Analysis of Nuclear Power Plants Involving Failure-Correlation of Subsystems Caused by Earthquake

Tieling Zhang, Wei Long and Yoshinobu Sato

Tokyo University of Mercantile Marine, 2-1-6 Etchujima, Koto-ku, Tokyo 135-8533, Japan

ABSTRACT

Earthquakes are unavoidable natural hazards and difficult to predict. Their damaging potential must be considered for sensitive constructions including dams, mines, nuclear power plants (NPPs), underground depositories for radioactive wastes. All seismically induced failures could be with common causes. There are many causes that induce dependent failures among components and subsystems. In probabilistic safety assessments (PSAs) of NPPs, many different practical techniques have been developed to handle correlations among structures and components.

Another important PSAs issue concerned in NPPs is the assessment of aging effects, which degrade the performance of components, systems and structures. This kind of degradation is time-dependent and comes from the interactions of many factors.

The treatments of dependent failures and aging effects are two comprehensive issues involved in PSAs of NPPs. Many studies and programs developed on seismic fragility evaluations include dependent failures but where aging effects are not involved. Virtually, these two aspects need to be incorporated into seismic PSAs of NPPs. In the present paper, an approach treating dependent failures among components is developed. That is applied to seismic fragility evaluation of a subsystem, where the aging effects on capabilities of components and subsystems are taken into account. An example is given to illustrate the approach developed.

INTRODUCTION

Earthquakes are natural hazards representing extreme and unavoidable geophysical events that are difficult to predict and over which human beings have little or no control measures. As occurrence of earthquake cannot be precisely predicted, seismic-resistant design must be incorporated into system safety assessment before constructing structures such as nuclear power and chemical plants, power transmission systems, high speed railway networks, etc. In the past twenty years, the seismic PSA of nuclear power plants (NPPs) has become an important field of the design and regulation of nuclear installations [1-7]. Today, it should not be neglect the fact that recent experiences of severe earthquake damage in the areas on both sides of the Pacific Ocean have caused significant psychological effects upon the NPP owners, and triggered motives to use this PSA for various decision makings associated with earthquakes. These motives are including further development of models, databases and criteria related to seismic safety design and assessment of NPPs using this tool [8].

In the United States and some other countries, the PSAs of NPPs have been much addressed and developed. They are applied to evaluate core damage frequency (CDF) induced by earthquakes and to identify vulnerability of NPPs to earthquakes. In Japan, the NPPs are strictly designed against seismic events under the current deterministic regulation to assure safety because of several large earthquakes occurred in the past century. A methodology for both seismic PSA of NPPs [9, 10] and an integrated computer code system named SECOM-2 (seismic core melt frequency evaluation code) as part of the task of system reliability analysis [7, 11] are developed by the Japan Atomic Energy Institute (JAERI).

In PSA of NPPs, the treatment of failure correlations (dependent failures) among components or subsystems is a very important issue. Many safety-related systems in NPPs are designed with redundant trains of equipment. As the result, the risk associated with the operation of these plants is often dominated by accidents where multiple components fail to perform their design functions. This kind of failures may occur as a result of the independent failure of each component involved or, more likely, as a result of a single event that renders multiple components unavailable (a dependent failure event). These dependent failure events are usually major contributors to the risk brought about by NPP operations. Obviously the probability of this set of events cannot be expressed as the simple product of the unconditional failure probabilities for the individual events. As concerns the treatment of dependent failures in PSA, many techniques have developed and applied. They are associated with analyses on system structure and common cause resources. Humphrey and Jenkins made a brief review on dependent failures developments [12].

Another unnegligible term in PSA is aging analysis. This may lead to time-dependent changes in engineering properties that may weaken the ability of systems to withstand various impacts from environment and accidents. The nuclear plant aging research program is addressing these concerns for components and systems that may affect safe plant operation [13]. Many of the research works on the impact of aging and deterioration in NPPs have focused on mechanical and electrical components. They could play an active role in mitigating accident sequences that arise from internal or external challenges to the safety-related systems in the plant. In contrast, structures are passive under normal operating conditions but play an essential role in mitigating extreme events initiated by earthquakes, wind and other external influences. Ellingwood described several issues related to structural aging in PSA of NPPs [14].

Correlation of failures and aging of components/subsystems are of two important issues in this field. However, they have been hardly incorporated into the seismic fragility evaluation of a subsystem. Some research programs focus on the correlation of failures while some others are addressing the other. As a matter of fact, these two aspects exist commonly in a real system. They need to be incorporated in seismic PSAs.

