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# MODELING POST-EARTHQUAKE LIFELINE SERVICEABILITY BASED ON RECENT EARTHQUAKE DAMAGE IN JAPAN

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## *Abstract*

Enhancement of disaster resilience in urban regions is an urgent issue to protect socio-economic activities and daily lives of citizens from devastation of major earthquakes such as the anticipated Nankai Trough Megathrust Earthquake and the anticipated Earthquakes directly beneath the Tokyo metropolitan area. Since urban functions heavily depend on lifelines, it is necessary to accurately estimate the initial outage and duration of disruption of lifeline functions in earthquake disasters. For this purpose, the assessment model for the post-earthquake serviceability of utility lifelines (electric power, water supply, and city gas supply systems) was proposed by the authors. The proposed model was validated using the case of the 2011 off the Pacific Coast of Tohoku Earthquake. As a result, both initial outage and the time required for restoration were found to be estimated fairly well except for the underestimation of damage due to the effect of tsunami damage. However, validation has not been done for recent earthquake damage in Japan.

With this background, in this study, post-earthquake lifeline serviceability was remodeled based on validation and modification of the proposed model taking advantage of the damage experiences in the recent earthquakes after the 2004 Niigata-ken Chuetsu Earthquake. Firstly, a database was compiled concerning initial outages and restoration processes of utility lifelines in the recent five earthquakes. The maps of shaking intensity distribution on the Japan Meteorological Agency (JMA) scale for respective earthquakes were also compiled. Secondly, the estimated and observed values of initial outages and the restoration processes were compared. As confirmed in the previous study, estimation for the 2011 off the Pacific Coast of Tohoku Earthquake was acceptable in terms of accuracy. On the other hand, in the cases of the remaining four earthquakes, time periods required for restoration were found to be overestimated, while initial outages of electric power and water system were well estimated. All of those four earthquake disasters are on a smaller scale than the two great earthquake disasters of Hanshin-Awaji and East Japan. Such a difference in disaster scale presumably affects the total amount of physical damage, emergency response, and recovery works. Accordingly, time periods required for restoration are considered to be affected by the disaster scale, which has not been incorporated in the proposed model.

To incorporate the effect of the disaster scale, two new indices were introduced. One is the index to represent the discrepancy between the estimated and observed number of accumulated people without lifeline services. The other index represents the disaster scale in terms of *PEX* (Population Exposure to Shaking Intensity) with a weighting factor in consideration of the effect of each seismic intensity level to lifeline malfunction. Adjustment factors were obtained so that the estimation and observation become consistent using a non-linear optimization method. Those factors shorten (or extend) estimation of time periods required for restoration in accordance with the small (or large) scale of the disaster. By using the adjustment method, although the variation was still large, the estimated values of time required for restoration in electric power and water systems were improved so as to agree with observed values.

*Keywords: utility lifelines; initial outage, restoration process; assessment model; weighted population exposure*

# 1. Introduction

Enhancement of disaster resilience in urban regions is an urgent issue to protect socio-economic activities and daily lives of citizens from devastation of major earthquakes such as the anticipated Nankai Trough Megathrust Earthquake and the anticipated Earthquakes directly beneath the Tokyo metropolitan area. Since urban functions heavily depend on lifelines, it is necessary to accurately estimate the initial outage and duration of disruption of lifeline functions in earthquake disasters.

For this purpose, the assessment model for the post-earthquake serviceability of utility lifelines (electric power, water supply, and city gas supply systems) was proposed by the authors [1, 2]. The proposed model was validated using the case of the 2011 off the Pacific Coast of Tohoku Earthquake. As a result, both initial outage and the time required for restoration were found to be estimated fairly well except for the underestimation of damage due to the effect of tsunami damage. However, the proposed model tends to slightly overestimate the time required for restoration with several earthquakes [2]. Emergency response and recovery works after an earthquake are different due to a difference in disaster scale representing the impact on lifeline services by spatial spread of strong motion. On the other hand, such a difference is not explicitly considered as model parameters in the proposed model. In addition, validation of the proposed model has not been done for recent earthquake damage in Japan [1].

With this background, in this study, post-earthquake lifeline serviceability was remodeled based on validation and modification of the proposed model taking advantage of the damage experiences in recent earthquakes after the 2004 Niigata-ken Chuetsu Earthquake [3].

In this paper, Section 2 briefly summarizes the assessment model [1] and the tool [2]. Section 3 describes the results of the initial outage and the decreasing process without lifeline services between estimations using the proposed model and the observations for recent earthquakes in Japan. Section 4 describes the new method for the modification of the assessment model using *PEX* [4] (Population Exposure to Shaking Intensity) and compares the results based on the modified model with those of Section 3.

# 2. Assessment model and tool for post-earthquake serviceability of utility lifelines

## 2.1 Assessment model [1]

The assessment model [1] was developed based on the damage and restoration data obtained in the 1995 Hyogoken-Nambu Earthquake, Japan. The two-step approach estimates functional damage and decreasing processes of utility lifelines. The first step is modeled, as shown in Eq. (1), the probability of the initial outage $p(I)$, which serves as a functional fragility relation. The probability is modeled by an increasing function for the Japan Meteorological Agency (JMA) seismic intensity $I$ (See Appendix A in reference [1]). A logistic regression model with parameters $b_0$ and $b_1$ has been employed.

$$p(I) = \frac{\exp[b_0 + b_1 \cdot I]}{1 + \exp[b_0 + b_1 \cdot I]} \tag{1}$$

The second step is modeled, as shown in Eqs. (2)-(4), an evaluation model for the subsequent duration of lifeline disruption under the condition that the initial outage occurred. The function is modeled by the probability of the non-exceedance of time $t$ required for restoration, denoted by $F(I, t)$, which is obtained using a gamma distribution as follows.

$$f(t \mid I) = \frac{t^{\alpha(I)-1} \exp\left(-\frac{t}{\beta(I)}\right)}{\beta(I)^{\alpha(I)} \Gamma(\alpha(I))}, \; F(t \mid I) = \int_0^t f(\tau \mid I) d\tau \tag{2}$$

$$\alpha(I) = \left(\frac{\mu(I)}{\sigma(I)}\right)^2, \quad \beta(I) = \frac{\sigma^2(I)}{\mu(I)} \tag{3}$$

$$\mu(I) = a_0 + a_1 I + a_2 I^2, \; \sigma(I) = c_0 + c_1 I + c_2 I^2 \tag{4}$$



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Parameters $\alpha$ and $\beta$ in Eq. (3) are represented by the mean and standard deviation of the gamma density function, which are modeled by quadratic functions of the JMA seismic intensity $I$ with model parameter $a_0$, $a_1$, $a_2$, $c_0$, $c_1$, and $c_2$, as shown in Eq. (4).

