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SEISMIC RISK ASSESSMENT OF LIFELINE CONSIDERING HOSPITAL FUNCTIONS

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ABSTRACT

Under destructive earthquakes, a medical sector should play a crucial role for taking care of injured people. Hospital building should also maintain their function. By the way, since a hospital has a system like a city, composing of buildings and many lifeline systems, seismic reliability of the hospital is not determined only by building but by lifeline facilities including inside and outside the hospital. Present paper proposes a seismic risk assessment method for hospital lifeline as a part of the Seismic Risk Management method. The assessment method is to evaluate availability of hospital systems, considering damage probability of building and lifeline facilities, and the loss related to pipeline damage. The proposed method is applied to ten hospitals in Osaka, and its applicability is discussed.

Keywords: lifeline systems, hospital lifeline, loss estimation, buried pipelines

1. INTRODUCTION

Hospitals in emergency situations, especially immediately after earthquakes, must care a large number of injured people. In actual cases of disasters and crises, emergency responses of the medical sector have been mostly characterized by their own organization and coordination based on emergency plans. That is based on ordinary emergencies such as traffic accidents, fire and mass food poisoning. In ordinary cases, medical facilities could run as in usual days and the hospital could accept many people. On the contrary, in earthquake emergencies, medical facilities may be also damaged. Reports from recent earthquakes cite that medical facilities, being out of function due to damage to facilities, are unable to receive injured people, and sometimes they force to evacuate the patients to outside facilities [1]. In fact emergency response of hospitals depends on not only coordination of medical resources and staff but also reliability of hospital facility itself. While the hospital building is generally constructed with better seismic design than the other buildings, lifeline facilities are complicated and easy to cause malfunction. Many researchers on the medical side note importance of the water in hospital following after the earthquake in Kobe. All of the lifelines in hospital should also be given careful

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consideration, because its reliability is determined by both inside and outside lifeline systems. Therefore, seismic risk of lifeline system at the medical facility should be assessed from a wider point of view.

Since a huge earthquake rarely occurs and its exact date and time are difficult to be predicted, a practical method to evaluate seismic risk considering investment costs and benefits under the possibility of earthquakes is strongly expected. In the earthquake engineering, the Seismic Risk Management (hereafter, SRM) method is currently applied to lifeline facilities as well as buildings [2]. As an example of the use, Shito and Hoshiya [3] propose a quantitative assessment method of water supply system by SRM method and show a procedure of decision-making for optimum choice among the seismic countermeasure programs. A lifeline company has also taken seismic reliability of medical sectors in emergency into consideration [4]. With regard to medical facilities, some researchers apply the SRM method to facilities inside hospital [5]. As components of the SRM method, medical facilities inside the hospital are assessed by Yao and Kuo [6] and Porter et al.[7]. Above studies on the SRM look on a systemic facility either inside hospital or outside hospital (such as water supply system itself). The reliability of the hospital, however, can be explained by the combination of inside and outside facilities. The authors have an objective to develop the SRM method of hospital lifeline system, which will be to evaluate seismic reliability of water lifeline considering hospital reliability and to assess the cost and effects after the renovation program. The present paper is a part of this study and proposes the seismic risk assessment of the hospital lifeline. The proposed method is applied to ten hospitals in Osaka City, Japan.

The present paper is composed of three parts, 1) developing fragility curves of components of hospital lifeline, 2) proposing the seismic risk assessment of hospital lifeline, and 3) application of the proposed method.

2. FRAGILITY OF HOSPITAL LIFELINE COMPONENTS

2.1 Hospital building

Fragility of hospital building is regarded as the one of reinforced concrete building. The damage states of building are defined as moderate damage and severe damage. Fragility function of the building are developed based on damage statistics of the reinforced concrete building during the 1995 Kobe earthquake, considering the revised year of Japanese seismic design code in 1981. The fragility function of building follows the cumulative lognormal distribution to the peak acceleration for each damage state (see as Figure 1). The parameters for fragility function are listed in Table 1. The states of moderate and heave damage are used for the event tree analysis.

2.2 Water supply system

Fragility functions of various components in a water supply system, P_w, are presented here. This study considers facilities inside and outside the hospital as components of water supply system. In case where the components are made of subcomponents (i.e., outside water pipeline, receiver tank, elevated tank, house pipes), the damage for these components are based on the probabilistic combination of subcomponent fragilities using the fault tree logic. In short, damage probability for water supply system is defined by availability due to damage to outside subsystem and inside subsystem. Therefore, the fault tree for damage has TWO primary OR branches: outside subsystem and inside subsystem, and THREE secondary OR branches under inside subsystem, as shown in the tree diagram of Figure 2. Followings introduce fragility functions of components of the water supply system.