This paper aims mainly analysis on correlation of component failures and at the same time aging of components and subsystems are taken into account. First of all, the treatment of correlation is outlined. After that the correlation of failures between components/subsystems is defined. Then the seismic fragility of subsystems is delineated. Moreover, aging-related degradation of components' functions is taken into account in fragility evaluations. In order to demonstrate the approach proposed in the present paper, an example is given to illustrate the generic fragility evaluation of the system by means of Monte Carlo simulation.

TREATMENT OF CORRELATION OF FAILURES IN SEISMIC PSAS

Definition and Nature of Correlation in PSAs

In carrying out the PSA of an NPP, the correlation of failures is quite essential issue in dealing with for calculating the probability of top event of a fault tree (FT) by the minimum cut set (MCS) method. Correlations among failures of components and structures arise from dependencies in many ways. Some of them are functional as are explicitly modeled in the logic models. Others arise from failure of multiple equipment due to a common cause or initiator. Still other dependencies come from treatment of the database [15]. Seismic PSAs have many dependencies due to similarities in both response and capacity parameters. Dependency occurs between components, and between structures with common responses and capacities. For example, if two components are located side by side in a building, there is a high response dependency. The structural capacities of two identical pumps are highly correlated. Thus, if one pump fails due to an earthquake, it is likely that the other pump also fails. This dependency is called correlation of component failures. Here the former is the correlation of responses; the latter is the correlation of capacities.

The correlation of responses is caused by common sources of variability (variation or fluctuation) of responses such as variability of seismic motion, amplification characteristics of soil, response characteristics of buildings, etc. Similarly the correlations of capacities arise from common sources of the capacity variability caused by design, manufacturing, maintenance of the components, etc. [7].

Measures of Correlation

The degree of correlation is measured by correlation coefficient. First, the correlation of failures between two components is defined as given in the following.

Suppose capacities and responses acted on the two components have the following distributions as shown in Table 1.

Table 1 Distribution parameters of capacities and responses

Component	Capacity	Response
1	$g_1(y_1)$ with μ_{f1} and σ_{f1}	$f_1(x_1)$ with μ_{r1} and σ_{r1}
2	$g_2(y_2)$ with μ_{f2} and σ_{f2}	$f_2(x_2)$ with μ_{r2} and σ_{r2}

The correlation coefficient between the two responses, ρ_{r1r2} and the correlation coefficient between the two capacities, ρ_{f1f2} are expressed as

$$\rho_{r1r2}=\frac{E\{[x_1-E(x_1)][x_2-E(x_2)]\}}{\sqrt{D(x_1)}\sqrt{D(x_2)}}=\frac{E(x_1x_2)-E(x_1)E(x_2)}{\sqrt{D(x_1)}\sqrt{D(x_2)}}$$

and

$$\rho_{f1f2}=\frac{E\{[y_1-E(y_1)][y_2-E(y_2)]\}}{\sqrt{D(y_1)}\sqrt{D(y_2)}}=\frac{E(y_1y_2)-E(y_1)E(y_2)}{\sqrt{D(y_1)}\sqrt{D(y_2)}}.$$

Let $\xi_1=x_1-y_1$ and $\xi_2=x_2-y_2$. If $\xi_1>0$, component 1 fails, similarly, $\xi_2>0$, component 2 fails. The correlation coefficient ρ_{12} is then obtained as

$$\rho_{12}=\frac{E\{[\xi_1-E(\xi_1)][\xi_2-E(\xi_2)]\}}{\sqrt{D(\xi_1)}\sqrt{D(\xi_2)}}. \tag{1}$$

If $\rho_{12}=k$ ($0<k<1$), the failure of component 1 and that of component 2 are correlated (dependent). Otherwise, they are independent (no correlation) when $\rho_{12} = 0$ or fully correlated when $\rho_{12} = 1$.

If both $y1$ and $x1$, and $y2$ and $x2$ are independent, Eq (1) can be simplified as

$$\rho_{12} = \frac{E\{[\xi_1 - E(\xi_1)][\xi_2 - E(\xi_2)]\}}{\sqrt{D(x_1)+D(y_1)}\sqrt{D(x_2)+D(y_2)}}$$

$$= \frac{E(x_1x_2) - E(x_1)E(x_2) + E(y_1y_2) - E(y_1)E(y_2)}{\sqrt{D(x_1)+D(y_1)}\sqrt{D(x_2)+D(y_2)}}$$

