Journal of Japan Association for Earthquake Engineering, Vol. 18, No. 3, 2018

SEISMIC VULNERABILITY OF A WATER-SUPPLY PIPELINE BASED ON THE DAMAGE ANALYSIS OF TWO EARTHQUAKES DURING THE GREAT EAST JAPAN EARTHQUAKE

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ABSTRACT: The city of Iwaki, located in Fukushima Prefecture, Japan, faced water outage twice because of the Tohoku earthquake that occurred on March 11, 2011, as well as the earthquake that followed on April 11, 2011. It is rare that two large earthquakes, each with different mechanisms, occur within a short period of one month. This study focuses on the pipeline damage in Iwaki due to these earthquakes and tries to clarify the seismic vulnerability of pipe attributes on the basis of the earthquake damage analysis on the water-supply pipeline. As the result of the analysis on the seismic vulnerability index of the pipe material, pipe diameter, and its geomorphological classification, the seismic vulnerabilities to pipe diameter and material were very similar between the two earthquakes. The seismic vulnerability to pipe diameter was also similar to that in earthquakes in the past, whereas polyvinyl chloride pipes (VPs) were evaluated to be stronger. The geomorphological classification factor does not always need to add seismic vulnerability depending on the evaluation of the seismic motion.

Keywords: the 2011 Tohoku earthquake, damage of water-supply pipeline, seismic vulnerability.

1. INTRODUCTION

The Tohoku earthquake, which occurred at 14:46 on March 11, 2011, caused a strong ground motion over a large area and caused extensive damage as a result of ground motion and a tsunami. The city of Iwaki, located in the southern part of Fukushima Prefecture, Japan, experienced tsunami damage in its coastal area of the Pacific Ocean. The city was hit again by a second strong earthquake centered beneath it at 17:16 on April 11, 2011 (hereafter called the induced earthquake, IE), one month after the initial Tohoku earthquake (hereafter called the main shock, MS). Both earthquakes interrupted the water-supply pipeline, which got broken and leaked. The maximum seismic intensity on the Japan Meteorological Agency scale in the city was recorded at six-upper in both earthquakes. It is rare for two huge earthquakes with different generation mechanisms to occur within a month of each other.

There is a lot of research focusing on analyzing the earthquake damage to water-supply pipelines.

Isoyama et al. [1] modeled the standard fragility function from the damage database of the water-supply pipelines in the cities of Ashiya and Nishinomiya during the 1995 Kobe earthquake, and they clarified the relationship between the PGA or peak ground velocity (PGV) and the pipeline damage ratio. This result is used to estimate the damage to water-supply pipelines by the Japan Water Works Association (JWWA) [2]. Takada et al.[3] also proposed a method to estimate the damage of the pipeline and its accessories by including the data from the area where the strong motion was observed and the building damage was extensive, such as Kobe, Ashiya, and Nishinomiya, as well as the area with moderate motion like Osaka, Takarazuka, and Amagasaki during the Kobe earthquake. Maruyama et al. [4] proposed an updated estimation model based on the pipeline damage data from the 2004 Niigata Chuetsu, the 2007 Noto Peninsula, and the 2007 Niigata Chuetsu-oki earthquakes in addition to the 1995 Kobe earthquake. These damage estimation models are based on the standard fragility function for a given ground motion, the correction coefficients for the pipe material, pipe diameter, and the geological conditions. The output from these models is the damage ratio at any given site. The standard fragility function is introduced from the correlation between the ground motion parameters and the damage ratio from the pipe material and diameter. The correction coefficients are obtained from the regression analysis by considering the seismic vulnerability of the other attributes. Since the correction coefficient for the geological conditions was not accurate enough from the Kobe earthquake data alone, Kuwata et al.[5] also analyzed the effect of the ground deformation due to a landslide on the damage data of the water-supply pipeline in the landslide area of the 2004 Niigata Chuetsu earthquake. The Japan Water Research Center (JWRC) [6] proposed a correction coefficient for geomorphology from the analysis of pipeline damage from several earthquakes between the 1995 Kobe earthquake and the 2011 Tohoku earthquake. The correction coefficient of the damage estimation method is useful in visualizing the seismic vulnerability of the pipeline in each region by a vulnerability index that is obtained as the weighted average of the correction coefficients of the pipe material and diameter by the installed length, as shown by Suzuki et al. [7]. This kind of study was conducted after the Tohoku earthquake too. Tsukiji et al.[8] proposed a fragility function based on data from the cities of Itako and Kamisu in Ibaraki Prefecture. Kuwata and Ohno[9] proposed a new correction coefficient for the pipe material and diameter from the damage recorded in the northwest of Miyagi Prefecture. The JWRC[10] modified the damage estimation especially for liquefied areas using a previous method[6].

In this study, the pipeline damage in the city of Iwaki, caused by the MS and the IE, is analyzed, and the vulnerability index of the pipeline that corresponds to the correction coefficient of the damage estimation method is obtained. The notion that the damage caused by the two earthquakes was different across the same region is clarified even though the analytical methods were based on the studies mentioned above. Moreover, the results from this study on the city of Iwaki will have potential for application in other regions, because Iwaki covers a wide area that was stricken by the Tohoku earthquake and it differs from the urban Hanshin area of the Kobe earthquake as the pipe material and diameter are the same as seen in rural areas.

2. OUTLINE OF IWAKI'S WATER-SUPPLY SYSTEM AND ITS EARTHQUAKE DAMAGE AND RESPONSE

The water service in Iwaki began in the town of Taira in 1921, and it includes the water services constructed in Yumoto-Honmachi, Ena, Yotsukura, and Onahama. Iwaki was established in October 1966 by the amalgamation of five cities, four towns, and five villages, and its water-supply service was a combination of the existing water-supply services of each municipality. The service is managed by four offices: the first water-service office, the second water-service office, the Nakoso construction office, and the Onahama construction office. Its service area is 463.59 km^2, the total pipeline length is 2,099 km, and the water is supplied to 330,000 people (120,000 households) within Iwaki. Polyvinyl chloride pipes (VPs) are used in 59% of the total length, and ductile iron pipes (DIPs) are used in 39%. The majority of the pipelines are made from these materials, and among the DIPs, 6% of the total are with earthquake-proof joint. Cast-iron pipes (CIPs) are still in use, making up 1% of the pipelines. In terms of pipe diameter, half the pipelines had a diameter between ϕ 100 and ϕ 150, and about a fourth of the pipelines had a smaller diameter of ϕ 75 or less.

