Proceedings of the International Symposium on Engineering Lessons Learned from
the 2011 Great East Japan Earthquake, March 1-4, 2012, Tokyo, Japan

DAMAGE ASSESSMENT ON WATER SUPPLY SYSTEM AND SEWERAGE SYSTEM AT THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE - CASE STUDY FOR THE DATA AT IBARAKI AND CHIBA PREFECTURES -

Satoshi NABA[1], Takuya TSUKIJI[2], Gaku SHOJI[3] and Shigeru NAGATA[4]

[1] Graduate Student, Graduate School of Systems and Information Engineering,
University of Tsukuba, Ibaraki, Japan, s1021001@u.tsukuba.ac.jp
[2] Collage of Engineering Systems, University of Tsukuba, Ibaraki, Japan, s0811228@u.tsukuba.ac.jp
[3] Associate Professor, Faculty of Engineering, Information and Systems,
University of Tsukuba, Ibaraki, Japan, gshoji@kz.tsukuba.ac.jp
[4] Kajima Technical Research Institute, Tokyo, Japan, nagata-shigeru@kajima.com

ABSTRACT: We evaluate the dependency of damage and restoration of water supply systems and sewerage systems on the seismic hazards in the 2011 off the Pacific Coast of Tohoku earthquake focusing on the damage at Ibaraki and Chiba prefectures. We collect the damage data of the systems by carrying out interviews for related local government sectors. We quantify two damage ratios R_N on physical damage points and R_L on disrupted pipeline lengths, for 14 municipalities in Ibaraki prefecture and 8 municipalities in Chiba prefecture.

Key Words: The 2011 off the Pacific Coast of Tohoku earthquake, water supply system, sewerage system, damage ratio, fragility curve

INTRODUCTION

Water supply systems and sewerage systems were severely damaged at the 2011 off the Pacific Coast of Tohoku earthquake and tsunami which occurred on March 11, 2011. It caused large influence to social and economic activities since our society is strongly dependent on water treatment systems. Water outages occurred at maximumly 2,105,091 houses as of March 11, 2011 in 187 municipalities such as 616,480 houses in Miyagi prefecture, 444,288 houses in Ibaraki prefecture and 373,069 houses in Chiba prefecture (Ministry of Health, Labour and Welfare 2011). Sewerage damage occurred at 120 treatment facilities, 112 pump stations, 1,061 km pipelines and 20,730 manholes (Ministry of Land, Infrastructure, Transport and Tourism 2011). The reason of these vast damage is that the related facilities and buried pipelines subjected to severe tsunami waves, strong ground excitations and large liquefaction. For predicting damage caused by future extreme earthquakes and tsunamis and planning effective restoration strategy for water treatment systems, it is much significant to analyze damage

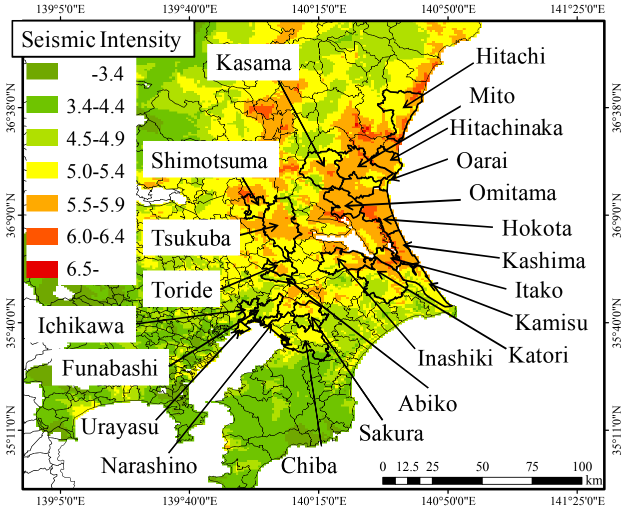


Fig. 1 Subject municipalities and seismic hazards distribution

data due to the earthquakes and tsunamis. From the reason above, we collect the damage data by carrying out interviews for related local government sectors focusing on the damage areas at Ibaraki and Chiba prefectures and evaluate the dependency of damage and restoration of water supply systems and sewerage systems on the induced seismic hazards. In addition, we compare the damage ratios in subject municipalities with estimated ones derived by our previously proposed seismic fragility curves.

