17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

EVALUATION OF DAMAGE CHARACTERISTICS OF WATER DISTRIBUTION PIPELINES AFTER RECENT EARTHQUAKES IN JAPAN

Y. Maruyama[(1)], Y. Taguchi[(2)]

[(1)] *Professor, Dept. of Urban Environment Systems, Chiba University, Japan, ymaruyam@tu.chiba-u.ac.jp*
[(2)] *Graduate Student, Dept. of Urban Environment Systems, Chiba University, Japan, aeca2064@chiba-u.jp*

Abstract

The water supply system is an extremely important lifeline facility in modern society. It took approximately 70 days for full restoration of water supply after the 1995 Kobe earthquake. Based on the lessons after the Kobe earthquake, the important facilities for water supply were retrofitted against a large earthquake. In addition, the emergency response strategy was also planned among the water suppliers. The restoration periods of water supply system after the recent earthquakes in Japan were shortened due to the efforts of water suppliers, however, the water supply was occasionally disrupted for several days or weeks because of a large earthquake.

Based on the background, this study evaluates the characteristics of damage incidents of water distribution pipelines after the recent earthquakes in Japan. This study employs the damage datasets compiled by the five municipalities after the three earthquakes: Kumamoto City and Mashiki Town after the 2016 Kumamoto earthquake, Sendai City and Iwaki City after the 2011 off the Pacific coast of Tohoku earthquake, and Kashiwazaki City after the 2007 Niigata Chuetsu-oki earthquake. The damage ratios of water distribution pipelines were calculated with respect to the pipe material and diameter. The damage ratios were evaluated with respect to the ground motion intensity and topographic condition based on Hayashi's quantification method I. The locations of liquefaction occurrences during these earthquakes were also considered in this study. The influence of ground motion intensity, topographic condition, and liquefaction on the damage ratios of water distribution pipes is revealed using the coefficients obtained by Hayashi's quantification method I. The results of this study will be helpful for mitigating the damage to water distribution pipelines against future earthquakes.

Keywords: water distribution pipeline; recent earthquakes in Japan; damage ratio; Hayashi's quantification method I

1. Introduction

The water supply system is an extremely important lifeline facility in modern society. Recent earthquakes in Japan occasionally caused severe damage to water distribution pipelines, and water supply was disrupted for weeks in the heavily affected area. The Kobe earthquake, which occurred on January 17, 1995 with a moment magnitude of 6.9, caused severe damage to water supply systems in Hyogo Prefecture [1]. It took approximately 70 days for full restoration of water supply after the 1995 Kobe earthquake.

Based on the lessons after the Kobe earthquake, the important facilities for water supply systems were retrofitted against a large earthquake. In addition, the emergency response strategy was also planned among the water suppliers. The restoration periods of water supply system after the recent earthquakes in Japan were shortened due to the efforts of water suppliers, however, the water supply was occasionally disrupted for several days or weeks because of a large earthquake. According to the Ministry of Health, Labor and Welfare of Japan (MHLW), the ratio of water distribution pipelines connected with earthquake resistant joints gradually increases, but it is still smaller than 40% in March 2019 [2]. Hence, it is anticipated that water supply will be disrupted for weeks in the heavily affected areas in the future Tokyo Inland [3] and Nankai Trough [4] earthquakes.

This study evaluates the characteristics of damage incidents of water distribution pipelines after the recent earthquakes in Japan. This study employs the damage datasets compiled by the five municipalities after the three earthquakes: Kumamoto City and Mashiki Town after the 2016 Kumamoto earthquake, Sendai City and Iwaki City after the 2011 off the Pacific coast of Tohoku earthquake, and Kashiwazaki City after the 2007 Niigata Chuetsu-oki earthquake. The damage ratios of water distribution pipelines are calculated with respect to the pipe material and diameter. The damage ratios are evaluated with respect to the ground motion intensity and topographic condition based on Hayashi’s quantification method I.

2. Datasets Employed in this Study

The damage datasets of water distribution pipelines employed in this study are shown in Fig. 1. The distributions of the peak ground velocities (PGV) and the locations of damage incidents are illustrated in Fig. 1. Table 1 summarizes the earthquake events and damage ratios of the water distribution pipelines. The damage ratio is defined as the number of damage incidents divided by the pipe length (km).

