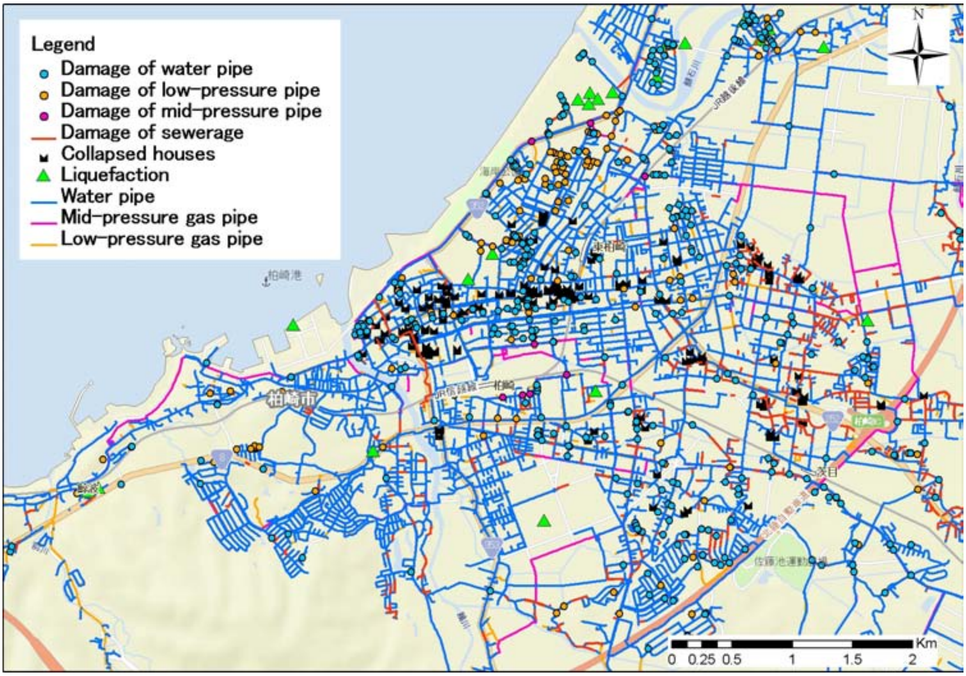


Fig. 1. Inventory data and damage data of lifeline systems in Kashiwazaki city due to the 2007 Niigata Chuetsu-Oki earthquake.

water and gas supply systems were also gathered, and all data were integrated on GIS, as shown in Fig. 1.

3. Characteristics of the Spatial Distribution of Buried Pipe Damages

3.1. *Relationship between the pipe damage distribution and geographical and topographical conditions*

The geographical and topographical feature datasets were overlapped with the damage datasets on GIS, and the damage ratios for the pipeline systems were calculated with respect to the geographical and topographical conditions. To evaluate the characteristics of the spatial distribution for damage incidents to buried pipes, the damage ratios of water, low-pressure gas, and mid-pressure gas pipes were defined as shown in Eq. (1). The damage ratio of sewage lines is described in Eq. (2):

$$\text{Damage ratio (1/km)} = \frac{\text{Number of damage incidents}}{\text{Total length of pipe (km)}} \tag{1}$$

$$\text{Damage ratio (\%)} = \frac{\text{Length of damaged sections (km)}}{\text{Total length of line (km)}} \times 100. \tag{2}$$

