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# Estimation of Damage Ratios of Wooden Houses and Water Distribution Pipelines in an Earthquake Scenario for the Tokyo Metropolitan Region

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## ABSTRACT

To enhance earthquake security, various governmental organizations in Japan make predictions regarding earthquake-induced damages. The Central Disaster Prevention Council of Japan drew up a 7.3 magnitude earthquake scenario for the Tokyo metropolitan area to predict the different types of damage that would result in the southern Kanto district. The damage ratios due to the scenario event were estimated by prefectural governments. However, the methods adopted for damage assessment differed from prefecture to prefecture. This study estimates the damage ratios of wooden houses and water distribution pipelines in Tokyo, Kanagawa, Saitama, and Chiba prefectures after a hypothetical earthquake in the Tokyo metropolitan region. Since the damage ratios are evaluated by common fragility functions, the amount of damage can be compared seamlessly for the different areas around the Tokyo metropolis. This study also considers the correlation between the damage ratios of wooden houses and water distribution pipelines with respect to postal address locations around Tokyo Bay. The areas associated with higher damage ratios for wooden houses and water pipelines are identified, and the delay of restoration work is anticipated in these areas.

## 1. INTRODUCTION

To enhance earthquake security, various governmental organizations in Japan make predictions regarding earthquake-induced damages. For some earthquake source faults, the

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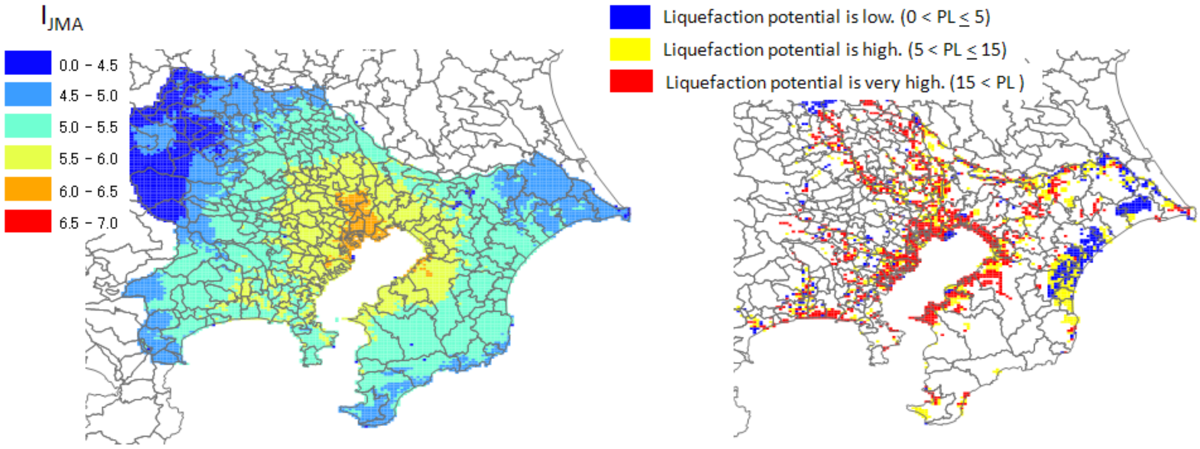



Fig. 1. Distributions of the JMA seismic intensity and the liquefaction index estimated by the Central Disaster Prevention Council of Japan for a northern Tokyo Bay earthquake scenario.

ground motion intensity and the occurrence of liquefaction are simulated for several events taking into consideration the geological and topographical conditions. The number of collapsed buildings, burned-out houses, casualties, and other data are derived from the estimated ground motions. Also predicted are the loss of lifeline systems (Hoshiya *et al.* 2004), e.g., disrupted water, gas, and electrical supplies. Based upon the impacts predicted by earthquake scenarios, disaster prevention planning and countermeasures are designed by local governments.

