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# PROBABILISTIC SEISMIC RISK ANALYSIS OF SYSTEM CONSISTING OF SEVERAL FACILITIES

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## Abstract

As well as the functions of individual facilities, the functions of the system consisting of several facilities, such as lifelines, networks, supply chains and so on, have to be secured in case of disasters in order to maintain the urban function and to reduce the secondary damage to urban. For the future earthquakes, it is adequate to employ probabilistic approach where uncertainty of ground motion intensity is expressed by seismic hazard curve and that of capacity of facility is given as seismic fragility curve. By combining these curves, risk curve can easily be evaluated, from which some useful figures such as annual failure probability are calculated.

However, in case of conducting the probabilistic risk analysis for system, such approach is not adequate since the seismic hazard curve cannot be applied to the system. It is apparent that applying the same seismic hazard curve to the facilities located in the different site is not correct. Applying the site specific seismic hazard curve to each facility is also not a proper procedure, since each earthquake is a common cause event for every facilities.

This paper propose the multi-event model in order to evaluate the seismic risk of system, where numerous earthquake events are generated with their magnitude and annual occurrence frequency. Correlation of ground motion intensity between two sites is given as a function of site-to-site distance, based on the regression analysis using K-NET and Kik-net data base in Japan. The functional relationship among the facilities in the system is evaluated by the fault tree approach. It must be noted that this procedure can duly include the effect of correlation of failure probability of each facility. The conventional probabilistic approach cannot handle the correlation, so that the interval estimation has been employed with large uncertainty, so far

As an application, a probabilistic risk analysis of a model system including a series system and a parallel one is conducted, followed by the comparison with the previous conventional procedure.

*Keywords: Seismic risk analysis; Multi-event model; Network; Fault tree; Risk curve*

## 1. Introduction

As well as the functions of individual facilities, the functions of the system consisting of several facilities, such as lifelines, networks, supply chains and so on, have to be secured in case of disasters in order to maintain the urban function and to reduce the secondary damage to urban. For the future earthquakes, especially for earthquakes whose characteristics are unknown, it is adequate to employ probabilistic approach where uncertainty of ground motion intensity is expressed by seismic hazard curve and that of capacity of facility is given as seismic fragility curve. It is noted both seismic hazard curves and fragility curves have been well studied in the field of nuclear industry. By combining these curves, risk curve can easily be evaluated as shown in Fig.1, from which some useful figures such as annual failure probability or failure probability for specified annual exceedance probability are calculated.

However, in case of conducting the probabilistic risk analysis for system consisting of plural facilities located in deferent sites, the approach mentioned above is not adequate since the seismic the specific hazard curve cannot be applied to the system. It is apparent that applying the same seismic hazard curve to the facilities located in the different sites is not correct. Applying the site specific seismic hazard curve to each facility is also not a proper procedure, since each earthquake is a common cause event for every facilities.

Therefore, it is necessary to employ other methodology that can evaluate the risk of portfolio of facilities located in deferent sites. This paper propose the multi-event model in order to evaluate the seismic risk of system, where numerous earthquake events are generated with their magnitude and annual occurrence frequency.