$$= \frac{E\{[x_1 - E(x_1)][x_2 - E(x_2)]\} + E\{[y_1 - E(y_1)][y_2 - E(y_2)]\}}{\sqrt{D(x_1)+D(y_1)}\sqrt{D(x_2)+D(y_2)}}$$

$$= \frac{\sigma_{r1}\sigma_{r2}}{\sqrt{\sigma_{r1}^2+\sigma_{f1}^2}\sqrt{\sigma_{r2}^2+\sigma_{f2}^2}}\rho_{r1r2} + \frac{\sigma_{f1}\sigma_{f2}}{\sqrt{\sigma_{r1}^2+\sigma_{f1}^2}\sqrt{\sigma_{r2}^2+\sigma_{f2}^2}}\rho_{f1f2}. \quad (2)$$

Suppose the above capacities and responses acted on component 1 and 2 follow lognormal distributions as follows:

$$f_1(x_1) = \frac{1}{\sqrt{2\pi}\beta_{R1}x_1} exp[-\frac{1}{2}(\frac{\ln(x_1)-\mu_{R1}}{\beta_{R1}})^2], \quad f_2(x_2) = \frac{1}{\sqrt{2\pi}\beta_{R2}x_2} exp[-\frac{1}{2}(\frac{\ln(x_2)-\mu_{R2}}{\beta_{R2}})^2];$$

$$g_1(y_1) = \frac{1}{\sqrt{2\pi}\beta_{F1}y_1} exp[-\frac{1}{2}(\frac{\ln(y_1)-\mu_{F1}}{\beta_{F1}})^2], \quad g_2(y_2) = \frac{1}{\sqrt{2\pi}\beta_{F2}y_2} exp[-\frac{1}{2}(\frac{\ln(y_2)-\mu_{F2}}{\beta_{F2}})^2].$$

Here, let $\xi_1 = \ln(x_1/y_1)$ and $\xi_2 = \ln(x_2/y_2)$. If $\xi_1 > 0$ *i.e.*, $x_1/y_1 > 1$, component 1 fails. Similarly, component 2 fails if $\xi_2 > 0$ ($x_2/y_2 > 1$). Similar to the above, if both $y1$ and $x1$, and $y2$ and $x2$ are independent, ρ_{12} can be derived as follows:

$$\rho_{12} = \frac{\beta_{R1}\beta_{R2}}{\sqrt{\beta_{R1}^2+\beta_{F1}^2}\sqrt{\beta_{R2}^2+\beta_{F2}^2}}\rho_{R1R2} + \frac{\beta_{F1}\beta_{F2}}{\sqrt{\beta_{R1}^2+\beta_{F1}^2}\sqrt{\beta_{R2}^2+\beta_{F2}^2}}\rho_{F1F2} \quad (3)$$

where,

$$\rho_{R1R2} = \frac{E\{[\ln(x_1)-\mu_{R1}][\ln(x_2)-\mu_{R2}]\}}{\beta_{R1}\beta_{R2}} = \frac{E[\ln(x_1)\ln(x_2)] - \mu_{R1}\mu_{R2}}{\beta_{R1}\beta_{R2}} \quad (4)$$

and

$$\rho_{F1F2} = \frac{E\{[\ln(y_1)-\mu_{F1}][\ln(y_2)-\mu_{F2}]\}}{\beta_{F1}\beta_{F2}} = \frac{E[\ln(y_1)\ln(y_2)] - \mu_{F1}\mu_{F2}}{\beta_{F1}\beta_{F2}}. \quad (5)$$

For the special case where $\rho_{f1f2} = 0$ and $\rho_{r1r2} = 1$, the correlation coefficient is obtained in a simple manner:

$$\rho_{12} = \frac{\mu_{r1}\mu_{r2}\zeta_{r1}\zeta_{r2}}{\sqrt{\mu_{r1}^2\zeta_{r1}^2+\mu_{f1}^2\zeta_{f1}^2}\sqrt{\mu_{r2}^2\zeta_{r2}^2+\mu_{f2}^2\zeta_{f2}^2}}. \quad (6)$$

According to Eqs (4) and (5), the correlation can be represented in terms of dependence between capacity values or/and between response values assuming both of them range from 0 to infinity. Such dependence comes from two parts: one is uncertainty of median values and the other is randomness of the values conditioned on the known median. Both the median values (uncertainty part) and those conditioned on the known median values (randomness part) can be correlated. For any two components having capacities/responses of above lognormal distributions, the correlation coefficient between capacities or between responses can be expressed by the following equations:

$$\rho = \frac{\beta_1^*\beta_2^*}{\beta_1\beta_2} \quad (7)$$

or

$$\rho = \frac{\beta_c^2}{\beta_1\beta_2} \quad (8)$$

where β_c is the common β-value for the two components. This value is obtained in two steps. First identifying the common parts of the variability in each of the component response and capacity factors. Then combining the common parts with

(SRSS) the square root of the sum of squares procedure [16]. The determination of β_c is very important in seismic fragility evaluation of components.

