SEISMIC RELIABILITY ASSESSMENT METHOD FOR LIFELINE SYSTEMS USING UNAVAILABLE TIME

Takanobu SUZUKI[1]

SUMMARY

This report presents a new assessment method for reliability of lifeline systems which takes into account the maintainability of key systems during and after an earthquake. A new reliability factor is calculated using the damage ratio and restoration time those are concerning to the experience in past disaster. The proposed reliability factor, referred to as unavailable time, is more useful for determining damage to lifeline systems. The results of assessment can be used to determine the effectiveness of certain measures, such as facilities hardening, systematic measures and restoration strategies, for minimizing the damage to lifeline systems caused by earthquakes.

INTRODUCTION

Several studies have examined methods for decreasing seismic damage to lifeline systems, which are essential to the functioning of cities. Damage to lifeline systems may affect a large area and have serious ramifications on city residents and industries. The lifeline system includes a large number of facilities, some of which are vulnerable to earthquakes. Weak points include old facilities, pipelines located in liquefaction areas, etc. The present study proposes a new method for determining the time required to restore downed lifeline systems. The proposed method directly expresses the degree of damage caused by an earthquake using a factor called unavailable time, which combines the damage ratio and the restoration time of the downed element of the lifeline system. A simple calculation method for parallel and serial systems is useful for estimating the damage to lifeline systems. Damage ratio can be calculated based on data compiled for damage caused by past earthquakes, and restoration time can be estimated based on previous disasters. A factor that combines both of these elements would be a convenient tool for close examination of the network on a local scale. In addition, this scale is convenient for estimating the effectiveness of countermeasures, such as strengthening of facilities, redundancy design, or quick restoration, which can be described sophisticatedly by time. Moreover, the mutual linkage of different services is shown to be possible by including the time in the basis of the scale. Users who have important tasks to perform after a disaster has occurred, should expect a highly reliable lifeline, and a micro-scale examination of the seismic countermeasures seems appropriate. Thus, the new evaluation measures proposed in the present paper seem to be effective.

CALCULATION METHOD OF SEISMIC UNAVAILABLE TIME

Assuming that the distribution of probability of the damage on one element follows a binomial distribution Bi(1,p), and assuming that the unit recovery time is t, the expected recovery time T of the element becomes

$$E(T) = E(tX) = t * p \qquad (1)$$

The occurrence probability is added to the recovery time in proportion to the received damage and the average time during which the lifeline element cannot offer service. Equation (1) is the definition of unavailable time u of the lifeline element due to a disaster. Unavailable time includes both reliability and maintainability, and is useful

[1] Toyo University , 2100 Kujirai, Kawagoe, Saitama, Japan, Fax:81-492-39-1405, Email: suzuki@eng.toyo.ac.jp

for estimation for the reliability of lifeline systems. Consideration of individual elements or individual users appears to be insufficient, whereas the reliability of the lifeline at the macro scale has been examined more carefully. Therefore, smaller scale seismic reliability in the lifeline system should be investigated, considering for example the social and economic maturation that has occurred particularly in the newer cities. The scale of the unavailable time proposed in the present study appears to be appropriate for evaluating the micro reliability of lifeline systems.
Applying the above concept, the unavailable time is calculated as a whole system by combining the elements serially or in parallel. The damage to each element directly affects the function, and the generation of damage is performed individually. The restoration of multiple damage positions is assumed to be a sequential single repair system, which promotes the formulation.

The simplest serial system, which consists of two elements, E1 and E2, is considered, as shown in Fig. 3(a). The damage received by each element follows the binomial distribution Bi(1,p1) and Bi(1,p2), respectively, and each unit restoration time of the element is t1 or t2, respectively. Table 1 shows the list of calculations for damage received by the system, the occurrence probability, and the restoration times. As shown in Table 1, the expectation value of the restoration time of the system is

$$\begin{aligned} \mathrm{E(T)} &= 0*(1-p_1)(1-p_2)+t_2 p_2(1-p_1)+t_1 p_1(1-p_2)+(t_1+t_2)p_1 p_2 \\ &= t_1 p_1 + t_2 p_2 = u_1 + u_2 = U_s \end{aligned} \quad (2)$$

This equation expresses the system unavailable time of the series system, Us. The case in which more than three elements are considered can also be inductively proven. In the case of n elements, the equation is

$$U_s = \Sigma u_i = \Sigma t_i p_i \quad (i=1,n) \quad (3)$$

In case of the series system, the system unavailable time is calculated as the simple sum of the unavailable time of all elements, as shown in Eq. (3).