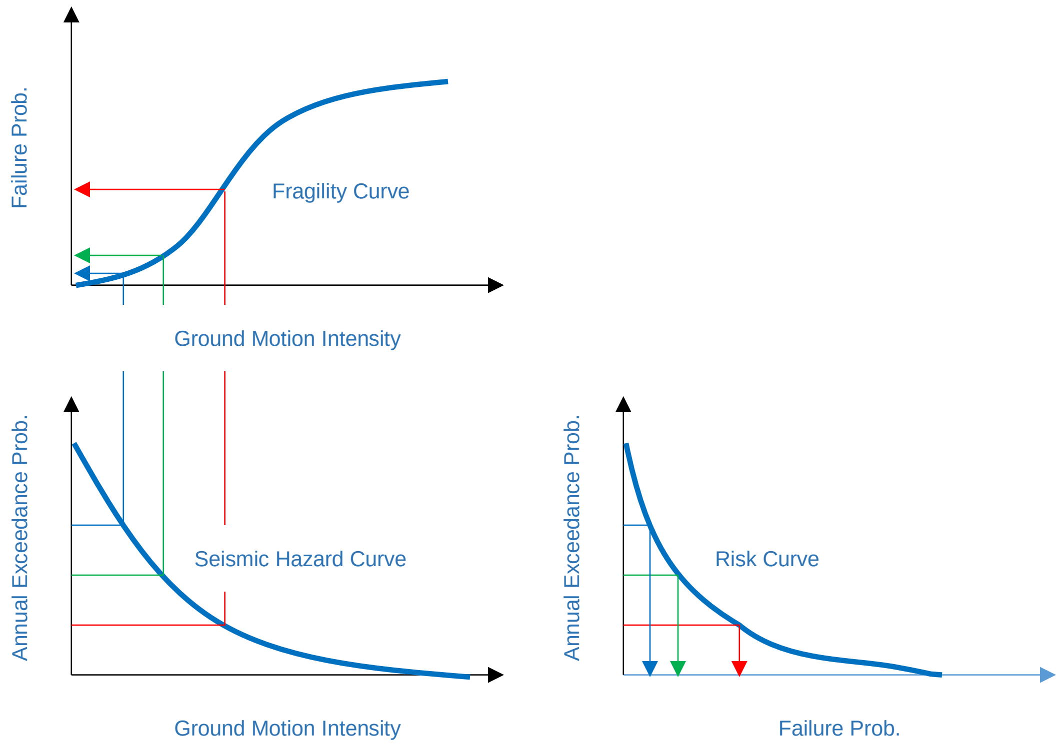



Fig. 1 – Concept of probabilistic approach for single exposure

## 2. Risk Evaluation by Multi-Event Model

This chapter illustrates how the risk curve of facilities located in deferent sites is obtained.

### 2.1 Concept of multi-event model

Figure 2 shows the concept of multi-event model, where events can be characteristic earthquake such as active faults or inter-plate earthquake, and discretized background earthquakes, as used in the seismic hazard analysis. For each event, the failure probabilities of facilities are calculated, followed by the fault tree analysis that gives the functional failure probability of the system.

### 2.2 Generation of events and estimation of ground motion intensity

Events are generalized from the seismic zone models around the portfolio of facilities. Each event has following information; location such as longitude, latitude and depth of reference point, shape such as strike, dip angle, fault length and focal width, magnitude and annual occurrence rate. These parameters are usually uses in calculating probabilistic seismic hazard curve.

Given events, ground motion intensities are estimated using attenuation relation. In many cases, ground motion intensity is peak ground acceleration or peak ground velocity, which may be selected so that seismic fragility curve has better shape, *i.e.* less variability. In this paper, ground motion for facility $j$ by event $i$ is hereinafter denoted by $x_{ji}$.