FRAGILITY EVALUATION OF SUBSYSTEMS

Fragility evaluation of components forms the basis of seismic PSAs of NPPs. Under the seismic hazards, analysis of any specific structure or component has two aspects: the definition of "failure" and the determination of the fragility. The fragility of a component is defined as the conditional probability of its failure as a function of a response parameter (usually as an acceleration parameter), such as peak ground- (PGA) or local spectral-acceleration. A family of "fragility curves" thus generated is typically characterized mathematically with lognormal expressions, anchored to median values and expressed with using various uncertainty parameters to capture both variability from randomness and uncertainty from lack of knowledge [17].

Consider failures of two components 1 and 2 under earthquake intensity a (PGA), the failure probabilities for 1 and 2 are given by definitions:

$$P_1(a)=\mathrm{P}(c_1 < a_{g1}), \tag{9}$$

$$P_2(a)=\mathrm{P}(c_2 < a_{g2}), \tag{10}$$

where c_1 and c_2 are component capacities, $a_{g1}= f_{g1}(a)$ and $a_{g2}= f_{g2}(a)$ are accelerations of responses due to the peak ground acceleration of an earthquake. Considering correlation between capacities, c_1 and c_2 can be expressed by $c_1'x$ and $c_2'x$. Here, c_1' and c_2' represent the independent parts of capacities whereas x is the common dependent part. Then the failure probability $P_1(a)$ and $P_2(a)$ can be given by follows:

$$P_1(a)=\mathrm{P}(c_1' < a_{g1}/x), \tag{11}$$

$$P_2(a)=\mathrm{P}(c_2' < a_{g2}/x). \tag{12}$$

Now, $P_{1\cap 2}(a)$, the probability of both components in failure and $P_{1\cup 2}(a)$, that of at least one in fault can be obtained by the following equations:

$$P_{1\cap 2}(a)= \int_0^{\infty} P\,(c_1' < a_{g1}/x)\,\mathrm{P}(c_2' < a_{g2}/x)\, p(x)\, dx, \tag{13}$$

$$P_{1\cup 2}\,(a)= P_1(a) + P_2(a) - P_{1\cap 2}(a) \tag{14}$$

where, $p(\mathrm{x})$ is probability density function of variable x.

In the case of lognormal distributions of capacities as given by $LN(m_{R1}, \beta_{R1})$ for c_1, $LN(m_{R2}, \beta_{R2})$ for c_2 and $LN(1.0, \beta_R^*)$ for x, $P_{1\cap 2}(a)$ and $P_{1\cup 2}(a)$ are obtained by the following integrations.

$$P_{1\cap 2}\,(a)= \int_0^{\infty} \Phi\left[\frac{1}{\beta_{R1}'}\ln(\frac{a_{g1}}{xm_{R1}})\right] \times \Phi\left[\frac{1}{\beta_{R2}'}\ln(\frac{a_{g2}}{xm_{R2}})\right] \phi\left(\frac{\ln x}{\beta_R^*}\right)\frac{dx}{x\beta_R^*}, \tag{15}$$

$$P_{1\cup 2}\,(a)=1- \int_0^{\infty} \left\{1-\Phi\left[\frac{1}{\beta_{R1}'}\ln(\frac{a_{g1}}{xm_{R1}})\right]\right\} \times \left\{1-\Phi\left[\frac{1}{\beta_{R2}'}\ln(\frac{a_{g2}}{xm_{R2}})\right]\right\} \phi\left(\frac{\ln x}{\beta_R^*}\right)\frac{dx}{x\beta_R^*}. \tag{16}$$

In the above equations, β_R^* is the portion of the randomness in logarithmic standard deviation common to the both components while β_{R1}' and β_{R2}' are obtained from the following equations:

$$\beta_{Ri}' = (\beta_{Ri}^2 - \beta_R^{*2})^{1/2}. \tag{17}$$

Details of how to determine the values of β_{R1}', β_{R2}' and β_R^* can be referred to [16].

FRAGILITY EVALUATION OF SUBSYSTEMS WITH AGING COMPONENTS

As a universal phenomenon, capacities of components deteriorate due to aging of materials, external impacts including earthquakes, wind and corrosions. Because of the aging impact, the median value of capacity decreases and the variability also increases with the elapsing time. In the following, the age-related deterioration factor is introduced into seismic fragility evaluation.