Combining Eq. (1) and $F(I, t)$ in Eq. (2), post-earthquake serviceability curves of utility lifelines which represent in Eq. (5) are obtained. Fig. 1 shows the results of each utility lifeline.

$$P(I,t)=\{1-p(I)\}+p(I)\cdot F(t|I) \tag{5}$$

The assessment model has been modified on occasions of application to account for local conditions regarding the vulnerability of networks and developments in earthquake disaster countermeasures (hereafter referred to as "conventional model") [5, 6].

## 2.2 Assessment tool [2]

To calculate population without lifeline services convenient, the representative values were set concerning "population with each lifeline service data" and "lifeline facilities data" by NS7.5" by EW11.5" units (approximately 500m by 500m square grid cells) in reference [1]. These data and JMA seismic intensity information of pre-, immediate-, and after- are overlaid. Thus, decreasing processes of the population without lifeline services $H(t)$ can be calculated in arbitrary administrative units (municipalities, prefectures, regional blocks and the entire Japan).

$$H(t)=\sum_m H_m(t)=\sum_m\left[N_m\{1-P(I_m,t)\}\right]=\sum_m\left[N_m\cdot p(I_m)\{1-F(t|I_m)\}\right] \tag{6}$$

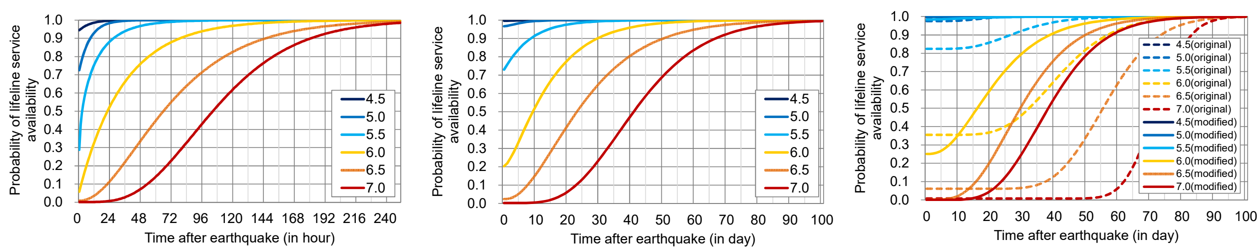
where $H_m(t)$ represents the decreasing process of the population without lifeline services in municipality $m$, $N_m$ represents the population with utility lifeline services in $m$ and $I_m$ represents the representative values of seismic intensity in $m$, respectively.

# 3. Decreasing process of the population without lifeline services for recent earthquakes

## 3.1 Earthquakes to be evaluated and data

This study evaluated six earthquakes in Japan: the 1995 Hyogoken-Nambu Earthquake (1995 Hyogo), the 2004 Niigata-ken Chuetsu Earthquake (2004 Chuetsu), the 2007 Niigata-ken Chuetsu-Oki Earthquake (2007 Chuetsu-Oki), the 2011 off the Pacific Coast of Tohoku Earthquake (2011 Tohoku), the 2016 Kumamoto Earthquake (2016 Kumamoto) and the 2018 Northern Osaka Earthquake (2018 Osaka).

Functional damages to utility lifelines and the decreasing process in these earthquakes were compiled based on references [2], [7, 8]. Seismic intensity information as input to the assessment model is represented by $I_m=\mu_{I_m}$ [2]. The mean of the JMA seismic intensity $\mu_{I_m}$ was obtained by weighting the JMA seismic intensity distributions [9, 10] in NS7.5" by EW11.5" units by the population of each municipality (the nighttime population distribution based on the 2005 census [11]). Fig. 2 shows $\mu_{I_m}$ in each municipality in




(a) Electric power supply system (b) Water supply system (c) City gas supply system

Fig. 1 – Post-earthquake serviceability curves of utility lifelines for various JMA intensities [1]



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six earthquakes.

### 3.2 Comparison of functional damages and the decreasing processes of the number of households without lifeline services between earthquakes

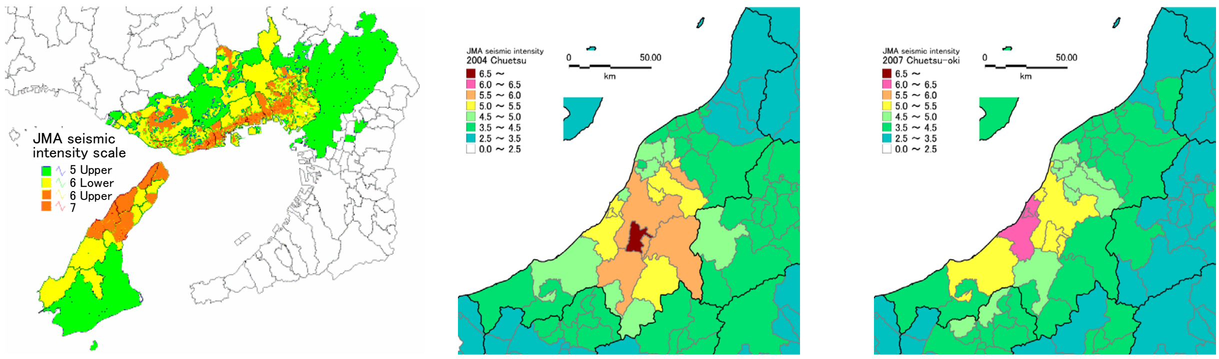
Fig. 3 and Fig. 4 show the initial outage of utility lifeline services and the decreasing process, respectively. Generally, the order of initial outage tends to be electric power, water supply, and city gas supply in descending order.