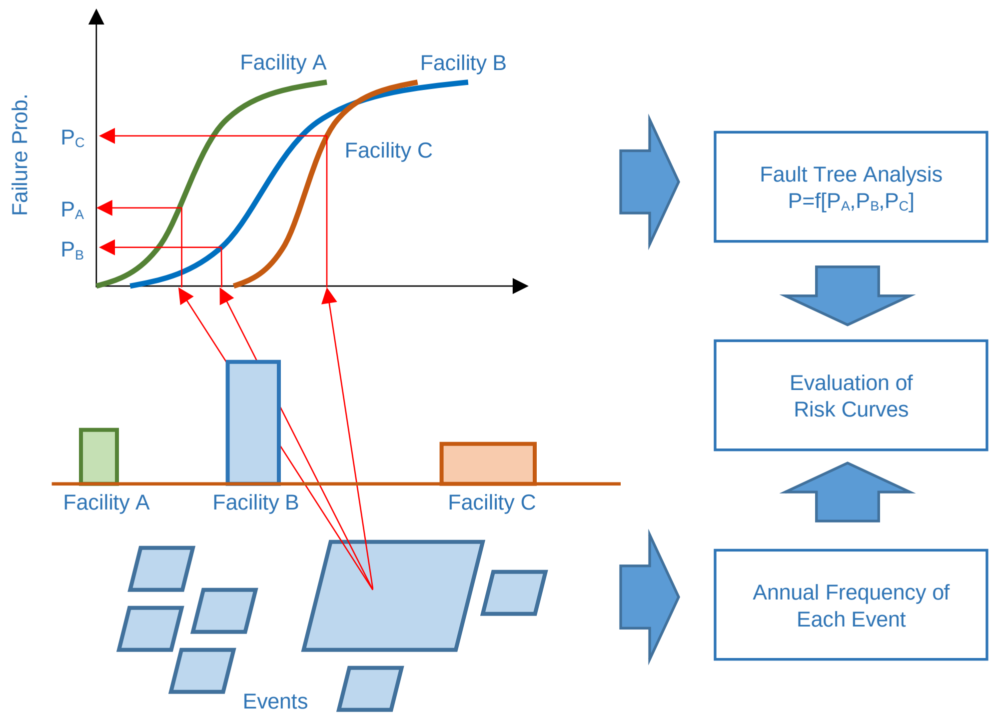



Fig. 2 – Concept of probabilistic approach using multi-event model

### 2.3 Calculation of failure probability

Capacity of each facility is expressed by the seismic fragility curve. This paper lets conditional failure probability for facility $j$ by event $i$ be $p_{kji}$, where expresses damage state, *e.g.* slight, moderate, severe and so on. The conditional failure probability $p_{kji}$ is obtained by the following equation,

$$p_{kji} = f_{kj}(x_{ji}) \tag{1}$$

where, the function $f_{kj}(\cdot)$ is the seismic fragility curve for facility $j$. The conditional failure probability of the system.

### 2.4 Statistical processing

In risk analysis, it is necessary to include the effect of variability in estimating failure probability. Factors that can bring uncertainty are errors in estimating ground motion prediction and capacity of facilities. In the analysis the effect of these uncertainties on failure probability are evaluated by Monte-Carlo simulation, where error in capacity of facility is independent to one another and error in ground motion intensity is dependent to one another reflecting the site-to-site distance.

For event $i$, the probability distribution function of failure probability of facility $j$ is denoted as $F_{kji}$. That of functional probability is also denoted as $F_{Fi}$. These probability density functions are evaluated by using probability paper with numerical results from Monte-Carlo simulation.

### 2.5 Evaluation of risk curve

Risk curve of failure probability $R_{kj}(p)$ of facility $j$ for given failure probability $p$ is obtained by following equation,

$$R_{kj}(p) = 1 - \exp\left[\sum_{i=1}^{n} \nu_i \cdot [1 - F_{kji}(p)]\right], \tag{2}$$

where, $\nu_l$ is annual occurrence frequency of event $i$. Risk curve of functional probability $R_F(p)$ is also given as follows,

$$R_F(p) = 1 - \exp\left[\sum_{i=1}^{n} \nu_i \cdot [1 - F_{Fi}(p)]\right]. \tag{3}$$

It is noted that annual failure probability of individual facilities as well as of portfolio can be calculated as the area surrounded by corresponding risk curve, x-axis and y-axis.

## 3. Application

This chapter shows a simple application of risk analysis of portfolio consisting both parallel system and series system.

### 3.1 Facilities

Figure 3 shows the location of facilities. Facilities A-1 to A-3 are connected in parallel so that the failure of the group-A occurs when all facilities damaged. As well as the group-A, facilities B-1 and B-2 are connected in parallel forming group-B. The group-A, the group-B and the facility C are connected in series, so at least one damage to them means the damage to the system.

For simplification, one damage state is assumed. The median capacity and lognormal standard deviation are summarized in Table-1.