A procedure based on the Monte Carlo simulation is taken to simulate the age-related deterioration of median capacities of components and structures. Considering the impacts of strong earthquakes on median capacities, the value mutations of associated distribution parameters will occur at the time of stronger earthquake occurrence. These two aspects which bring about changes of parameters are included in the Monte Carlo simulation. The flow chart is shown in Fig. 1.

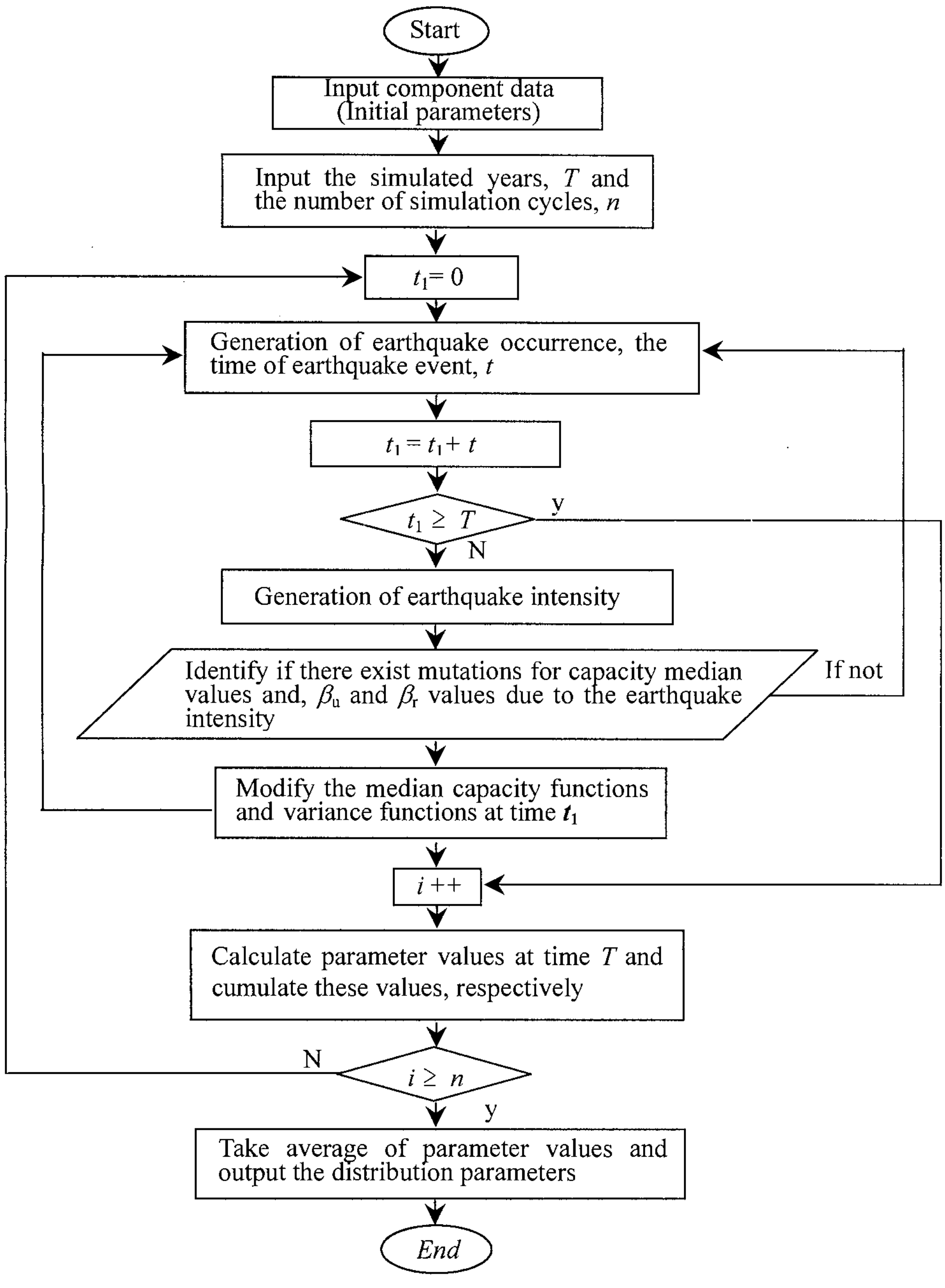

Fig. 1 Flow chart of the Monte Carlo simulation

AN EXAMPLE

The above procedure is applied to a subsystem, which is composed of three components A, B and C. Component A has capacity correlation with B and C, respectively. Further, B and C have capacity correlation. Their distribution and correlation parameters are shown in Table 2.