Table 1. Parameters of fragility function for hospital building

	Moderate damage		Severe damage	
	Mean a_0 (gal)	Deviatio n β	Mean a_0 (gal)	Deviation β
Building (constructed before 1980)	1,164	0.33	1,212	0.29
Building (constructed after 1981)	1,525	0.37	1,920	0.40

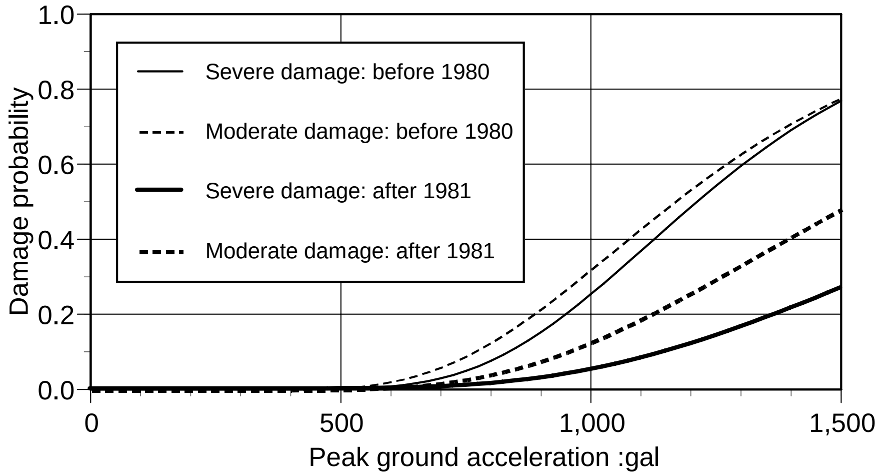


Figure 1. Fragility curve of hospital building

(a) Outside water system unavailability (P_{ow})

Under a presupposition that pipeline shapes one-way series from a reservoir to a hospital without pump stations and branches, the unavailability of outside water system comes down on the connectivity of long pipeline. In case that a pipeline is made of several links of pipeline under certain level of ground motion, the unavailability is expressed by using the product of damage probability of link on the pipeline.

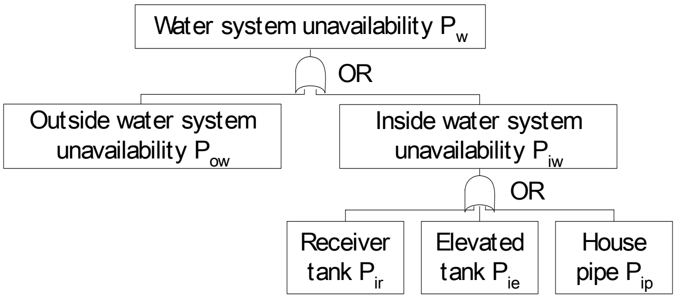


Figure 2. Fault tree of water supply system

$$P_{ow} = 1 - \prod_i (1 - p_{ui})^{L_i/\Delta l} \tag{1}$$

where, p_{ui}: damage probability of pipe unit on link *i*, L_i :pipe length of link *i* (m), and Δl :length of pipe unit (m).

The damage probability can be referred to a formula of damage ratio proposed by Takada et al. [8], which is based on statistical analysis on pipe damage during the Kobe earthquake and expressed the average damage ratio corresponding to the peak ground motion with three correction factors: pipe material, diameter and liquefaction condition.

(b) Fragility of receiver tank (P_{ir}) and elevated tank (P_{ie})

Based on reports of past earthquake damage, the receiver and elevated tanks easily move and bolts at the bottom of tanks are pulled out. We modeled a tank on truss board referring to the seismic design of building equipments [9] based on modified seismic coefficient method. At first, the peak response acceleration of the tank is introduced from peak ground acceleration, *a*. Then, the tensile force at the bolt caused by moment at the bottom of truss is calculated as follow.

$$F(a) = \frac{K_H(a) W_0 (h_{OG} + H)}{\alpha_1 \cdot L} - \frac{W}{\alpha_2}(1 - \frac{K_H(a)}{2}) \tag{2}$$

where, W : weight of tank, W_0 : effective weight at narrow side, h_{OG} :height of gravity center, *H*: height of truss board, *L*: width at narrow side, α_1 : number of frames, α_2 : number of columns

$$K_H(a) = a / g \cdot K_1 \cdot Z \cdot \beta \cdot I \tag{3}$$

where, $K_H(a)$: horizontal seismic coefficient, g: gravity, K_1: amplification ratio at floor (1.0 to 2.0), *Z*: seismic zone factor, β :amplification ratio of tank according to the location, *I*: importance factor.