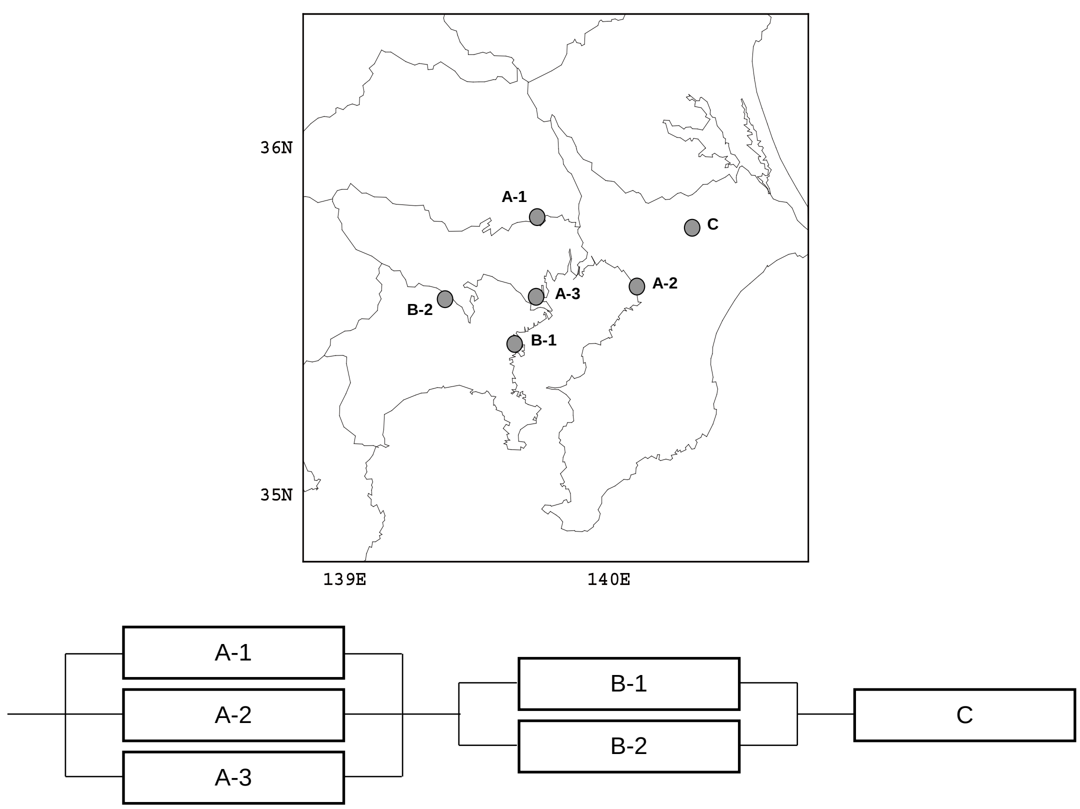



Fig. 3 – Location and connectivity of facilities forming portfolio

Table 1 – Capacity of eac facility

| Facilities | Capacity Acceleration | |
|---|---|---|
| | Median Capacity [cm/s/s] | Log-normal Standard Deviation |
| A-1, A-2, A-3 | 200 | 0.4 |
| B-1, B-2 | 400 | 0.4 |
| C | 800 | 0.4 |

### 3.2 Seismic source zones and ground motion prediction

Seismic source zone model is based on J-SHIS2012 [1]; Japan Seismic Hazard Information Station, 2012 ver., where 4 types of source models are established as shown in Fig. 4.

Rectangle source corresponds to active fault. Irregular shape source consists of numerous points for calculation of distance from site. These two sources are categorizes as characteristic earthquake. Circular source shows location of focal point with equivalent source area corresponding to magnitude so that distance to the site is magnitude dependent. Discretized rectangular source consists of group of rectangular sources to express the uncertainty of location. These two sources are categorizes as background earthquake.

Ground motion prediction is done using attenuation formula by Si and Midorikawa (1999). Peak ground acceleration at surface is selected as a ground motion measure, which is given by the following equation,

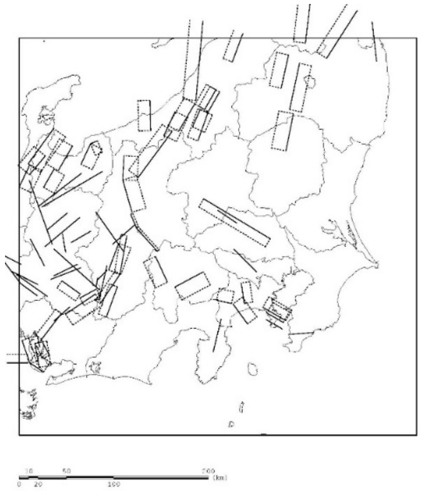
$$\begin{aligned} \log a &= 0.5M_w + 0.0043h + d + 0.61 - \log(d) + 0.002r \\ d &= r + 0.028 \cdot 10^{0.5M_w} \end{aligned} \tag{4}$$

where, $a$ is a peak ground acceleration, $r$ is the shortest distance from the source, $h$ is a focal depth, $d$ is a coefficient corresponding to earthquake type, and is a moment magnitude, respectively.

