# Seismic Risk Assessment Procedures for a System Consisting of Distributed Facilities - Part One - Basic Method of the Procedures

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ABSTRACT: In This paper, practical seismic risk assessment procedures for a system consisting of multiple facilities located in a vast area are presented. The estimated risk information is expressed as the seismic risk curve of the system, which has been considered time-consuming to evaluate. The major features of proposed procedures are discrete expressions of seismic damage states of the system and of seismic hazard. Event tree models are used to enumerate seismic damage states of facilities as well as of the system accounting for physical and functional losses of the system. The seismic hazard is represented as a set of scenario earthquakes with occurrence ratios, which enables to evaluate interacted system seismic losses. The procedures are explained with a very simple example.

## 1 INTORODUCTION

The earthquake disaster is one of the great threats to human beings. As the occurrence of an earthquake can be neither controlled nor even predicted exactly. What we can do is designing and constructing facilities with enough strength to withstand the effects of earthquakes. However, stronger facilities require additional costs and large earthquakes are very seldom to occur. We are required to decide the adequate strength level to be given to facilities. In order to deal with this question, the risk based design or risk management procedures may be useful, where the seismic risk is balanced against the costs of the facility.

The authors have been developing practical seismic risk assessment procedures to be used for risk management of facilities. The seismic risk assessment procedures for individual facility are already proposed at the previous ICOSSAR by one of the authors (Mizutani, 1998).

These procedures are:

- 1) Enumerate seismic damages of the facility uniquely to its site conditions, to structures and to its functions.
- 2) Model the above seismic damages in to several physical damage states, which are expressed as sequences of seismic events by using an event tree.
- 3) Assign loss amount to each physical damage state, the end branch of the event tree, considering physical and functional losses when the facility is in the state.
- 4) Evaluate conditional expected loss curve to the ground motion level, SLF (Seismic Loss Function), by quantifying the event tree at each ground motion level.
- 5) Estimate probabilistic seismic hazard curve, PSHC, at the site considering every possible seismic source.

– 6) Then evaluate the annual expected loss by convoluting the SLF with the PSHC at the site. Or modify the SLF into the risk curve by converting coordinates with PSHC.

These procedures make it possible to analyze the major contributor to the seismic risk of the facility and to examine the efficiency of potential counter measures. However, the seismic risks of systems consisting of multiple facilities located in the vast area, such as highway systems, electricity supply systems, logistic systems, insurance portfolios etc., may not be evaluated in the same manner as for the individual facility. The reasons are that there are significant dependencies between seismic hazards of their locations, and that the seismic loss of the system as a whole is not as simple as the summation of each facility loss.

For such systems the conditional seismic risks to a scenario earthquake may be evaluated assuming a source event. But the seismic risk information considering only limited number of scenario earthquakes is not enough for the risk management. However, when the seismic hazard circumstances for the area of entire system is fully expressed by a set of scenario earthquakes, the seismic risks may be assessed by statistical analysis of the results from all scenarios. In this case, huge computational efforts have been considered essential.

In this series of studies, practical seismic risk assessment procedures for a system consists of multiple facilities scattered in the vast area are proposed. In the part one of the studies, the basic procedures are explained with a simple example. In the part two, a seismic hazard model consisting of scenario earthquakes in and around Japan is presented, which is to be used for this purpose. A seismic risk assessment of an insurance portfolio as an example system that consists of multiple buildings scattered in Japan is conducted in the part three of this study to show the applicability of the procedures.

## 2 RISK REPRESENTATION AND UNCERTAINTIES INVOLVED IN THE SEISMIC RISK ASSESSMENT

Earthquake damages are very seldom to occur and we do not have enough experiences to fully understand them. In other words, there are lots of uncertainties in the earthquake damages. When dealing with phenomena containing uncertainties, the risks should be considered. In this series of papers, the uncertainties involved in the seismic risk assessment are classified and modeled by probabilistic expressions.

### 2.1 *Risk representation*

The representations of the seismic risks in this paper are an annual expected loss (AEL) and/or a risk curve. The AEL is the single value that represents the magnitude of seismic risk of a facility or a system. Whereas the risk curve expresses a full probability distribution of seismic loss amount of a facility or a system, which is shown as the exceedance probability curve on the loss amount coordinate in general. The relation between those two is that the gravity point of the probability density function of the loss distribution is the AEL.