As for the decreasing process, electric power is the most rapid of all, city gas supply is very time consuming, and water supply is an intermediate tendency between the two. After the case of 1995 Hyogo, time periods required for restoration tend to be shortened. The main factors for this are that initial outage was reduced by the promotion of seismic countermeasures by lifeline operators and enhancement of post-event recovery efforts as well [8]. Moreover, the influence of the difference in disaster scale affects time periods required for restoration is significant, as shown in the next subsection.

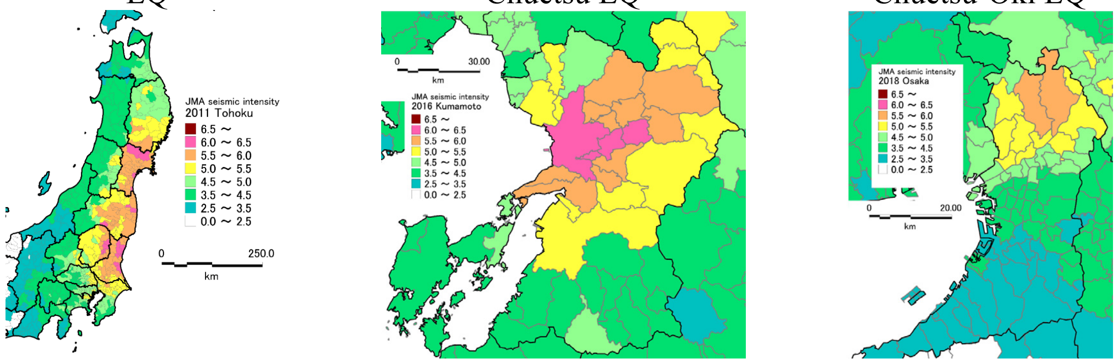
### 3.3 Comparison of observations and estimations of the population without lifeline services

In this subsection, five earthquakes during 2004-2018 are evaluated, and initial outages of the population without lifeline services between estimations and observations are compared. Estimations are based on applying average intensity $I_m = \mu_{I_m}$ . Observations were converted from households to population using a method proposed in reference [2].

Fig. 5 compares estimations and observations for the initial outage of the population without lifeline services. The results show fairly good agreement except for several cases. The ratio of the observations to the estimations is shown in Fig. 6. Notably, the results of the estimations for electric power and water supply represent well those of observation that are in range within ± 20%.




(a) The 1995 Hyogoken-Nambu EQ (b) The 2004 Niigata-ken Chuetsu EQ (c) The 2007 Niigata-ken Chuetsu-Oki EQ



(d) The 2011 off the Pacific Coast of Tohoku EQ (e) The 2016 Kumamoto EQ (f) The 2018 Northern Osaka EQ

Fig. 2 – JMA seismic intensity distributions of major earthquakes in Japan [9, 10].



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Fig. 7 shows the decreasing process of the population without lifeline services; the results of the modified model in 4.4 for electric power and water supply are also shown. As seen in Fig. 5 and Fig. 6, the initial outages of the population without lifeline services are well estimated except in several cases. However, the decreasing processes of estimation tend to be overestimated. In this regard, estimations and the

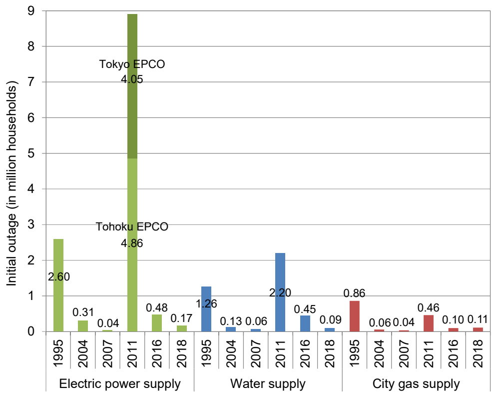
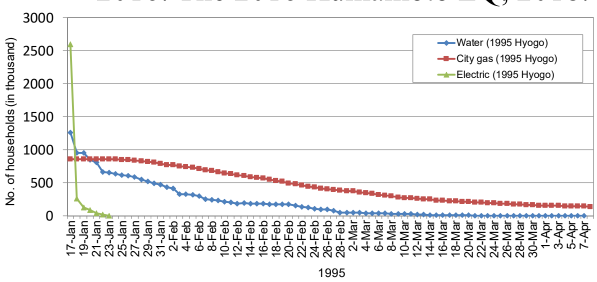
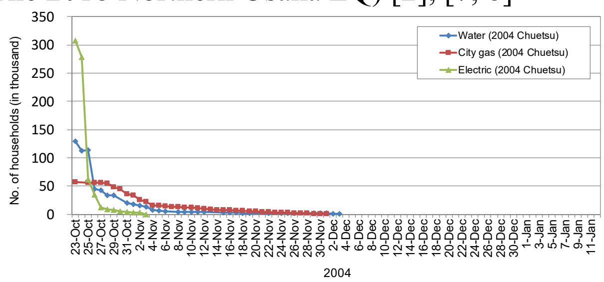