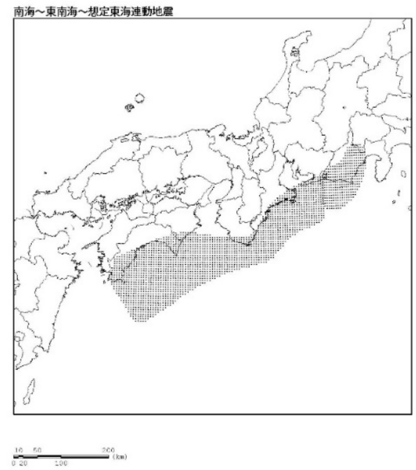
Standard deviation of ground motion prediction is given by Hayashi (2006) [2], by which inter-event standard deviation is 0.239 (in common logarithms) and intra-event one is 0.198 (in common logarithms), respectively. Intra-event correlation $\rho$ is given by the following equation,

$$\rho = \exp(-0.042 \cdot z^{1.033}) \tag{5}$$

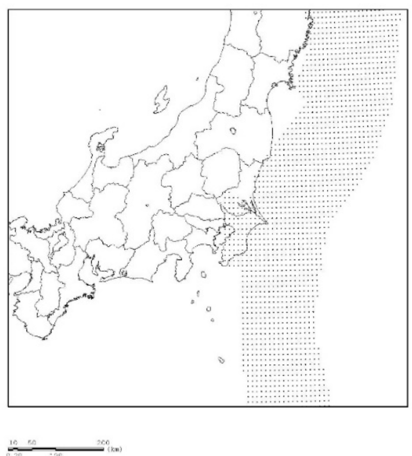
where, $z$ is a distance between sites.



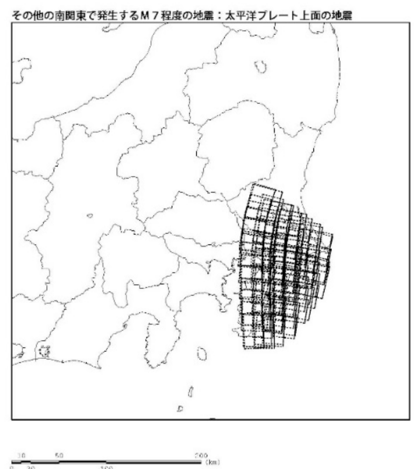
(1) Rectangle source




(2) Irregular shape source



(3) Circular source




(4) Discretised rectangular source

Fig. 4 – Examples of seismic source zones

## 3.3 Conditions for conducting risk analysis

In the analysis of probability density functions $F_{kji}$ and $F_{Fi}$, the results of Monte-Carlo simulation are directly used, i.e. probability density functions are evaluated by counting numbers of samples whose failure probability exceed the given threshold. The number of trial in simulation is set to 500.

Failure probabilities of parallel system and series system are obtained assuming that failure of each facilities are perfectly independent, as follows,

$$R_F(p) = \prod R_j(p), \tag{6}$$

$$R_F(p) = 1 - \prod [1 - R_j(p)]. \tag{7}$$

### 3.4 Evaluation of risk curves

Using 44000 generated events from the seismic source zones, risk curves of failure probabilities were obtained. Figure 4 shows the risk curves for individual facilities.

Risk curves are dominated by both seismic hazard and building capacity. Risk of facilities A-2 and A-3 are large since seismic hazard in southern Kanto region is high and capacity of the facilities are low. On the other hand, the risk of facility A-1 is smaller than A-2 and A-3 because of low hazard activity. Risk of facilities B-1 and B-2 are smaller than those for the group-A facilities, and the risk of facility C is the smallest. This tendency is harmonic with capacity of facilities.