The damage probability of tank is considered as exceedance probability of tensile force $F(a)$ to allowable tensile force of the bolt $\overline{F_i}$. When mean and lognormal deviation are given as $\overline{F_i}$ and $\sigma_{\ln F_i}$, the damage probability can be obtained as following cumulative lognormal distribution. Variation coefficient is assigned as value ranging from 0.42 to 0.46.

$$P_i = \Phi((\ln F_i(a) - \ln \overline{F_i}) / \sigma_{\ln F_i}) \tag{4}$$

(c) Fragility of in-house pipe (P_{ip})

Since in-house pipe is generally fixed on either building wall or pipe space, its damage state is caused to bending failure due to the deformation between floors. In case where an edge of a pipe beam is fixed and the other is given a displacement, the pipe damage is defined by the maximum bending stress $\sigma_{\max}$ to the allowable bending stress. The equation of bending stress and moment for one-supported beam can be introduced following one by the equation of displacement and angle for un-supported edge.

$$\sigma_{\max} = \frac{Mr}{I} = \frac{2EI\Delta}{{H_F}^2} \cdot \frac{r}{I} = \frac{dER}{H_F} \tag{5}$$

where, M : bending moment(kNm), r : pipe radius(m), I :moment of inertia of area(m^4), E : Young modulus of pipe(kN/m^2), H_F : floor height(m), R: deformation angle for building, and d : pipe diameter(m).

The deformation angle between floors are determined in terms of damage state as R>1/30 for severe damage, R>1/110 for moderate damage, and R>1/300 for slight damage. Therefore, the relation function of exceedance probability of deformation angle is obtained for the maximum bending stress when a level of acceleration is given.

Figure 3 shows fragility curves of receiver tank, elevated tank and house pipe. Referring to actual damage data in the 2004 Niigata Chuetsu earthquake, Japan, damage probabilities of 14.2% (1 out of 7 hospitals) for elevated tank, 14.2% for receiver tank and 28.4 (2 out of 7) for in-house pipe are reported in Nagaoka City (observed 468gal of peak ground acceleration), while 50% (1 out of 2 hospitals) for elevated and received tanks and 100%(2 out of 2) for in-house pipe are in Ojiya City (1,308 gal). Although small number of samples, proposed curves correspond to actual damage.

2.3 Electric power system

Unavailability of electric power system, P_e, is similarly evaluated by the fault tree (FT) analysis (Figure 4) as the water system. This study considers that a normal commercial power service would be cut and only emergency generator in the cooling water type is relied on for electric power. Damage probability of emergency generator system has FIVE primary OR branches: damage probabilities of generator, diesel tank, switch gear and cooling water tank, and water unavailability. The damage probabilities of power-related facilities besides the water system are is explained by fragility function, which evaluates to the tensile force to pull the bolt based on seismic designs of the building equipments [9]. Figure 5 shows the fragility function of electric power facilities.