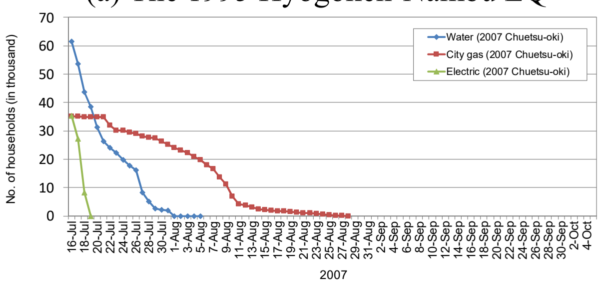

Fig. 3 – Comparison of the initial outage of lifeline services for major earthquakes in Japan (1995: The 1995 Hyogoken-Nambu EQ, 2004: The 2004 Niigata-ken Chuetsu EQ, 2007: The 2007 Niigata-ken Chuetsu-Oki EQ, 2011: The 2011 off the Pacific Coast of Tohoku EQ, 2016: The 2016 Kumamoto EQ, 2018: The 2018 Northern Osaka EQ) [2], [7, 8]



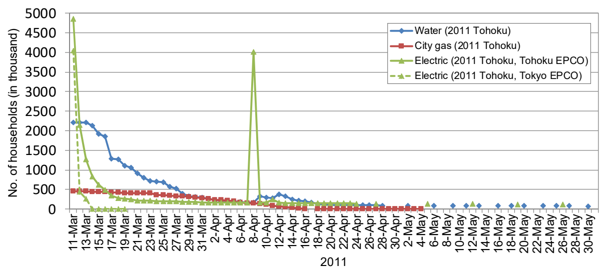

(a) The 1995 Hyogoken-Nambu EQ



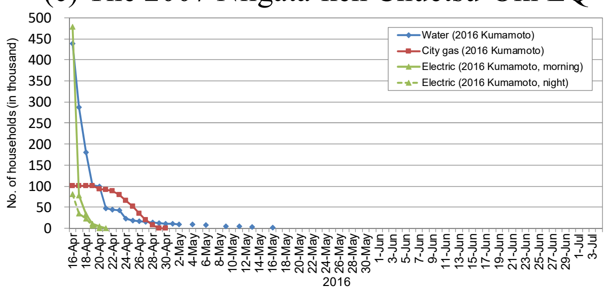

(b) The 2004 Niigata-ken Chuetsu EQ



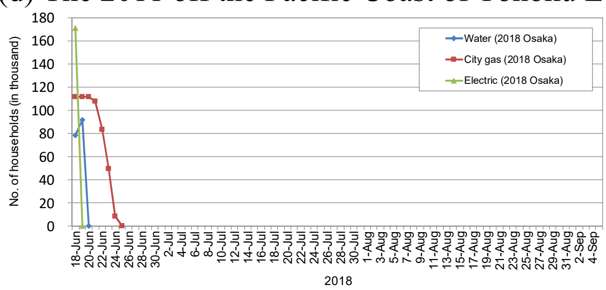

(c) The 2007 Niigata-ken Chuetsu-Oki EQ




(d) The 2011 off the Pacific Coast of Tohoku EQ




(e) The 2016 Kumamoto EQ




(f) The 2018 Northern Osaka EQ

Fig. 4 – Comparison of the decreasing process of the number of households without lifeline services



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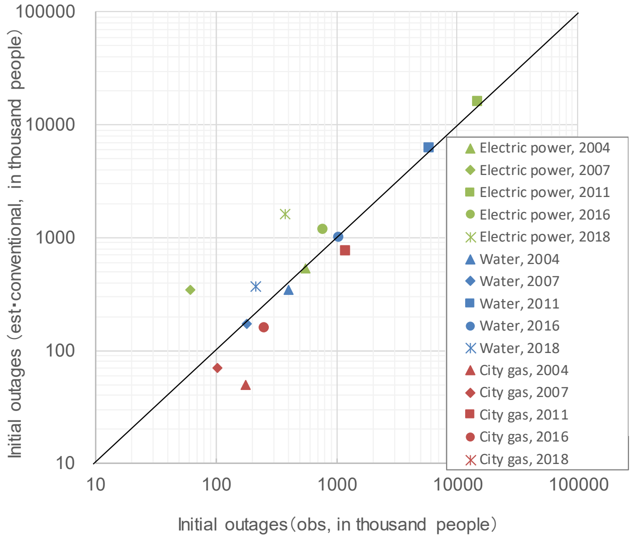


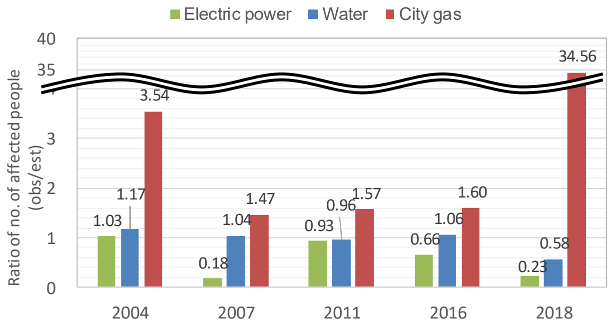


Fig. 6 – Ratio of the initial outages of the population without lifeline services (Observation/Estimation)

Fig. 5 – Initial outages of the population without lifeline services (observation and estimation)

observations for 2011 Tohoku are roughly consistent. The assessment model was developed mainly based on the damage and restoration data for 1995 Hyogo, since earthquakes are in large scale, and the initial outages are massive. On the other hand, the cases of four earthquakes are in relatively small scale. Such a difference in disaster scale leads to the total amount of initial damage, emergency response, and recovery works.

However, the difference in disaster scale had not considered obviously as model parameters. Therefore, quantitative evaluation is performed in the next section by paying attention to the fact that the difference in disaster scale affects the initial outage and time periods required for restoration.

## 4. Modification and validation of the assessment model

### 4.1 Method to improve the assessment model

In the previous section, the cases of four earthquakes except for 2011 Tohoku, the time periods were found to be overestimated, while initial outages of electric power and water system were well estimated. To incorporate the effect of the disaster scale, two new indices are introduced in this section. One is the index described in 4.2 to represent the discrepancy between the estimated and observed number of accumulated people without lifeline services. The other index described in 4.3 is the disaster scale in terms of *PEX* [4] with a weighting factor in consideration of the effect of each seismic intensity level to lifeline malfunction. Adjustment factors are obtained so that the estimation and observation become consistent using a non-linear optimization method. Those factors shorten (or extend) estimation of time periods required for restoration in accordance with the small (or large) scale of the disaster.