The next step is to consider the impacts of aging and earthquake events occurred in the past on seismic fragility of the subsystem. The median value, m_r is time's function, which is evaluated by $m_r(t) = m_r(t_0) - \gamma t$, where $m_r(t_0)$ is the initial value of m_r and t_0 is the initial time. The coefficient, γ, depends on the aging inherent law. It may be a function of time. Both other parameters β_r and β_u can be expressed in a similar manner. In case an earthquake occurs at some time, t, the values of $m_r(t)$ will decrease with a mutation of it and the other two terms of β_r and β_u may also have increase with some magnitude corresponding to the earthquake intensity. In such a manner, a Monte Carlo simulation is carried out to estimate these values of the parameters at a predetermined time, for example, 50 years. Then the seismic fragility evaluation of the subsystem in the 50th year in future can be obtained. In the simulation, the strong earthquake hazard rate in an area is given 1×10^{-2}/year. The earthquake intensity follows a lognormal distribution, $LN(0.62, 0.45)$. Earthquake intensities are divided into 5 grades that represent the degrees of impacts on system structures. Age-related deterioration law of capacities is obtained from synthetic analyses and by referring to opinions of experts. Parameter values are assumed to increase or decrease a corresponding range in a proportion to earthquake degrees. In the manner, the Monte Carlo simulation is carried out according to the initial values shown in Table 2 and the parameter values in the 50^{th} year are obtained through associating with judgments of experts as shown in Table 3. In the table, the correlation coefficient between A and B is 0.44 while the correlation coefficients are 0.46 and 0.39 in uncertainty portion and randomness aspect (assuming no change in the simulation), respectively. The correlation coefficient between A and C is 0.50 while 0.43 is associated with uncertainty and 0.67 reflects the degree of correlation in randomness portion.

Table 2 Distribution and correlation parameters of components A, B and C

Component Properties				Group Dependencies			
						Common Variability	
Components	m_r (g)	β_u	β_r	Group	Components	β_u*	β_r*
A	0.73	0.28	0.30	1	A, B	0.20	0.18
B	0.73	0.33	0.28	2	A, C	0.16	0.20
C	0.86	0.27	0.24				

Table 3 Distribution and correlation parameters of components A, B and C

Component Properties				Group Dependencies			
						Common Variability	
Components	m_r (g)	β_u	β_r	Group	Components	β_u*	β_r*
A	0.51	0.45	0.30	1	A, B	0.31	0.18
B	0.61	0.46	0.28	2	A, C	0.27	0.20
C	0.71	0.38	0.24				

Table 4 Selection of median values

Sample	Independent			Dependent		Correlated values (g)		
	A	B	C	A, B	A, C	A	B	C
	m_{rA}=0.51, β_{uA}'=0.18,	m_{rB}=0.61, β_{uB}'=0.34,	m_{rC}=0.71 β_{uC}'=0.27	$m_{A,B}$=1.0 β_u*=0.31	$m_{A,C}$=1.0 β_u*= 0.27	m_{RA}	m_{RB}	m_{RC}
1	0.546	1.10	0.232	0.919	0.913	0.458	1.01	0.212
2	0.427	0.806	0.902	1.24	0.823	0.436	0.999	0.742
3	0.210	0.460	0.753	0.919	1.65	0.482	0.423	0.489
4	0.585	0.139	0.691	1.81	0.420	0.445	0.252	0.290
5	0.833	0.633	1.21	0.347	1.02	0.295	0.220	1.23
6	0.468	0.552	0.587	0.759	1.26	0.465	0.419	0.740

The values shown in columns A, B and C (independent) and those in (A,B) and (A,C) in Table 4 are taken from Latin Hypercube sampling. Where, β'_{ui} is taken by

$$\beta'_{ui} = (\beta_{ui}^2 - \Sigma \beta_{uj}^{*2})^{1/2} \quad (i = \mathrm{A}, j = 1 \text{ and } 2;\ i = \mathrm{B}, j = 1 \text{ and } i = \mathrm{C}, j = 2). \tag{18}$$