The Tokyo metropolitan area was affected by serious damages from three large earthquakes: the 1923 Kanto earthquake (M7.9), the 1703 Genroku earthquake (M8.4), and the 1855 Ansei Edo (M7) earthquake. Whereas the former two seismic events occurred along the offshore interface between the subducting Philippine Sea Plate and the North American Plate, the latter event is considered to have occurred in the northern part of Tokyo Bay (Furumura 2005). The Central Disaster Prevention Council of Japan calculated the distribution of seismic intensities for a northern Tokyo Bay earthquake (Koketsu and Miyake 2006), which was mainly used to predict disaster scenarios for the southern Kanto district.

After the Tokyo metropolitan government's study (2006), the Saitama (2008), Chiba (2008), and Kanagawa (2009) prefectural governments also estimated earthquake-induced damages assuming a northern Tokyo Bay earthquake. Since the methods differed from prefecture to prefecture, it was difficult to compare the amount of earthquake damages seamlessly for the areas around the Tokyo metropolis. In the event of such an earthquake occurring, extended cooperation for restoration work would be necessary due to the tremendous amount of expected damages. To develop a coordinated strategy for restoration work, a uniform method for damage estimation is vital.

In this study, the damage ratios of wooden houses and water distribution pipelines in the Tokyo, Kanagawa, Saitama, and Chiba prefectures are predicted using common fragility functions and employing the inventory datasets compiled by each local government. This study also considers the combination of damage to wooden houses and water distribution pipes with respect to postal address areas neighboring Tokyo Bay. The areas associated with high damage to both wooden houses and water pipes are identified as likely trouble spots for reconstruction efforts.

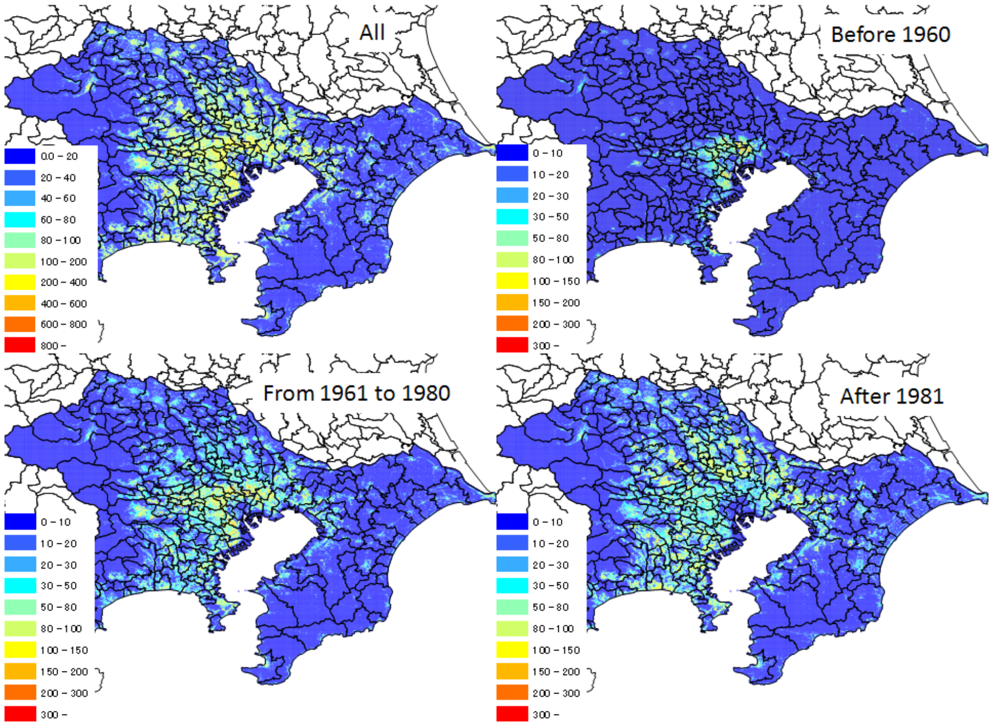



Fig. 2. Number of wooden houses in the southern Kanto district.