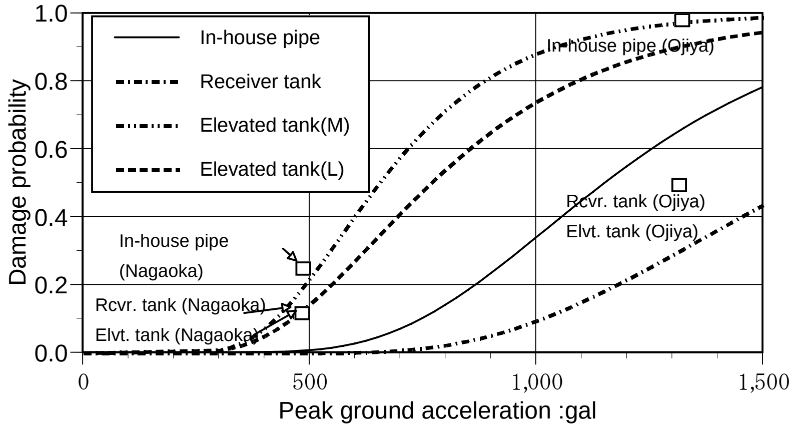


Figure 3. Fragility curves of water facilities

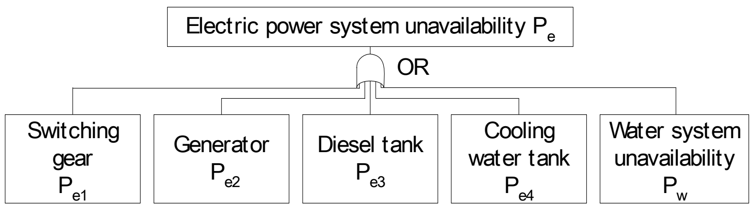


Figure 4. Fault tree of electric power system

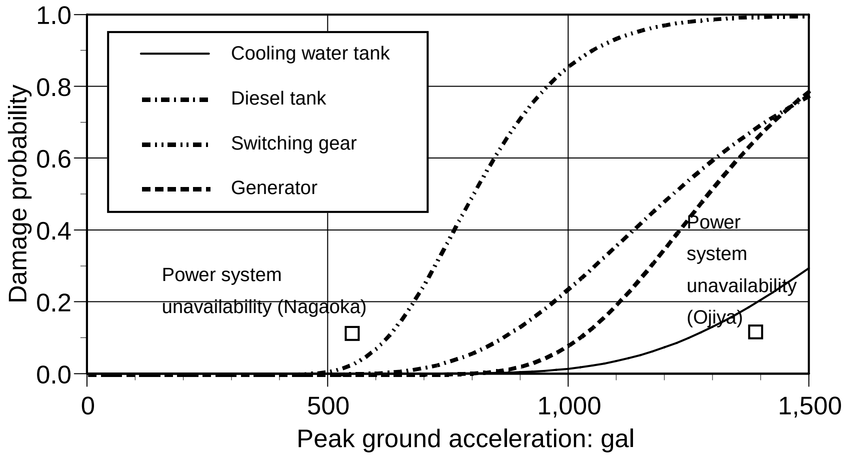


Figure 5. Damage probability curves of electric power facilities

3. ASSESSMENT OF HOSPITAL LIFELINE

3.1 Hospital system assessment by event tree

Hospital damage state due to an earthquake is modeled by the event tree with combination of three damage factors (building damage, and water and electric power unavailability). The event tree (ET) model can probabilistically expresses the damage mode as subsequently produced events when an initial event of earthquake occurs. The total of 9 hospital damage modes is introduced ranging from "no damage" in damage mode 1 to "severely damaged building" in damage mode 9 in this study (see as left side of Figure 6). Each damage mode has occurrence probability P_M when an earthquake occurs (in condition $\Sigma P_M = 1$).