Then the values in columns A, B and C (correlated) are generated by a scaling, for example, 0.458 in column A (correlated value) is calculated by 0.546×0.919×0.913. The conditional failure probability of system is evaluated by

$$P_{A\cup B\cup C}(a) = \frac{1}{0.18\times0.20}\int_0^{\infty}\int_0^{\infty}\left\{1-\left(1-\Phi\left[\frac{1}{\beta'_{RA}}\ln(\frac{a_{g1}}{x_1 x_2 m_{RA}})\right]\right)\left(1-\Phi\left[\frac{1}{\beta'_{RB}}\ln(\frac{a_{g2}}{x_1 m_{RB}})\right]\right)\right.$$

$$\left(1-\Phi\left[\frac{1}{\beta'_{RC}}\ln(\frac{a_{g3}}{x_2 m_{RC}})\right]\right)\Bigg\}\phi\left(\frac{\ln x_1}{0.18}\right)\phi\left(\frac{\ln x_2}{0.20}\right)\frac{dx_1}{x_1}\frac{dx_2}{x_2}, \quad (19)$$

where,

$$\beta'_{Ri}=(\beta_{ri}^2-\sum\beta_{rj}^{*2})^{1/2} \quad (i=\mathrm{A}, j=1 \text{ and } 2;\ i=\mathrm{B}, j=1 \text{ and } i=\mathrm{C}, j=2). \quad (20)$$

In the real example, $a_{g1}=0.80a$, $a_{g2}=0.75a$ and $a_{g2}=0.80a$ are taken. The fragility curves of the system are obtained as shown in Fig. 2. This figure offers us information of seismic risk in future, which is of significance for us to maintain and to control the operation of an NPP.

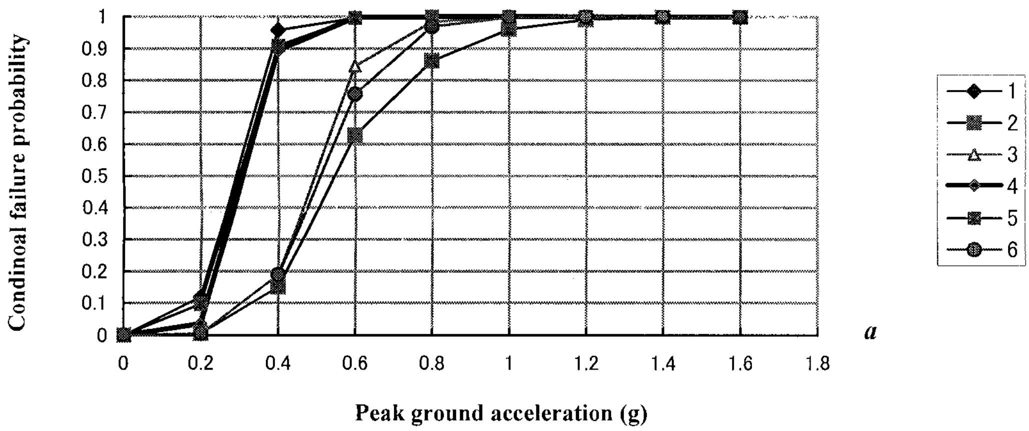

Fig. 2 Seismic fragility curves

The example can be extended to be applied to fragility evaluation of subsystems in NPPs such as one consisting of auxiliary building shear wall, pump enclosure of crib house roof collapse and interconnecting piping when considering the correlation between each other.

CONCLUSIONS

Two important issues involved in PSAs of NPPs are the treatment of correlation failures between components or between structures, and their aging analysis. It concerns a more complex process to incorporate these two aspects into seismic PSAs of NPPs. In the paper, the correlation failure between components is described in detail. As the basis of PSAs of NPPs, the seismic fragility evaluation for components is developed to a subsystem involving correlations between components and/or structures, where aging impacts on seismic fragilities are taken into account. The aging impacts can be quantified through the identification by experts and by means of the Monte Carlo simulation. The reduced median capacities of components and structures induced from aging and mutation in median capacity values due to earthquake events happened in the past are incorporated into the subsystem fragility evaluation.

In order to illustrate the method developed in this paper, an example is analyzed. Through it, however, the important issue for getting reliable solution of interests is placed on accurate analysis on aging mechanisms of components/structures and accumulation of knowledge on identification of mutations in median capacity values induced from earthquakes.