However, those factors such as damage due to tsunamis, intensive liquefaction, system interactions, power outages at critical facilities, and damage to hierarchically high-ranked facilities were excluded for improving the assessment model as in references [1, 2].

### 4.2 Ratio of the number of accumulated people without lifeline services

Once lifeline facilities are damaged, the effect of disruption continues until those function recovers. To represent the cumulative effect of the duration without lifeline services, the new index using the number of accumulated people without lifeline services is introduced. The decreasing process of the population without lifeline services, as shown in Eq. (6), the ratio *R* represents the discrepancy between the estimations and observations is defined in Eq. (7).



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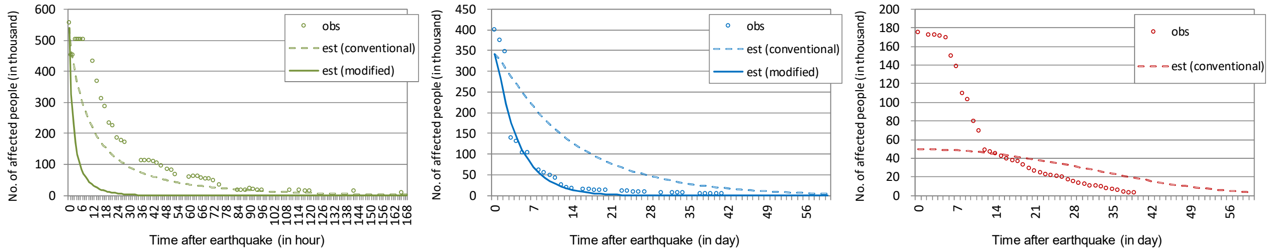
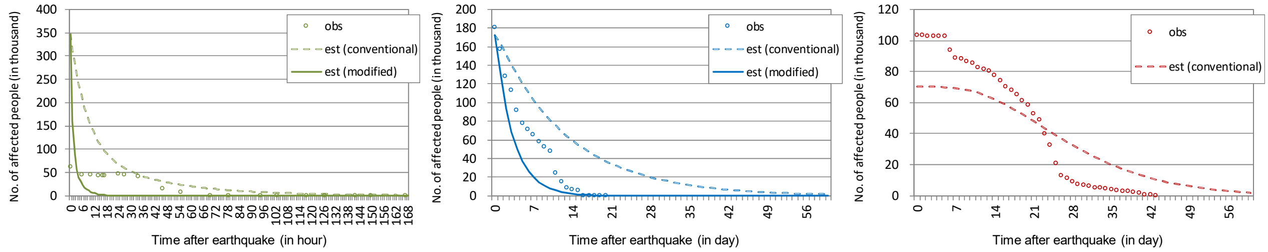
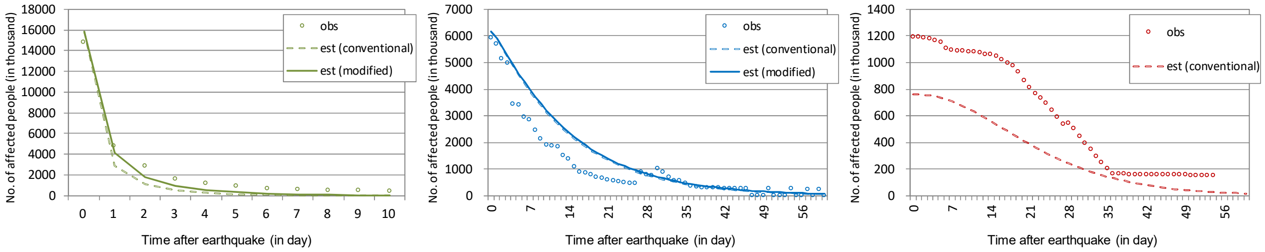
Electric power supply system | Water supply system | City gas supply system



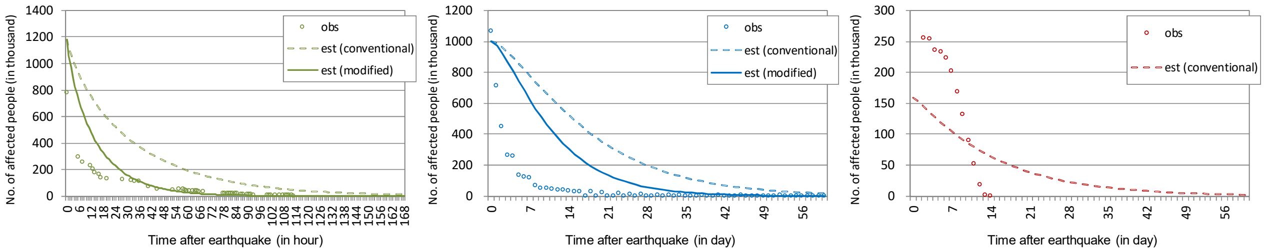

(a) The 2004 Niigata-ken Chuetsu EQ[2] (b) The 2004 Niigata-ken Chuetsu EQ[2] (c) The 2004 Niigata-ken Chuetsu EQ[2]



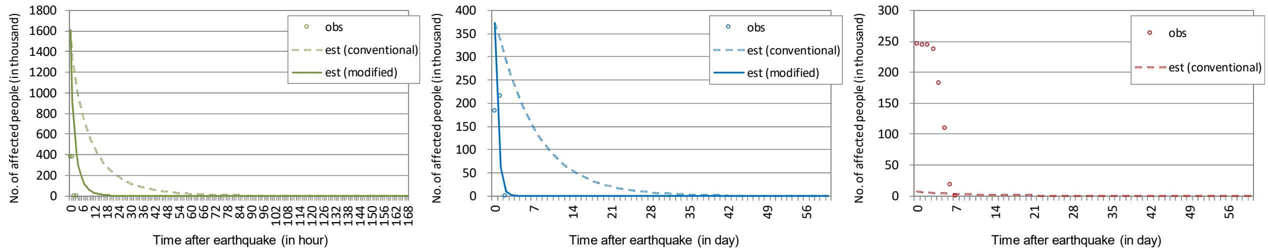

(d) The 2007 Niigata-ken Chuetsu-Oki EQ (e) The 2007 Niigata-ken Chuetsu-Oki EQ (f) The 2007 Niigata-ken Chuetsu-Oki EQ