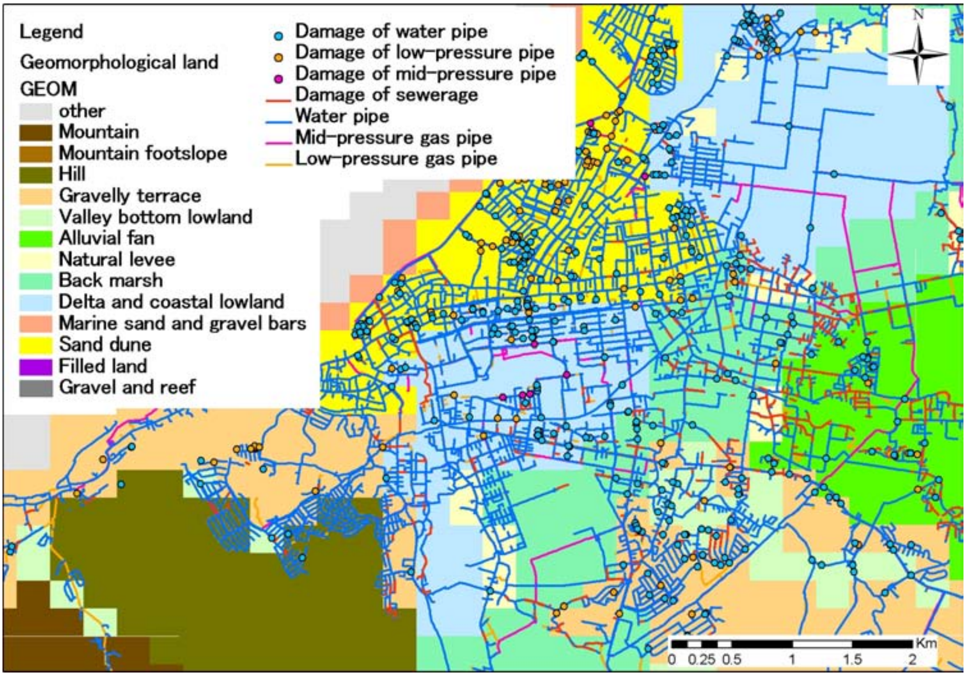
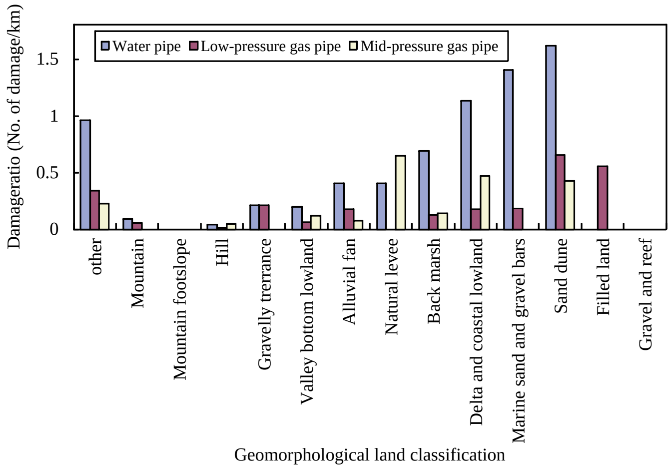


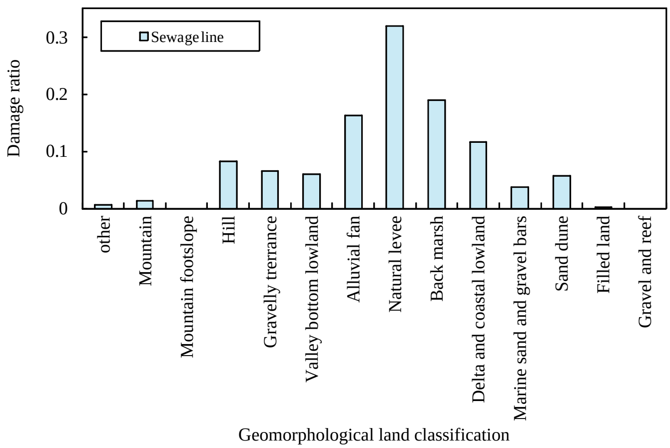
Fig. 2. Damage incidents to buried pipes in Kashiwazaki city after the 2007 Niigata Chuetsu-Oki earthquake illustrated on the geomorphological land classification map by Wakamatsu *et al.* [2006].

For the inventory and damage datasets of the sewage line, the total length of the line and affected sections due to the earthquake were available on GIS. Thus, the length of the sewage line with respect to the geographical and topographical conditions was assumed to be proportional to that of the water distribution pipe.