SETTING OF ANALYZED DATA

Fig.1 shows subject municipalities at Ibaraki and Chiba prefectures. For analysis of water supply systems, we select 21 municipalities: Hitachi, Hitachinaka, Mito, Kasama, Oarai, Hokota, Omitama, Shimotsuma, Tsukuba, Kashima, Inashiki, Toride, Kamisu at Ibaraki prefecture and Katori, Abiko, Funabashi, Ichikawa, Sakura, Chiba, Narashino, Urayasu at Chiba prefecture. Among them, Toride data includes the damage data at the areas managed by South Ibaraki Waterworks Agency. For analysis of sewerage systems, we select 19 municipalities: Hitachinaka, Mito, Kasama, Oarai, Hokota, Omitama, Shimotsuma, Tsukuba, Kashima, Itako, Inashiki, Kamisu at Ibaraki prefecture and Katori, Abiko, Funabashi, Sakura, Chiba, Narashino, Urayasu at Chiba prefecture. For total 22 municipalities, we carried out field surveys and interviews at Hitachinaka (6/1, 6/29, 12/26, 2011), Mito (1/10, 2012), Kasama (12/8, 2011), Oarai (12/22, 2011), Tsukuba (12/22, 2011), Kashima (12/20, 2011 and 1/6, 2012), Itako (6/28, 9/26,11/16, 2011 and 1/6, 2012), Toride (5/31, 2011), Kamisu (6/28, 9/26, 12/20, 2011 and 1/6, 2012) at Ibaraki prefecture and Katori (6/28, 2011), Abiko (5/31, 12/26, 2011), Funabashi (12/6, 2011), Sakura (12/26, 2011), Chiba (6/3, 9/2, 2011 and 1/13, 2012), Urayasu (6/3, 2011) at Chiba prefecture.

For water supply systems, we analyze total pipeline lengths L, disrupted pipeline lengths L_d, the number of physical damage points N_p, their damage modes and the restoration periods for districts of a town in the relevant municipalities. We distinguish types of pipelines and diameters of pipelines on conduits, transmission pipes, distribution pipes and service pipes. Similarly, for sewerage systems, we analyze total pipeline lengths L, disrupted pipeline lengths L_d, the number of physical damage points N_p, their damage modes, the periods of restriction for use for sewerage systems and temporary restoration periods for districts of a town in the relevant municipalities. We distinguish types of pipelines and diameters of pipelines on sanitary pipes, rainwater pipes and combined sewer pipes.

We quantify two damage ratios R_N and R_L: R_N defined by the ratio of number of physical damage points N_p divided by total lengths L of the systems as following equation,

$$R_N = \frac{N_p}{L} \tag{1}$$

and R_L defined by the ratio of disrupted lengths L_d divided by total lengths L of the systems as following equation,

$$R_L = \frac{L_d}{L} \tag{2}$$

In order to analyze relation of damage ratios R_N and R_L with related seismic hazards, we compute seismic hazards distribution on seismic intensity with third meshes by spatial interpolation based on simple kriging method (Cressie 1993) by using the observed strong ground motions data by Japan Meteorological Agency (2011), and National Research Institute for Earth Science and Disaster Prevention (2011), and by using information of moment magnitude M_w and location of hypocenter by Japan Meteorological Agency (2011). For estimating seismic intensity IJ_b at the layer with V_s of 500m/s for subject areas, we use mean values derived by attenuation relationship proposed by Si and Midorikawa (1999) and for estimating amplification factor of seismic intensity at the ground surface with seismic intensity IJ_b we use the relationship proposed by Fujimoto and Midorikawa (2006). For the following analysis, we use median of estimated seismic intensities IJ_m for third meshes overlapped to the areas of subject municipalities.