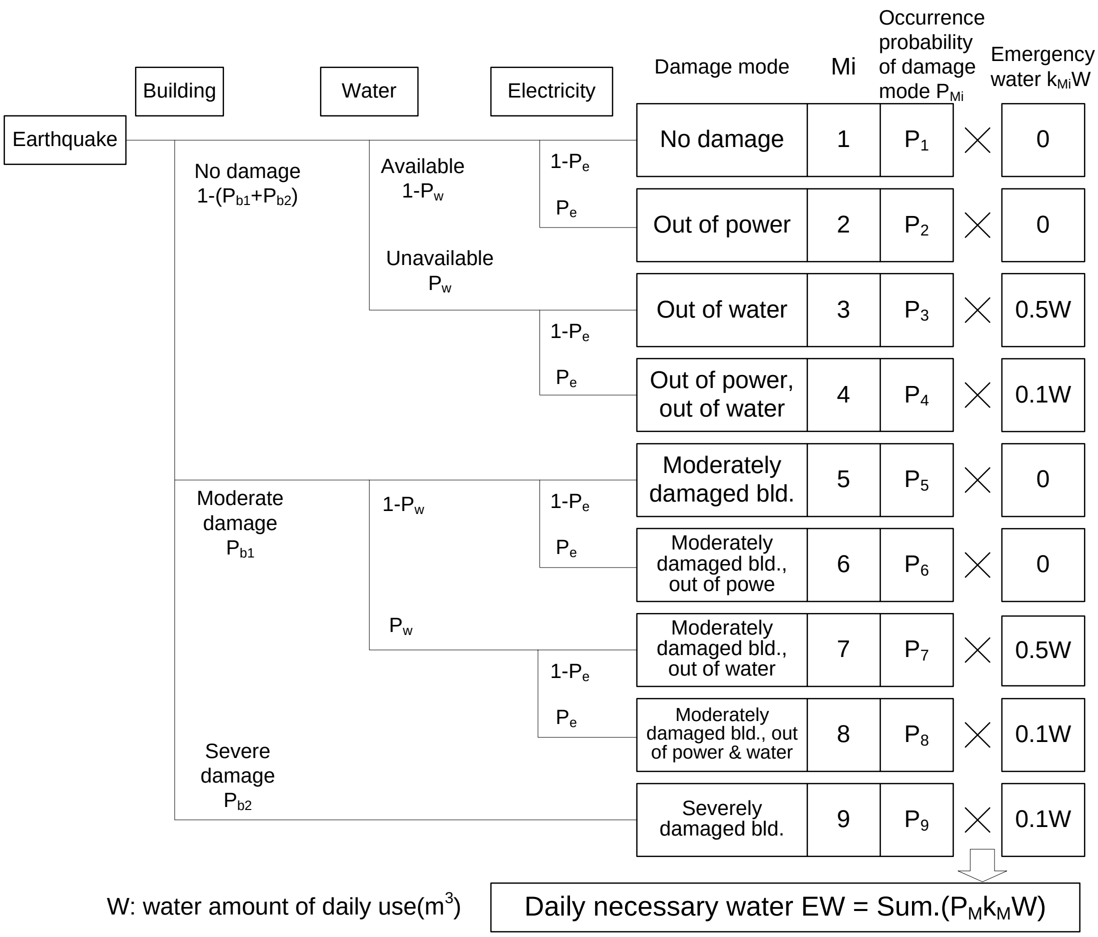


Figure 6. Event tree of hospital damage mode and necessary water

3.2 Loss of emergency drinking water to hospital

In order to evaluate the degree of hospital damage related to saving-lives from a water company's point of view, the calculation of amount of necessary water for hospital is presented. Moreover, loss of emergency drinking water to hospital is introduced to compare with other losses. When the amount of necessary water under each damage mode is determined by the ratio to daily water usage, the daily amount of necessary water at the hospital, *EW*, is probabilistically introduced as follow.

$$EW = \sum P_M k_M W \tag{6}$$

Where, k_M: ratio of necessary water under a damage mode *M* to daily water usage, *W*: daily water usage (*t*).

The ratio of necessary water under a damage mode is determined based on following considerations: 1) if a hospital has damage to building and other lifeline facilities, the medical equipments in operation, experiment, cannot run even water comes; 2) water companies distributed water tanks as emergency drinking water in terms of 0.1 to 0.3 times as daily water usage in recent earthquakes in Japan [10].

On the other hands, the restoration days of the pipeline to hospitals, R_{day}, is calculated by summation of restoration days of each link on the same pipeline as follows,

$$R_{day} = \sum_i D_{pi} \cdot L_i / C_r(i) \tag{7}$$

where, $D_{pi}(i)$: damage ratio of link *i* (Number/ km), $C_r(i)$: pipe restoration number per day (Number/ day), depending on pipe diameter, 2 for diameter $< \phi$ 400mm, 0.25 for diameter ϕ 400mm or more (based on records for the Kobe earthquake, Japan).

Once getting known the daily amount of necessary water at the hospital and the restoration days of pipeline to the hospital, we can estimate the total amount of necessary water to the hospital by the product of *EW* and R_{day}. Moreover, when this amount of water is distributed by emergency water tank on the truck, the loss of emergency drinking water to hospital, L_{hp}, can be counted by the cost of water distributed by the truck.

$$L_{hp} = EW \cdot R_{day} \cdot C_V \tag{8}$$

where, C_V: cost of water distributed by the truck (USD/m^3), 340 USD used in this study.

3.3 Total losses of pipeline to hospital

Once a pipeline to hospital has damage, various kinds of loss come out. We consider the losses related to the pipe repair and emergency drinking water to the customer, to whom the water is supplied through the pipeline, as well as the emergency drinking water to hospital. The loss of pipe repair, L_r, is calculated by the failure number of pipe (=$\Sigma D_{pi}.L_i$) and the cost of pipe repair, while the loss of emergency drinking water to customers, L_c, is calculated by daily necessary water to customers, the restoration days, and the cost of water distributed by truck. The necessary water per one customer is determined based on the disaster plan of water company, not daily water usage. The loss L_c can be calculated like by Eq.(8) with daily necessary water to customers instead of *EW*. The total loss of pipeline to hospital, L_{all}, is the summation of L_r, L_c and L_{hp}.

4. APPLICATION

4.1 The target area and hazard factor

The method of seismic risk assessment is applied to ten emergency hospitals in Osaka City, Japan. Five scenario earthquakes caused by five faults (Uemachi, Ikoma, Arima-Takatsuki, Chuo, and Nankaido) are considered to Osaka area, and the strong ground motions of these earthquakes in terms of peak ground acceleration and peak ground velocity are predicted for damage estimation.

