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Damage assessment of water distribution pipelines after the 2011 off the pacific coast of Tohoku earthquake

2011年東北地方太平洋沖地震之后的配水管道损伤评估

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Abstract - **The 2011 off the Pacific coast of Tohoku earthquake occurred on March 11, 2011 with a moment magnitude of 9.0. The water supply was disrupted for approximately 2.2 million households because of this event. In this study, the applicability of empirical fragility functions of water distribution pipelines is evaluated using the damage ratios calculated for the above earthquake. To achieve this objective, the damage dataset compiled by the Ministry of Health, Labor and Welfare of Japan is employed to calculate the damage ratios. The damage ratios are obtained with respect to pipe material and diameter. Empirical fragility functions are compared with the actual damage ratios, and the accuracy of estimation is discussed.**

Keywords – **2011 off the Pacific Coast of Tohoku earthquake, water distribution pipe, damage ratio, fragility function.**

I. INTRODUCTION

On March 11, 2011, the 2011 off the Pacific coast of Tohoku earthquake occurred with a moment magnitude of 9.0. Lifeline facilities such as electric power supply, water supply, sewage, city gas supply, and telecommunication systems were affected by the ground motion and tsunami. The water supply was disrupted for approximately 2.2 million households [1]. The Ministry of Health, Labor and Welfare of Japan (MHLW) investigated the incidents of damage to water distribution pipelines after this event [2]. According to their report, pipe breakages were found in Iwate, Miyagi, Fukushima, Tochigi, Ibaraki, and Chiba Prefectures. They recorded the locations of pipe breakages, as well as the pipe materials and diameters in these locations.

In this study, the damage ratios of water distribution pipes are calculated in the six prefectures using the damage dataset compiled by MLHW. The relationship between the damage ratios and the ground motion intensity is evaluated, and the applicability of fragility functions developed in previous studies [3-6] is discussed. Lastly, a damage estimation method on a regional scale is proposed in the case of occurrence of a gigantic earthquake.

II. DATASETS EMPLOYED IN THIS STUDY

The damage dataset of water distribution pipes compiled by MHLW is employed in this study. The locations of damage incidents were revealed using the Geographical Information System (GIS). The GIS dataset that identifies the water-supply areas in Iwate, Miyagi, Fukushima, Tochigi, Ibaraki, and Chiba Prefectures, compiled by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), is also employed [7]. The National Institute of Advanced Industrial Science and Technology (AIST) of Japan developed a system named QuiQuake to draw a map of the distribution of ground motion intensity just after an earthquake [8]. QuiQuake provides wide and detailed strong ground motion maps based on the observed ground motion records.

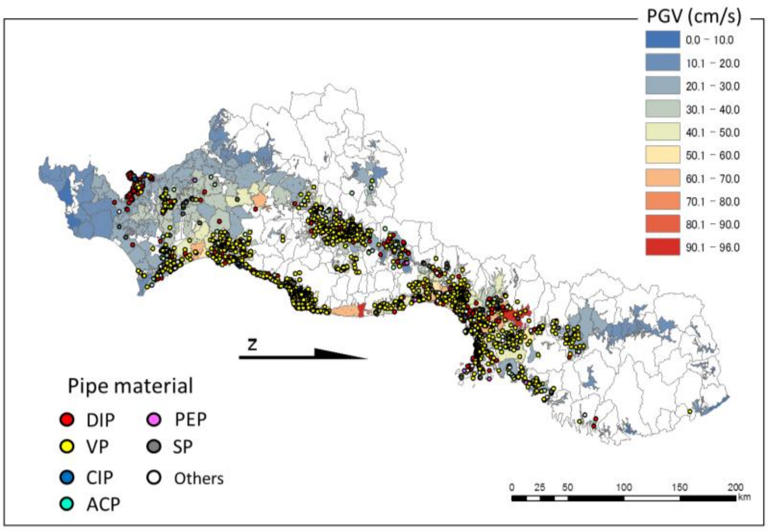


Fig. 1. Locations with incidents of damage to water distribution pipes, and distribution of the peak ground velocities in the water-supply areas after the 2011 off the Pacific coast of Tohoku earthquake.