Figure 2 shows the distribution of damage to lifeline systems plotted on the geomorphological land classification map. The geomorphological land classifications used in this study are part of a nationwide digital map constructed by Wakamatsu *et al.* [2006]. According to this classification map, the central part of Kashiwazaki city is mainly classified as sand dunes, delta, and coastal lowlands, and back marshes. The damage ratios of water, low-pressure gas, and mid-pressure gas pipes with respect to the geographical land classification are shown in Fig. 3(a). The damage ratio of the sewage system is plotted in Fig. 3(b). The damage ratio of water distribution pipes is highest in sand dunes (1.62), followed by marine sand and gravel bars (1.41). Similarly, the damage ratio of low-pressure gas pipes is the highest in sand dunes (0.66), followed by filled land (0.55). For the water and low-pressure gas pipes, the damage ratios are high for geomorphological classes mainly comprised of soft soil. The damage ratio of mid-pressure gas pipes is the highest in natural levees (0.65) and second highest in deltas and coastal lowlands (0.47). The damage ratio of sewage line is the highest in natural levee (32%) while it is 12%



(a)



(b)

Fig. 3. Damage ratios of (a) water pipes, low-pressure, and mid-pressure gas pipes, and (b) the sewage line with respect to geographical land classifications.

in delta and coastal lowland. For the mid-pressure gas pipes and sewage lines, the damage ratios are high in natural levees.

Figure 4 shows the locations of damage incidents (breaks/leaks) for lifeline systems and the altitude model, which was developed by the Geographical Survey Institute of Japan [2001]. The altitude is shown in $50 \times 50\,\mathrm{m}^2$ grid cells. The damage ratios for the water, low-pressure gas, and mid-pressure gas pipes with respect to altitude are shown in Fig. 5(a), and that of the sewage line is shown in Fig. 5(b). The damage ratios for the water, low-pressure gas, and mid-pressure gas pipes are highest at altitudes of 0–5 m. The damage ratio of the sewage lines is highest when the altitude is 10–15 m. The damage ratio of the sewage line is still high for

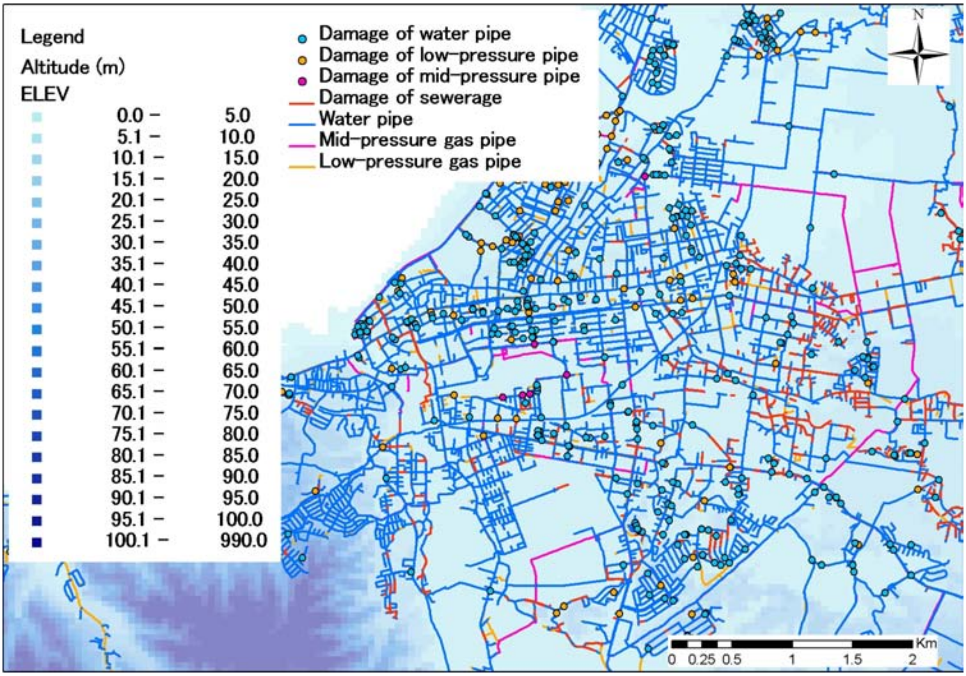


Fig. 4. Spatial distributions of altitude and damage incidents to buried pipes in Kashiwazaki city after the 2007 Niigata Chuetsu-Oki earthquake.

altitudes of 0–10 m. For the water, low-pressure gas, and mid-pressure gas pipes, no notable differences were observed in the trends for the damage ratios among the three buried pipes.