4.2 Assessment of pipeline

Figure 7 depicts the network of water distribution pipelines from reservoir tanks to emergency hospitals. Hereafter we call the ten hospitals as HP1 to HP10. The water distribution pipeline is composed of four kinds of pipeline in terms of material and joint types. Most of them are ductile iron pipe without aseismic joint. The damage ratio of them under the scenario earthquake is referred to the formula of damage ratio used in the disaster management plan in Osaka City. Table 2 lists damage ratio and restoration days of outside water system to hospitals. During the Uemachi and Ikoma scenario earthquake, most of outside water systems have high damage probabilities because of higher level of strong ground motion than the other scenario earthquakes. The overall damage probability of outside water systems to HP3 and HP5 is higher than others because of many vulnerable cast iron pipes.

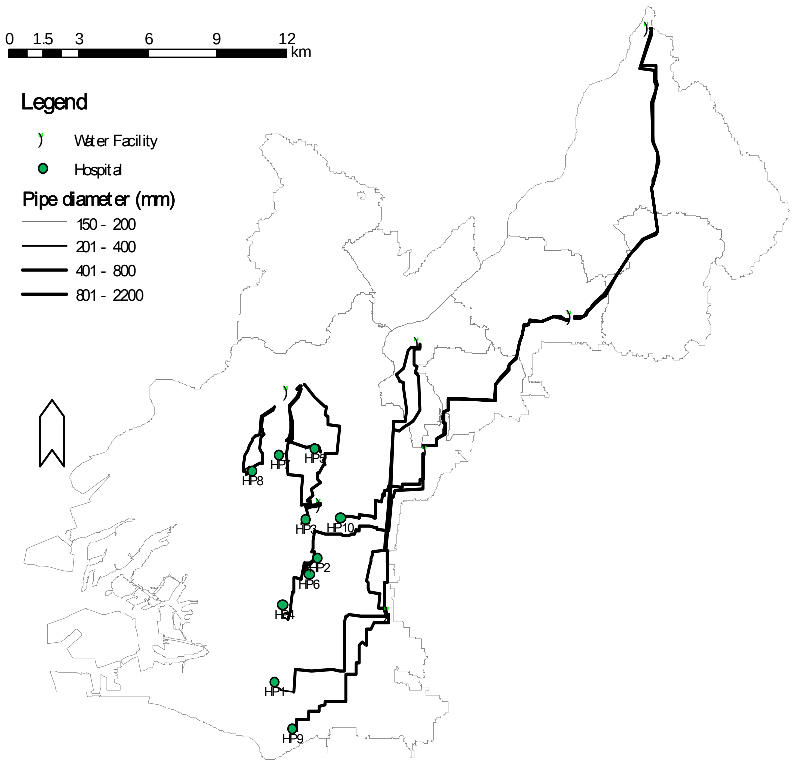


Figure 7. Water supply pipelines to ten hospitals in Osaka, Japan

Table 2. Damage probability of outside water system and restoration days

Hospital	Pipe length (km)	Uemachi		Ikoma		Arima-Takatsuki		Chuo		Naknkaido	
		P_{ow}	R_{day}	P_{ow}	R_{day}	P_{ow}	R_{day}	P_{ow}	R_{day}	P_{ow}	R_{day}
HP1	36.3	75.8	7.9	71.4	7.6	20.8	1.5	8.4	0.5	0.6	0.0
HP2	61.9	53.8	3.5	55.1	3.8	15.8	0.8	3.4	0.2	0.1	0.0
HP3	16.5	88.8	16.7	60.7	6.9	38.3	3.7	7.6	0.7	12.2	1.0
HP4	66.9	74.8	6.1	78.5	7.0	39.7	2.3	17.3	0.9	16.2	0.8
HP5	8.3	86.7	14.0	50.6	4.8	39.4	3.5	10.5	0.8	11.8	0.9
HP6	63.6	57.1	3.8	58.4	4.0	17.5	0.9	3.4	0.2	0.1	0.0
HP7	4.4	81.0	6.0	44.7	2.1	34.7	1.6	8.4	0.4	9.5	0.4
HP8	9.5	69.3	9.8	34.9	3.9	27.3	3.5	4.3	0.6	5.7	0.9
HP9	38.5	81.1	8.2	72.7	7.6	19.4	1.5	12.2	0.7	0.9	0.1
HP10	59.2	44.2	2.8	41.9	2.8	12.6	0.7	2.7	0.2	0.6	0.0

Note P_{ow}: Damage probability of outside water system, R_{day}: Restoration days of outside water system

Based on the proposed fragility curves and event tree, occurrence probability of hospital damage mode is assessed for 10 hospitals under 5 scenario earthquakes. Information on hospital buildings and lifeline facilities is investigated by our questionnaire survey in advance. Figure 8 shows damage modes of HP3, which has the highest damage probability of outside water system during the Uemachi earthquake, as an example. In case of HP3, severe damage mode more than M5 does not appear, while during the Uemachi earthquake, water and electric power systems do not work and cause to malfunction to the hospital system. This is reason that outside water system is weak and water facilities are broken.