ACRONYMS & NOMENCLATURES

NPP	=	nuclear power plant
PSA	=	probabilistic safety assessment
PGA	=	peak ground acceleration
$D(\cdot)$	=	variance of a variable
$\Phi(\cdot)$	=	the standardized cumulative normal distribution
$\phi(\cdot)$	=	the standardized normal density function
$f_i(x)$	=	probability density function of response i
$g_i(y)$	=	probability density function of capacity i
$E(X)$	=	expectation of variable X

$LN(\mu, \beta)$ = lognormal distribution with pdf of $\frac{1}{\sqrt{2\pi}\beta\, x} exp[-\frac{1}{2}(\frac{\ln(x/\mu)}{\beta})^2]$

m_r = median value of capacity of a component

β_u = logarithmic standard deviation associated with uncertainty portion

β_r = logarithmic standard deviation associated with randomness portion

β_u^* = logarithmic standard deviation of common variability associated with uncertainty portion

β_r^* = logarithmic standard deviation of common variability associated with randomness portion

β_{ui}' = logarithmic standard deviation of independent variability associated with uncertainty portion, i = A, B, C

β_{Ri}' = logarithmic standard deviation of independent part associated with randomness portion, i = A, B and C

σ_{fi} = standard deviation of a capacity distribution, $i = 1, 2$

σ_{ri} = standard deviation of a response distribution, $i = 1, 2$

μ_{fi} = mean of a capacity distribution, $i = 1, 2$

μ_{ri} = mean of a response distribution, $i = 1, 2$

ζ_{fi} = coefficient of variation of a capacity distribution, $i = 1, 2$

ζ_{ri} = coefficient of variation of a response distribution, $i = 1, 2$

REFERENCES

1. Newmark N.W., Hall W., "Development of Criteria for Seismic Review of Selected Nuclear Power Plants", Report NUREG/CR-0098, U.S. Nuclear Regulation Commission, 1978.
2. Kennedy R.P., et al., "Probabilistic Seismic Safety Study of An Existing Nuclear Power Plant", *Nuclear Engineering and Design*, Vol. 59, 1980, No. 2, pp. 315-338.
3. Smith P.H., et al. "Seismic Margins Research Program", Phase I Final Report-Overview, Vol.1, NUREG/CR-2015, 1981.
4. Cover L.E., et al., "Handbook of Nuclear Power Plant Seismic Fragilities", Report NUREG/CR-3558, Lawrence Livermore National Laboratory and U.S. Nuclear Regulatory Commission, 1985.
5. Cummings G.E., "Summary Report on The Seismic Safety Margins Research Program", Report NUREG/CR-2015, in 10 Volumes, Lawrence Livermore National Laboratory and U.S. Nuclear Regulatory Commission, 1986.
6. Duke Power Company, McGuire Nuclear Station IPEEE Submittal Report, 1994.
7. Oikawa T., Kondo M., Mizuno Y., et al., "Development of Systems Reliability Analysis Code SECOM-2 for Seismic PSA", *Reliab. Engineering & System Safety*, Vol. 62, 1998, No. 3, pp. 251-271.
8. Kondo S., and Muramatsu K., "Editorial: Seismic PSA for NPP Safety Design and Assessment", *Reliab. Engineering & System Safety*, Vol. 62, 1998, pp. 155-156.
9. Muramatsu K, et al., "Development of Seismic PSA Methodology at JAERI", *The Third International Conference on Nuclear Engineering* (ICONE-3), 1995.
10. Sobajima M., et al., "Seismic Probabilistic Safety Assessment Methodology Development and Application to A Model Plant", *The Tenth Pacific Basin Nuclear Conference*, Kobe, 1996.
11. Fukuoka H., et al., "Reliability Analysis in Seismic Probabilistic Safety Assessment and Application of The SECOM Code", PSA'93, Clearwater Beach, 1993.
12. Humphey P., Jenkins A.M., "Dependent Failures Developments", *Reliab. Engineering & System Safety*, Vol. 34, 1991, No. 3, pp. 417-427.
13. Vora J.P., et al., "Nuclear Plant Aging Research (NPAR) Program Plan", Report NUREG-1144, Washington DC: US Nuclear Regulatory Commission, 1991.
14. Ellingwood B.R., "Issues Related to Structural Aging in Probabilistic Risk Assessment of Nuclear Power Plants", *Reliab. Engineering & System Safety*, Vol. 62, 1998, 171-183.
15. Rasmuson D.M., "Some Practical Considerations in Treating Dependencies in PRAs", *Reliab. Engineering & System Safety*, Vol. 34, 1991, pp. 327-343.
16. Reed W. J. et al. "Analytical Techniques for Performing Probabilistic Seismic Risk Assessment of Nuclear Power Plants", ICOSSAR'85, Vol. III, *The 4th International Conference on Structural Safety and Reliability*, pp. 253-263.
17. NEA/CSNI/R(97)22 (1997), pp. 12-34.