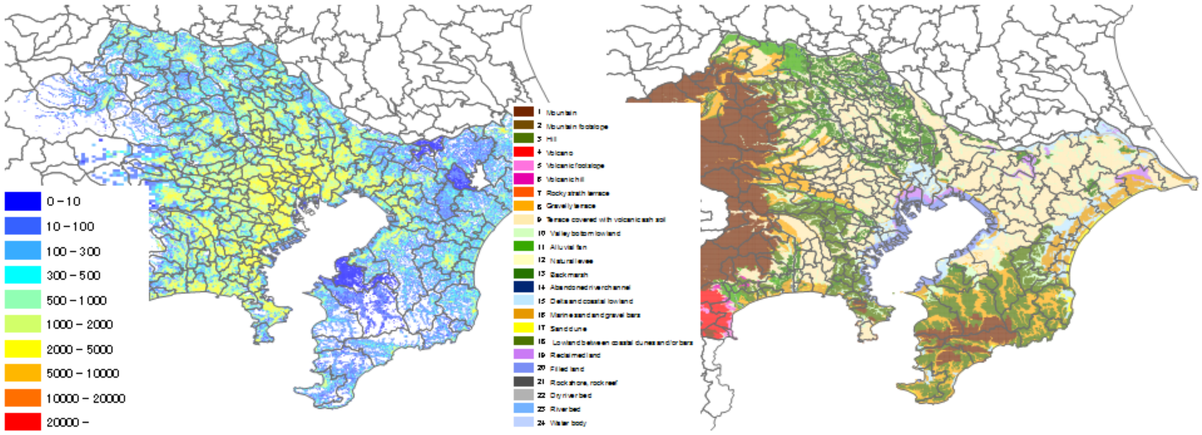
## 2. INVENTORY DATASET FOR THE SOUTHERN KANTO DISTRICT

Figure 1 shows the distributions of the JMA (Japan Meteorological Agency) seismic intensity and the liquefaction index (PL value) estimated by the Central Disaster Prevention Council of Japan for a northern Tokyo Bay earthquake scenario (M7.3). These distributions are represented in 1 × 1 $km^2$ grid cells. Severe ground motion with a JMA seismic intensity of more than 6.0 is anticipated in the eastern part of the Tokyo metropolis. A JMA seismic intensity of more than 5.5 would be widespread in the areas surrounding Tokyo Bay. The liquefaction potential is very high in these areas.

Figure 2 shows the number of wooden houses in the southern Kanto district. The wooden houses are classified into three construction periods: before 1960, 1961-1980, and after 1981. The number of wooden houses is represented in 250 × 250 $m^2$ grid cells.

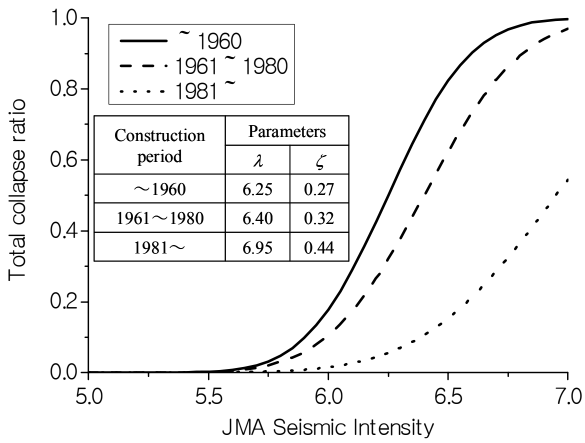
Figure 3(a) shows the layout of water distribution pipes in the southern Kanto district, which is also represented in 250 × 250 $m^2$ grid cells. In the dataset, we consider six types of pipe materials: cast iron pipe (CIP), ductile cast iron pipe (DIP), polyethylene pipe (PEP), vinyl pipe (VP), steel pipe (SP), and asbestos cement pipe (ACP). The lengths of water distribution pipelines are compiled with respect to their diameters: smaller than 75 mm, 100–150 mm, 200–450 mm, and larger than 500 mm.