(g) The 2011 off the Pacific Coast of Tohoku EQ (h) The 2011 off the Pacific Coast of Tohoku EQ (i) The 2011 off the Pacific Coast of Tohoku EQ




(j) The 2016 Kumamoto EQ (k) The 2016 Kumamoto EQ (l) The 2016 Kumamoto EQ




(m) The 2018 Northern Osaka EQ (n) The 2018 Northern Osaka EQ (o) The 2018 Northern Osaka EQ

Fig. 7 – Decreasing process of the population without utility lifeline services
(Open circles: observation, dashed line: the conventional model, solid line: the modified model)



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$$R = \frac{\sum_t H_{obs}(t)}{\sum_t H_{est}(t)} \tag{7}$$

Fig. 8(a) shows the relationship between $\sum H_{obs}(t)$ and $\sum H_{est}(t)$ of the conventional model in five earthquakes. The results of the electric power and water supply are almost overestimated. In the city gas supply, although $\sum H_{est}(t)$ and $\sum H_{obs}(t)$ look consistent, the initial outage and the decreasing process are different, as shown in Fig. 7(c)(f)(i)(l)(o).

The results of *R* are shown in Fig. 8(b). The range of *R* is generally from 0.1 to 1.8. Estimations tend to be overestimated.

### 4.3 Adjustment factors based on *PEX*

As mentioned in 3.3, the difference in disaster scale leads to that in the total amount of physical damage at lifeline facilities, emergency response, or recovery works that affect time periods required for restoration. This study employs *PEX* [4] to incorporate the difference in disaster scale. The distribution of lifeline facilities is highly correlated with the population. By the same token, the scale of damages to lifeline facilities is highly correlated with *PEX*.

*PEX* [4] is defined as "*An aggregation of spatially distributed population exposed to a certain level of seismic intensity*." Fig. 9 shows *PEX* with 6 lower or greater for six earthquakes. *PEX* with 6 lower or greater (denoted as 6L+), 6 upper or greater (denoted as 6U+), and 7 are 182～6,314 thousand people, 0～1,703 thousand people, and 0～ 514 thousand people, respectively. By comparing Fig. 3 and Fig. 9, it can be observed that the shape of Fig. 3 is similar to that of Fig. 9. The higher the JMA seismic intensity, the greater the impact on lifeline disruption. Therefore, the second index is introduced corresponding to the degree of contribution depending on the JMA seismic intensity.

Thus, *IEX* (Index Exposure to Shaking Intensity) represents the disaster scale in terms of *PEX* with a weighting factor *w*, as shown in Eq. (8). Here, *w* is a variable in consideration of the effect of each seismic intensity level to lifeline malfunction, and its constrained condition is represented in Eq. (9). The subscript *j* represents an arbitrary evaluation earthquake and $j$ = 0 represents the case of 1995 Hyogo. The subscript $i$ (=1, 2) represents the values corresponding to JMA seismic intensity, specifically, $i$ =1 for 6 lower (6L) and $i$ =2 for 6U+. In addition, the ratio $r_j$ of $IEX_j$ to $IEX_0$ is defined as shown in Eq. (10) where $\lambda$ is a parameter for adjusting the disaster scale.

$$IEX_j = \sum_{i=1}^{2} (w_i \cdot PEX_i) \tag{8}$$

$$w_1 + w_2 = 1 \tag{9}$$

$$r_j = \left( \frac{IEX_j}{IEX_0} \right)^{\lambda}, \ \lambda > 0 \tag{10}$$

Adjustment factors *w* and $\lambda$ were obtained so that the estimations and observations become consistent using a non-linear optimization method called the L-BFGS-B method. However, city gas supply system was excluded from the improvement because estimations and observations of initial outages were inconsistent. The goodness of fit of the assessment model was evaluated by root mean square error (RMSE). Table. 1 shows the list of model parameters and RMSE. As for *w* of electric power, the ratio is approximately 3:7 for 6L and 6U+. In contract, as for *w* of water supply, the influence of 6U+ is dominant.

*IEX* for each lifeline and the results of *r* are shown in Fig. 10 and Fig. 11, respectively. The disaster scale is smaller than the case of 1995 Hyogo except for that of 2011 Tohoku. The order of disaster scale is the case of 2016 Kumamoto, 2004 Chuetsu, 2018 Osaka, and 2007 Chuetsu-Oki in descending order.



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Fig. 12 shows the relationship between $R$ shown in Fig. 8(b) and $r$ shown in Fig. 11. Although the variation is considerable, there is a correlation between the two indices.

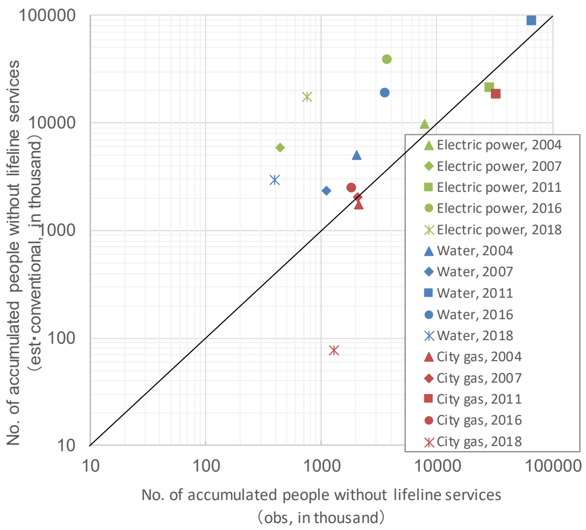
## 4.4 Modification of the assessment model based on adjustment factors