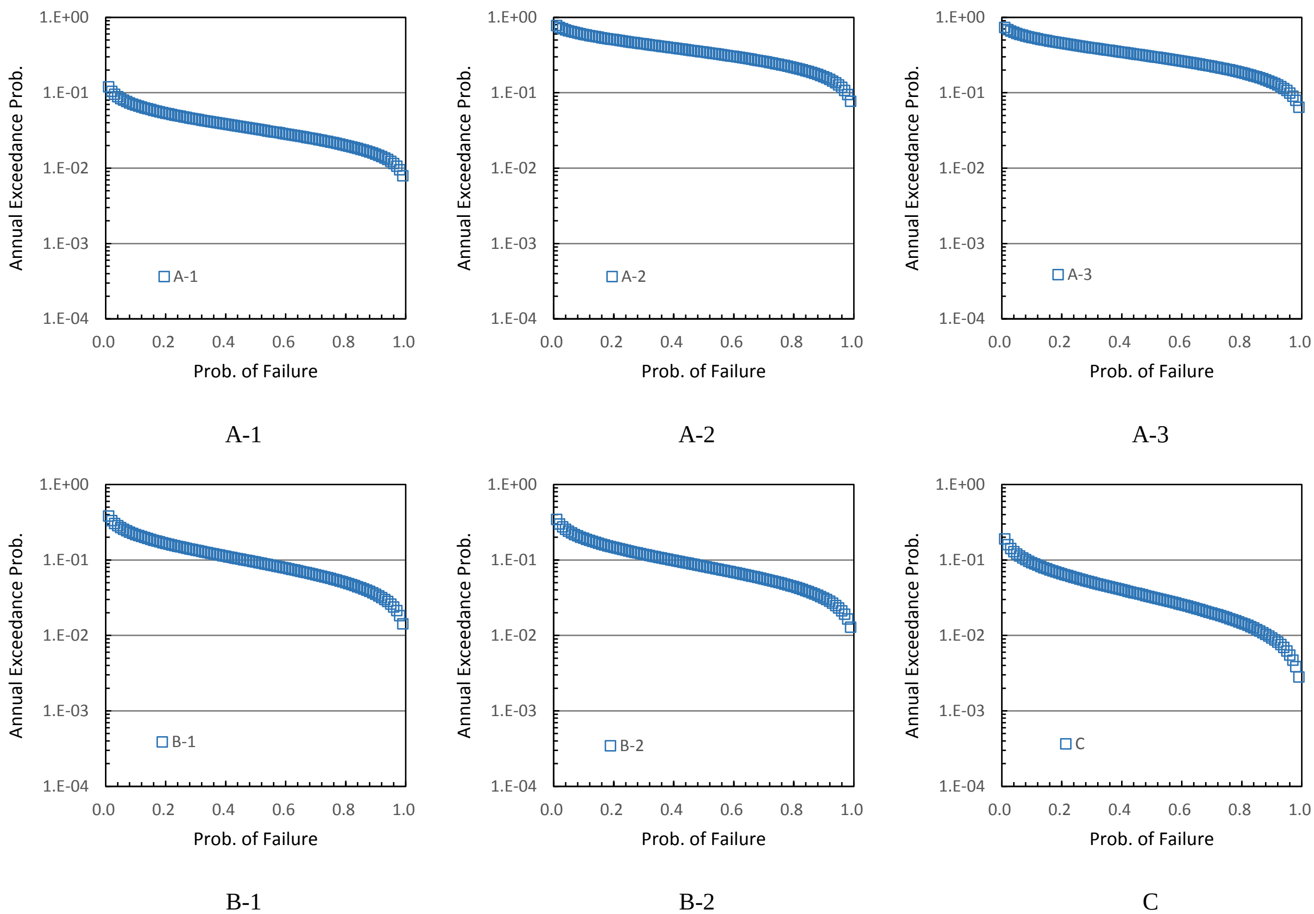
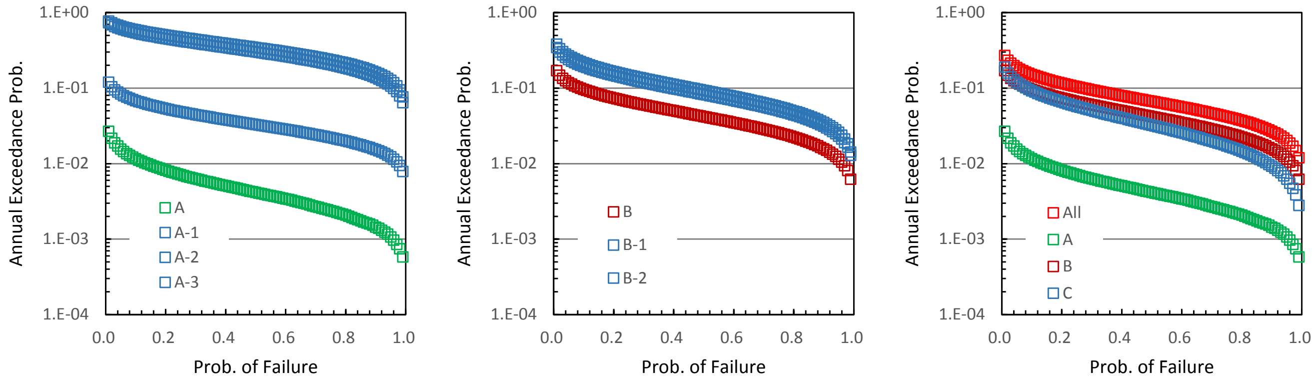