The Kumamoto Japan earthquake sequence started with an event at 21:26 (Local time) on April 14, 2016. It includes the main event on April 16, 2016 with a moment magnitude (Mw) of 7.0. The water supply systems in Kumamoto City and Mashiki Town were disrupted for approximately seven days and 40 days, respectively [5]. Figure 1(a) shows the locations of damage incidents of water distribution pipelines in Kumamoto City and Mashiki Town. The damage ratios in Kumamoto City and Mashiki Town are 0.08 and 0.89, respectively. The distribution of the PGV during the main shock is also illustrated in Fig. 1(a). The 1,141 ground motion records obtained by Japan Meteorological Agency (JMA), municipalities, National Research Institute for Earth Science and Disaster Resilience (NIED), and Saibu Gas., Co. Ltd. were considered to draw the distribution of the PGV [6].

The 2011 off the Pacific coast of Tohoku earthquake with a Mw of 9.0 caused severe damage to lifeline facilities. The water supply system was interrupted at approximately 230 thousand households in Sendai City. Figure 1(b) shows the locations of damage incidents to water distribution pipes in Sendai City. The vinyl pipes (VP) and ductile cast iron pipes (DIP) without earthquake resistant joints were mainly affected. The seismically induced damage to water distribution pipelines concentrated in the hilly residential areas developed with cutting and leveling the hills and then filling the valleys for the past several ten years [7]. The water supply systems were disrupted by the ground motion and tsunami, and pipe breakages were found in Iwate, Miyagi, Fukushima, Tochigi, Ibaraki, and Chiba Prefectures [8]. In Iwaki City, Fukushima Prefecture, the water supply was disrupted approximately one month. Figure 1 (c) shows the locations of pipe breakages in Iwaki City. The damage ratio of water distribution pipelines was 0.09 [9].