### 4.4.1 How to modify the assessment model

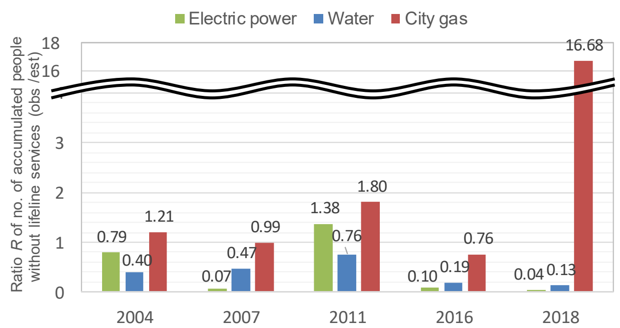
The new method reflecting the difference in disaster scale to modify the conventional model is described below. The new model is referred to as a "modified model" hereafter. Adjustment factors shorten (or extend) estimated mean of time periods required for restoration $\mu'(I)$ in accordance with the small (or large) scale of the disaster using $r$, because the conventional model was developed mainly based on the damage and restoration data obtained in the case of 1995 Hyogo. In addition, it is assumed that a coefficient of variation is constant; the standard deviation of time periods required for restoration $\sigma'(I)$ is also shortened (or extended) using $r$. Therefore, $\mu'(I)$ and $\sigma'(I)$ in the modified model are given, as shown in Eq. (11).

$$\mu'(I) = \mu(I) \cdot r_j \,, \quad \sigma'(I) = \sigma(I) \cdot r_j \tag{11}$$

In the modified model, Eq. (11) is used instead of Eq. (4). As a result, parameters $\alpha'(I)$ and $\beta'(I)$ are

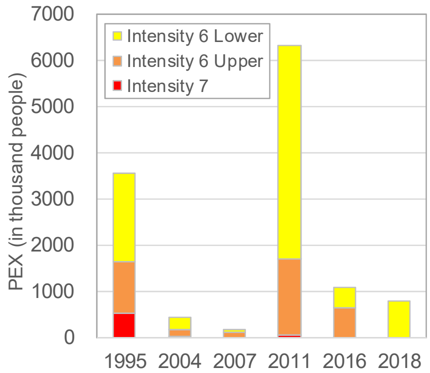


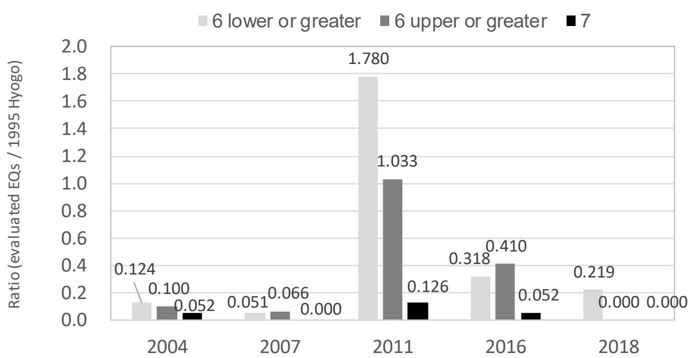

(a) Number of accumulated people without lifeline services




(b) Ratio $R$ of the number of accumulated people without lifeline services (Observation/Estimation)

Fig. 8 – Number of accumulated people without lifeline services (The conventional model)




(a) *PEX* (Added in reference[8]) (b) Ratio of evaluated earthquakes to the case of 1995 Hyogo

Fig. 9 – Comparison of *PEX* according to the JMA seismic intensity scale between earthquakes



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represented by Eq. (12) using Eq. (3) and Eq. (11). The difference in disaster scale appears only in $\beta'(I)$.

$$\alpha'(I)=\left(\frac{\mu'(I)}{\sigma'(I)}\right)^2=\left(\frac{\mu(I)\cdot r}{\sigma(I)\cdot r}\right)^2=\left(\frac{\mu(I)}{\sigma(I)}\right)^2,\quad \beta'(I)=\frac{\sigma'^2(I)}{\mu'(I)}=\frac{\sigma^2(I)\cdot r^2}{\mu(I)\cdot r}=\frac{\sigma^2(I)\cdot r}{\mu(I)} \tag{12}$$

4.4.2 Comparison of the number of the population without lifeline services (observation/estimation)

Fig. 7 shows the results of the comparison of the decreasing process of the population without electric power and water supply.

As for the decreasing process of electric power disruption, the results for the cases of 2011 Tohoku, 2016 Kumamoto, and 2018 Osaka in the modified model are improved from those of the conventional model. However, the cases of 2004 Chuetsu and 2007 Chuetsu-Oki partly become worse than those of the conventional model, possibly because of factors such as damage to facilities and road damage.

The results of the modified model for water disruption are improved well from those of the conventional model as a whole. Notably, in the cases of 2004 Chuetsu and 2018 Osaka estimations and observations are highly consistent. The case of 2011 Tohoku is generally consistent, as in reference [1].

The comparison of estimations in the modified model and observations of the number of accumulated people without lifeline services is shown in Fig. 13(a) and that of $R$ is shown in Fig. 13(b). Estimations are improved so as to agree with observations. From the above results, it can be said that the modified model generally improves the accuracy of estimation.

## 5. Conclusions and future developments

The major conclusions derived from this study are listed below.

1. A database was compiled concerning initial outages and restoration processes of utility lifelines in the recent six earthquakes. Generally, the order of initial outages tended to be electric power, water supply, and city gas supply in descending order as in references [1, 2]. That of the decreasing process tended to be electric power, water supply, and city gas supply in ascending order. The time periods required for restoration tended to be shortened compared to the case of 1995 Hyogo.

2. The estimated and observed values of initial outages and the restoration processes were compared to major earthquakes in Japan during 2004-2018. As confirmed in the previous study [1], estimation for the case of 2011 Tohoku was acceptable in terms of accuracy. On the other hand, in the cases of the remaining four earthquakes, the time periods required for restoration were found to be overestimated, while initial outages of electric power and water system were well estimated. Such a difference in disaster scale leads to the differences in the total amount of initial damage, emergency response, and recovery works.