### 2.2 *Uncertainties involved in the seismic risk assessment*

As mentioned previously, there are lots of uncertainties in the seismic risk assessment. In this section, they are listed up and are modeled according to the proposed procedures.

#### 2.2.1 *Seismic sources*

The seismic sources are the most uncertain factor in the seismic risk assessment. We cannot predict when, where and how large earthquakes will occur. In the probabilistic seismic hazard analysis, such uncertain sources are modeled into map of seismic regions, where the average occurrence ratio, probability distribution function of magnitudes and locations are listed. In the computer algorism of seismic hazard analysis, this information is translated in to a set of earthquakes, each of which is characterized with an occurrence ratio, a magnitude and a location. The number of these earthquakes is in general huge but finite.

We use this kind of seismic source maps to express the uncertainty of source events. More practically, we generate a set of earthquakes with occurrence ratios distributed in the area of concern based on a map. The occurrence of each earthquake is assumed to be independent. Then this set is the discrete presentation of the uncertain seismic circumstances. The detail explanation of the generation process of the set will be found in the part two of this series of study.

### 2.2.2 *Ground motions*

When the earthquake is determined, the ground motion at any site is still uncertain. As for the ground motion estimation, an attenuation relationship is useful. The attenuation relationship is an empirical model of ground motion intensity as a function of focal parameter and site location. The attenuation relationship has a variability as is evaluated statistically from many ground motion records.

We use the attenuation relationship for the ground motion intensity estimation and the uncertainty of the estimation is expressed as the variability of the relationship. However, ground motion intensity obtained by the relationship is not the time history of the ground motion itself. This fact will induce another uncertainty and it should be considered in the response estimation.

### 2.2.3 *Modeling of damage states of a facility and /or system*

Damage states of a facility and/or system caused by a ground motion are also uncertain. As for a facility there is variety of earthquake damage modes, from no damage to total collapse. A system consisting of multiple facilities shows more variation of damage modes depending on the combination of individual facility damage state.

In order to represent this variability, we develop event tree (ET) models, which discretize the seismic damages of facilities and/or systems into multi-nominal states. When an earthquake occur the facility or the system is to be in one of these damage states, as these states are mutually exclusive and totally exhausted.

The facility event tree is used to enumerate physical damage states of the facility in the forms of the sequences of seismic events such as landslides, ground liquefaction, structural shaking damages and vibratory infill damages. Another ET for a system is utilized to develop the all the combinations of each facility’s damage states in order to express the damage states of the whole system.

### 2.2.4 *Loss assignment*

The loss amounts of a facility and /or a system due to earthquake damages contain uncertainty. However, in the proposed procedures, we modeled multiple damage states and assigning unique loss value for each state: We assumed deterministic loss amount for each damage state, the end branch of the system event tree. Both physical and functional losses are considered here. The uncertainty of loss amount should be examined by sensitivity analysis.

### 2.2.5 *Response of structure*

When ground motion intensity at a site is obtained by an attenuation relationship, the response of a structure is not deterministically estimated as the ground motion intensity is not a time history and the analytical model of the response estimation is not always correct.

We assumed lognormal distribution for the response value of the structure in order to represent this uncertainty.

### 2.2.6 *Capacities of facility*

We need to know the strength of the facility to evaluate the branch probability in the event tree model of the facility. The strength or the capacity of a facility here means the limit surface of each seismic event, which corresponds to the branch in the event tree. Then there are multiple capacities even for an individual facility. The capacity or the limit surface of each seismic event is unique to the facility and its estimation has considerable uncertainty.

We also assumed lognormal distribution to represent this uncertainty. Each branch probability in the facility event tree is calculated as the probability that the response excesses the corresponding capacity.

2.2.7 *Modeling uncertainties*

Except for the uncertainties listed in the above, there should be modeling uncertainties. The modeling uncertainty is not a random uncertainty but is the uncertainty counting for the error of the modeling. To evaluate the modeling uncertainty, we need to check the evaluated results with the experienced data. In this series of paper, we neglected most of the modeling uncertainties, which means we are presenting the best estimate results.

## 3 FLOWCHART OF THE PROCEDURES

Figure 3-1 shows the flowchart of the proposed procedures to assess a seismic risk of a system consisting of distributed facility. In this chapter, these procedures are explained with a very simple example.