In case of the Uemachi earthquake, Figure 9 compares the damage modes of ten hospitals. On the overall the damage modes M4 is predominant among the other damage mode, and damage modes more than M4 have few occurrence probabilities. HP3 has the high damage probability of outside water system, but the occurrence probability of damage mode 4 at HP3 is less than that at HP5 because of high damage probabilities of other facilities inside the hospital. In short, the result shows the proposed event tree can assess the outside water system and inside facilities comprehensively.

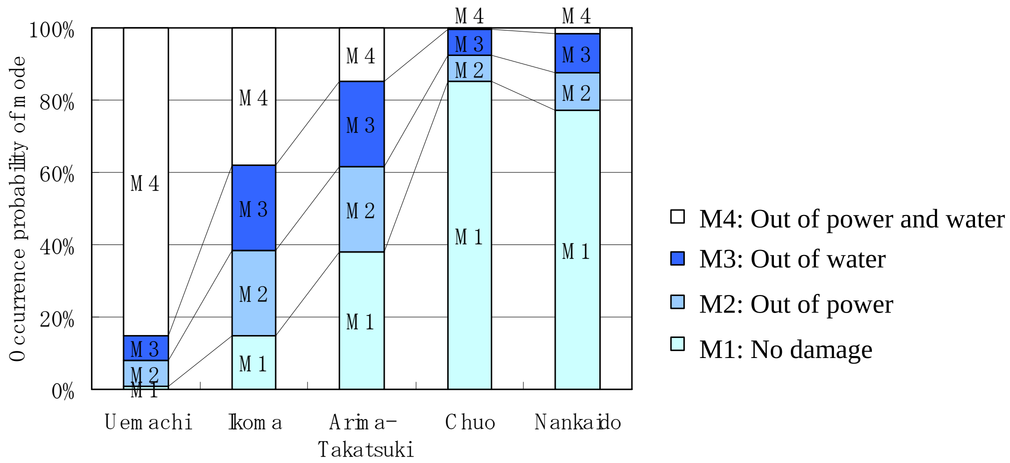


Figure 8. Damage mode at hospital HP3

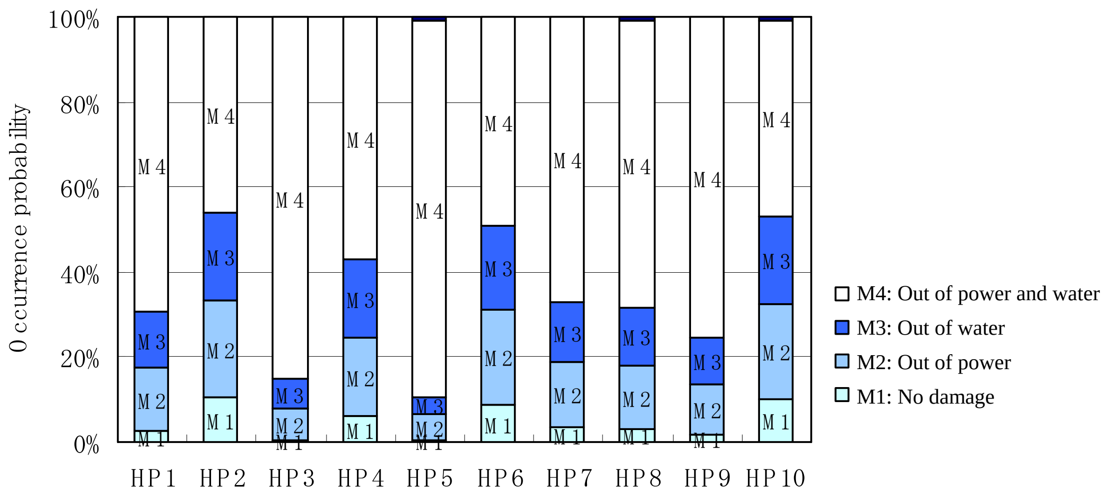
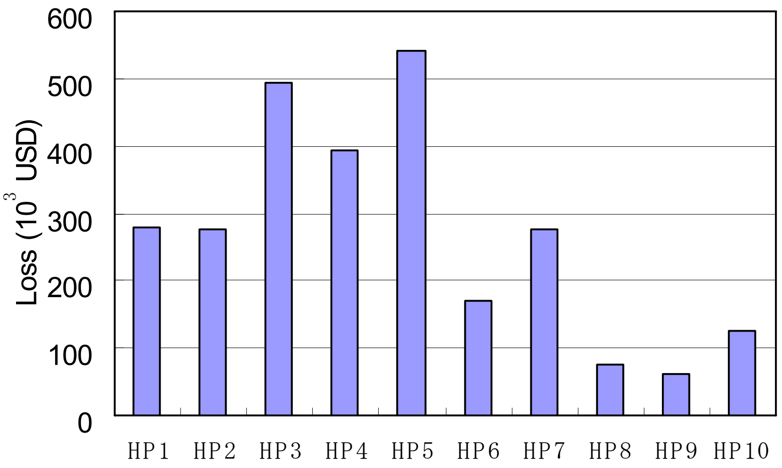