As mentioned above, the IE[11] with a seismic intensity six-upper occurred in Iwaki one month after the MS[11] with the same seismic intensity. The MS was the earthquake that was generated from the Eurasian Plate and the subducting Pacific Plate, whereas the IE was a crustal earthquake with normal faulting. Sato et al.[12] pointed out that the ground motion in high frequency of the IE was almost the same as the mean value of the crustal earthquake, and the ratio of response spectrum in the fault-orthogonal direction to those in the parallel direction was larger than that of an earthquake with reverse faulting. The predominance of the Rayleigh wave contributes to this observation. Earthquakes over M3.0 in the vicinity of the epicenter of the IE have been few since 1997, but earthquakes with a seismic intensity five have frequently occurred after the MS, and the seismic activity was high[13]. According to the observed records, the PGV was 40.5 cm/s in the MS and 20.0 cm/s in the IE at K-NET Iwaki (KS011) station in the northern Taira area, whereas PGV was 52.0 cm/s in the MS and 49.8 cm/s in the IE at K-NET Nakoso (KS012) station in the southern Onahama area. It can be said that the ground motions of the MS and the IE were almost the same in the southern part of Iwaki.

Shortly after the MS, even though many cities in East Japan suffered from power outages, the power supply to Iwaki was maintained. However, because of the water leak from the damaged pipelines, the water supply was interrupted to the whole city. Afterwards, because of the leakage of radioactive material from a nuclear power plant, the pipe construction workers evacuated the city, the disaster logistics were delayed, the disaster support from other cities was canceled, and the recovery works were delayed. In addition, the old pipelines on the trunk line were damaged at several locations, and so the time needed to restore the controlling water pressure was prolonged. However, 97% of the water service was achieved on April 10, and the pipeline restoration was almost complete. After the IE on April 11, the water supply stopped again because of a power outage, and further damage to the pipelines also occurred. The water supply was restarted within about two weeks. After both earthquakes, the water supply to the whole city was stopped. However, it was restored earlier after the IE because of the gained experience of pipeline recovery after the MS.

3. DATABASE OF DAMAGE TO WATER-SUPPLY PIPELINES AND BASIC ANALYSIS

In order to analyze the damage to the water-supply pipelines, a database in GIS format that was constructed by the Research Committee of Lifeline Damage Database in the JEEA[14] was used. Due to the fact that the pipeline data in Iwaki was not constructed in the Shape file format, the committee digitalized an image map of the pipeline network. The pipeline data was made by scanning the paper-based pipeline map offered by the Iwaki Waterworks using a large-scale scanner, followed by overlaying it with the roadway data from the Geographical Survey Institute[15], and processing the polylines. The polyline attribute of the pipe material and diameter was assigned. The data of each damage location on the pipe material, diameter, pipe type (main pipe or branch pipe), the type of earthquake (MS or IE), and damage mode (crack or leak) were assigned on the basis of the data offered by the city of Iwaki. Which earthquake caused the damage is distinguished by the date of the pipe repair, because damage caused by the MS was almost fully recovered before the IE. Fig. 1 shows the distribution of the damage locations on the pipeline network as distinguished by the MS and the IE. The damage caused by the MS was concentrated around the inland areas of Taira and Yumoto, whereas the damage caused by the IE was concentrated in the areas of Onahama and Nakoso, the south coast of the city. Since the seismic zone of the IE was in Western Yumoto, there were many damage locations in the inland area. In terms of pipe material, the locations of the damaged CIP were concentrated in the Onahama area, but the damaged locations of VP and DIP were widely distributed in the city.

By comparing the GIS data and the statistics of the Iwaki Waterworks, the accuracy of the database was confirmed. The pipeline from the GIS data was a little longer, but the difference is remarkable for pipelines with a small diameter. Pipelines with a small diameter of ϕ 50 or less are generally used to connect the main pipe to a house. The ownership of the pipe is either the waterworks or the householder, dependent on the location of the water meter. The difference is thought to be due to the fact that the end of the pipeline cannot be easily distinguished because there is no information on the location of the water meter in the pipeline map.

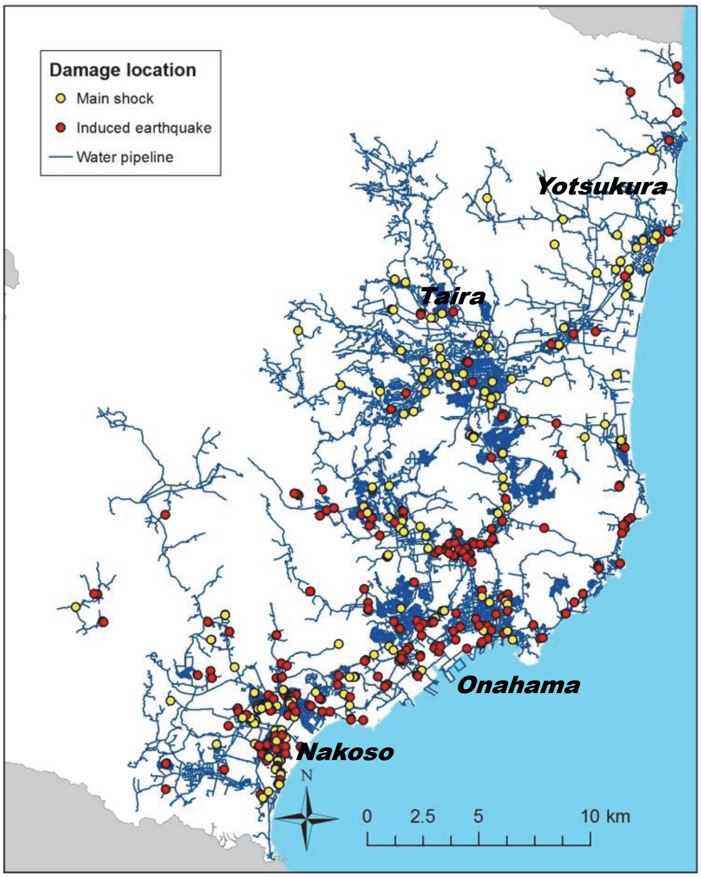


Fig. 1 Locations of damage to the water-supply pipeline (215 locations after the MS and 268 locations after the IE)

In order to clarify the geological condition at the location of pipeline damage, the 250 m-by-250 m mesh that is one-fourth size of standard regional was used. Each grid square is given an engineering geomorphological classification that was proposed by Wakamatsu et al.[16] Fig. 2 shows the city map as classified by the engineering geomorphological classification, and Fig. 3 shows the ratio of pipeline lengths according to the engineering geomorphological classification. The pipeline is installed in a range of different areas classified as hills, gravelly terraces, back marshes, and coastal lowlands, although the majority of the city of Iwaki is in the mountains or hills.