Next, the simple parallel system is considered. This system consists of the two elements shown in Figure 3(b) as is the case for the serial system. The probability distribution of the damage received by the element and the restoration time are the same as that for the serial system. The damage received, the occurrence probability and the restoration time are shown in Table 1. In the case of the parallel system, the system ceases to function when both elements become damaged and is restored when the functionally of one of the elements is restored. By assuming that the probability of the selection is determined by the element unavailable time in inverse proportion, the predicted restoration time of the system is obtained. In other words, the probability of choosing E1 is q1, and probability of choosing E2 is q2, as shown below

$$q_1 = u_2/(u_1+u_2) \quad q_2 = u_1/(u_1+u_2)$$

$$\begin{aligned} \mathrm{E(T)} &= p_1 p_2 (q_1 t_1 + q_2 t_2) \\ &= p_1 p_2 (1/p_1 + 1/p_2)/(1/u_1 + 1/u_2) = U_p \end{aligned} \quad (4)$$

Up should be 0, because the system unavailable time of the parallel system in pi =0. Similarly, when the number of elements is more than three, the following equation can be applied, as in case of n elements.

$$U_p = \frac{(\Pi p_i)(\Sigma 1/p_i)}{\Sigma(1/u_i)} \quad (5)$$

In the combination serial-parallel system shown in Figure 2, some simplified calculation is needed. Subsystem Si is the partly serial system, and ni is the number of elements included in Si. The gives probability pij and the recovery operation time tij in hours, which is the damage of the j element of the subsystem i. The probability Pci, which indicates the probability of no damage of the subsystem Si, is obtained in the following equation.

$$P_{ci} = \Pi(1-p_{ij}) \quad (j=1,n_i) \quad (6)$$

Next, the system unavailable time Usi for subsystem Si is given by the following.

$$U_{si} = \Sigma t_{ij} p_{ij} \quad (j=1,n_i) \quad (7)$$

Subsystem Si is considered to be one element following Bi(1,1-Pci), and the expectation of the quantity of received damage is calculated as.

(8)

$$U_p = \frac{(\Pi(1-P_{ci})(\Sigma 1/(1-P_{ci}))}{\Sigma(1/U_{si})} \qquad (i=1,m) \bullet \tag{8}$$

However, the condition Usi=0 in Pci=1 is similar. The system unavailable time of the lifeline can be calculated by combining Eqs. (3) and (5). The operation formula is in simplified form, and is simply required from the combination of damage probability and recovery operation time of each element.

Since the lifeline system is supplies services via a center-to-end network, the total unavailable time is an important factor for some users located at the end side. However, elements or subsystems located at the center side are generally used for many users, and in the unitary scale of the unavailable time, the effect of the whole system can not be sufficiently expressed. Then, the subsystem or element function is expressed well with available service quantity per unit time, and the function in the system is regarded two-dimensionally as both the unavailable time and service. Figure 3(a) shows the two-dimensional function. The degree of the effect on downtime is expressed as the area of the rectangle given by the product of service quantity q0 and unavailable time u0. Service quantity per unit time seems to be identical to the number of users that the element undertakes and also has an equal effect on the unavailable time two-dimensional expression.
Next, we consider the series system which consists of four elements. As shown in Fig. 3(b), elements E1 to E4, have been placed in series, and the function undertaken by each element is q1 to q4. The element unavailable time is u1 to u4. The two-dimensional expression of function and time is shown in Fig. 3(b). This two-dimensional illustration method is well expressed because the lifeline system is fundamentally a serial system.

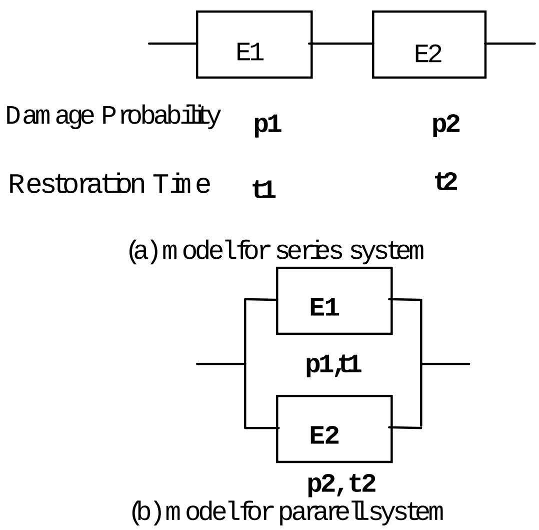

Figure 1 Illustration of serial and parallel system

Table 1 List of calculation parameters

Number	,dP	,dQ	Probability	Restoration time in serial system	Restoration time in parallel system
1	safe	safe	(1-p1)(1-p2)	0	0
2	safe	down	(1-p1)p2	t2	0
3	down	safe	p1(1-p2)	t1	0
4	down	down	p1p2	t1+t2	t1 or t2

