研 究 速 報
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Seismic Reliability Analysis of Lifeline Systems〔1〕

ライフラインの耐震信頼性解析

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Summary

This short note deals with a methodology of the seismic risk assessment of lifeline systems*** from the viewpoint of reliability theory or graph theory. The methodology is applied to some case-studies in a certain model lifeline.

1. Model Lifeline (Network and Area Model)

The design of model lifeline may be devided into two stages; that is, the design of network model and that of seismic intensity map. Here we suppose that our network model is a kind of electric power system which is often employed in Japanese metropolises (Tokyo, Nagoya or Osaka). The network model shown in Fig. 1 consists of seventeen nodes (substations) and twenty links (transmission lines), and contains two interconnection lines in it in order to improve its reliability.

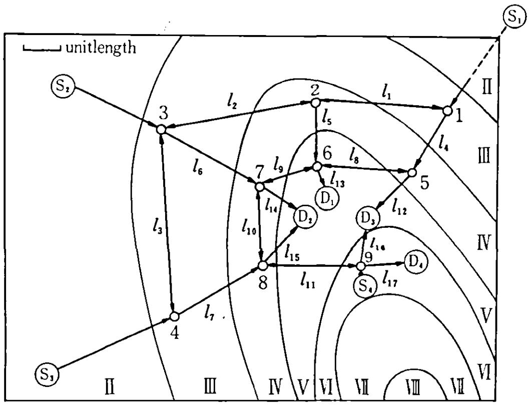

Fig. 1　Model Lifeline

The seismic intensity map must be determined so that it could give a certain seismic risk to each region. Nowadays several techniques of microzoning will enable us to draw such a map by treating historical data statistically. So we assume the map shown in Fig. 1 is available, where an area is regionalized by Modified Marcalli Intensity.

Next we would like to calculate each component of

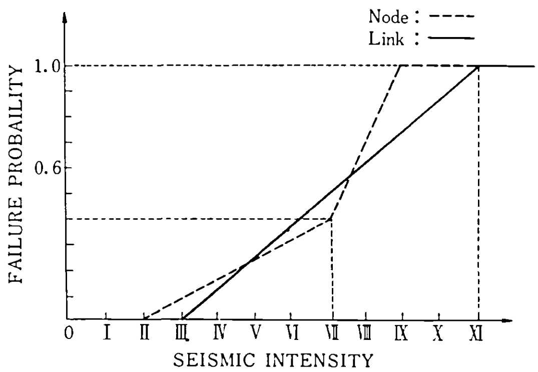

Fig. 2　Seimic Intensity

network. Then we assume the fragility relation between a seismic intensity and a failure probability of a node or a unit length link is described in Fig. 2. By using topographical information from Fig. 1 and the fragility relation, the failure probability of the *i th* link can be estimated by the following equation,

$$P_i = 1 - \prod_K (1 - f_K)^{l_K / l_i}{}^{*} \qquad (1)$$

where　P_i:　failure probability of the *i th* link,

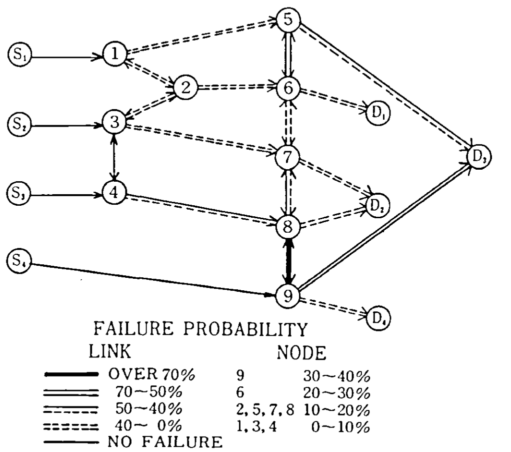

Fig. 3　Failure Probability

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***Lifeline means the utility network indispensable to urban communities; *e.g.* electric power, gas, water, sewage or communication system.

l_K : crossing length over k-zone,

τ^* : unit length,

f_K : failure probability of a unit length link on k-zone.

We see Eq. (1) represents a reliability of a series system well known in the reliability theory. Fig. 3 shows a failure probability of each component of lifeline system.

2. Lifeline Seismic Reliability Analysis

We evaluate the seismic risk of a lifeline system by the terminal reliability which means the probability that there exists at least one path from a specific supply node to a specific demand node.