In order to estimate the damage ratios of water pipelines, geomorphological land classifications are required. Wakamatsu and Matsuoka (2006) proposed the Japan Engineering Geomorphologic Classification Map (JEGM) based on a new engineering-based



(a) (b)

Fig. 3. (a) Lengths of water distribution pipelines in the southern Kanto district and (b) geomorphological land classifications.




| Construction period | Parameters | |
|---|---|---|
| | $\lambda$ | $\zeta$ |
| ～1960 | 6.25 | 0.27 |
| 1961～1980 | 6.40 | 0.32 |
| 1981～ | 6.95 | 0.44 |

Fig. 4. Total collapse ratios of wooden houses with respect to their construction periods estimated from Eq. (1).

geomorphologic classification scheme. The classifications in the southern Kanto district are shown in Figure 3(b), which are assigned using a 250 × 250 $m^2$ pixel grid.

## 3. ESTIMATION OF DAMAGE RATIOS AFTER AN EARTHQUAKE SCENARIO FOR THE TOKYO METROPOLITAN REGION

### 3.1. Damage Ratio of Wooden Houses

This study considers damage to wooden houses caused by shaking. The effects of fires, liquefaction, landslide, and other sources of building damage are excluded from this study. The damage ratios of wooden houses are estimated from Eq. (1) (Yamaguchi *et al.* 1998). The parameters of Eq. (1), $\lambda$ and $\zeta$, are defined using the construction period of the buildings. Figure 4 shows the relationship between the total collapse ratios of wooden houses and JMA seismic intensity ($I$) estimated using Eq. (1).

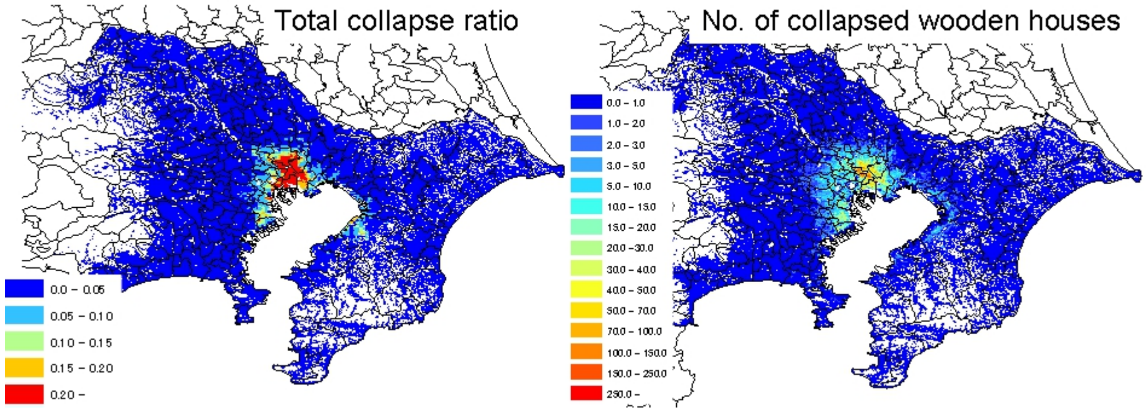
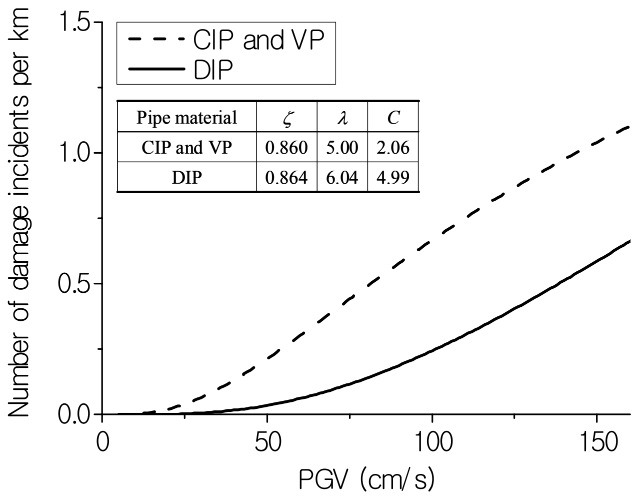