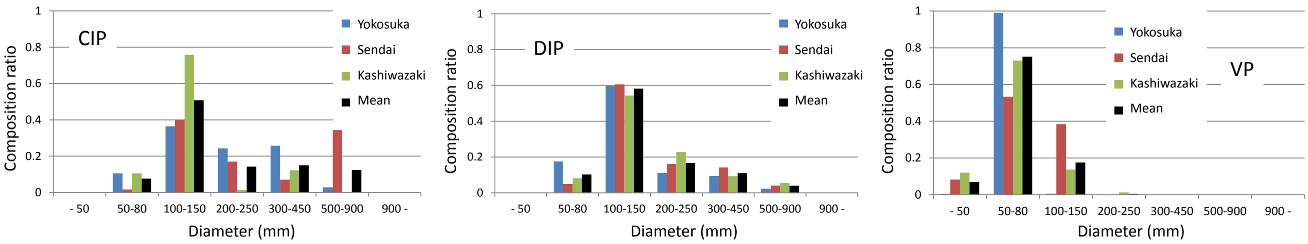


Fig. 2. Composition ratios of pipe length vs. diameter for CIP, DIP, and VP.

Figure 1 shows the locations that had incidents of damage to water distribution pipes, and the distribution of the mean of the peak ground velocity (PGV) for each water-supply area. Symbols assigned to the damage incidents were classified based on the pipe material: ductile cast iron pipe (DIP), vinyl pipe (VP), cast iron pipe (CIP), asbestos cement pipe (ACP), polyethylene pipe (PEP), steel pipe (SP), and others. In all, 5,656 pipe breakages are considered in this study.

The damage ratio of a water distribution pipeline is defined as the number of pipe breakages divided by the pipe length (km). The length of pipes, grouped based on material, in each water-supply area is available from the 2011 census data compiled by Japan Water Works Association (JWWA) [9], but the length of pipes, grouped based on diameter, is not compiled in the census data. Hence, the proportions of pipe lengths for different diameters are estimated using the detailed GIS datasets for water pipelines in the three municipalities: Yokosuka City (Kanagawa Prefecture), Sendai City (Miyagi Prefecture), and Kashiwazaki City (Niigata Prefecture). Figure 2 shows the composition ratios of pipe lengths with respect to diameter for CIP, DIP, and VP. The mean of the ratios were multiplied by the total length of pipes of a particular material to calculate the damage ratio for that material for different diameters.

III. Evaluation of Damage Ratios of Water Distribution Pipes

Figure 3 shows the distribution of damage ratios for DIP with diameters in the range of 50-80, 100-150, 200-250, 300-450, and 500-900 mm. The damage ratios were larger in the areas where intense ground shaking and extensive liquefaction were observed.

To estimate the damage ratios of water pipes, the following formula is commonly used in Japan [3].

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

where R_m is the damage ratio, C_p, C_d, C_g, and C_l are correction coefficients for the pipe material, diameter, geological condition, and liquefaction occurrence, respectively, and v is the PGV of ground motion. $R(v)$ is the estimate for the damage ratio of CIP with diameter in the range of 100–150 mm; this is also proposed in other studies [4-6].