Now let E_i be the event that the i th path exists. Obviously the terminal reliability R_T can be written such that

$$R_T = P[\bigcup_{n=1}^{n} E_i] \qquad (2)$$

where n is the total number of path.

Although Eq. (2) may be expanded into the following by the exclusion-inclusion principle, that is,

$$R_T = \sum_i P[E_i] - \sum_{i<j} P[E_i \cap E_j] + \cdots + P[\bigcap_k E_k] \qquad (3)$$

but we adopt the Boolean algebraic method[3] for calculating the terminal reliability. If a union of events $\bigcup_{i=1} E_i$ could be decomposed into a direct sum of disjoint events $\bigoplus_{i=1}^{n'} \tilde{E}_i$ ($\tilde{E}_i \cap \tilde{E}_j = \phi$ for all i and j, n': total number of disjoint event) by the Boolean algebraic method, the terminal reliability would be obtained by the following equation

$$R_T = \sum_{i=1}^{n'} P[\tilde{E}_i]. \qquad (4)$$

Table. 1

S \ D	D_1	D_2	D_3	D_4
S_1	0.631 0.379	0.610 0.373	0.520 0.371	0.096 0.036
S_2	0.673 0.415	0.792 0.612	0.433 0.201	0.129 0.064
S_3	0.673 0.389	0.792 0.600	0.582 0.140	0.132 0.065
S_4	0.080 0.029	0.212 0.118	0.438 0.293	0.611 0.415

upper: node reliable case
lower: node vulnerable case

By the method just mentioned above, the terminal reliability of each supply-demand pair in the model lifeline can be computed. The results of computation are listed in Table 1 where the node perfectly reliable case and the node vulnerable case are compared with each other. This evaluation by the terminal reliability will give us some information about the most vulnerable points in the lifeline system.

3. Lifeline Seismic Reliability Analysis with Consideration of Flow

Since the actual component of lifeline system has its own capacity, the possible flow through the lifeline system must be restricted below some maximum value. So we try to evaluate the seismic risk of lifeline system with consideration of flow.

First we consider the index of shortage which denotes the ratio of a shortage of flow in the hazardous state, to the maximum flow in the normal state. Then convoluting the index of shortage over all the probable events, we can get an expected value of the index of shortage. We define the flow reliability such that

$$R_F = 1 - \sum_{(x)} P(x) \cdot \frac{\Delta F(x)}{F} \qquad (5)$$

where R_F : flow reliability

x : a binary vector which corresponds to one state

$P(x)$: occurrence probability of a state

$\Delta F(x)$: shortage of flow in a state

F : Maximum flow in the normal state.

The maximum possible flow through the lifeline system is computed by the labelling method[6] in the computer program. From Eq. (5), we can recognize the flow reliability means the ratio of the expected maximum flow to the

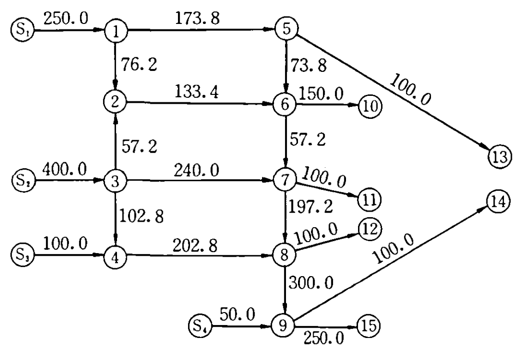

Fig. 4 Normal Load Flow Distribution

Table. 2

	Flow Reliability	Expected Max. Flow (Normal Flow)
Demand 1	0.5925	89 (150)
Demand 2	0.5428	109 (200)
Demand 3	0.2967	56 (190)
Demand 4	0.1882	47 (250)
Total	0.3811	301 (790)

maximum flow in the normal state.

Fig. 4 shows the flow pattern in the normal state computed by the DC flow method[4] which is one of methods to calculate the electric power flow. The computation result of flow reliability is given in Table 2.

4. Conclusion

This paper proposes one of methodologies for the seismic risk assessment of lifeline system. But the more complex and the larger the lifeline system becomes, the computation of terminal reliability or flow reliability requires the larger amount of CPU time and memory area. So this computational barrier will have to be solved by any approximate method. In the next report to appear, we will discuss a measure of seismic importance and find out its characteristics.

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