DAMAGE OF WATER SUPPLY SYSTEMS AND SEWERAGE SYSTEMS

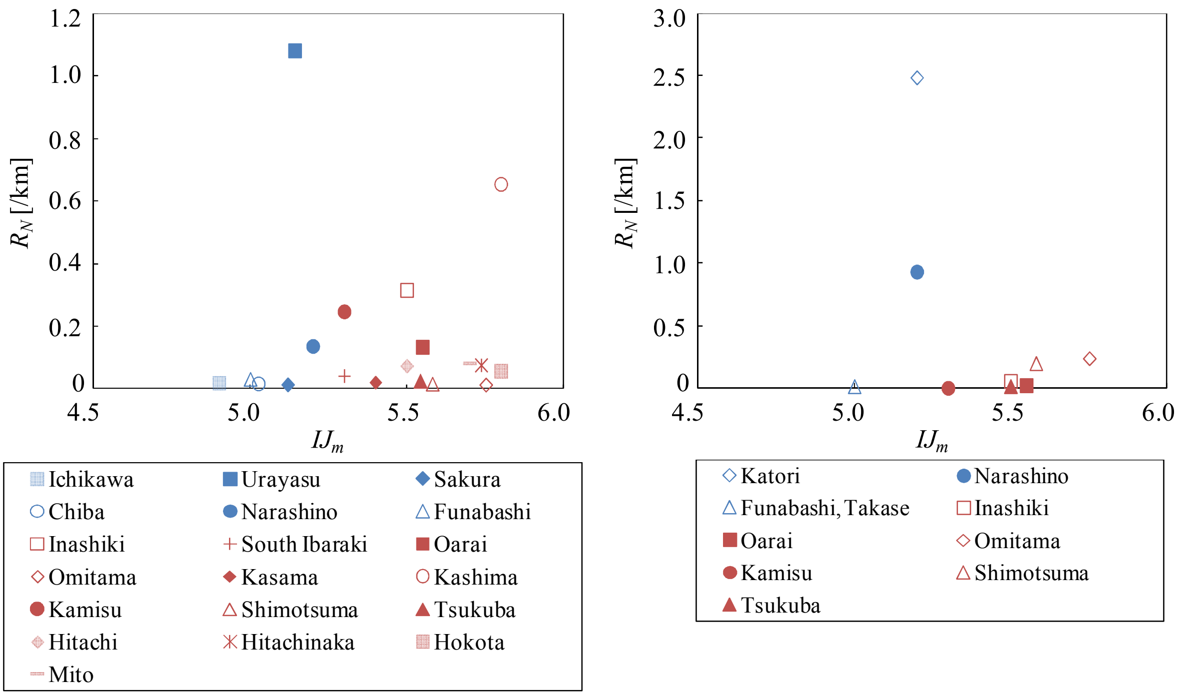
Analysis on damage ratios

Fig. 2 shows the relation between the damage ratios R_N and IJ_m for subject municipalities. Fig. 3 shows the relation between the damage ratios R_L and IJ_m for same ones. We compute R_N and R_L for distribution pipes of water supply systems. We compute R_N and R_L for sanitary pipes of sewerage systems except for the values for Tsukuba data which include sanitary pipes and rainwater pipes, except for Katori data which include sanitary pipes and combined sewer pipes and except for Narashino data which include sanitary pipes, rainwater pipes and combined sewer pipes.

In terms of water supply systems, from Fig. 2(a), the values of R_N are classified into the following 4 ranges. R_N for Urayasu data with IJ_m of 5.1 shows the remarkably largest value of 1.081/km and R_N for Kashima data with IJ_m of 5.8 shows the next largest value of 0.654/km. These two cities are classified into extremely severe affected municipalities. R_N for Inashiki and Kamisu data with IJ_m of 5.3 to 5.5 show relatively larger values of 0.247/km to 0.316/km which are classified into severe damage. R_N for Hitachi, Hitachinaka, Mito, Oarai, Hokota and Narashino data with IJ_m of 5.2 to 5.8 show the values in the relatively middle range of 0.0571/km to 0.136/km. R_N for Kasama, Omitama, Shimotsuma, Tsukuba, South Ibaraki Waterworks Agency, Funabashi, Ichikawa, Sakura and Chiba data with IJ_m of 4.9 to 5.8 show relatively smaller values of 0.0130/km to 0.0416/km. In the above, Kashima and Inashiki data show large R_N due to strong seismic intensities of 5.5 to 6.0. In contrast, Kamisu and Urayasu data show also large R_N in spite of relatively lower seismic intensities of 5.0 to 5.5. The reason of the damage is possibly due to the large-scaled liquefaction at the areas.