Figure 4 shows the relationship between PGV and the damage ratios of water distribution pipes with the diameter in the range of 100-150 mm. In this figure, the estimations done by previous studies [3-6] based on Eq. (1) are also indicated. The correction coefficient for the pipe material (C_p) is set to be 0.3 for DIP, 1.0 for VP, and 1.0 for CIP. C_d is set to be 1.0 based on the study by Isoyama *et al.* [3]. The effects of

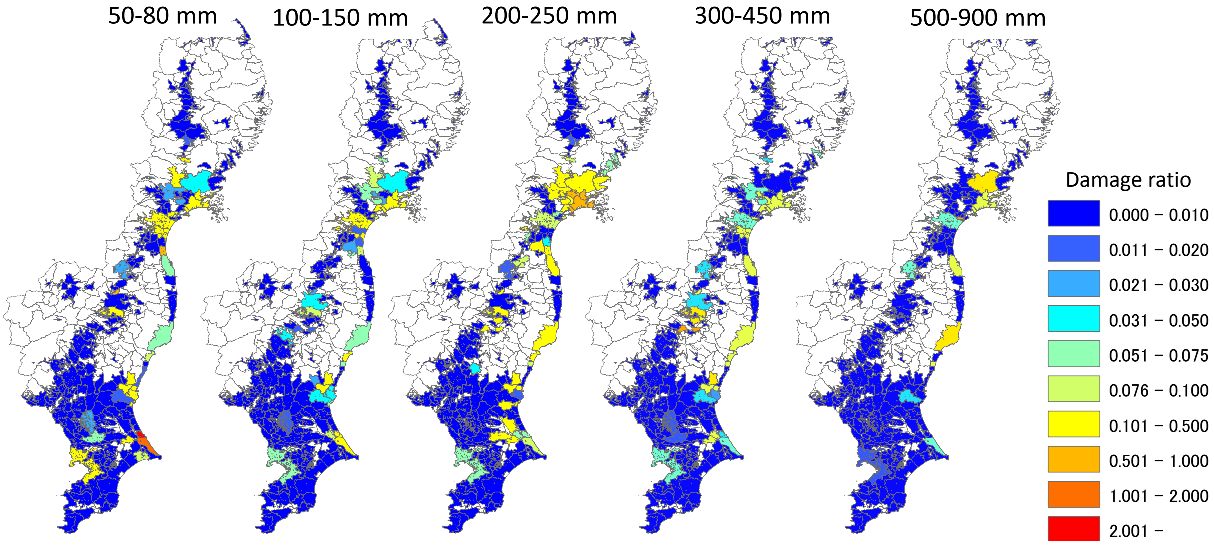


Fig. 3. Distribution of the damage ratios for DIP with the diameter range of 50-80, 100-150, 200-250, 300-450, and 500-900 mm.

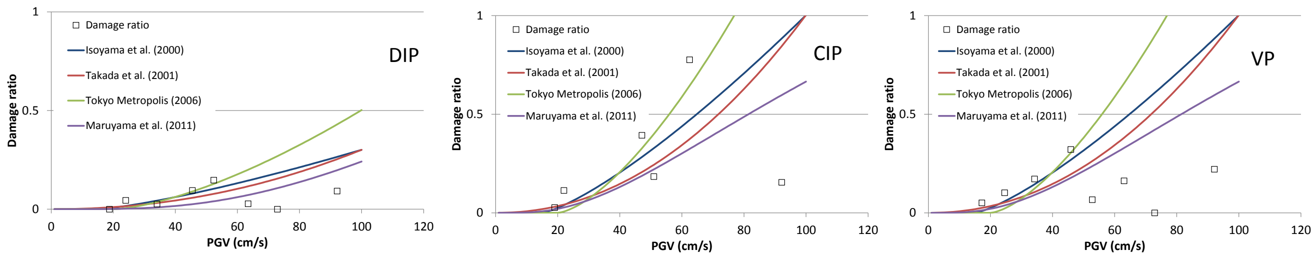


Fig. 4. Comparison of the damage ratios of water distribution pipes and the damage ratios estimated by previous studies [3-6].

geological conditions are not considered in this study (C_g = 1.0), because the distribution of PGV reflects those of geological conditions [10]. The correction coefficient for liquefaction is also not considered in this study (C_l = 1.0). According to the results, the damage ratios during the 2011 earthquake are in complete agreement with the empirical fragility functions.