When the location of the damaged pipeline in Fig. 1 and the engineering geomorphological classifications in Fig. 2 are compared, the damage caused during the MS is concentrated in locations of back marshes, sand bars, and coastal lowlands in the areas of Taira and Yotsukura located in the northern part of Iwaki. The damage during the IE is concentrated in the delta and coastal lowland of Nakoso and Onahama areas in the south.

The pipeline's length and the number of damaged locations developed by the GIS are summarized in terms of the pipe material and diameter, as listed in Table 1. The number of the damaged pipeline locations is 483 on the GIS, whereas 454 locations were reported by the city of Iwaki[14]. Due to the fact that two or more adjacent damaged locations may have been counted as one single location in the

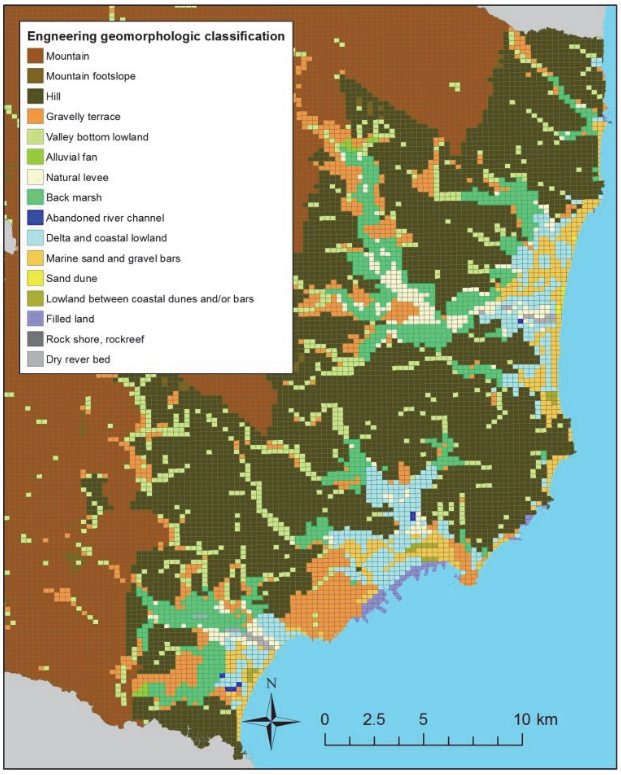


Fig. 2 Engineering geomorphological classification[14)]

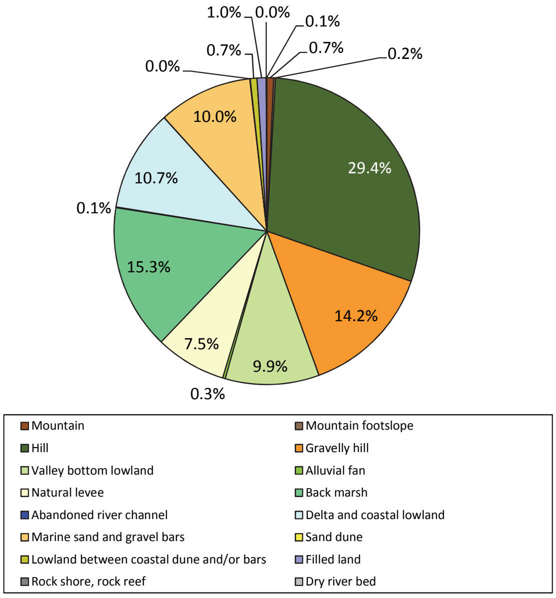


Fig. 3 Ratio of pipeline lengths in terms of the engineering geomorphological classification

restoration report of the city, the GIS data was used in this study. Although water leaks from the pipeline occurred even after restarting the water supply after the IE, the number of damaged locations was treated as the damage was repaired before restarting.

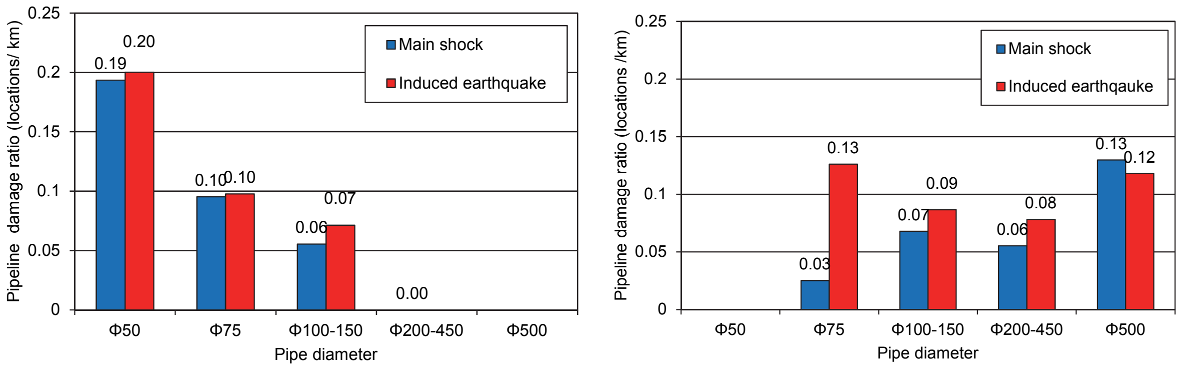
Comparing the pipeline damage ratios in terms of pipe material, the ratios for steel pipes (SPs) and asbestos cement pipes (ACPs) were remarkably high. The correction coefficient of pipeline damage estimation by JWWA[2)] was also high for ACPs. However, this is because the installed lengths of both types of pipelines were short, only 6 km of ACPs and 21 km of SPs, compared to the other pipe material, and therefore the pipeline damage ratio may be overvalued. The damage ratio of VP became smaller than that of CIP although the correction coefficients of the damage estimation for both pipe materials were determined to be the same. It is thought that a contributing factor may be the fact that many VPs were installed on hills and the ground motion at the VP sites was therefore relatively small. In terms of pipe diameter, the pipeline damage ratio increases as the diameter gets smaller, excluding the category of ϕ 500 or more.