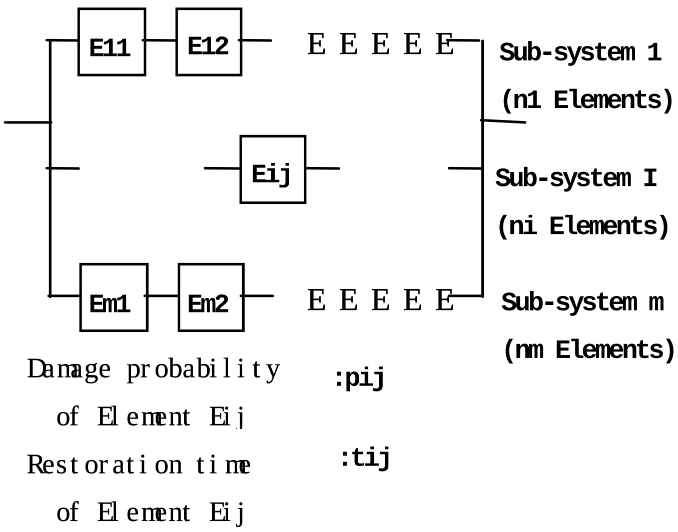

Figure 2 Illustration of serial-parallel system

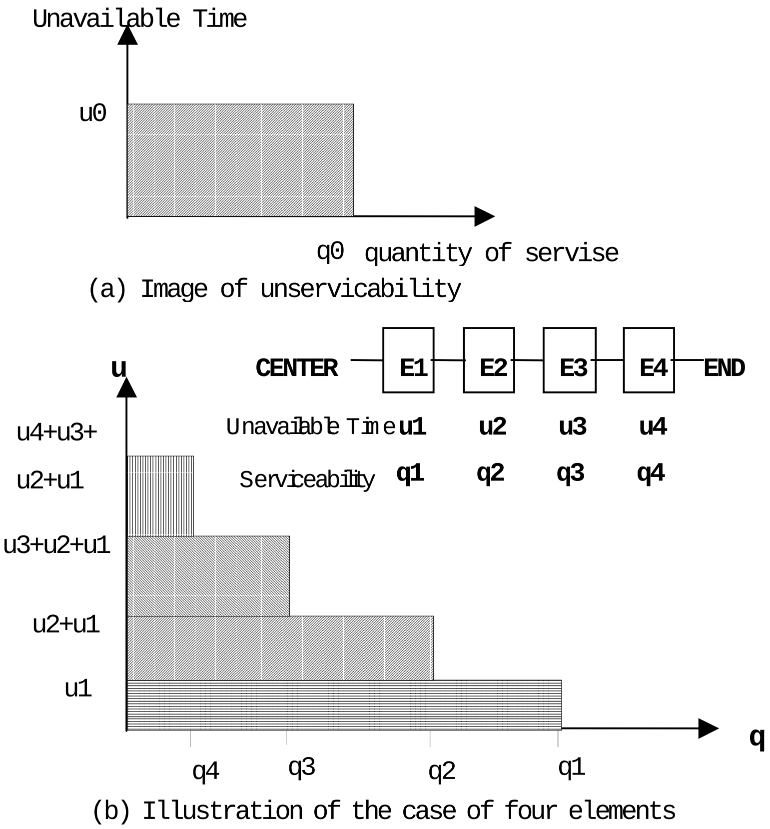

Figure 3 examples on unavailable time calculation

EXAMPLES CALCULATED USING THE PROPOSED METHOD

Concrete calculation is carried out based on the findings described earlier. Here, some simple conditions are set in order to simplify the calculations. There are three main factors for the reliability estimation: earthquake conditions, facilities and ground conditions. The conditions assumed for Example 1 are shown in Table 1, and the illustration of the simple network model is shown in Fig. 4. Only two kinds of ground conditions are considered in Example 1, the size of the earthquake motion of the examined area is fixed, and in order to show the damage ratio at Table 2(a), the structural requirement is held constant. The received damage and restoration time in the area are calculated, as shown in Table 2(b). Facility compositions of the Route A and Route B are shown in Table 2(c). Recovery time per damaged point is calculated from the received damage and restoration time. When the non-operation time of the element is calculated using the above-described method, for normal ground the restoration time is 0.04 days/km, and for soft ground the restoration time is 0.2 days/km. The unavailable time of the system after the disaster is calculated, and is shown in Fig. 5. Values of 0.0025 for Route A and 0.135 for Route B are given for calculating the probability of connectivity. Compared with the values of 0.8 days and 2.4 days shown in Fig. 4, the degree of damage appears to have been directly expressed by the unavailable time.