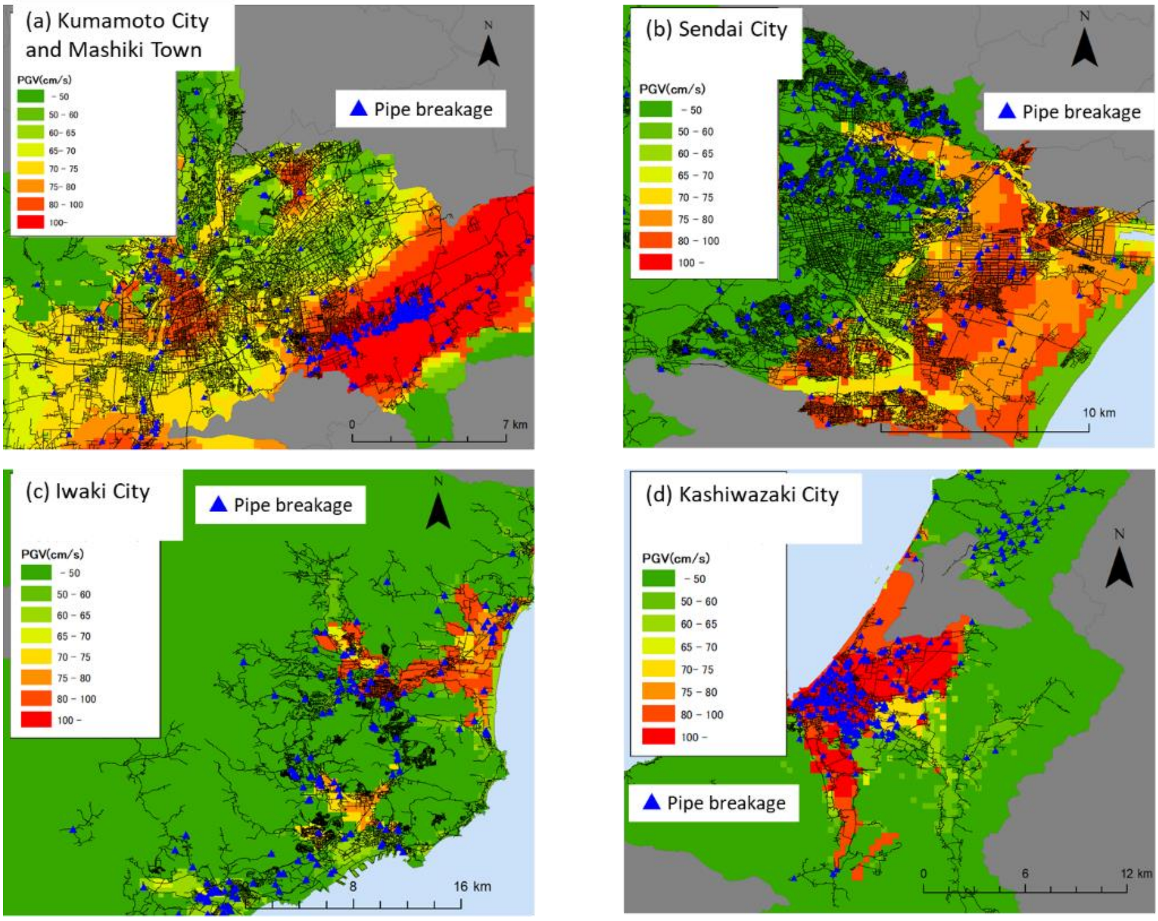

Fig. 1 – Locations of damage incidents to water distribution pipes in (a) Kumamoto City and Mashiki Town after the 2016 Kumamoto earthquake, in (b) Sendai City and (c) Iwaki City after the 2011 off the Pacific coast of Tohoku earthquake, and in (d) Kashiwazaki City after the 2007 Niigata Chuetsu-oki earthquake

The 2007 Niigata Chuetsu-oki earthquake with a Mw of 6.6 occurred in the northwest Niigata region of Japan. In Kashiwaki City, Niigata Prefecture, severe ground motion with an intensity scale of upper 6 on the JMA scale was observed. The water supply was disrupted at approximately 61,000 households, and it lasted approximately 40 days. The number of damage incidents to the water distribution pipelines was 524, and the total length of the water pipes was 852.6 km [10]. The locations of damage incidents to water distribution pipes in Kashiwazaki City are shown in Fig. 1(d).

The distributions of the PGV during the 2011 off the Pacific coast of Tohoku earthquake and the 2007 Niigata Chuestu-oki earthquake were estimated by Quick estimation system for earthQuake maps triggered by observation records (QuiQuake) [11]. The system estimates the distribution of ground motion intensity using the observation records of the NIED and Japan Engineering Geomorphologic Classification (JEG) Map [12].

3. Characteristics of Damage Ratio of Water Distribution Pipes

3.1 Equations for prediction of damage ratios of water distribution pipes in Japan

The Japan Water Research Center (JWRC) proposed the equations to predict the damage ratios of water distribution pipelines in 2012, and they evaluated the applicability of the equations for the damage dataset in

Table 1 – Outline of the damage datasets of water distribution pipelines used in this study

Earthquake	Mw	Municipality	No. of pipe breakages	Total lengh of water pipes (km)	Damage ratio
2016 Kumamoto	7.0	Kumamoto City	263	3,414	0.08
		Mashiki Town	199	222.8	0.89
2011 Tohoku	9.0	Sendai City	437	4,458	0.10
		Iwaki City	216	2408.5	0.09
2007 Niigata Chuetsu-oki	6.6	Kashiwazaki City	430	901.7	0.48

Kumamoto City after the 2016 Kumamoto earthquake [12]. The equations to predict the damage ratio R_m are shown in Eqs. (1) and (2).

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

$$R_m = C_p C_d R_L \tag{2}$$

where C_p, C_d, and C_g are correction coefficients for the pipe material and type of joint, diameter, and geological condition, respectively. $R(v)$ is a function to estimate the damage ratio of the ductile cast iron pipe with A type joint (DIP-A) with a diameter of 100-150 mm. $R(v)$ is defined as Eq. (3).

$$R(v) = 9.92 \times 10^{-3} \times (v - 15)^{1.14} \tag{3}$$

where v is the PGV. If a certain area is suffered from liquefaction, Eq. (2) is used to estimate the damage ratio of water distribution pipes. R_L shows the damage ratio of DIP-A with a diameter of 100-150 mm in the liquefied area, and it is set to be 5.5.

The correction coefficients for the water distribution pipes are empirically determined mainly from the damage dataset after the 1995 Kobe earthquake. Table 2 shows the values of correction coefficients proposed by the JWRC [13].