The composition ratio of the amount of pipeline damage shows a similar tendency in pipe material between the MS and the IE: VP is about 60%, DIP is about 25%, and SP is about 10%, although the total number of damaged locations due to both earthquakes is different. The composition ratio in the pipe diameter also shows a similar tendency between both earthquakes: ϕ 50 or less is about 30%, ϕ 75 is about 20%, ϕ 100–150 is about 30–40%, ϕ 200–450 is about 10%, and ϕ 500 or more is about 5%. The pipeline damage ratio of the MS and the IE in terms of pipe diameter for VP and DIP is shown in Fig. 4. There is a similar tendency in the pipeline damage ratio between the MS and the IE, except that the DIP ϕ 75 has a few differences. The majority of VPs have a diameter of ϕ 150 or less. The pipeline damage ratio in these diameters increases as the diameter becomes smaller. On the other hand, most of the DIPs have a diameter of ϕ 100–450. The pipeline damage ratio of pipes with a diameter of ϕ 100–150 is larger than that with ϕ 200–450. Note that the pipeline damage ratios of ϕ 75

Table 1 Pipelines' lengths and damage locations in terms of pipe material and diameter

		ϕ 50 or less	ϕ 75	ϕ 100–150	ϕ 200–450	ϕ 500 or more	Subtotal	Damage ratio (locations/km)
VP	Pipeline length (km)	299.7	409.8	757.4	0.3	0.0	1467.3	
	MS (locations)	59	39	42			140	0.10
	IE (locations)	60	40	54			154	0.10
	Subtotal of damage locations	119	79	96			294	0.20
SP	Pipeline length (km)	3.4	2.1	8.6	4.7	2.5	21.3	
	MS (locations)	6	3	4	4		17	0.80
	IE (locations)	5	2	17	5		29	1.36
	Subtotal of damage locations	11	5	21	9		46	2.16
DIP	Pipeline length (km)	0.0	39.6	323.4	306.8	84.7	754.4	
	MS (locations)		1	22	17	11	51	0.07
	IE (locations)		5	28	24	9	66	0.09
	Subtotal of damage locations		6	50	41	20	117	0.16
SUP	Pipeline length (km)	0.5	0.4	2.7	2.0	0.7	6.3	
	MS (locations)	0	0	0	0	0	0	0.00
	IE (locations)	0	0	0	0	0	0	0.00
	Subtotal of damage locations	0	0	0	0	0	0	0.00
PP	Pipeline length (km)	10.8	0.1	0.2	0.0	0.0	11.1	
	MS (locations)	0	0	0	0	0	0	0.00
	IE (locations)	0	0	0	0	0	0	0.00
	Subtotal of damage locations	0	0	0	0	0	0	0.00
NC	Pipeline length (km)	0.0	0.3	1.4	1.0	0.3	3.0	
	MS (locations)	0	0	0	0	0	0	0.00
	IE (locations)	0	0	0	0	0	0	0.00
	Subtotal of damage locations	0	0	0	0	0	0	0.00
DS	Pipeline length (km)	0.0	0.0	2.4	55.9	12.1	70.4	
	MS (locations)	0	0	0	0	0	0	0.00
	IE (locations)	0	0	0	0	0	0	0.00
	Subtotal of damage locations	0	0	0	0	0	0	0.00
ACP	Pipeline length (km)	1.0	1.5	3.0	0.5	0.0	6.0	
	MS (locations)		3				3	0.50
	IE (locations)		3	5	2		10	1.66
	Subtotal of damage locations		6	5	2		13	2.16
DNS, DSII, DS, DKF, DUF	Pipeline length (km)	0.0	3.2	8.5	29.4	14.8	55.8	
	MS (locations)	0	0	0	0	0	0	0.00
	IE (locations)	0	0	0	0	0	0	0.00
	Subtotal of damage locations	0	0	0	0	0	0	0.00
CIP	Pipeline length (km)	0.0	0.5	3.4	8.9	0.0	12.8	
	MS (locations)		3		2		5	0.39
	IE (locations)		3	5			8	0.63
	Subtotal of damage locations		6	5	2		13	1.02
HP	Pipeline length (km)	0.0	0.0	0.0	0.1	0.0	0.1	
	MS (locations)	0	0	0	0	0	0	0.00
	IE (locations)	0	0	0	0	0	0	0.00
	Subtotal of damage locations	0	0	0	0	0	0	0.00
Total	Pipeline length (km)	315.6	457.4	1110.9	409.4	115.2	2408.5	
	MS (locations)	65	49	68	23	11	216	0.09
	IE (locations)	65	53	109	31	9	267	0.11
	Subtotal of damage locations	130	102	177	54	20	483	0.20
Damage ratio (locations/km)	MS (locations/km)	0.21	0.11	0.06	0.06	0.10	0.09	
	IE (locations/km)	0.21	0.12	0.10	0.08	0.08	0.11	
	Subtotal (locations/km)	0.41	0.22	0.16	0.13	0.17	0.20	

Note. VP: polyvinyl chloride pipe; SP: steel pipe; DIP: ductile iron pipe; SUP: stainless-steel pipe; PP: polyethylene pipe; DS: ductile iron pipe with sleeve; ACP: asbestos cement pipe; DIP with seismic joints (NS, SII, S, KF, and UF types); CIP: cast-iron pipe; HP: Hume pipe.