Fig. 5. Estimated total collapse ratio of wooden houses and number of collapsed wooden houses after a northern Tokyo Bay earthquake.




| Pipe material | $\zeta$ | $\lambda$ | $C$ |
|---|---|---|---|
| CIP and VP | 0.860 | 5.00 | 2.06 |
| DIP | 0.864 | 6.04 | 4.99 |

Fig. 6. Damage ratios of water distribution pipes with respect to the peak ground velocity estimated from Eq. (3).

$$P(I) = \Phi((I - \lambda)/\zeta) \qquad (1)$$

where $\Phi(x)$ is the cumulative distribution function of the standard normal distribution.

Figure 5 shows the total collapse ratio of wooden houses and the number of collapsed wooden houses estimated by Eq. (1). According to Figure 1, the eastern part of the Tokyo metropolis will be affected by severe ground motion with a JMA seismic intensity of more than 6.0. The number of wooden houses constructed before 1960 is also large in this area (see Figure 2). Hence, more collapsed buildings are expected in the eastern part of Tokyo.

3.2. Damage Ratio of Water Distribution Pipes

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

Table 1. Correction coefficients in Eq. (2) in this study.

| Pipe material | $C_p$ |
|---|---|
| ACP | 1.2 |
| CIP | 1.0 |
| VP | 1.0 |
| SP | 2.0 |
| PEP | 0.1 |

| Diameter (mm) | $C_d$ |
|---|---|
| ~ 75 | 1.6 |
| 100 ~ 150 | 1.0 |
| 200 ~ 450 | 0.8 |
| 500 ~ | 0.5 |

| PL value | $C_l$ |
|---|---|
| 0 ~ 5 | 1.0 |
| 5 ~ 15 | 2.0 |
| 15 ~ | 2.4 |

| Geological condition | Code of geomorphological land classifications in Fig. 3(b) | $C_g$ |
|---|---|---|
| Firm ground | 1, 2, 3, 4, 5, 6, 7, 8, 21, 22 | 0.4 |
| Alluvial plain | 11, 12, 13, 14, 15, 16, 17, 18, 19, 20 | 1.0 |
| Valley or river channel | 10, 23, 24 | 3.2 |
| Terrace | 9 | 1.5 |

$$R_m(v) = C_p C_d C_g C_l R(v) \tag{2}$$

where $R_m$ is the damage ratio, $C_p$, $C_d$, $C_g$, and $C_l$ are correction coefficients for the pipe material, diameter, geological condition, and liquefaction occurrence, respectively, and $v$ is the peak ground velocity (PGV).

$R(v)$ estimates the damage ratio for cast iron pipe (CIP) with a diameter of 100–150 mm. Maruyama *et al.* (2011) proposed Eq. (3) to estimate the pipe damage ratios. The three parameters in Eq. (3), $C$, $\lambda$, and $\zeta$, are defined with respect to two cases: one is to estimate the damage ratios of CIP and VP, and the other is to estimate those of DIP. Figure 6 shows the relationship between the PGV and damage ratios of water pipelines estimated from Eq. (3).

$$R(v) = C\Phi\left((\ln v - \lambda)/\zeta\right) \tag{3}$$

The correction coefficients in Eq. (2) are shown in Table 1. $C_p$, $C_d$, and $C_l$ are based upon the values used in the damage estimations performed by the prefectural governments in the south Kanto district. The correction coefficient for geological condition, $C_g$, is assigned following the geomorphological classifications in Figure 3(b) (Chiba Prefectural Government 2008).