3.2 Use of Hayashi's quantification method I to evaluate the correction coefficients

The influence of pipe material and joint, ground motion intensity, topographic condition, and liquefaction on the damage ratios of water distribution pipes is investigated based on Hayashi's quantification method I [14]. Hayashi's quantification method I is a method to predict the quantitative external criterion variable based on the information concerning the qualitative attributes of each categorical variable. It is also employed to analyze the influence of each attribute to the criterion variable.

This study assumed Eq. (4) to perform Hayashi's quantification method I. The damage ratio of water distribution pipes R_m is supposed to be influenced by the pipe material and joint, diameter, geological condition, PGV, liquefaction, and border of Japan Engineering Geomorphologic Classification (JEG).

$$R_m = A_p \times A_d \times A_g \times A_v \times A_l \times A_b \times R_0 \tag{4}$$

Table 2 – Correction coefficients of Eqs. (1) and (2) proposed by the JWRC

Pipe material* and joint	C_p		Diameter (mm)	C_d		Japan Engineering Geomorphologic Classification (JEG)	C_g
DIP-A	1.0		50-80	2.0		Group A: Mountain, Mountain footslope, Hill, Volcano, Volcanic footslope, and Volcanic hill	0.4
DIP-K	0.5		100-150	1.0		Group B: Gravelly terrace, and Terrace covered with volcanic ash soil	0.8
DIP-T	0.8		200-250	0.4		Group C: Valley bottom lowland, Alluvial fan, Back marsh, and Delta and coastal lowland	1.0
DIP with earthquake resistant joint	0.0		300-450	0.2		Group D: Natural levee, Abandoned river channels, Marine sand and gravel bars, and Sand dune	2.5
CIP	2.5		500-900	0.1		Group E: Filled land, Reclaimed land, and Lake	5.0
VP-TS	2.5						
VP-RR	0.8						
SP with welded joint	0.5/0.0						
SP with screwed joint	2.5						
ACP	7.5						
PE with fusion joint	-						

* DIP: ductile cast iron pipe, CIP: cast iron pipe, VP: vinyl pipe, SP: steel pipe, ACP: asbestos cement pipe, PE: polyethylene pipe

where A shows the correction coefficient for each categorical variable. R_0 is defined as the reference damage ratio, i.e. the damage ratio of DIP-A, K, or T, with a diameter of 100-150 mm, laid on Group C of JEG, subjected to PGV of 30-40 cm/s, without liquefaction occurrences, and laid away from the border of JEG. The categorical variables and attributes assumed in this study are shown in Table 3.

Hayashi's quantification method I was performed by taking the common logarithm of both sides of Eq. (4) [15]. Figure 2 shows the correction coefficients A of Eq. (4) obtained in this study. The coefficient of determination R^2 was 0.66. As for the correction coefficients for pipe material and joint, that for CIP was the largest. The coefficient for SP with welded joint was the second largest although the correction coefficient determined by the JWRC is small. The SPs with welded joint show large damage ratio under the 2016

Table 3 – Categorical variables and attributes for Hayashi's quantification method I performed in this study

Categorical variable	Attributes
Pipe material and joint	DIP-A, K, or T*, CIP, PE, SP with welded joint, SP with screwed joint, VP
Diameter (mm)	-40, 50-75, 100-150*, 200-250, 300-450, 500-900
Japan Engineering Geomorphologic Classification (JEG)	Group A, B, C*, D, E
PGV (cm/s)	-30, 30-40*, 40-50, 50-60, 60-70, 70-80, 80-90, 90-100, 100-110, 110-120, 120-130, 130-
Liquefaction	With liquefaction, Without liquefaction*
Border of JEG	On the border, Away from the border*