(a) Pipeline damage ratio (VP) (b) Pipeline damage ratio (DIP)

Fig. 4 Pipeline damage ratios of the MS and IE in terms of the diameter of VP and DIP

and more than ϕ 500 of DIPs may be overestimated or underestimated, as the installation lengths are shorter than the others. In addition, when comparing the pipeline damage ratio of VPs and DIPs at ϕ 100–150, those of DIPs were somewhat high regardless of which earthquake caused the damage.

4. EVALUATION OF PIPELINE VULNERABILITY OF THE CITY OF IWAKI

4.1 Regression Analysis

The vulnerability index of the pipeline is examined from the earthquake damage by referring to the calculation method of the correction coefficient of pipeline damage as an estimation to clarify the vulnerable pipelines to an earthquake by quantifying the pipeline attributes and the engineering geomorphological classification. The formula of pipeline damage estimation of JWRC[6)] introduces the pipeline damage ratio and is given by the product of the standard pipeline damage ratio and the correction coefficients for pipe material, diameter, and geomorphology as shown in the following equation:

$$R_m(v) = C_p C_d C_g R(v), \quad (1)$$

where $R_m(v)$ is the pipeline damage ratio for a given PGV v (locations/km); C_p, C_d, and C_g are the correction coefficients for the pipe material, diameter, and geomorphology, respectively; and $R(v)$ is the standard pipeline damage ratio for PGV v (locations/km).

In a word, the value of the correction coefficient indicates that when the coefficient is more than 1.0, the pipe will be more vulnerable than the standard pipe and its likelihood of earthquake damage increases. In this study, the value corresponding to the correction coefficient is called the vulnerability index of the pipeline. The value of the vulnerability index for pipe material, diameter, and engineering geomorphological classification was also examined. There is evidence that the pipeline damage varied with pipe material, diameter, and ground condition and that these factors are independent of the previous studies. It is thought that the difference in the vulnerability due to the two earthquakes can be confirmed because the vulnerability indexes are obtained for each earthquake in the analysis for the city of Iwaki. Moreover, quantifying the vulnerability index enables the comparison of those in other regions and from past earthquakes.

The engineering geomorphological classification in 250 m grids as determined by Wakamatsu[16)] is used for geography in this study. The formula deals with DIPs, diameters of ϕ 100–150, and the engineering geomorphological classifications of valley lowlands, alluvial fans, back marshes, and delta and coastal lowlands. The number of items in each category for the regression analysis was determined as two of VP and DIP for the pipe material category; five of ϕ 50 or less, ϕ 75, ϕ 100–150, ϕ 200–450, and ϕ 500 or more for the diameter category; and five in the geomorphology group as well as the JWRC: Group 1 (mountains, mountain footslopes, hills, volcanoes, volcanic footslopes, and volcanic hills), Group 2 (gravelly hills, terraces covered with volcanic ash-soil), Group 3 (valley bottom lowlands, alluvial fans, back marshes, and delta and coastal lowlands), Group 4 (natural levees, abandoned river channels, marine sand and gravel bars, and sand dunes), and Group 5 (filled lands, reclaimed lands, and water bodies). Note that the above classification includes the ones that are not in the city of Iwaki, such as volcanic soils, terraces covered with volcanic ash-soil, reclaimed lands, and water bodies. DIPs with a seismic joint were excluded from the data because the length is short and there is no earthquake damage. Moreover, the area liquefied along the abandoned river channel is reported as part of the city[17]. Its pipeline and damage locations were also excluded.

The earthquake ground motion in the city is different, and the pipeline damage ratio of the standard attribute seems to be different too. The effect of this ground motion variation will be considered in the following analysis. At first, the pipeline damage ratio of the standard attribute is given one value for each earthquake. The number of damage locations and the pipeline length are accounted for by combining each attribute. The quantification theory in the logarithm field is analyzed with an objective variable of the damage ratio of the attribute combination. In the analysis, weight is given by the pipeline length by the combination of each attribute:

$$R = C_p C_d C_g R', \tag{2}$$

where R is the pipeline damage ratio of each attribute (locations/km) and R' is the pipeline damage ratio of the standard attribute (locations/km).

Four cases were examined in the regression analysis: the damage data of only the MS (called the MS case), the damage data of only the IE (called the IE case), the damage data in which both earthquakes are accounted for separately (called the independent case), and the damage data integrated (called the whole case). In the analysis of the independent case, additional variables for either the MS or the IE were given. A total of 411 damage locations, in which 191 locations were from the MS and 220 locations were from the IE, were used as the data for the regression analysis. The standard pipeline damage ratio R' was 0.07 locations/km for the MS case, 0.12 locations/km for the IE case, and 0.19 locations/km for the whole case.

As for each correlation coefficient, the MS case was 0.93, the IE case was 0.96, the independent case was 0.79, and the whole case was 0.93. As a whole, high correlations were obtained. Fig. 5 shows the vulnerability index of each pipeline attribute according to the analytical cases. Comparing the indexes between the cases, the index of pipe material and diameter can be seen to vary within the range of 0.5 points, except in the case of a diameter of ϕ 500 or more. The pipeline with a diameter of ϕ 500 or more is only a DIP, and the damage locations were 11 after the MS and 9 after the IE. The number of damage locations does not seem to be very different between the two earthquakes, but it is considered to be due to a difference in geomorphology. Overall, it was confirmed that the index of DIPs is a little bit smaller than that of VPs, and it becomes smaller as the diameter gets larger, excluding the case of ϕ 500 or more. These tendencies are similar to the pipeline damage ratio of DIPs as mentioned in Fig. 4. In a word, the obtained indexes of pipe material are adjusted to the result of past earthquakes, whereas the indexes of diameter are evaluated for VPs that have not been damaged as easily compared to previous research reports.

While the indexes of pipe material and diameter indicate similar values between the cases, the index of the geomorphology group shows a large difference. In particular, the indexes of Group 4 and Group 5 show an opposite tendency to the MS and IE cases. These groups are marine sand and gravel bars, sand dunes, and filled lands. Since the pipeline length in filled lands is only about 1% of the total, it is thought that the index was either overvalued or undervalued. Moreover, there is a good reason to believe that the seismic ground motion of the IE was locally higher than of the MS, and those in the northern part and the southern part of the city were different even in the same geomorphology group.