3.2. *Evaluation on the cooccurrence of buried pipe damages*

As shown in the previous section, the spatial distribution characteristics for damage incidents seem to have common features in the lifeline systems. In particular, many of the damage incidents for the water distribution pipe and low-pressure gas supply pipe were observed in geomorphological classes indicating the existence of soft soil and at altitudes of 0–10 m. If both types of pipes are affected due to an earthquake, the leaked water moves into the broken gas pipe, which prevents rapid restoration work by the gas supply company. Hence, the possibility of synchronicity in damage occurrences among the lifeline systems was evaluated by using the damage dataset for the 2007 Niigata Chuetsu-Oki earthquake.

To evaluate the possibility that damage to different lifeline systems can be observed in neighboring areas, the shortest distances between locations of the various damage incidents were analyzed. The distances to neighboring damage incidents were obtained for all damage incidents (Fig. 6), and the shortest distances were then determined for all locations of damage to water, low-pressure gas, and mid-pressure

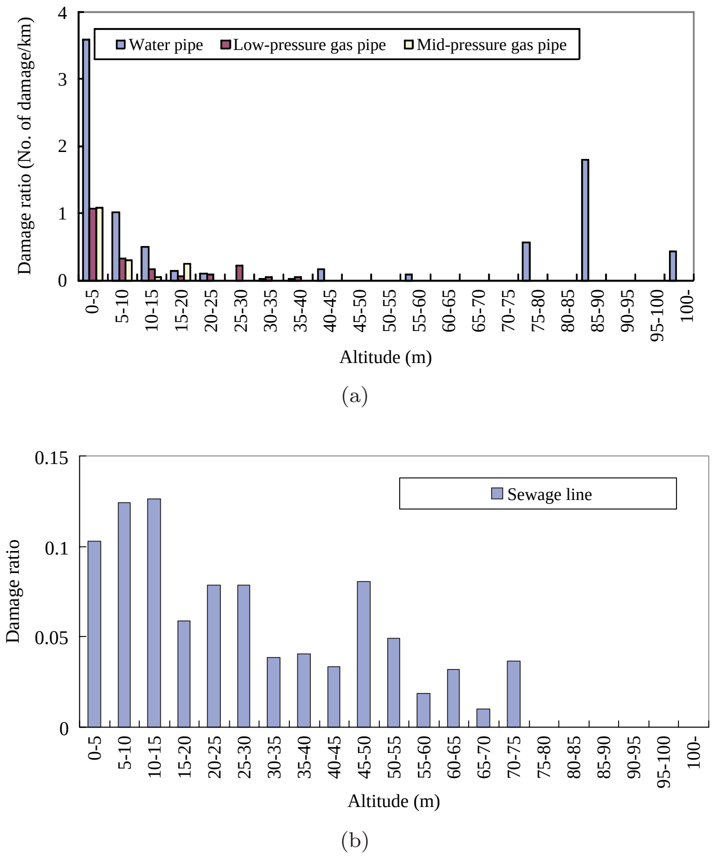


Fig. 5. Damage ratios of (a) water, low-pressure gas, and mid-pressure gas pipes and (b) sewage line with respect to altitude.

gas pipes; affected sections of sewage lines; collapsed houses; and liquefaction occurrences. Because of the data structure in GIS, polylines, which indicate the affected sections of sewage lines, were divided into points with 1 m intervals; the shortest distances were then calculated.