IV. Damage Estimation Method on a Regional Scale in Case of Gigantic Earthquake

The Headquarters for Earthquake Research Promotion of Japan evaluated the national seismic hazard, and provided the Probabilistic Seismic Hazard Maps [11]. According to their assessment, the probability of occurrence of an earthquake in the Tokyo Metropolitan Area is approximately 70% within 30 years. It is also anticipated that an earthquake with a magnitude of 8-9 may occur in the Nankai Trough, which forms the plate interface between the subducting Philippine Sea Plate and the overriding Amurian Plate. In case these gigantic earthquakes occur, estimation of possible damage to various facilities on a regional scale will be required, in order to have a prompt disaster response at an early stage.

In the previous section, the applicability of the empirical fragility functions for water distribution pipes was discussed. They provide reasonable estimation for the water-supply areas where pipe breakages were found after the 2011 earthquake. On the other hand, as observed in Fig. 1, water-supply areas without pipe breakages were also found, even though the PGV is large enough to cause damage to water pipes. Hence, in order to perform damage estimation on a regional scale immediately after the occurrence of an earthquake, it is essential to identify the areas where pipe breakages may occur.

A logistic regression model is considered to evaluate the probability of occurrence of pipe breakages as shown in the equation below.

$$p = \frac{\exp(b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4)}{1 + \exp(b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4)} \quad (2)$$

where b_i is the regression coefficient, x_1 is the PGV, x_2 is the length of the water distribution pipes, x_3 is the vulnerability factor for pipe material [12], and x_4 is the vulnerability factor for ground condition, which is the mean of the correction factor C_g [3] in the water-supply area; p is the probability of occurrence of pipe breakages in the water-supply area. If pipe breakages were found in a specific water-supply area, 1.0 was substituted for the random variable Y. Y was assumed to be 0.0 for the areas without pipe breakages. Hence, p can be expressed as

$$p = \Pr(Y = 1.0 | x_1, x_2, x_3, x_4) \quad (3)$$

$$1 - p = \Pr(Y = 0.0 | x_1, x_2, x_3, x_4) \quad (4)$$

	Estimation	
Observation	Positive	Negative
True	True positive (TP)	False negative (FN)
False	False positive (FP)	True negative (TN)

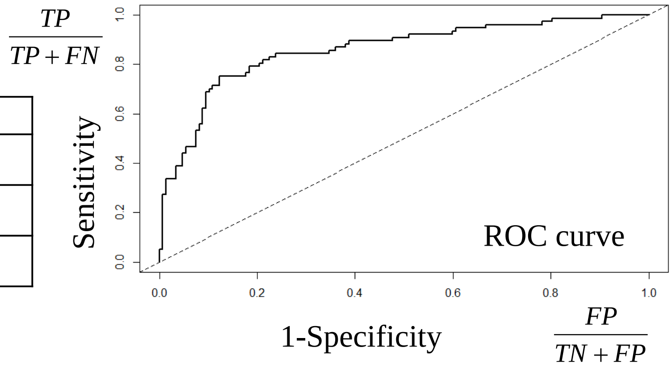
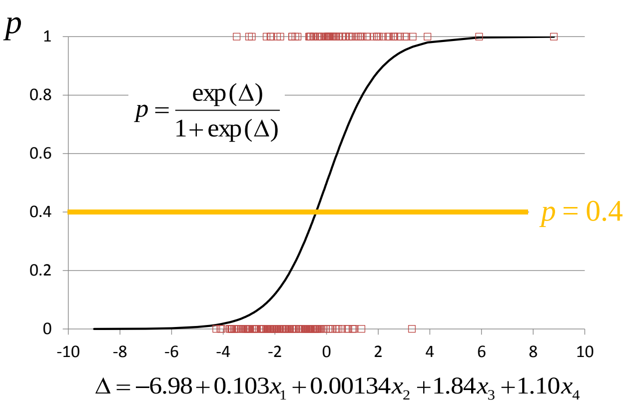


Fig. 5. Receiver operating characteristics (ROC) curve and definitions of the different fractions to draw ROC curve.