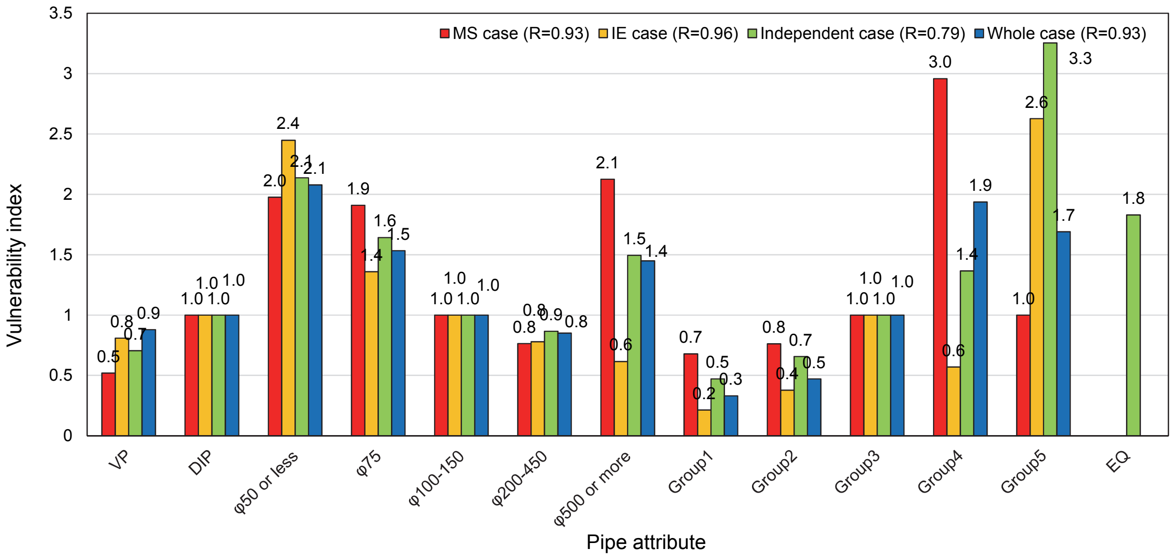


Fig. 5 Vulnerability index of pipe attributes from each regression analysis case. *Note 1*. The index shows the MS case, IE case, independent case, and whole case from the left bar. *Note 2*. The number of () in the legend means the correlation coefficient of the regression analysis. *Note 3*. The value of EQ means the index of the IE when the earthquakes are dealt separately.

4.2 Proposal for the Vulnerability Index

The regression analysis dealt with the DIP and VP pipelines and accounted for 97% of the total length. This section considers the quantitative evaluation of the pipeline vulnerability, including the other pipe materials. At first, Table 2 lists the vulnerability index proposed by this study on the basis of the result of the regression analysis and simple accounts. The proposed index is basically referred to as the value of the regression analysis. The attribute that was not analyzed in the regression analysis is referred to as the result of simple accounts and the correction coefficients of the existing damage estimation model. The value of the simple accounts is the ratio of the given pipeline damage ratio to the standard pipeline damage ratio with respect to the pipe material, diameter, and geomorphology group.

The value of JWRC[6] in the table is calculated as the ratio to the coefficient of the standard attribute of DIP, ϕ 100–150, and engineering geomorphological classification as the valley bottom lowlands, alluvial fans, back marshes, and delta and coastal lowlands. Due to the fact that the division of diameter in the JWRC study does not correspond directly to the division in this study, it is shown in order to understand the value of each coefficient.

The proposed vulnerability index of the pipeline is explained as follows. The index of VP is determined as 1.0, the same as that of DIP, although it was evaluated to be smaller than the DIP in the regression analysis, because it relies heavily on the value of a previous study. The reason why the DIP received higher damage than the VP is the influence due to corrosion deterioration by the causticity of the soil, as established from interviews with the local engineers. It will be necessary to examine the influences rather than just the seismic ground motion in the future. The simple accounts of SP indicated a very high value, exceeding 10.0. The MS damaged not only vulnerable SPs with a small diameter but also SPs with a large diameter that had not been welded from the inside. The pipeline damage ratio of SP is 0.8 locations/km after the MS and 1.36 locations/km after the IE. These values of simple accounts seem to be overevaluated. The vulnerability index is determined to be 2.5 from the value of the correction coefficient of SPs (excluding the welded pipeline) in the JWRC study. The index of stainless steel pipe (SUS) is determined to be 0.0 because the pipeline did not exhibit any damage at this time and the pipeline length was short. The index of CIP is also dealt with similarly to the SP, and it was determined to be 2.5, that is, the correction coefficient of CIP in the JWRC study. As for the ACP, the JWRC recommends that the correction coefficient is set to be 7.5, but if the length of the ACP is less than several tens of kilometers, the water supplier can judge the coefficient.

Table 2 Vulnerability indexes of pipe material, diameter, and engineering geomorphological classification

			Simple accounts			Result of regression analysis				JWRC[6)]	The proposed vulnerability index
			MS case	IE case	Total	MS case	IE case	Whole case	Independent case		
Pipe material		VP	1.4	1.2	1.3	0.5	0.8	0.9	0.7	2.5	1.0
		SP	11.8	15.5	13.9	-	-	-	-	0.5/2.5	2.5
		DIP	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
		SUS	0.0	0.0	0.0	-	-	-	-	-	0.0
		CIP	5.8	7.2	6.6	-	-	-	-	2.5	2.5
		ACP	7.4	19.0	13.9	-	-	-	-	7.5	7.4
Diameter		Φ50	3.4	2.1	2.6	2.0	2.4	2.1	2.1	2.0	2.0
		Φ75	1.7	1.2	1.4	1.9	1.4	1.5	1.6	2.0	1.5
		Φ100–150	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
		Φ200–250	0.9	0.8	0.8	0.8	0.8	0.8	0.9	0.4	0.8
		Φ300–450								0.2	
		Φ500 or more	1.6	0.8	1.1	2.1	0.6	1.4	1.5	0.1	0.5
Engineering geomorphological classification	Group 1	Mountain	0.0	1.2	0.6	0.7	0.2	0.3	0.5	0.4	0.3
		Mountain footslope	0.0	0.0	0.0						
		Hill	1.0	1.0	1.0						
	Group 2	Gravelly hill	1.2	1.5	1.3	0.8	0.4	0.5	0.7	0.8	0.5
	Group 3	Valley bottom lowland	1.1	1.3	1.2	1.0	1.0	1.0	1.0	1.0	1.0
		Alluvial fan	0.0	3.1	1.5						
		Back marsh	2.5	2.5	2.5						
		Delta and coastal lowland	1.9	4.8	3.4						
	Group 4	Natural levee	5.7	1.2	3.4	3.0	0.6	1.9	1.4	2.5	1.9
		Abandoned river channel	0.0	0.0	0.0						
		Marine sand and gravel bars	2.3	6.0	4.2						
		Sand dune	21.5	0.0	10.7						
		Lowland between coastal dune and/or bars	6.1	6.1	6.1						
	Group 5	Filled land	0.0	3.6	1.8	1.0	2.6	1.7	3.3	5.0	3.3
Correlation coefficient						0.93	0.96	0.93	0.79		