* Reference of attribute

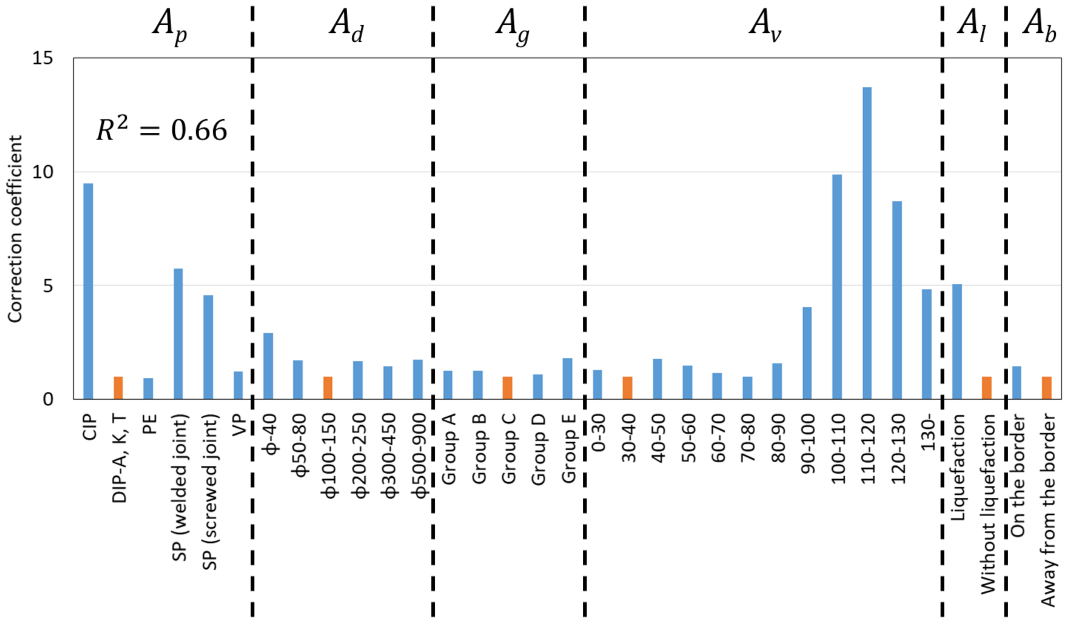

Fig. 2 – Correction coefficients based on Hayashi's quantification method I. The orange bars show the references of categorical variables.

Kumamoto earthquake mainly due to deterioration over time. Hence, the result of this study shows larger correction coefficient for the SP with welded joint. The correction coefficient for the PE is as large as that for the DIP-A, K, or T.

The correction coefficients for the PGV show almost similar values under the PGV of smaller than 90 cm/s. When the PGV becomes larger than 90 cm/s, the coefficients for the PGV become drastically larger. The damage ratio in the liquefied area is approximately five times larger than that in the area where liquefaction is not caused.

In order to compare the contributions to the damage ratios of water distribution pipes among the categorical variables, the ranges of coefficients are calculated. The contribution to the damage ratios is larger

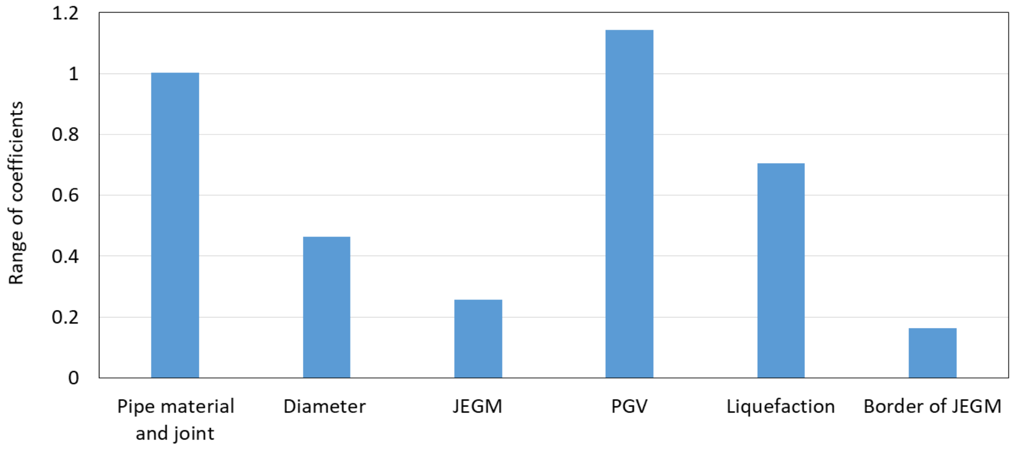

Fig. 3 – Ranges of coefficients with respect to the categorical variable based on Hayashi's quantification method I

as the range is larger. Figure 3 compares the ranges of coefficients among the categorical variables. The PGV, pipe material and joint, and liquefaction occurrences show large contributions to the damage ratios of water distribution pipes.