Figure 7 shows the damage ratios of water distribution pipelines and the number of pipe breaks in the southern Kanto district. It should be noted that the PGV in the scenario is estimated by converting the JMA seismic intensity to PGV using an empirical equation (Karim and Yamazaki 2002). According to the figure, the damage ratios of water pipelines in Chiba prefecture are larger than those in the Tokyo metropolis even though the seismic intensity is larger in the east of Tokyo. ACP, which is fragile against an earthquake, is still widely used in Chiba prefecture and the percentage of DIP, which is relatively strong against an earthquake, is not so large in Chiba prefecture (Nojima 2008). This resulted in the differences in damage ratios for water distribution pipes.

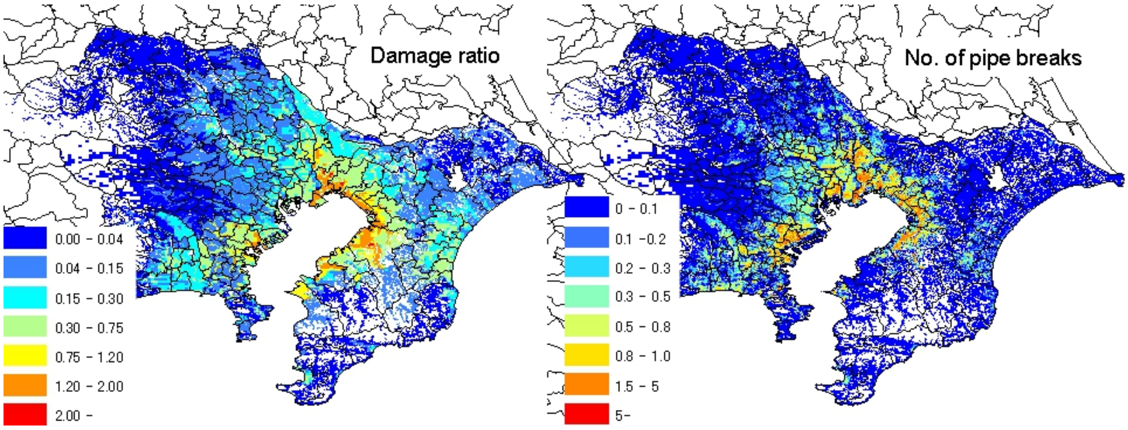



Fig. 7. Estimated damage ratio of water distribution pipelines and number of pipe breaks due a scenario northern Tokyo Bay earthquake.

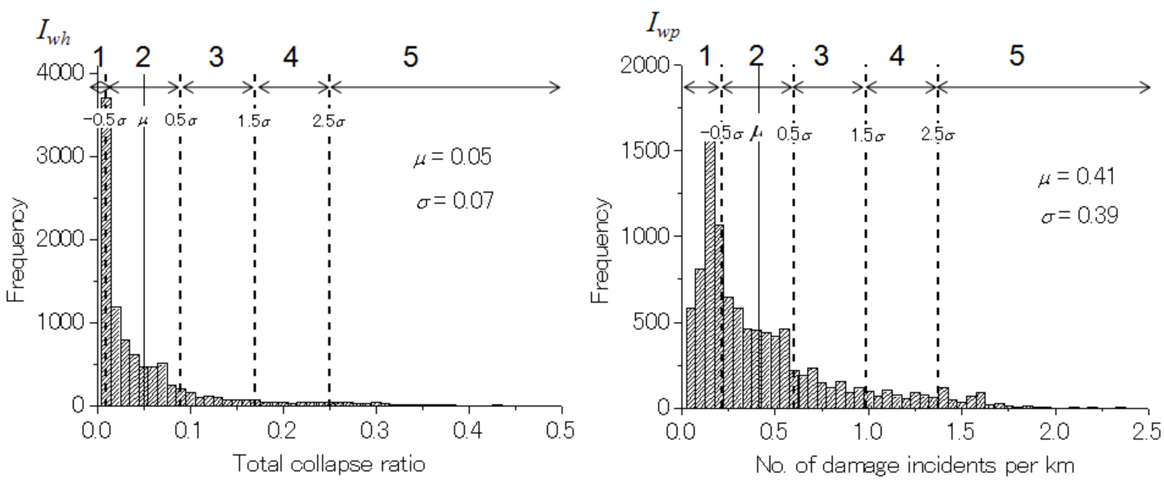



Fig. 8. Definition of damage ranks of wooden houses ($I_{wh}$) and water distribution pipes ($I_{wp}$) based on the mean and standard deviation of damage ratios.