The vulnerability index of ACP is determined to be 7.4, which is from the MS case of the simple accounts because the index is almost the same as 7.5 of the JWRC.

With respect to the vulnerability indexes of the diameter, the index of a diameter of ϕ 50 or less is determined to be 2.0 because the whole case in the regression analysis and the correction coefficient of the JWRC show similar values. The indexes of diameters ϕ 75 and ϕ 200–450 are determined to be 1.5 and 0.8, respectively, from the result of the whole case in the regression analysis. The index of ϕ 500 diameter pipes was determined to be 0.5, referring to our previous study[9] in the northwest of Miyagi Prefecture, which showed a 0.5-fold coefficient for pipes of diameter ϕ 100–150, though the result of the regression analysis was larger than the correction coefficient of the JWRC.

With respect to the vulnerability indexes of the engineering geomorphologic classification, the index for each geomorphology group is proposed since the geomorphology is divided into five groups by referring to the grouping of the JWRC study. The indexes from Group 1 to Group 4 are determined to be 0.3, 0.5, 1.0, and 1.9, respectively, on the basis of the result of the whole case of the regression analysis. The index of Group 5 is determined to be 3.3, taking the value between the result of the whole case in the regression analysis and the correction coefficient of JWRC. The reason for taking a smaller value than the coefficient of JWRC is that the JWRC considers the liquefaction potential. However, the liquefied area was excluded from the regression analysis of this study.

4.3 Relationship between Pipeline Damage and Seismic Ground Motion in Considering the Vulnerability Index of Both Earthquakes

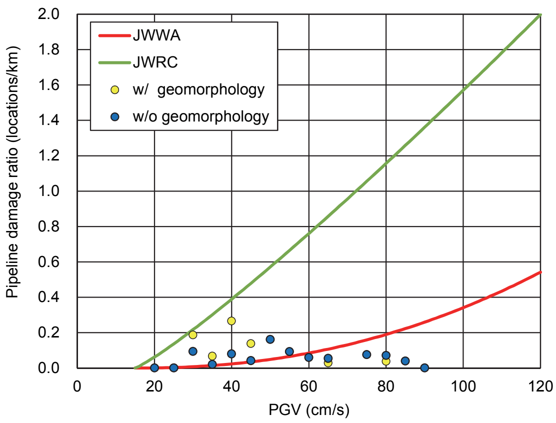
The IE caused more localized strong seismic ground motion than the MS, and the ground motion may differ between the northern and southern parts of the city even in the same geomorphologic classification. Thus, in order to analyze the influence of the seismic ground motion on the pipeline damage, the standard pipeline damage ratio converted from the raw pipeline damage ratio divided by the proposed vulnerability index is calculated and compared with the function of the standard pipeline damage ratio in previous studies.

Using the PGV distributions of the MS and IE as estimated by the "Quick estimation system for earthQuake maps triggered by observation records" (called QuiQuake)" [18] and provided by the National Institute of Advanced Industrial Science and Technology (AIST), the amount of pipeline damage and the pipeline length in the grid assigning the PGV were assessed.

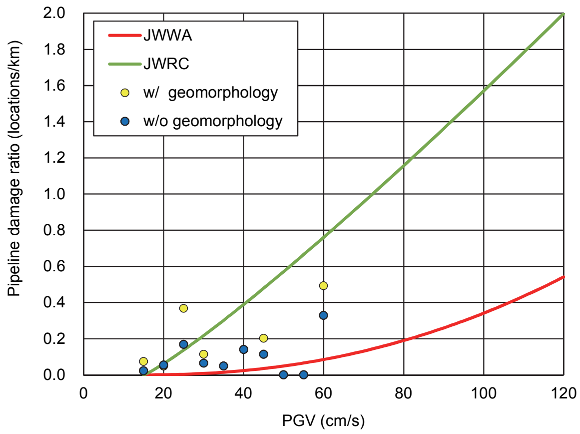
The normalized number of damage locations is calculated by dividing the raw number of damage locations by the proposed vulnerability index in order to make the number the standard attribute (DIP, ϕ 100–150, and engineering geomorphological classification as the valley bottom lowland, alluvial fan, back marsh, and delta and coastal lowland). Then, the pipeline damage ratio was obtained by the normalized number of damage locations and the pipeline length in each PGV = 5 cm/s.

Since the PGV which estimated the seismic motion on the ground surface by QuiQuake is considered as a site amplification by the engineering geomorphological classification, the index not considering the site amplification was also considered. Fig. 6 shows the relationship between the PGV and the pipeline damage ratio during the MS and IE. The functions of the standard pipeline damage ratio of the JWWA[2] as well as the JWRC[6] are drawn together. As for the JWWA, the function of CIP originally proposed is converted to the one for DIP by multiplying by the correction coefficient. Note that the data is excluded from the figure if the pipeline length classified by 5 cm/s is less than 1% of the total pipeline length.

Most of the pipeline damage ratios of the MS and IE are distributed around the JWWA curve and are smaller than the JWRC curve. Although the influence of locality on strong areas of ground motion in the IE was considered in the above analysis, the pipeline in the strong area was short and the tendency of the result does not change by this. However, the pipeline damage ratio of the IE reacts sensitively to the PGV rather than that of the MS. The ground motion estimated by interpolation of the observed records may not explain the locality of the strong ground motion well if the seismic zone is in the interpolation range. Moreover, when the index of geomorphology is not considered, the pipeline damage ratio corresponds well to the JWWA curve. This, therefore, suggests that when the estimated ground motion is considered, the site amplification by the engineering geomorphologic classification and multiplying the correction coefficient of geomorphology leads to doubly evaluating the effect of the geomorphology.