### 3.1 *Seismic hazard information interpretation*

The seismic hazard information is a seismic source map around the area where the system facilities are located. From the map, seismic circumstances are modeled as a set of scenario earthquakes, each of which has the occurrence ratio, the magnitude and the fault location. The set of earthquakes should be fine enough to express the seismic hazard of each facility site included in the system. Some of these sets of earthquakes representing entire Japan seismic hazard will be presented in the companion paper.

The seismic hazard information for the example case is modeled as a set of only two earthquakes for the sake of simplicity, although this model is unrealistic as the number of the scenario earthquakes is far larger in general. One earthquake, EQ1, is located at certain place with occurrence ratio of 1/100 per year and of magnitude 6.5, and the other earthquake, EQ2, located at another place with occurrence ratio 1/1000 and of magnitude 8.0.

### 3.2 *System information interpretation*

The system information includes that of the system itself and that of each facility in the system, such as system function configuration, value of the system, each facility function, location, seismic capacity of equipment and structure, physical value of each facility etc. This information is modeled into event trees for individual facilities and into an event tree for the system.

The event tree for an individual facility expresses seismic damage states of the facility as sequences of seismic events such as land slides, structural failures and equipment failures. The damage state probabilities are calculated based on the branch probabilities in the event tree, which are evaluated as the occurrence probabilities of corresponding seismic events given ground motion intensities. The calculated damage state probabilities of each facility are to be used in the quantification of the system event tree.

The event tree for the system is developed to represent damage states of the entire system as the combination of damage states of every included facility. The loss amount corresponding to each system damage state is assigned considering physical loss of facilities and functional loss of the system. The major role of the system event tree is to take account of the interactions of functional losses of individual facilities as a whole system. The damage state probabilities of the system are calculated using those of individual facilities conditional to each earthquake.

The example system is consisting of two facilities, facility A and B, located different places. Each facility has its own function and the system needs both functions for the complete performance. When one of these facilities looses its function, the system performance degrades and it results as a system functional loss. Figure 3-2 shows each facility event tree model, which is very simple in this example case. In the realistic assessment, the size of facility event tree is far larger.