Fig. 5 – Risk curves for individual facilities

Figure 6 shows the risk curves of system and its individual facilities. From the risk curves of group-A and group-B, it can be seen that risk is largely reduced by introducing parallel system. On the contrary, it is apparent that risk of individual facilities must remain small in case of the series system.

For the model portfolio, the dominant facilities to system risk are facility B-1 and B-2, followed by facility C. Therefore retrofitting activity shall be given to these facilities even though the risks of facilities A-2 and A-3 are much larger.




Group-A Group-B All

Fig.6 – Risk curves for systems

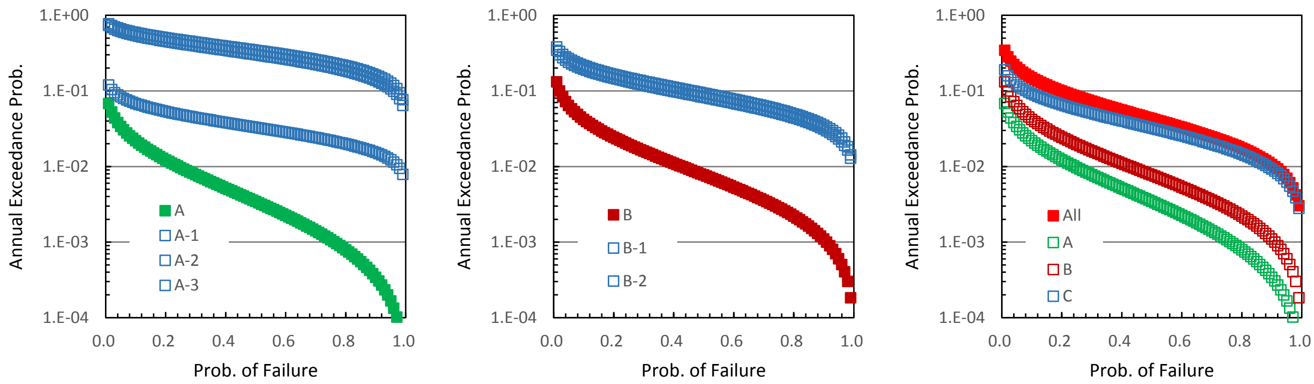
## 4. Discussion

Figure 7 shows the risk curves of systems, which were obtained from the risk curves of individual facilities. This approach assumes that the variabilities in damage to different facilities are perfectly independent to one another, so that the risk is estimated smaller than reality in case of parallel system. On the contrary, it can easily be anticipated that the risk is estimated larger than reality in case of series system.

Instead of assuming the variabilities damage to different facilities are perfectly independent, risk curves can be obtained under the condition that the variabilities are perfectly dependent in case that the facilities are located close to one another. Figure 8 shows the risk curves of systems from the risk curves of individual facilities considering they are perfectly independent.