Table 2 shows the percentages of damage incidents with shortest distances of less than 250 m. According to the results in Table 2, there is an 82.2% probability of damage to a low-pressure gas pipe located within a 250 m radius of the reference damage location. High percentages were also found for locations close to damage incidents to water distribution pipes and sewage lines (83.8%). As estimated in the previous section, 88% of the damage incidents to low-pressure gas pipes have water distribution pipes within 250 m. The damage locations to these two buried pipes have similar tendencies in the spatial distribution, and the synchronicity between the two kinds of damages should be properly considered when estimating the functional loss of lifeline systems.

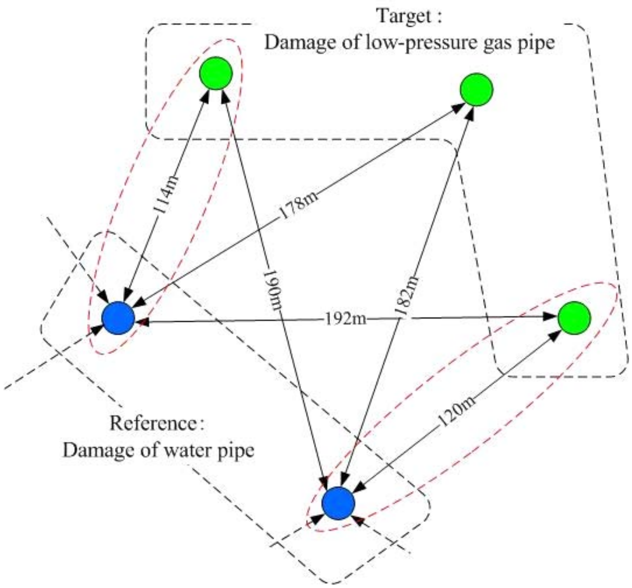


Fig. 6. Definition of the shortest distances between damage incidents.

Table 2. Percentage of damage incidents with shortest distances of less than 250 m.

Target Reference	Water pipe	Low-pressure gas pipes	Mid-pressure gas pipe	Sewage line	Liquefaction	Collapsed house
Water pipe	77.6	63.0	12.2	83.8	20.8	32.8
Low-pressure gas pipe	88.0	82.2	19.0	72.8	22.2	27.8
Mid-pressure gas pipe	57.7	34.6	28.0	61.5	19.2	3.8
Sewage line	45.1	26.4	4.8	97.7	8.6	14.9
Liquefaction	44.6	35.7	12.5	62.5	57.1	3.6
Collapsed house	93.3	63.3	2.4	92.4	5.2	99.0

As a whole, the obtained results indicate that the probability that damage incidents are caused simultaneously to buried pipes is high. In other words, if a break occurs in a pipe, there is a high probability that a break can be found in a neighboring pipe.

4. Relationship Between the Peak Ground Velocity and Damage Ratio of Water Distribution Pipes in Kashiwazaki City

4.1. *Fragility curves of water distribution pipe*

In this section, the damage ratio of water distribution pipes is compared with existing fragility curves. Various governmental organizations in Japan predict various quantities of earthquake-induced damage, e.g. the number of collapsed buildings, burned-out houses, causalities, etc. The damage assessment for buried pipes is also performed to estimate the functional loss of lifeline systems. To achieve these objectives, fragility curves are constructed for different structures based on damage datasets mainly compiled from the 1995 Kobe earthquake.

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

$$R_m(v) = C_p C_d C_g C_l R(v), \tag{3}$$

where R_m is the damage ratio; C_p, C_d, C_g, and C_l are the 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 a cast-iron pipe (CIP) with a diameter of 100–150 mm and is given as

$$R(v) = c(v - A)^b, \tag{4}$$

where b, c, and A are regression coefficients. Using the damage dataset for the 1995 Kobe earthquake, Isoyama *et al.* [2000] obtained the following result for $R(v)$

$$R(v) = 3.11 \times 10^{-3}(v - 15)^{1.30}. \tag{5}$$

They assumed A to be between 0 and 30 cm/s, and regression analyses were performed by changing A in increments of 5 cm/s. A was determined to be 15 cm/s because the correlation coefficient between the PGV and damage ratio attained its maximum value at this point.