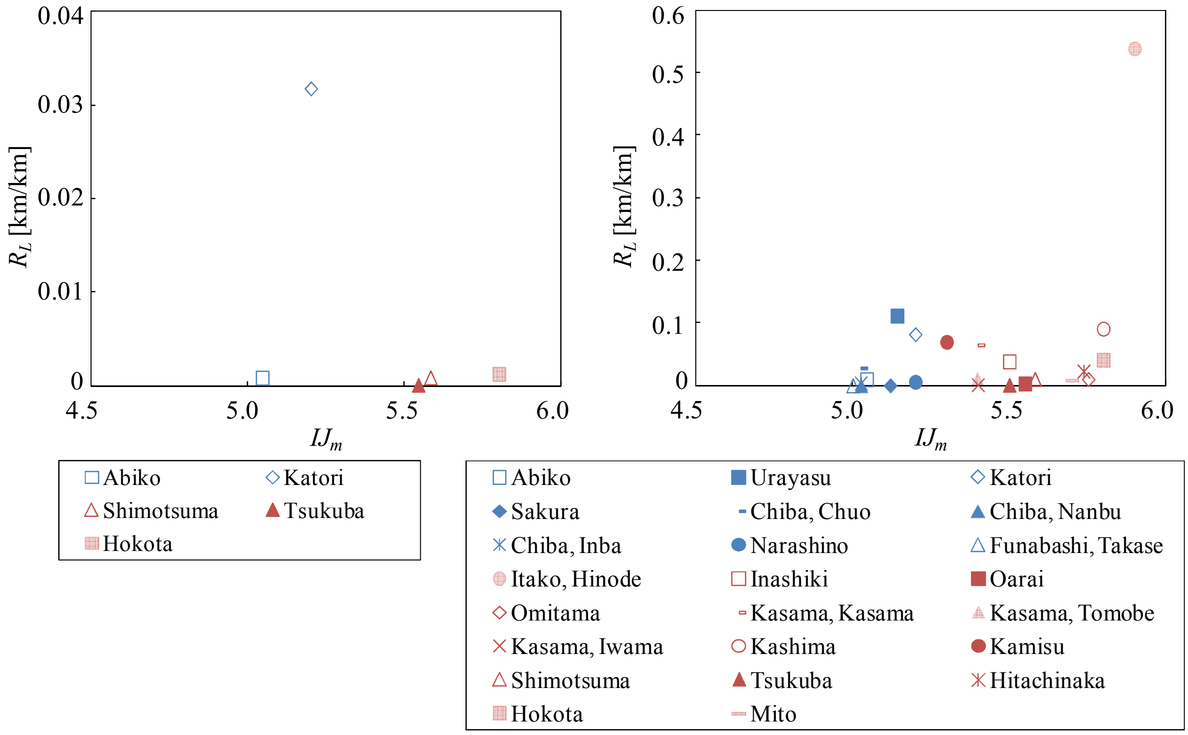
From Fig. 3(a), the values of R_L for water supply systems are classified into the following 2 ranges. R_L for Katori data with IJ_m of 5.2 shows the remarkably largest value of 0.0317km/km. R_L for Hokota, Shimotsuma, Tsukuba and Abiko data with IJ_m of 5.0 to 5.8 show relatively smaller values of 0.0000573km/km to 0.00124km/km. The trends of R_N and R_L for both Shimotsuma and Tsukuba data are same.

In terms of sewerage systems, from Fig. 2(b), the values of R_N are classified into the following 4 ranges. R_N for Katori data with IJ_m of 5.2 shows the remarkably largest value of 2.484/km and R_N for Narashino data with IJ_m of 5.2 shows the next largest value of 0.930/km. These two cities are



(a) Water supply systems (b) Sewerage systems

Fig. 2 Relation between damage ratio R_N and IJ_m



(a) Water supply systems (b) Sewerage systems

Fig. 3 Relation between damage ratio R_L and IJ_m

classified into extremely severe affected municipalities. R_N for Omitama and Shimotsuma data with IJ_m of 5.6 to 5.8 show relatively larger values of 0.198/km to 0.237/km. R_N for Oarai and Inashiki data with IJ_m of 5.5 to 5.6 show the values in the relatively middle range of 0.0218/km to 0.0540/km. R_N for Tsukuba data and for Takase treatment areas in Funabashi data with IJ_m of 5.0 to 5.5 show relatively smaller values of 0.0135/km to 0.0142/km. In the above, R_N for Katori and Narashino data show the remarkably large values of R_N in spite of relatively lower seismic intensity of 5.2. The reason of the damage is due to the large-scaled liquefaction at the reclamation areas used for water ways at Katori and at the coastal areas at Narashino.