## 4. CORRELATION BETWEEN THE DAMAGE RATIOS OF WOODEN HOUSES AND WATER DISTRIBUTION PIPELINES

The results of damage estimations shown in Figures 5 and 7 are represented in 250 × 250 m$^2$ grid cells for the entire southern Kanto district. We compile the damage ratios with respect to the postal address in the areas where the JMA seismic intensity is estimated to be more than 5.5 (see Figure 1). Then, the correlation between the total collapse ratio of wooden houses and the damage ratio of water distribution pipes is evaluated with respect to the postal address areas. By analyzing the correlation, different disaster scenarios can be drawn. If the damage ratios of both wooden houses and water pipelines are large, a delay in restoration work of water pipelines is anticipated because of limited accessibility due to debris. Even if the damage ratios of wooden

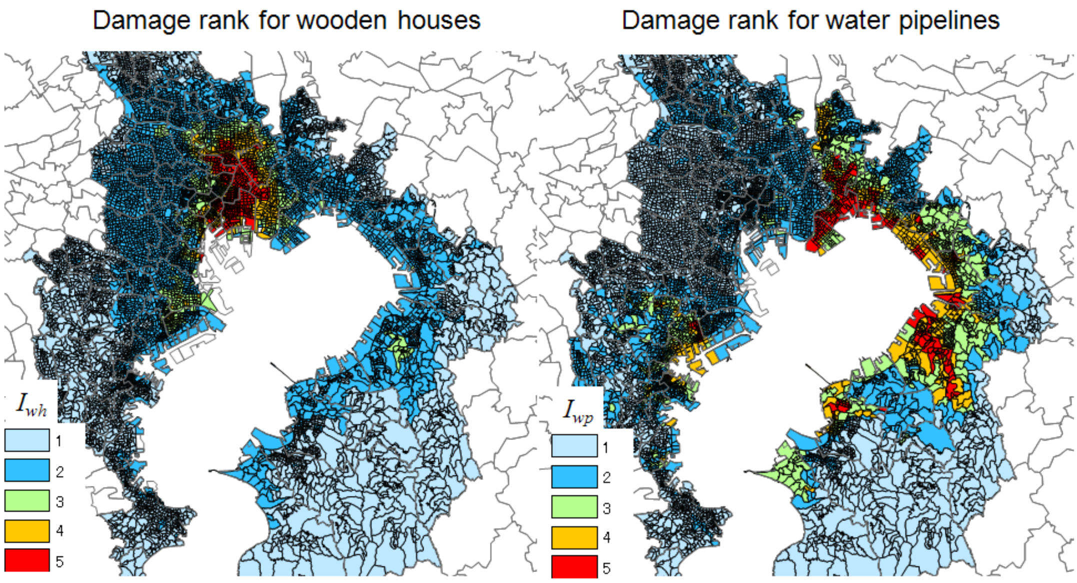



Fig. 9. Damage ranks of wooden houses ($I_{wh}$) and water distribution pipelines ($I_{wp}$) with respect to the postal address.