(a) MS



(b) IE

Fig. 6 Relationship between PGV and pipeline damage ratio considering the vulnerability index

5. CONCLUSIONS

The pipeline vulnerability indexes of pipe material, diameter, and geomorphology were examined in this study by the analysis of the earthquake damage to the water-supply pipeline in the city of Iwaki, in order to clarify the seismic vulnerability to two earthquakes in the same area, since two earthquakes with different mechanisms occurred within a short timeframe.

- As a result of the regression analysis, the vulnerability indexes of pipe material and diameter have similar values in both earthquakes. The vulnerability index of the pipe diameter shows an adjustment to the results from the study of past earthquakes, whereas for the pipe material, the VPs were evaluated to be stronger.
- The vulnerability index of geomorphology varied widely compared with that of the pipe material and diameter. Whereas the epicenter of the MS is far and the ground motion with a similar level was estimated widely, the strong ground motion of the IE was locally different. The difference of the strong ground motion affects the evaluation of the vulnerability index of geomorphology.
- This suggests that when the estimated ground motion is considered, the site amplification by the engineering geomorphologic classification and multiplying the correction coefficient of geomorphology leads to a double evaluation of the effect of geomorphology.

ACKNOWLEDGMENT

This study used the database that was originally offered by the Iwaki waterworks bureau and digitalized by the Research Committee of Lifeline Damage Data-base in the JEEA. The authors would like to express special thanks to them.

REFERENCES

1) Isoyama, R., Ishida, E., Yune, S., Shiramizu, Y.: Study on earthquake damage estimation of water pipeline, Journal of Japan Water Works Association 67(2), pp.25-40, 1998 (in Japanese).
2) Japan Water Works Association: *Study on earthquake damage estimation for water-supply pipeline*, 1998 (in Japanese).
3) Takada, S., Fujiwara, M., Miyajima, M., Suzuki, Y., Yoda, M., Tojima, T.: Study of seismic

damage estimation procedure for water pipelines based on the characteristics of inland seismic hazards, Journal of Japan Water Work Association 70(3), pp.21-37, 2001 (in Japanese)
4) Maruyama, Y., Yamazaki, F.: Estimation of Damage Ratio of Water Distribution Pipe Based on Recent Earthquake Damage Data, Proceedings of the JSCE Earthquake Engineering Symposium, Vol.30, pp.565-574, 2009 (in Japanese)
5) Kuwata, Y., Takada, S., Gonsoku., Y. and Javanbarg, M, B.: Slope effects to water pipeline damage; a case study during the 2004 Niigata Chuetsu earthquake, Journal of Japan Association for Earthquake Engineering, Vol.5, No.4, pp.1-14, 2005. (in Japanese)
6) Japan Water Research Center: Guideline of earthquake damage estimation for water-supply pipeline, 2011 (in Japanese)
7) Suzuki, Y., Satoh, H., Nojima, N., Sugito, M.: Estimation model of post-earthquake functional performance of utility lifeline considering vulnerability of underground pipeline, Proceedings of annual conference of the Japan Society of Civil Engineers, vo.58, pp.697-698, 2003 (in Japanese).
8) Tsukiji, T., Terajima, R., Shoji, G., Nagata, S.: Damage Assessment on Water Supply Systems in the 2011 Off the Pacific Coast of Tohoku Earthquake - Case Study for the Data at Itako City and Kamizu City -, Journal of Japan Society of Civil Engineers, Ser. A1, Vol.69, No.4, ppI_260-I_279, 2013 (in Japanese)
9) Kuwata, Y., Ohno, A.: Characteristic on Pipeline Damage in the Northwest of Miyagi Prefecture During the 2011 off the Pacific Coast of Tohoku Earthquake, Journal of Japan Society of Civil Engineers, Ser. A1, Vol.69, No.4, ppI_734-I_741, 2013. (in Japanese)
10) Japan Water Research Center: Report on the study for development of earthquake damage estimation for water-supply pipeline, 2013 (in Japanese).
11) Japan Meteorological Agency: Earthquake Information. http://www.jma.go.jp/en/quake/ (last accessed in April 18, 2018)
12) Satoh, T., Tsutsumi, H.: Short-period spectral level, path and site-amplification derived from strong motion records during the normal-faulting earthquakes in Hamadori, Fukushima Prefecture in 2011, Journal of Japan Association for Earthquake Engineering, Vol.12, No7, pp.7.1-7.18, 2012 (in Japanese)
13) Headquarters for Earthquake Research Promotion: Evaluation of seismic activity after the 2011 off the Pacific Coast of Tohoku earthquake, https://www.jishin.go.jp/main/index-e.html/(last accessed in April 18, 2018)
14) Kuwata, Y.: Development of GIS database of water-supply pipeline of Iwaki City and pipeline damage analysis due to geomorphology, Proceedings of JAEE annual conference 2012, pp.332-333, 2012 (in Japanese)
15) Geospatial Information Authority of Japan: http://www.gsi.go.jp/BOUSAI/h23_tohoku.html (in Japanese, last accessed in April 18, 2018)
16) Wakamatsu, K., Matsuoka, M.: Development of geomorphology 250 m mesh map according to world geodetic system, Proceedings of JAEE annual conference 2011, pp. 84-85, 2011(in Japanese).
17) Wakamatsu, K.: Liquefaction during the Great East Japan Earthquake, for seismic of water-supply facility, Water Technology Forum, No. 129, 2014 (in Japanese).
18) National Institute of Advanced Industrial Science and Technology: QuiQuake- Quick Estimation System for Earthquake Maps Triggered by Observation Records -, https://gbank.gsj.jp/QuiQuake/QuakeMap/about.en.html (last accessed in April 18, 2018)

(Original Japanese Paper Published: July, 2016)
(English Version Submitted: April 25, 2018)
(English Version Accepted: May 21, 2018)