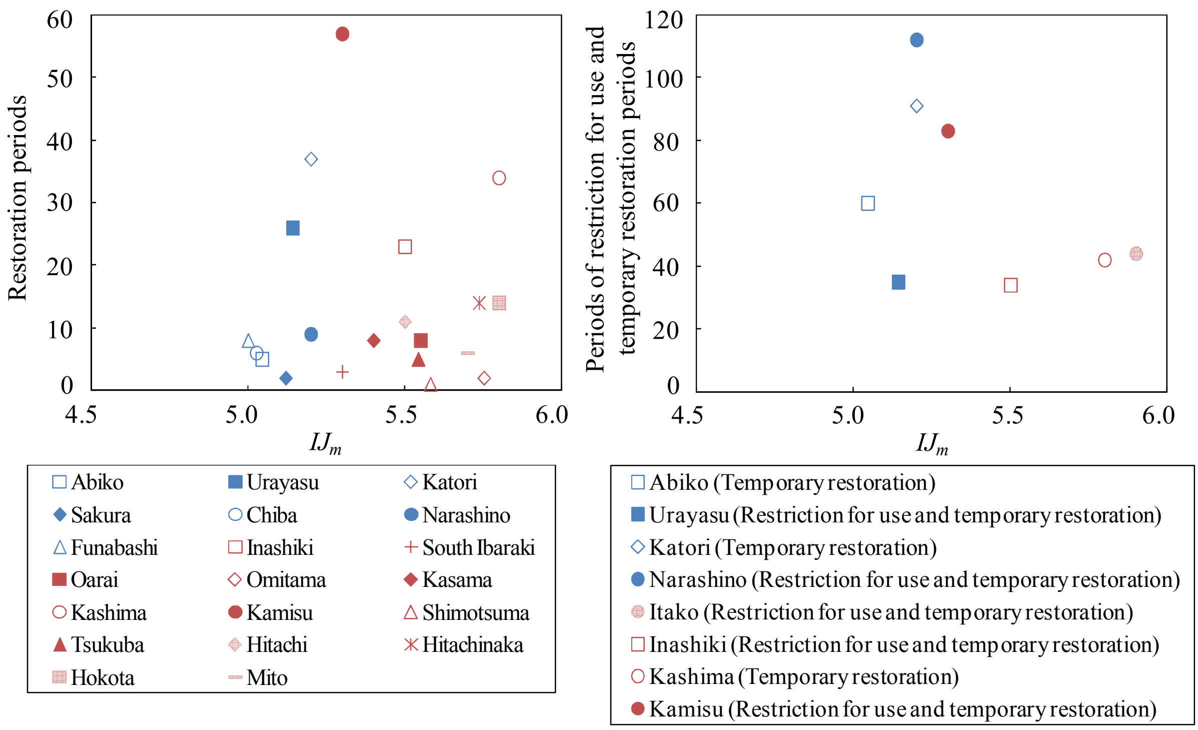
From Fig. 3(b), the values of R_L for sewerage systems are classified into the following 5 ranges. R_L for Hinode areas in Itako data with IJ_m of 5.9 shows the remarkably huge value of 0.538km/km compared with other data for subject municipalities. R_L for Kashima and Urayasu data with IJ_m of 5.1 to 5.8 show the remarkably largest values of 0.0907km/km to 0.112km/km. R_L for Kamisu, Katori data and for Kasama treatment areas in Kasama data with IJ_m of 5.2 to 5.4 show the next largest values of 0.0649km/km to 0.0818km/km. R_L for Hitachinaka, Hokota, Inashiki data and for Chuo treatment areas in Chiba data with IJ_m of 5.0 to 5.8 show the values in the relatively middle range of 0.0228km/km to 0.0412km/km. R_L for Mito, Oarai, Omitama, Shimotsuma, Tsukuba, Abiko, Sakura, Narashino data and for Tomobe treatment areas in Kasama data, Iwama treatment areas in Kasama data, Takase treatment areas in Funabashi data, Inba treatment areas in Chiba data with IJ_m of 4.9 to 5.8 show relatively smaller values of 0.000237km/km to 0.0115km/km. In the above, Hinode areas in Itako data show the remarkably huge R_L due to the strongest seismic intensity of 5.9 and the intensive liquefaction at the reclamation areas of swamp. Kashima and Urayasu data show the remarkably largest values due to strong seismic intensities of 5.8, and liquefaction at harbor areas at Kashima and large-scaled liquefaction at Urayasu.

Analysis on restoration periods

Fig.4 shows relation of restoration periods for water supply systems with seismic intensity IJ_m and relation of periods of restriction for use for sewerage systems and temporary restoration periods for sewerage systems with seismic intensity IJ_m.