The constant A gives the minimum PGV that causes damage to water distribution pipes. Thus, the results of Isoyama *et al.* [2000] given in Eq. (5) indicate that water distribution pipes fail for PGVs greater than 15 cm/s. The constant A obtained from analyzing damaged datasets of other earthquake events sometimes differs. For example, the following formulas were developed to simulate the number of damage incidents for water pipes [Tokyo Metropolitan Government, 2006; Takada *et al.*, 2001]:

$$R(v) = 2.24 \times 10^{-3}(v - 20)^{1.51} \tag{6}$$

$$R(v) = 6.33 \times 10^{-5} v^{2.10}. \tag{7}$$

These fragility curves were primarily constructed from the damage dataset of a single event (the Kobe earthquake). Maruyama and Yamazaki [2010] compiled the damage datasets of water distribution pipes following three recent earthquakes: the 2004 Niigata Chuetsu, 2007 Noto-Peninsula, and 2007 Niigata Chuetsu-Oki earthquakes. The damage datasets from the 1995 Kobe earthquake and these three earthquakes were employed to construct the fragility curves. To use the fewest parameters when determining the lowest PGV that causes damage to water

Table 3. Fragility curve parameters obtained by Maruyama and Yamazaki [2010] (Eq. (8)).

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

distribution pipes and the largest damage ratio, we chose the scaled log-normal distribution [Maruyama *et al.*, 2008]. Explicitly

$$R(v) = C\Phi((\ln v - \lambda)/\zeta), \tag{8}$$

where $\Phi(x)$ is the cumulative distribution function of the standard normal distribution and λ, ζ, and C are constants determined by regression analysis. With this formula, three parameters also need to be determined but the lowest PGV that causes damage is not necessary to assign.

Table 3 lists the parameters of the obtained fragility curves. For the damage datasets of the three recent earthquakes, CIPs were not widely used as water distribution pipes in the affected areas. Therefore, it was difficult to perform a regression analysis using the damaged datasets including recent earthquakes for CIPs. Conversely, ductile cast-iron pipes (DIPs) and vinyl pipes (VPs) were the primary types of pipes used in the areas affected by the three recent earthquakes. The correction coefficient C_p for the pipe material in Eq. (3) was defined to be 1.0 for VPs based on the damaged dataset obtained after the 1995 Kobe earthquake. Using the correction coefficient C_p and damaged datasets for the recent earthquakes, the fragility curves for water distribution pipes were constructed to estimate the damage ratio of CIPs, VPs, and DIPs. The correction coefficient C_p was set to be 0.3 in Eq. (3). The damage ratios of DIPs were estimated by multiplying C_p with Eqs. (5)–(7), as shown in the next section.

4.2. *Evaluation of the damage ratio of water distribution pipe in Kashiwazaki city*

The damage ratios of water distribution pipe in Kashiwazaki city after the 2007 Niigata Chuetsu-Oki earthquake are compared with the different fragility curves shown in the previous section. As shown in Fig. 7, 10 seismometers were installed in the affected area during the event, and the PGVs were recorded (Table 4). Since the inventory data for the water pipes in Kariwa village were not available, the seismometers in Kariwa village were not considered in this study.

Table 4 lists the PGVs observed by seismometers and the damage ratios of the water distribution pipes. The damage ratios were calculated in areas located within 2 km from the seismometers (Fig. 7), and they were defined with respect to the material of the pipe (CIP, VP, and DIP). The number of pipe breaks in the alluvial plain was divided by the length of the water distribution pipes in the alluvial plain to obtain the damage ratio shown in Table 4.