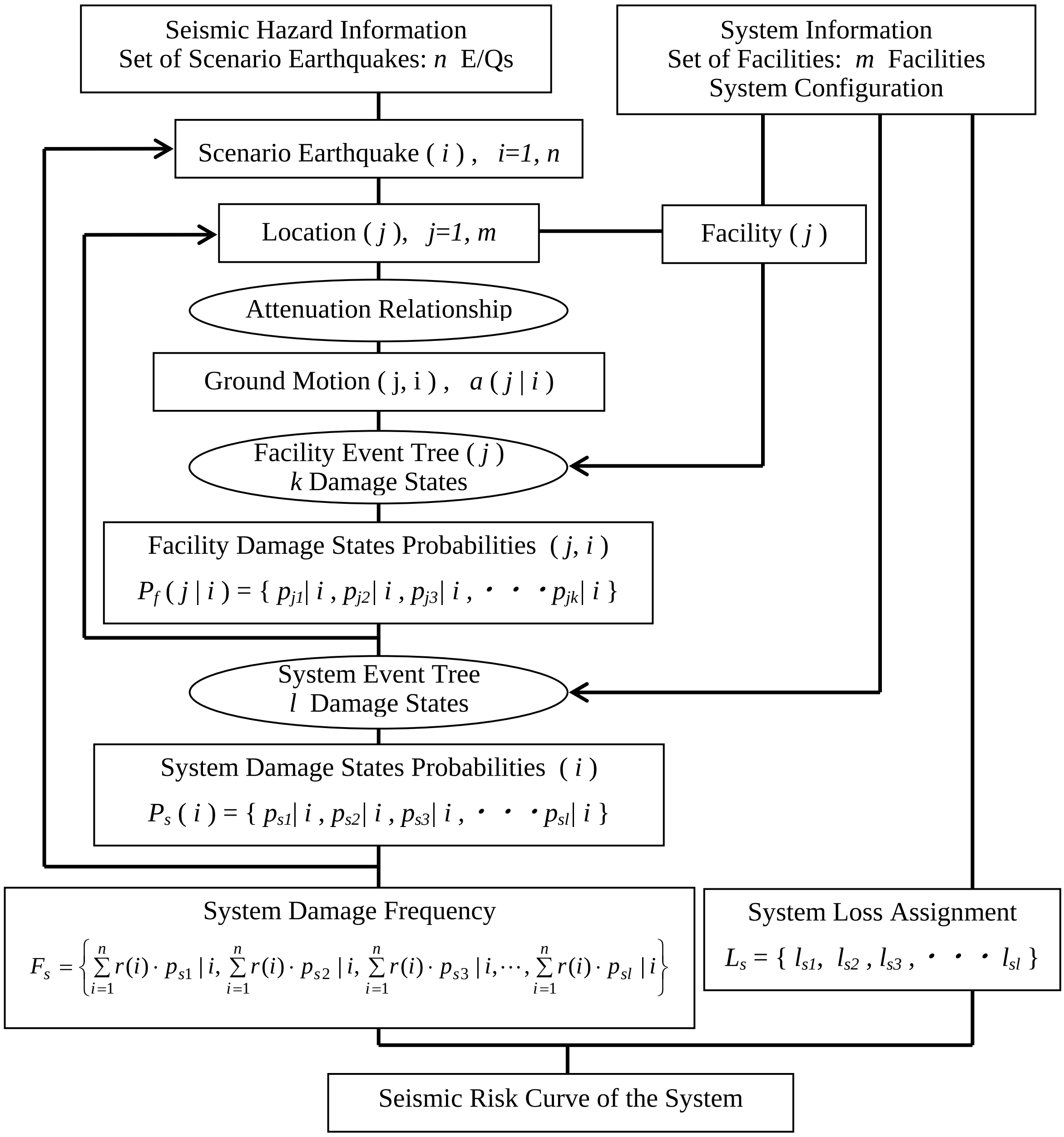


Figure 3-1 Flowcharts of the Procedures

The system event tree model for the example is depicted in Figure 3-3, which has 9 end branches or damage states as each of two facilities has 3 damage states. Loss amount assigned to each system damage state is calculated based on the summation of facilities physical losses and on the system functional loss considering the damage configurations; the combination of each facility damage state.

3.3 *Evaluation of ground motion*

The ground motion intensity of each facility location is evaluated via attenuation relationship given a scenario earthquake. By calculating ground motions of all locations simultaneously, the dependencies of different site ground motions are treated. The calculation result at each location indicates the median value of log normally distributed ground motion estimation. The variability of ground motion should be counted in the probabilistic evaluation of response of structure. If there is significant correlation in the ground motion intensities of different locations, it should be treated in the response evaluation. This treatment makes the calculation a little complicated and we neglect the correlation in this presentation.

For the example case, at the site of facility A median ground motion is 300 cm/s$^2$ of peak ground acceleration and 200cm/s$^2$ at the site location of facility B in the case of EQ1. In EQ2, 400cm/s$^2$ at facility A and 600 cm/s$^2$ at facility B are evaluated as shown in Figure 3-4.

### 3.4 *Quantification of facility event tree*

The quantification of each facility event tree is conducted for each scenario earthquake by calculating branch probabilities in the event tree based on the estimations of probabilistic responses of the structure and probabilistic capacities of the facility against corresponding seismic events.

The branch probabilities and the quantified damage state probabilities of each example facilities are as shown in Figures 3-4 for each scenario earthquake.

### 3.5 *Quantification of system event Tree*

The quantification of system event tree is repeated for each scenario earthquake, using the damage state probabilities of each facility evaluated by the facility event tree. The calculated damage state probabilities show that the system will be in the state with the corresponding probability when the scenario earthquake occurs. Based on the quantified results, the seismic loss distribution of the