From Fig. 4(a), water supply systems (WSS) at Kamisu were restored in 57 days which show the longest restoration periods due to larger R_N. WSS at Kashima, Inashiki, Katori and Urayasu show the second largest restoration periods of 23 days to 37 days: 26 days to 34 days at Kashima and Urayasu due to largest R_N, 23 days at Inashiki due to larger R_N, 37 days at Katori due to largest R_L. WSS at Hitachi, Hitachinaka, Oarai, Hokota and Narashino were restored in 8 days to 14 days which show longer restoration periods due to middle range of R_N. In contrast, WSS at Kasama and Funabashi were restored in 8 days which also show longer restoration periods in spite of smaller R_N. In case of Kasama, it is caused by water outages in Kasama district because of lengthening of restoration periods due to water leakages at transmission pipes managed by Ibaraki Enterprise Bureau. Furthermore, R_N at Kasama becomes small since we compute R_N by including buried pipeline lengths L in Tomobe treatment areas and Iwama treatment areas in addition to Kasama treatment areas. In case of Funabashi, it is caused by lengthening of restoration periods due to the damage of large-diameter pipe of more than 500mm at the coastal areas suffered by liquefaction. WSS at Mito, Tsukuba, Abiko and Chiba show middle range of restoration periods of 5 days to 6 days: 6 days at Mito due to middle range of R_N, 5 days to 6 days at Tsukuba and Chiba due to smaller R_N, 5 days at Abiko due to middle range of R_L. WSS at Omitama, Shimotsuma, South Ibaraki Waterworks Agency and Sakura were restored in 1 days to 3 days which show smaller range of restoration periods due to smaller R_N.

From Fig. 4(b), in terms of periods of restriction for use for sewerage systems, sewerage systems (SS) at Narashino were restored in 112 days which show the longest restoration periods due to next largest R_N. SS at Kamisu were restored in 83 days which show the second longest restoration periods due to next largest R_L. SS at Itako, Inashiki and Urayasu were restored in 34 days to 44 days which show longer restoration periods due to largest and middle range of R_L. In terms of temporary restoration periods for sewerage systems, SS at Narashino were restored in 112 days which show the longest restoration periods due to next largest R_N. SS at Kamisu and Katori were restored in 83 days to 91 days which show the second longest restoration periods due to next largest R_L. SS at Kashima, Itako, Inashiki and Urayasu were restored in 34 days to 44 days which show longer restoration periods



(a) Water supply systems

(b) Sewerage systems

Fig. 4 Relation between restoration periods and IJ_m

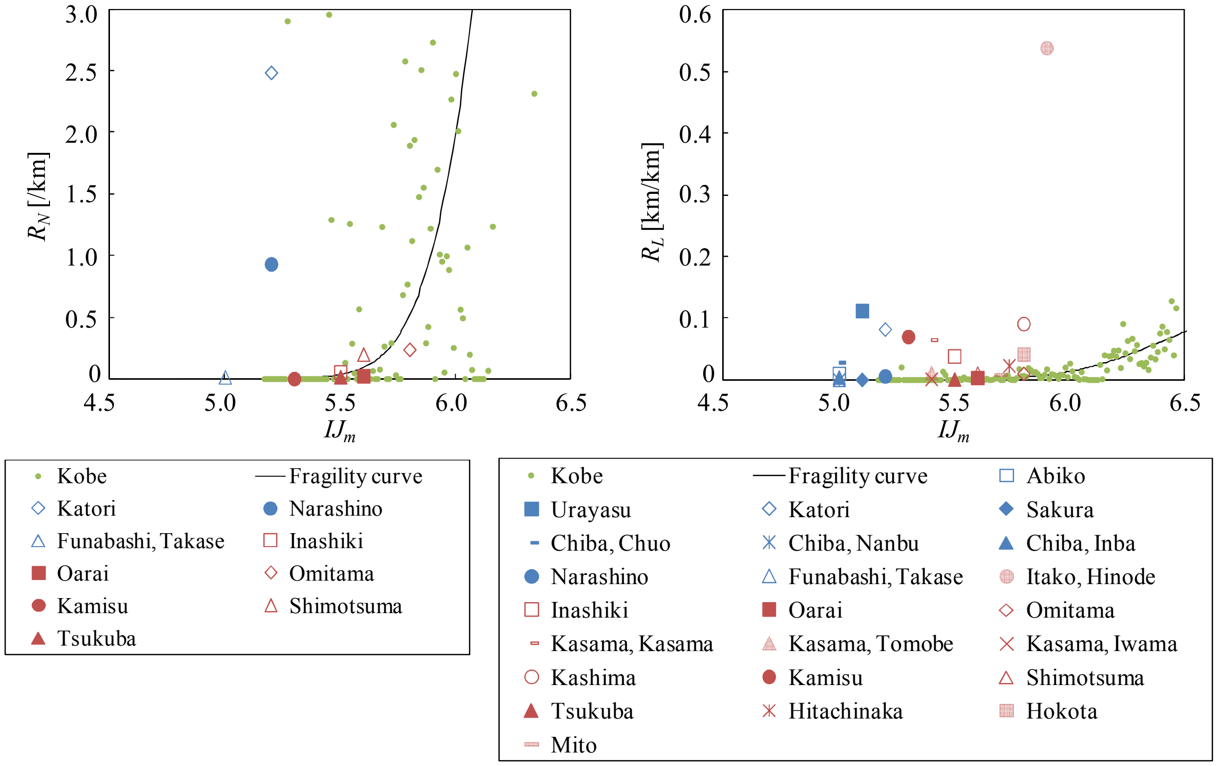
due to largest and middle range of R_L. In contrast, SS at Abiko were restored in 60 days which show longer restoration periods in spite of smaller R_L.