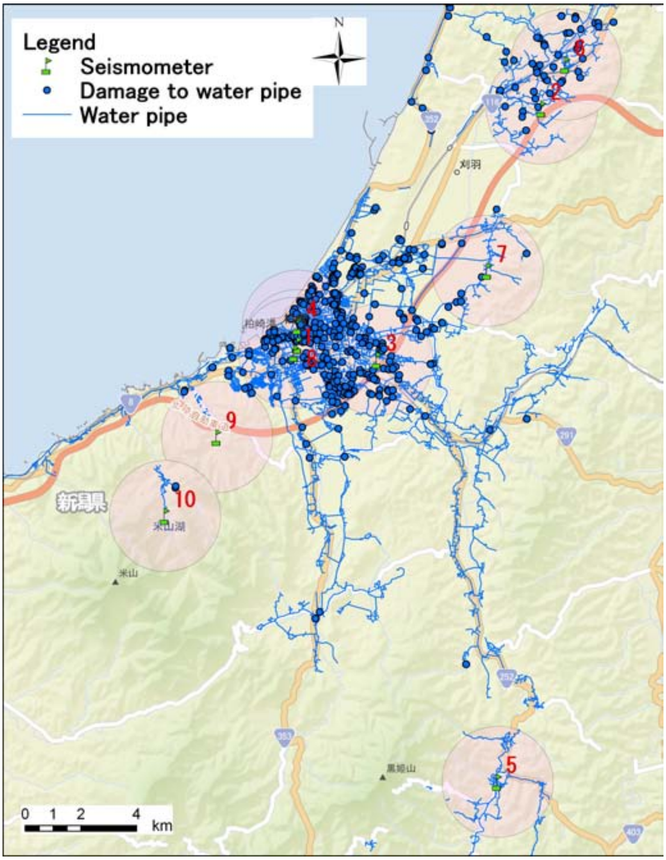


Fig. 7. Location of seismometers in Kashiwazaki city and damage incidents to water distribution pipe after the 2007 Niigata Chuetsu-Oki earthquake.

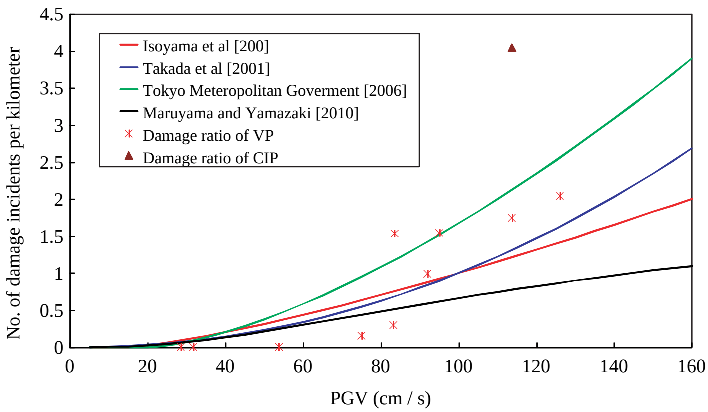
The damage ratios shown in Table 4 were compared with the different fragility curves in Fig. 8. CIPs were not widely used in the affected area, and that is indicated in Table 4. They were mainly deployed only in the central area of Kashiwazaki city. Therefore, the areas where the damage ratios of CIPs were obtained overlapped for three seismic observation stations (Kashiwazaki railway station, K-NET Kashiwazaki, and Kagamimachi gas supply station). Based on these facts, the damage ratio of the CIP obtained at Kagamimachi gas supply station is illustrated in Fig. 8.

According to the figure, the damage ratios for VPs are lower than the fragility curve estimations when the PGV is smaller than approximately 80 cm/s. The fragility curve used by the Tokyo Metropolitan Government [2006] provides good estimations if the PGV is in the range of 100–130 cm/s. The damage ratio of CIPs is much higher than the estimations of the fragility curves. For the DIPs, the damage ratios are lower than the estimations when the PGVs are smaller than

Table 4. Seismic observation stations and damage ratios of water distribution pipes in Kashiwazaki city after the 2007 Niigata Chuetsu-Oki earthquake.