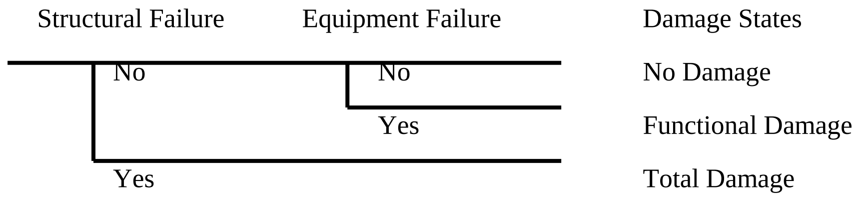


Figure 3-2 Facility Event Tree of the Example

| Facility A | Facility B | Damage States | Losses Physical | Losses Functional | Losses Total |
|---|---|---|---|---|---|
| No | No | #1 No Damage | 0 | 0 | 0 |
| | Functional Damage | #2 Partial Damage | 20 | 25 | 45 |
| | Total Damage | #3 Partial Damage | 80 | 400 | 480 |
| Functional Damage | No | #4 Partial Damage | 15 | 40 | 55 |
| | Functional Damage | #5 Partial Damage | 35 | 130 | 165 |
| | Total Damage | #6 Partial Damage | 95 | 305 | 400 |
| Total Damage | No | #7 Partial Damage | 50 | 240 | 290 |
| | Functional Damage | #8 Partial Damage | 70 | 255 | 325 |
| | Total Damage | #9 Total Damage | 130 | 830 | 960 |

Figure 3-3 System Event Tree of the Example

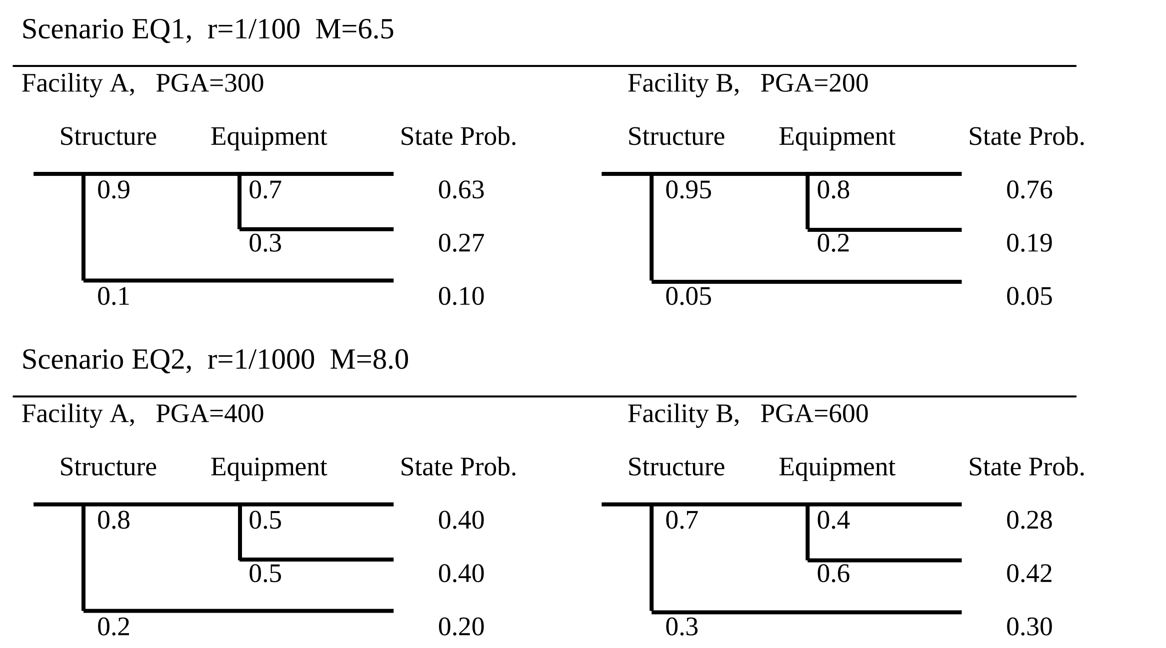


Figure 3-4 Quantification of Facility Event Tree

system is obtained.

### 3.6 *Statistical analysis of system seismic loss*

When the seismic loss distribution of the system corresponding to each scenario earthquake is evaluated. The seismic risk curve of the system is statistically estimated. As each scenario earthquake has its occurrence ratio, the conditional seismic loss distribution is converted into occurrence ratio of damage states by multiplying the occurrence ratio of the earthquake and state probability. As the scenario earthquakes are modeled to occur independently, the occurrence ratios of a damage state evaluated by different earthquakes are to be summed to estimate the occurrence ratio of the damage state concerning all the earthquakes that represents the seismic hazard of the system. Thus the seismic risk curve of the system is obtained.