Figure 9. Damage modes of ten hospitals under the Uemachi earthquake

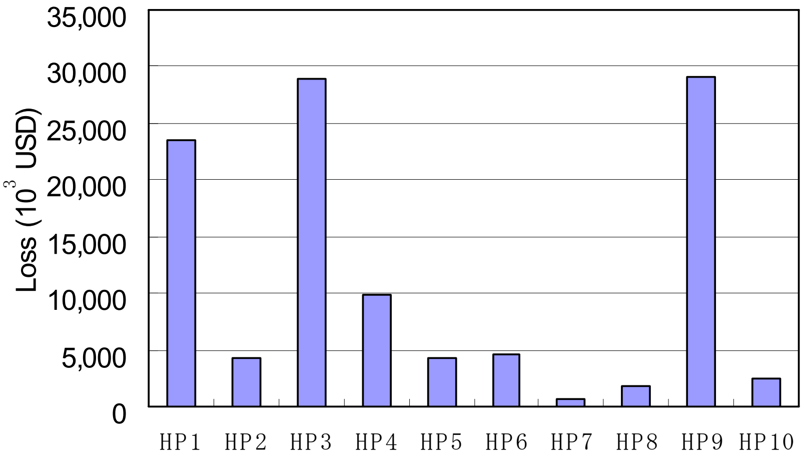
4.3 Loss estimation for pipeline to hospital

Figure 10 shows the loss of emergency drinking water to hospital, L_{hp}, and the total losses of pipeline to hospital, L_{all}, in case of the Uemachi earthquake. As HP3 and HP5 have more severe damage mode than the others do, the losses of emergency drinking water are higher too. HP4 does not have so severe damage mode in Figure 9, but the loss L_{hp} is high because of large amount of daily water usage. With respect to the total losses of pipeline to hospital, L_{all}, the pipelines to HP1, HP3 and HP9 have extremely high losses. The pipelines to HP1 and HP9 distribute water to a large number of customers, while it takes long for the restoration of the pipeline to HP3. In comparison with losses of L_{hp} and L_{all}, we can see a couple of points: 1) The loss L_{hp} is quite smaller number than the total loss L_{all}. 2) The pipeline having high L_{hp} does not always have high total loss L_{all}. In the seismic risk management of water pipeline, the water company used to improve reliability of water supply to general customers. However, from the point of saving human lives, if the renovation program is done to the pipeline with high L_{all}, it may not provide good effects on the water supply to hospitals. It is necessary to examine the pipe renovation to maintain the water supply to hospitals considering the effects to neighbor customers.

Although present paper does not present the seismic risk management of hospital pipeline, the proposed method can count the seismic risk of hospital lifeline quantitatively and it can be applied to one of risk components in the seismic risk management. Introducing this method to the seismic risk management is the next challenging in future.



(a) Loss of emergency drinking water to hospitals



(b) Loss of pipe damage and emergency drinking water

Figure 10. Losses of outside water system to hospitals in case of the Uemachi earthquake

5. CONCLUSIONS

We proposed seismic risk assessment method for hospital lifeline incorporating lifeline facilities outside facilities, and then applied to ten hospitals in Osaka, Japan. Followings can be concluded.

- Fragility functions of water and electric facilities were proposed based on the seismic design of building equipments. Proposed curve meets well with actual damage in recent earthquakes.
- Losses of emergency drinking water to hospital and customer at the same pipeline are not always related to each other. For pipeline renovation to hospital, the reliability of water to hospital should be paid attention to.
- Although present paper does not present the seismic risk management of hospital pipeline, the proposed method can count the seismic risk of hospital lifeline quantitatively and it can be applied to one of risk components in the seismic risk management in future study.

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