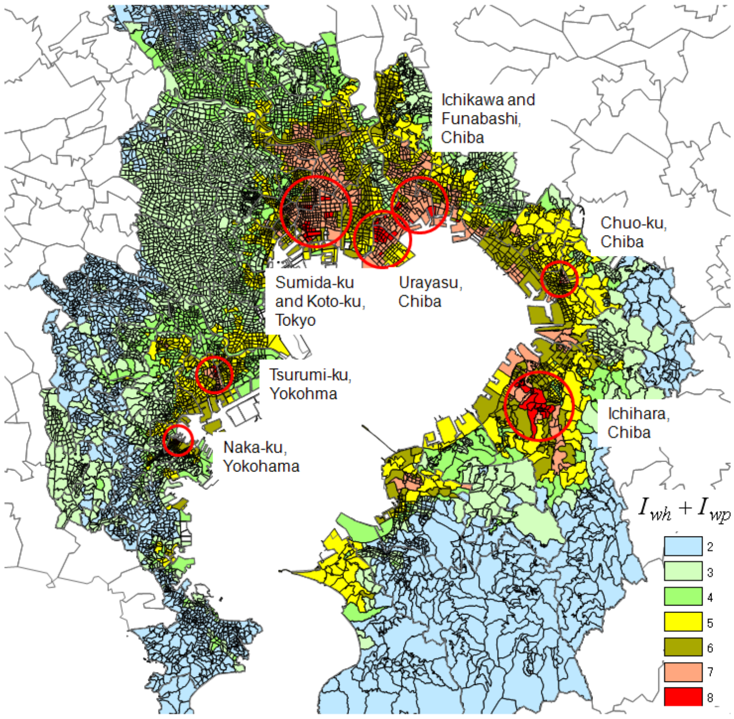



Fig. 10. Summations of the damage ranks of wooden houses and water distribution pipelines.

houses are small, the residents in areas with more water pipe breaks may still suffer from a long term disruption of their water supply.

Damage ranks, denoted as $I_{wh}$ and $I_{wp}$, are defined for the damage ratios of wooden houses and water distribution pipes, respectively. Each damage rank is assigned based on the mean $\mu$ and standard deviation $\sigma$ of damage ratio as shown in Figure 8. The threshold values are set to be $\mu$ - 0.5$\sigma$, $\mu$ + 0.5$\sigma$, $\mu$ + 1.5$\sigma$, and $\mu$ + 2.5$\sigma$. The damage rank is given a rating from 1 to 5 as shown in Figure 8.

Figure 9 shows the damage ranks of wooden houses and water distribution pipelines with respect to their postal address locations. $I_{wh}$ shows larger values in the eastern part of the Tokyo metropolis, while $I_{wp}$ shows larger values in the western Chiba Prefecture and a part of Yokohama City, Kanagawa Prefecture. We calculate a combined damage ratio of wooden houses and water distribution pipelines by taking the summation of $I_{wh}$ and $I_{wp}$ (Fig. 10). The sum of the damage ranks is equal to 8 in Sumida and Koto Wards, the eastern Tokyo metropolis, and other areas in Chiba and Kanagawa Prefectures. In these areas, this scenario predicts heavy damage to both wooden houses and water pipelines and a delay of restoration work due to possible damage interactions among buildings and lifeline systems.

## 5. CONCLUSIONS

This study estimated the damage ratios of wooden houses and water distribution pipelines in a northern Tokyo Bay earthquake scenario. The inventory datasets used by each prefectural government to estimate earthquake impacts were compiled for the southern Kanto district, Tokyo, Kanagawa, Saitama, and Chiba Prefectures. Then, the damage ratios were predicted by common fragility functions to obtain estimations that were uniform and consistent for all the prefectures.

Based on the damage estimations, we defined damage ranks for wooden houses and water distribution pipelines to evaluate the correlations between damage ratios. For some areas, even though the damage ratios of wooden houses were small, the associated damage ratios of water distribution pipelines were large. The residents in these areas may be affected by a lengthy disruption of water supply.

Taking the summation of the two damage ranks, the areas where the damage ratios of both wooden houses and water pipelines are large were revealed. A significant delay of restoration work is anticipated in these areas since accessibility may be restricted due to debris from collapsed houses and buildings.

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