Table 3-1 shows calculations to develop the seismic risk curve of the example system. Figure 3-5 depicts annual system loss frequencies and the seismic risk curve of the example system is in Figure 3-6. The annual expected loss (AEL) of the system is calculated as 1.035U.

Table 3-1 Calculations of annual frequency of seismic damage states

| System Damage states | Loss amount | Occurrence ratio By EQ1 | Occurrence ratio By EQ2 | Total Occurrence ratio |
|---|---|---|---|---|
| 1 | 0 U | 0.004788 | 0.000112 | 0.004900 |
| 2 | 45 U | 0.001197 | 0.000168 | 0.001365 |
| 3 | 480 U | 0.000315 | 0.000120 | 0.000435 |
| 4 | 55 U | 0.002052 | 0.000112 | 0.002164 |
| 5 | 165 U | 0.000513 | 0.000168 | 0.000681 |
| 6 | 400 U | 0.000135 | 0.000120 | 0.000225 |
| 7 | 290 U | 0.000760 | 0.000056 | 0.000816 |
| 8 | 32 U | 0.000190 | 0.000084 | 0.000274 |
| 9 | 960 U | 0.000050 | 0.000060 | 0.000110 |

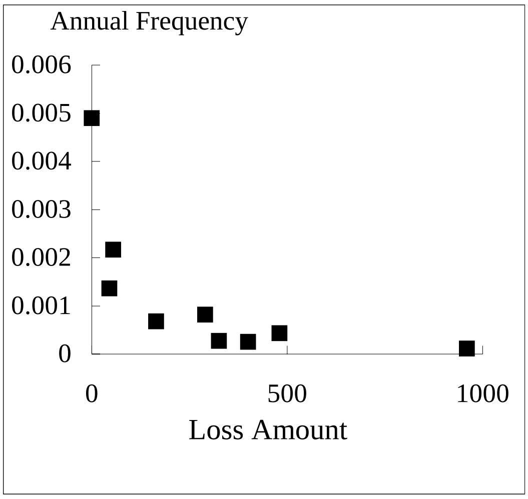


Figure 3-5 Seismic Loss Distributions

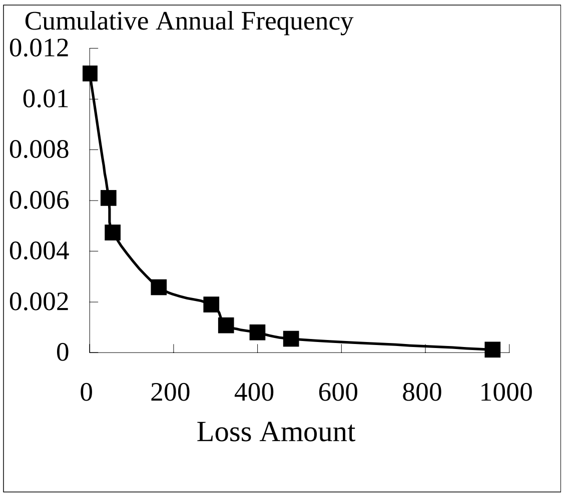


Figure 3-6 Seismic Risk Curve

## 4 CONCLUDING REMARKS

In this paper a practical procedures to evaluate the seismic risk curve for a system with widely distributed facilities are proposed and with a very simple example the procedures are explained. In general this kind of estimations is considered highly time consuming, but with the discrete expressions of the seismic hazard as a set of scenario earthquakes and of the system damage state variability by event tree modeling, seismic risk curve of the system is evaluated with an adequate efforts.

The probability density function of seismic loss due to an earthquake is often modeled in bell shape one in order to estimate risk curves. However it is not true. The shape is more or less bathtub type when considering individual facility. The modeling of seismic damage states via event tree can represents more realistic loss distribution of the facility and this leads to the better evaluation of seismic loss distribution of the system.

In the realistic applications, the size of an event tree would be huge however the calculation method is very simple and needs small computational effort. The generation of a system event tree is not simple, as it should count for the complicated system configuration. Most efforts should be concentrated on the system event tree modeling as well as that of each facility. When these models are prepared, the computation is straightforward. This merit enables us to do various sensitivity studies, which are essential to perform a risk management.

The seismic hazard modeling and realistic application of the proposed procedures must be of interest. In the part two and three of this series of study, these topics are presented.

## Reference

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