Next, the reliability evaluation method is applied to the combination of different services. The degree to which a service is decreased may be expressed as the simple sum of the unavailable times of other services. The assumed damage ratio and other conditions are identical to those in Example 1 shown in Table 2. Additional conditions are 0.5 days of unavailable time for supplying energy and 0.3 days unavailable time for facilities. These values are calculated from both the damage ratio and the restoration time. Figure 6 shows the compound model for different systems. Figure 6 shows the calculation results for the network combined energy supply system. These results are expressed in the form of unavailable duration of equipment and energy supply as serial elements. When different services are included in the total system, it is possible to evaluate the effect of the down time calculated as a serial element. Because the expectation for assumed restoration time, i.e. unavailable time, is a common parameter in different services.

Table 2 Assumed condition for Example 1

(a) Damage ratio

ground condition	damage ratio
soft	1.0 point/km
normal	0.2 point/km

(b) Results of total damages

items	assumed value
number of damages	100 points
restoration time	20 days

(c) Condition of Route A and Route B

Route A	(supplying users=100) length in normal=10 km (supplying users=10) length in normal=10 km
Route B	(supplying users=100) length in normal=5 km, in soft=5 km (supplying users=10) length in normal=5 km, in soft=5 km

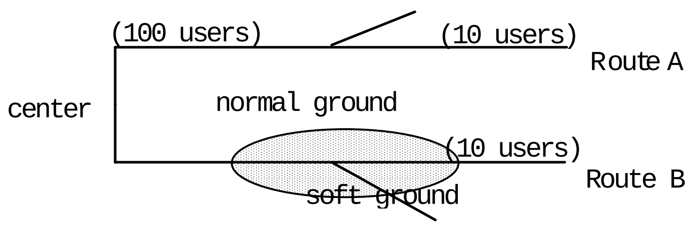

Figure 4 Simplified network model for example 1

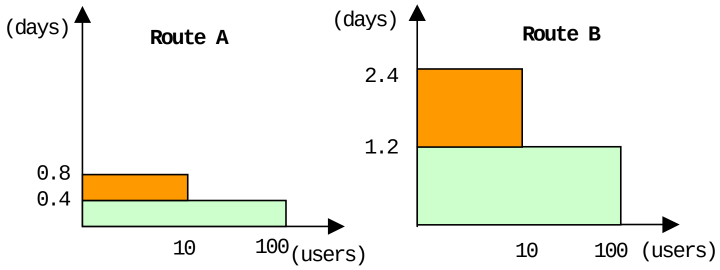

Figure 5 Comparison of calculation results

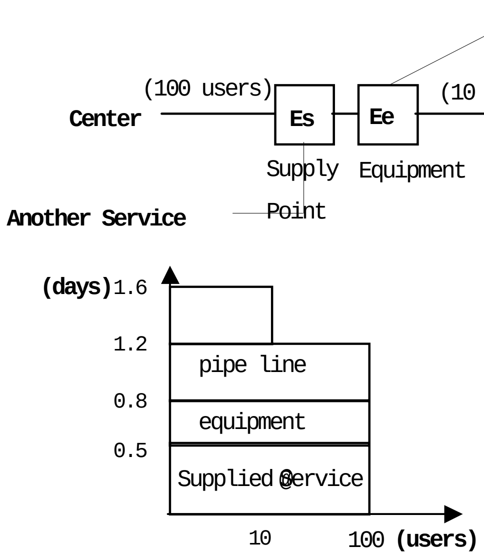

Figure 6 Simplified network model for example 2 and the result

CONCLUSION

The present report proposed a method for estimating the reliability of lifeline systems. The practical scale of reliability is needed for creating earthquake countermeasures. The ease with which facilities are damaged and the difficulty with which they are restored are important factors. Data collected for previous disasters can be used to estimate the damage ratio and restoration time. By combining these two factors, practical estimation is possible using unavailable time for the disaster. Multiplying the damage ratio by the restoration time, the estimated non-operation time is a useful estimation scale. Time is a commonly used scale when other services, which may be down due to the disaster, are connected to the network. Unavailable time allows the balance between reliability and the importance of superior facilities to be clarified.

REFERENCES

Shiomi, *Introduction of reliability engineering*, Maruzen Co. (1982)