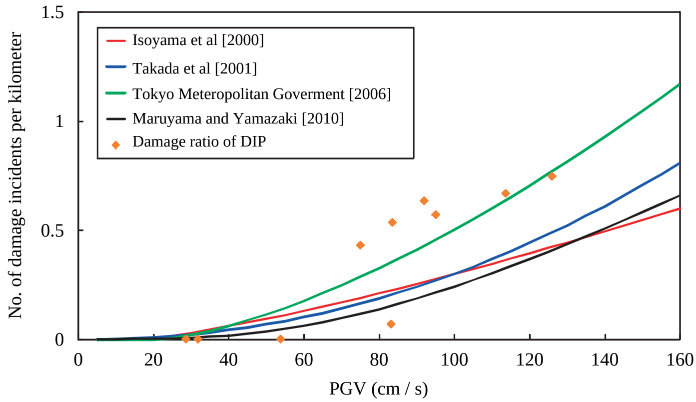
No.	Seismic observation station	PGV (cm/s)	CIP Length (km)	CIP Damage ratio	VP Length (km)	VP Damage ratio	DIP Length (km)	DIP Damage ratio
1	Kashiwazaki JR station	95.05	3.215	4.04	44.081	1.54	105	0.57
2	Nishiyama interchange, NEXCO	75.05	0	—	6.409	0.16	16.2	0.43
3	Kashiwazaki interchange, NEXCO	91.98	0	—	31.272	0.99	75.5	0.64
4	K-NET Kashiwazaki station	126.06	3.215	4.04	45.557	2.04	104	0.75
5	Takayanagi Town hall	53.78	0	—	2.441	0	1.05	0
6	Nishiyama Town hall	83.53	0	—	5.213	1.53	13	0.54
7	Yoshii plant, JAPEX	83.20	0	—	6.774	0.30	14.2	0.07
8	Kagamimachi gas supply station	113.71	3.215	4.04	47.525	1.75	107	0.67
9	Kouchi dam	31.77	0	—	0.609	0	1.71	0
10	Tanne dam	28.55	0	—	2.02	0	1.74	0

Note: JR, Japan Railways; NEXCO, Nippon Expressway Co., Ltd.; and JAPEX, Japan Petroleum Exploration Co., Ltd.



(a)

Fig. 8. Comparisons of damage ratios of water distribution pipes for (a) CIP and VP and (b) DIP after the 2007 Niigata Chuetsu-Oki earthquake with different fragility curves.



(b)

Fig. 8. (*Continued*)

approximately 80 cm/s. The damage ratios are higher than the estimations when the PGVs are 80–100 cm/s.

As a whole, the damage ratios of water distribution pipes after the 2007 Niigata Chuestu-Oki earthquake are higher than estimations following previous earthquakes in Japan. This may be a result from the effects of periodic characteristics in ground shaking and geographical and topographical conditions in the affected area. Further research is needed to draw solid conclusions.

5. Conclusions

In this study, the spatial distribution of pipe damage caused by the 2007 Niigata Chuetsu-Oki earthquake was analyzed with the aid of GIS. The damage ratios of buried pipes were obtained with regard to the geographical and topographical conditions. The possibility of synchronicity in damage occurrences among lifeline systems was evaluated through the damage dataset for the 2007 Niigata Chuetsu-Oki earthquake. In the current database, especially for water distribution pipes and low-pressure gas supply pipes, many damage incidents were commonly observed in the geomorphological classes indicating the existence of soft soil and at altitudes of 0–10 m. The probability that damage incidents occurred simultaneously in these two kinds of buried pipes is high.

The damage ratio for water distribution pipes during the 2007 Niigata Chuetsu-Oki earthquake was investigated by comparing different fragility curves that were constructed based on damage data from previous earthquakes. The damage ratios in Kashiwazaki city were calculated by focusing on areas within 2 km from the seismic observation stations. The damage ratios for CIP and VP were higher than the fragility curve estimations for PGV of 100–130 cm/s, and those of DIP were higher for PGV of 80–100 cm/s. Since the effects of periodic characteristics for ground shaking and geographical and topographical conditions in the affected area may have caused these observations, further research is necessary to draw solid conclusions.

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