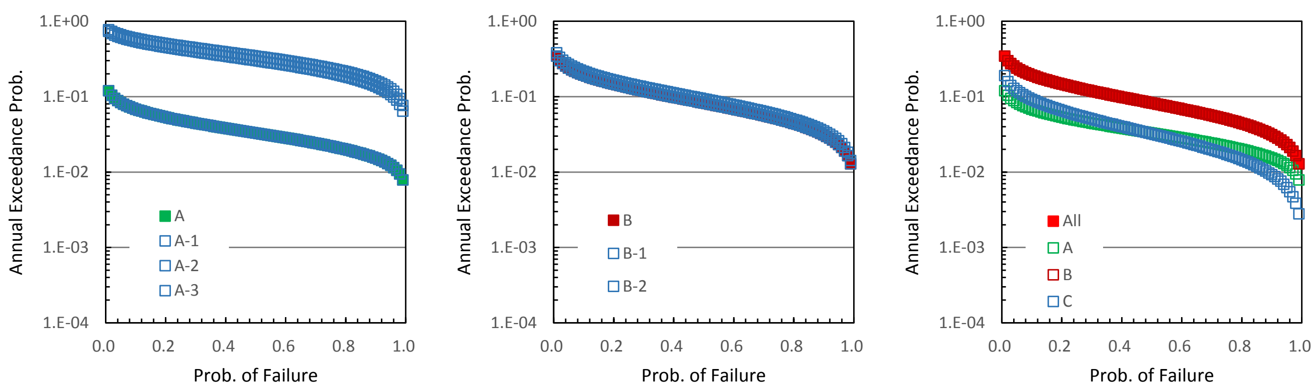
Though above two kinds of risk curves obtained from individual ones are, of course, not correct, they are often used to express the risk of systems for their easiness in calculation, especially in the field of nuclear industry where numerous facilities and equipment are of concern. It is noted that these two kinds of risk curve are employed simultaneously, so that the interval of two curves can express the uncertainty in estimating the damage correlation. This is a practical way, however, the interval may sometimes be too wide to estimate the true risk.

Figure 9 shows the comparison of the risk curves obtained from the deferent methods. From the figure it is seen that the risk curve by the multi-event model is between the two approximate risk curves. As stated above, the true risk will be between two assumptions; perfectly independent and perfectly dependent, the multi event model can give a proper result, which may be close to the true one.



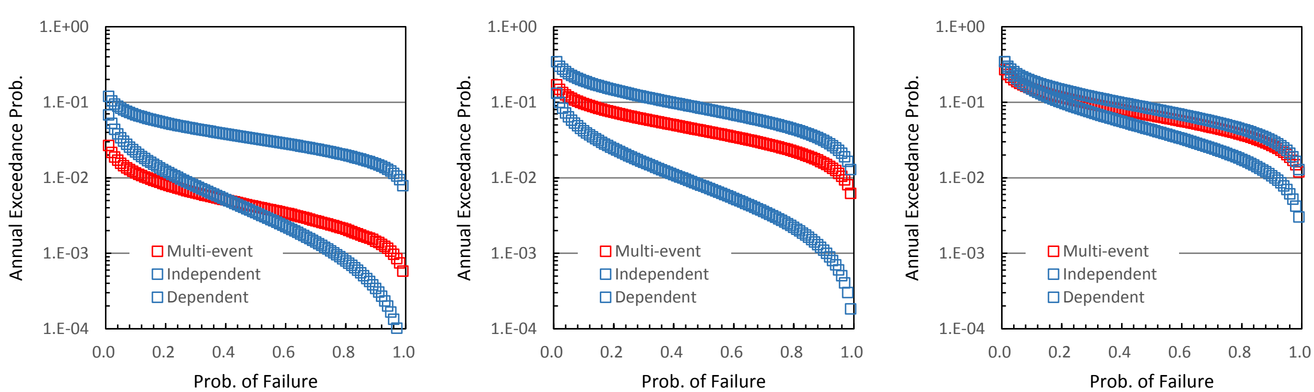

Group-A Group-B All

Fig.7 – Risk curves for systems obtained from risk curves of individual facilities (perfecly independent case)




Group-A Group-B All

Fig.8 – Risk curves for systems obtained from risk curves of individual facilities (perfecly dependent case)




Group-A Group-B All

Fig.9 – Comparison of risk curves

## 5. Conclusion

This paper proposed a risk analysis method based on the multi-event model, by which seismic risk of the portfolio consisting of plural facilities can be evaluated taking the correlation of failure of each facility into account.

Though the application for simple portfolio, it was demonstrated that the multi-event model gives the results between ones by independent and dependent assumptions. In many realistic cases, failures of facilities must be partially dependent, since ground motion intensity for each facility is partially dependent. Therefore, the multi-event model is considered effective in analyzing risk of portfolio of facilities.

## References

[1] Japan Seismic Hazard Information Station, National Research Institute for Earth Science and Disaster Prevention, (http://www.j-shis.bosai.go.jp/)

[2] Hayashi, T., Fukushima, S. and Yashiro, H. (2006). "Effects of the spatial correlation between ground motion intensities on the seismic risk of portfolio of buildings" J. Structural and Construction Engineering, AIJ, 600, 203-210