COMPARISON OF ANALYZED DATA WITH PREVIOUS SEWERAGE DAMAGE

Fig.5 shows comparison of R_N and R_L with estimated ones derived by our proposed seismic fragility curves (Shoji et al. 2011).

From Fig. 5(a), R_N at all subject municipalities except for Katori and Narashino show good agreement with the values by seismic fragility curve. R_N of 2.484/km at Katori and R_N of 0.930/km at Narashino are large due to not only relatively lower seismic intensity but also huge liquefaction. Then, the values of R_N at Katori and Narashino do not show good agreement with the values by seismic fragility curve since the seismic fragility curve considers no effect of liquefaction.

From Fig. 5(b), R_L at Mito, Kasama treatment areas in Kasama, Tomobe treatment areas in Kasama, Oarai, Omitama, Shimotsuma, Takase treatment areas in Funabashi, Sakura, Nanbu treatment areas in Chiba, Inba treatment areas in Chiba and Narashino show good agreement with the values by seismic fragility curve. In contrast, R_L of 0.583/km at Hinode areas in Itako with IJ_m of 5.9 shows remarkably larger value than those derived by the seismic fragility curve due to the strongest ground excitation among the subject municipalities and the intensive liquefaction at the areas. R_L of 0.00994 to 0.112 at Katori, Abiko, Chuo treatment areas in Chiba and Urayasu with IJ_m of nearly 5.0 show larger values than those derived by the seismic fragility curve due to damages by severe liquefaction. On the other hand, R_L at Hitachinaka, Hokota, Kashima and Inashiki with IJ_m of nearly 5.5 show larger values than the values derived by the seismic fragility curve due to the strong ground motions and liquefaction. Furthermore, R_L at Kasama treatment areas in Kasama with IJ_m of 5.4 also shows larger values due to the damage on aged pipes.



(a) For R_N (b) For R_L

Fig. 5 Comparison of damage ratios for the Tohoku earthquake with those for the Kobe earthquake

CONCLUSIONS

We evaluate the dependency of damage and restoration of water supply systems and sewerage systems on the seismic hazards in the 2011 off the Pacific Coast of Tohoku earthquake focusing on the damage at Ibaraki and Chiba prefectures. We collect the damage data of the systems by carrying out interviews for related local government sectors. We quantify two damage ratios R_N and R_L for 14 municipalities in Ibaraki prefecture and 8 municipalities in Chiba prefecture: R_N defined by the ratio of number of physical damage points N_p divided by total lengths of the buried pipelines L and R_L defined by the ratio of disrupted lengths L_d divided by total lengths of the buried pipelines L. In addition, we compare the values of R_N and R_L with estimated ones derived by previously proposed seismic fragility curves. Following conclusions are deduced.

(1) R_N for water supply systems are classified into the following 4 ranges: extremely large values of 0.654/km to 1.081/km at Urayasu and Kashima data with seismic intensity IJ_m of 5.1 to 5.8, larger values of 0.247/km to 0.316/km at Inashiki and Kamisu data with IJ_m of 5.3 to 5.5, middle values of 0.0571/km to 0.136/km at Hitachi, Hitachinaka, Mito, Oarai, Hokota and Narashino data with IJ_m of 5.2 to 5.8 and smaller values of 0.0130/km to 0.0416/km at South Ibaraki Waterworks Agency and other municipalities data with IJ_m of 4.9 to 5.8. R_L for water supply systems are classified into the following 2 ranges: extremely large value of 0.0317km/km at Katori data with IJ_m of 5.2, smaller values of 0.0000573km/km to 0.00124km/km at Hokota and other municipalities data with IJ_m of 5.0 to 5.8.