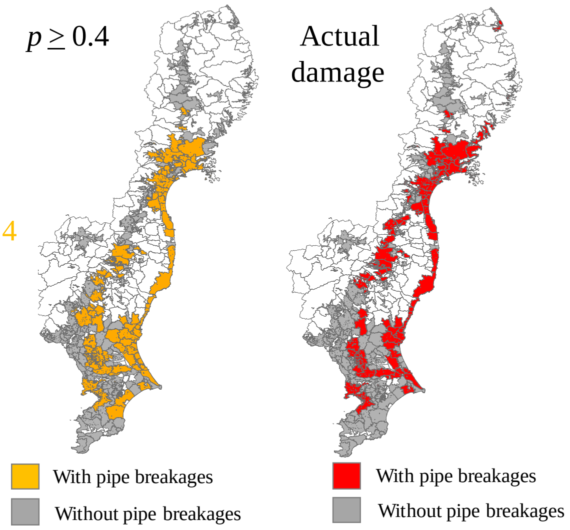


Fig. 6. Logistic regression model and the result of discrimination of the water-supply areas with/without pipe breakages.

A logistic regression analysis was performed using Eqs. (2)-(4). The threshold value of p to discriminate the water-supply area with/without pipe breakages properly is evaluated based on the receiver operating characteristics (ROC) curve (Fig. 5). In the ROC curve, the true positive rate (sensitivity) is plotted as a function of the false positive rate (1-specificity) by changing the threshold value of p [13]. The definitions of different fractions are also shown in Fig. 5. The area under the curve (AUC) was calculated as 0.86, which corresponds to a model with good discrimination. The best threshold of p was found to be 0.42, with true positive rate of 0.75, and true negative rate of 0.88.

Based on the results, the threshold value of p to discriminate the water-supply areas with/without pipe breakages was assumed to be 0.4. If p is larger than 0.4, the water-supply areas are considered to have the possibility of pipe breakages. Figure 6 shows the logistic regression model and the result of discrimination. In this figure, the water-supply areas with pipe breakages after the 2011 earthquake are also illustrated. The water-supply areas with pipe breakages could be identified reasonably well based on the logistic regression model constructed by this study.

This study tried to estimate the number of pipe breakages for water supply systems on a regional scale. First, the water-supply areas with pipe breakages are identified using the logistic regression model (Eq. (3)). Then, the empirical fragility functions are applied to estimate the damage ratios of water distribution pipes. Lastly, the number of pipe breakages is obtained as the product of damage ratios and the lengths of the water pipes.

Figure 7 compares the number of pipe breakages after the 2011 earthquake and those estimated using the empirical fragility functions [6]. The estimated values are slightly smaller than the actual number of pipe breakages for VP and CIP. The actual number of pipe breakages for DIP is three times larger than the estimated value. The locations of pipe breakages are very much concentrated in the water-supply areas in Chiba and Ibaraki Prefectures where extensive liquefaction was observed after the earthquake [14]. They were also concentrated in the developed hilly areas for residential purpose, such as Sendai City, Miyagi Prefecture [15]. The estimated values in this study are calculated using Eq. (1); however the correction coefficients for liquefaction (C_l) and geological condition (C_g) were assumed to be 1.0 in the calculation. This study underestimated the number of pipe breakages because the effects of larger strain due to liquefaction and landslide in the developed hilly areas were not considered. To obtain more accurate results, the correction coefficients for liquefaction and developed hilly areas should be properly considered in the estimation method.