4. Conclusions

This study performed Hayashi's quantification method I to evaluate the influence of various causes on the damage ratios of water distribution pipes after earthquakes. To achieve the objective, the damage datasets compiled in five municipalities after the three recent earthquakes in Japan were employed. The damage ratios of water distribution pipes were calculated with respect to the pipe material and joint, diameter, Japan Engineering Geomorphologic Classification (JEG), peak ground velocity (PGV), liquefaction, and border of JEG. Totally, six categorical variables and 33 attributes were considered in Hayashi's quantification method I.

As for the pipe material and joint, the correction coefficients for CIP and SP were large. The correction coefficients for DIP-A, K, or T and PE showed similar values. When the PGV is larger than 90 cm/s, the correction coefficients for the PGV increase drastically. The influence of liquefaction occurrence on the damage ratio of water distribution pipes was quite large.

In the future study, reliability of damage ratios will be considered. The damage ratio is defined as the number of damage incidents divided by the length of the pipes. The reliability of the damage ratios relies on the length of the pipes. According to the dataset compiled by this study, the lengths of pipes are different with respect to the categorical variable and attribute. Hence, the reliability of the damage ratios will be considered in Hayashi's quantification method I performed in this study.

Acknowledgements

This work was supported by the Tokyo Metropolitan Resilience Project.

References

[1] Isoyama R, Ishida E, Yune K, Shirozu T (2000): Seismic damage estimation procedure for water supply pipelines, *Water Supply*, **18** (3), 63-68.

[2] Ministry of Health, Labor and Welfare (2020): https://www.mhlw.go.jp/stf/seisakunitsuite/bunya/topics/bukyoku/kenkou/suido/taishin/index.html (in Japanese)

[3] Ministry of Land, Infrastructure, Transport and Tourism (2020): http://www.mlit.go.jp/river/earthquake/en/capital/index.html

[4] Ministry of Land, Infrastructure, Transport and Tourism (2020): http://www.mlit.go.jp/river/earthquake/en/nankai/index.html

[5] Nojima N, Maruyama Y (2016): Comparison of functional damage and restoration processes of utility lifelines in the 2016 Kumamoto earthquake, Japan with two great earthquake disasters in 1995 and 2011, JSCE Journal of Disaster FactSheets, FS2016-L-0005, 9p.

[6] Matsuoka M (2018): Shake Map Estimation of the 2016 Kumamoto Earthquake by Observed Strong Motion Records, *Proceedings of the annual conference of the institute of social safety science*, **42**, 23-26 (in Japanese).

[7] Wakamatsu K, Nagata S, Maruyama Y, Ozawa K (2016): Sendai Water Pipeline Response to the 2011 Tohoku Earthquake, Journal of Civil Engineering and Architecture, **10**, 461-470.

[8] Maruyama Y, Nagata S, Wakamatsu K (2015): Damage assessment of water distribution pipelines after the 2011 off the Pacific Coast of Tohoku Earthquake, *Journal of Energy Challenges and Mechanics*, **2** (4), 144-149.

[9] Kuwata Y, Sato K, Soji K (2016): Seismic vulnerability of water-supply pipeline based on damage analysis of two earthquakes during the Great East Japan earthquake, *Journal of Japan Association for Earthquake Engineering*, **16** (8), 145-155 (in Japanese).

[10] Maruyama Y, Kimishima K, Yamazaki F (2011): Damage assessment of buried pipes due to the 2007 Niigata Chuetsu-oki earthquake in Japan, *Journal of Earthquake and Tsunami*, **5** (1), 57-70.

[11] National Institute of Advanced Industrial Science and Technology (2020): QuiQuake - Quick Estimation System for Earthquake Map Triggered by Observed Records -, https://gbank.gsj.jp/QuiQuake/index.en.html

[12] Wakamatsu K, Matsuoka M (2013): Nationwide 7.5-arc-second Japan engineering geomorphologic classification map and vs30 zoning, *Journal of Disaster Research*, **8** (5), 904-911.

[13] Japan Water Research Center (2016): http://www.jwrc-net.or.jp/chousa-kenkyuu/kanro-higaiyosoku_rev.html (in Japanese)

[14] Tanaka Y (1979): Review of the methods of quantification, *Environment Health and Perspectives*, **32**, 113-123, 1979.

[15] Ishida E, Isoyama R (2019): Analyses on water pipeline damage in Sendai City caused by the Great East Japan earthquake, *Journal of Japan Association for Earthquake Engineering*, **19** (1), 1-20 (in Japanese).