(2) R_N for sewerage systems are classified into the following 4 ranges: extremely large values of 0.930/km to 2.484/km at Katori and Narashino data with IJ_m of 5.2, larger values of 0.198/km to 0.237/km at Omitama and Shimotsuma data with IJ_m of 5.6 to 5.8, middle values of 0.0218/km to 0.0540/km at Oarai and Inashiki data with IJ_m of 5.5 to 5.6, smaller values of 0.0135/km to

0.0142/km at Tsukuba and Takase treatment areas in Funabashi data with IJ_m of 5.0 to 5.5. R_L for sewerage systems are classified into the following 5 ranges: remarkably huge value of 0.538km/km at Hinode areas in Itako data with IJ_m of 5.9, extremely large values of 0.0907km/km to 0.112km/km at Kashima and Urayasu data with IJ_m of 5.1 to 5.8, next largest values of 0.0649km/km to 0.0818km/km at Kasama treatment area at Kasama, Kamisu and Katori data with IJ_m of 5.2 to 5.4, middle values of 0.0228km/km to 0.0412km/km at Hitachinaka, Hokota, Inashiki and Chuo treatment areas in Chiba data with IJ_m of 5.0 to 5.8, smaller values of 0.000237km/km to 0.0115km/km at Tomobe treatment areas in Kasama and other municipalities data with IJ_m of 4.9 to 5.8.

(3) Water supply systems (WSS) at Kamisu were restored in longest restoration periods of 57 days due to larger R_N, WSS at Kashima, Inashiki, Katori and Urayasu were restored in second longest restoration periods of 23 days to 37 days: 26 days to 34 days at Kashima and Urayasu due to largest R_N, 23 days at Inashiki due to larger R_N, 37 days at Katori due to largest R_L. WSS at Hitachi, Hitachinaka, Oarai, Hokota and Narashino were restored in longer restoration periods of 8 days to 14 days due to middle range of R_N. WSS at Kasama and Funabashi were restored in longer restoration periods of 8 days in spite of smaller R_N. WSS at Mito, Tsukuba, Abiko and Chiba were restored in middle range of restoration periods of 5 days to 6 days: 6 days at Mito due to middle range of R_N, 5 days to 6 days at Tsukuba and Chiba due to smaller R_N, 5 days at Abiko due to middle range of R_L.

(4) In terms of periods of restriction for use for sewerage systems, sewerage systems (SS) at Narashino were restored in the longest restoration periods of 112 days due to next largest R_N. SS at Kamisu were restored in the second longest restoration periods of 83 days due to next largest R_L. SS at Itako, Inashiki and Urayasu were restored in longer restoration periods of 34 days to 44 days due to largest and middle range of R_L. In terms of temporary restoration periods for sewerage systems, SS at Narashino were restored in the longest restoration periods of 112 days due to next largest R_N. SS at Kamisu and Katori were restored in the second longest restoration periods of 83 days to 91 days due to next largest R_L. SS at Kashima, Itako, Inashiki and Urayasu were restored in longer restoration periods of 34 days to 44 days due to largest and middle range of R_L. SS at Abiko were restored in longer restoration periods of 60 days in spite of smaller R_L.

(5) From comparison of R_N with estimated ones derived by our proposed seismic fragility curves, R_N at all subject municipalities except for Katori and Narashino show good agreement with the values by seismic fragility curve. From comparison of R_L with estimated ones derived by our proposed seismic fragility curves, R_L at Mito and other 10 municipalities show good agreement with the values by seismic fragility curve. R_L at Hinode areas in Itako with IJ_m of 5.9 shows remarkably larger value than the value derived by the seismic fragility curve due to the strongest ground excitation among the subject municipalities and the intensive liquefaction at the areas. R_L at Katori, Abiko, Chuo treatment areas in Chiba and Urayasu with IJ_m of nearly 5.0 show larger values than the values derived by the seismic fragility curve due to damages by severe liquefaction. R_L at Hitachinaka, Hokota, Kashima and Inashiki with IJ_m of nearly 5.5 show larger values than the values derived by the seismic fragility curve due to the strong ground motions and liquefaction. R_L at Kasama treatment areas in Kasama with IJ_m of 5.4 also shows larger values due to the damage on aged pipes.

ACKNOWLEDGEMENTS

We appreciate valuable cooperation of all subject municipalities. This study was sponsored by the development of restoration simulation system on seismic sewerage damage financially supported by MLIT from 2009 to 2010 (leader, Dr. S. Nagata at Kajima Technical Research Institute), the 2011 off the Pacific Coast of Tohoku earthquake research project at University of Tsukuba (leader, Professor T. Kanakubo) and the integrated risk management project for complex disasters on large-scale earthquakes at University of Tsukuba (leader, Professor Y. Yagi).

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