3. To incorporate the effect of the disaster scale, two new indices were introduced. One is the index to represent the discrepancy between the estimated and observed number of accumulated people without lifeline services. The other index is the disaster scale in terms of *PEX* with a weighting factor in consideration of the effect of each seismic intensity level to lifeline malfunction. Adjustment factors were obtained so that the estimation and observation become consistent using a non-linear optimization method. Although the variation was considerable, there was a correlation between the two indices.

4. Those factors shorten (or extend) estimation of time periods required for restoration in accordance with the small (or large) scale of the disaster. By using the adjustment method, although the variation was still large, the estimations of the time periods required for restoration in electric power and water systems were improved so as to agree with observations.



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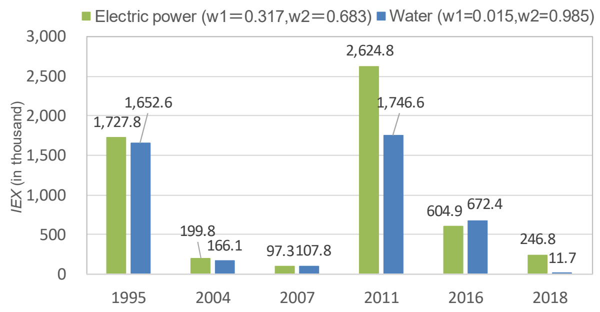



Fig. 10 – *IEX*

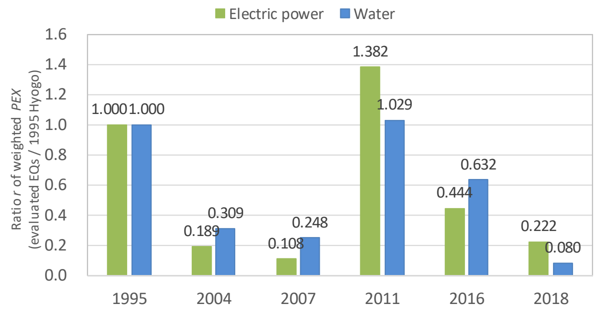



Fig. 11 – Ratio $r$ of weighted $PEX$

Table 1 – Model parameters for each lifeline

| | Electric Power | Water |
|---|---|---|
| $w_1$ | 0.317 | 0.015 |
| $w_2$ | 0.683 | 0.985 |
| $\lambda$ | 0.773 | 0.511 |
| RMSE | 0.322 | 0.255 |

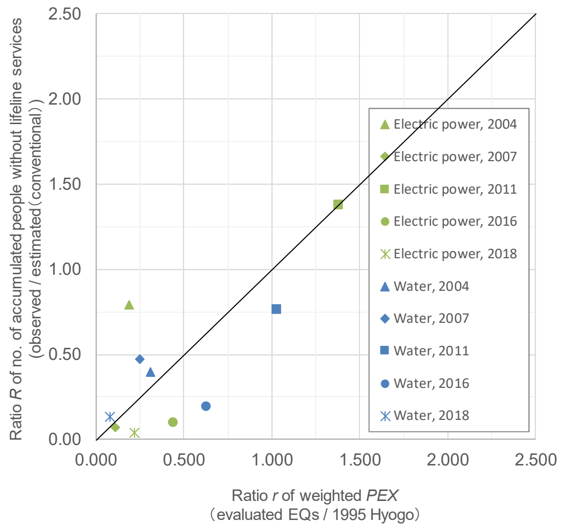
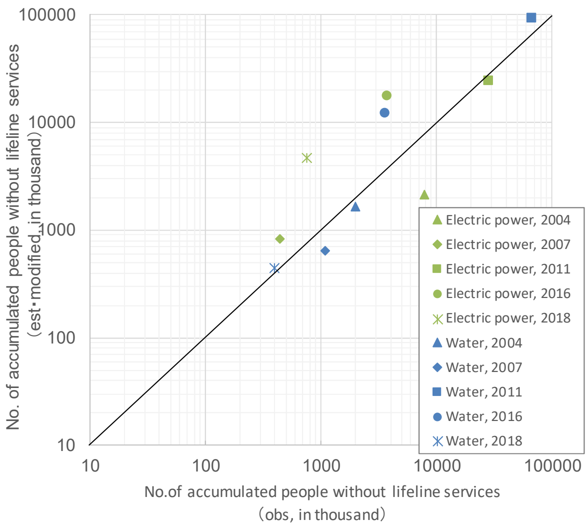
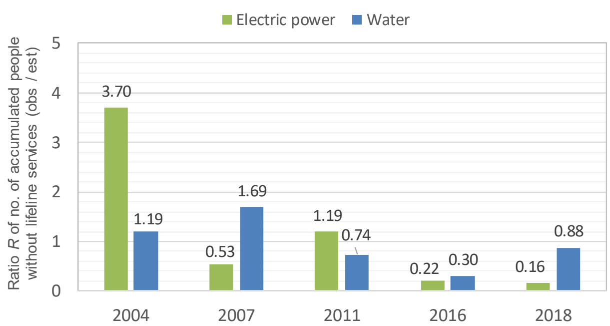



Fig. 12 – Relationship between $R$ and $r$
(vertical axis: $R$, horizontal axis: $r$)




(b) Ratio $R$ of the number of accumulated people without lifeline services (Observation/Estimation)

(a) Number of accumulated people without lifeline services
(vertical axis: estimations, horizontal axis: observations)

Fig. 13 – Comparison of the number of accumulated people without lifeline services
(The modified model)



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For future developments, it is necessary to compile data for various earthquakes of damage and restoration process, and validate the assessment model continuously. As for the estimation of city gas supply excluded from this study, we plan to improve the assessment model considering the revision of criteria for shut-off by the Ministry of Economy, Trade and Industry (METI) [12].

## 6. Acknowledgements

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