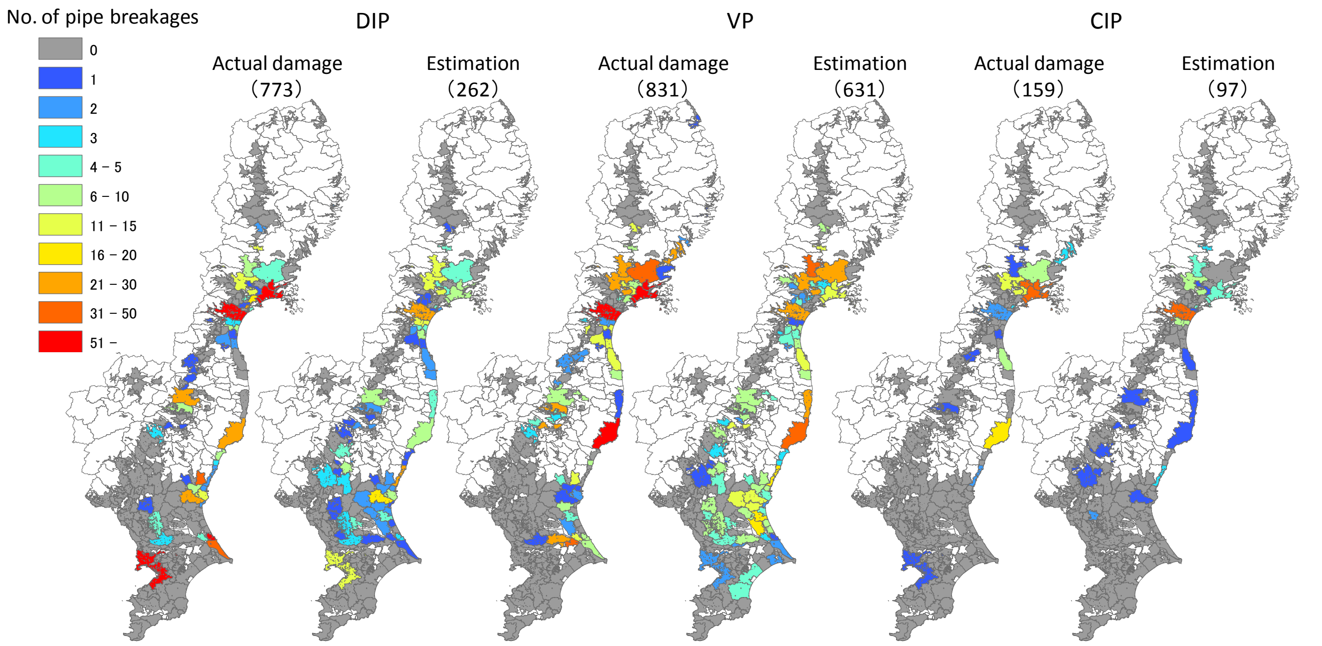


Fig. 7. Comparison of the number of pipe breakages for the pipes with diameter range of 100-150 mm after the 2011 earthquake and those estimated by this study.

V. Conclusion

This study evaluated the damage ratios of water distribution pipes after the 2011 off the Pacific coast of Tohoku earthquake based on the damage dataset compiled by MLHW. In order to obtain the damage ratios of water pipes, the length of pipes for different diameter ranges is estimated for different pipe materials, based on the detailed inventory data and the census data compiled by JWWA. The damage ratios were evaluated with respect to PGV, and the relationships were compared with the empirical fragility functions developed by the previous studies. The estimated values obtained from the fragility functions were reasonable and compared well with the actual damage ratios after this event.

To estimate the number of pipe breakages for water supply system after a gigantic earthquake, a damage estimation method on a regional scale is proposed. First, the water-supply areas with the possibility of pipe breakages are identified based on the logistic regression model. The model constructed by this study has a good discriminating ability based on the assessment of ROC curve. Further, the number of pipe breakages was estimated using the empirical fragility functions for the identified water-supply areas. The number of pipe breakages for VP and CIP show good agreement, but the number of breakages for DIP was underestimated. The correction coefficients for liquefaction and geological condition should be properly considered to obtain a more accurate estimation.

Acknowledgment

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