An approach of Evaluation Method for Seismic Fragility Correlation based on Earthquake Data

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1. Introduction

After Fukushima accident which caused by catastrophic disasters, concerns for earthquake and tsunami are being raised. The one of challenging issues in seismic probabilistic safety assessment (SPSA) is how to consider seismic fragility correlations between components or structures. Because it was proved that seismic fragility correlation affects a risk seriously [1], a development of clear guidance is needed to estimate seismic fragility correlation.

2. Seismic Fragility Correlation: A Review

There have been many considerable studies to consider the seismic fragility correlation between the components or structures. However, an untied method or rule which takes into account seismic fragility correlation realistic is not yet proposed although there have been considerable researches established by experts. The researches were based on theoretical modeling and judgments instead of data owing to absence of earthquake data. In this chapter, some representative methods are introduced.

2.1 Seismic Safety Margins Research Program (SSMRP)

The seismic safety margins research program (SSMRP) was performed in the early 1980s. The rules for assigning seismic response correlation between two components placed at same or different positions under the same earthquake, generally called as the thumb rule, were proposed by Bohn and Lambright [2,3], as shown in Table I. As well as developing the seismic response correlation rule, the correlated failure probability of components or structures was proposed. It was calculated by systematic evaluation of important safety improvement measures (SEISIM) code. SSMRP has been used in most of the classical SPSA, however, the real world is more complicated and a sophisticated approach is needed.

2.2 Japan Nuclear Energy Safety Organization (JNES)

The research team in Japan nuclear energy safety organization (JNES) led by Ebisawa [4] focused on developing the correlation coefficient matrix of seismic response between two components by using a computational simulation code instead of following the thumb rule. They performed sensitivity studies with the various heights of installation, damping factors and periods assuming specific input seismic motions and building structure. This method can be applied to both intra-unit and inter-unit NPPs. They also defined capacity correlation coefficient as 1 for components in a same building and 0 for components in different buildings. The correlation coefficient matrix for one example is shown in Fig. 1.

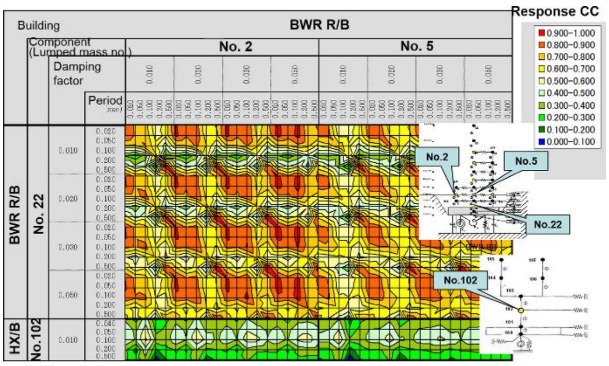

Fig. 1. Correlation coefficient matrix obtained by JNES

Table I: Rules for assigning response correlation

1. Components on the same floor slab, and sensitive to the same spectral frequency range (i.e. zero period acceleration (ZPA), 5–10 ZHz, or 10–15 Hz) will be assigned response correlation = 1.0
2. Components on the same floor slab, sensitive to different ranges of spectral acceleration will be assigned response correlation = 0.5
3. Components on different floor slabs (but in the same building) and sensitive to the same spectral frequency range (ZPA, 5–10 Hz or 10–15 Hz) will be assigned response correlation = 0.75
4. Components on the ground surface (outside tanks, etc.) shall be treated as if they were on the grade floor of an adjacent building
5. 'Ganged' valve configurations (either parallel or series) will have response correlation = 1.0
6. All other configurations will have response correlation equal to zero

2.3 Reed et al.

Reed et al. proposed the other approach to estimate seismic fragility correlation between components failures [5]. They separated capacity of components into an independent part and a common part meaning the dependency. The correlated probability of failure between components are calculated by assuming lognormal distribution with two types of correlation coefficients: an uncertainty part and a randomness part.

2.4 Korea Atomic Energy Research Institute (KAERI)

The research team in Korea atomic energy research institute have been studied seismic fragility correlation, especially in multi-unit NPPs [6]. In single-unit NPP, it was simply assumed that the components located at the same floor had fully dependencies and those located at the different floor had independencies. In case of multi-unit NPPs, the correlation coefficient between two components in different is defined first. And then, n/n CCF alpha factor is calculated by dividing the probability simultaneous failure of n components with a defined correlation coefficient into that of n components with a fully dependency. The other CCF alpha factors (1/n, 2/n, …, n-1/n) are obtained by using the ratio of generic CCF alpha factors provided in NUREG report [7]. It also has a difficult to define correlation coefficient between two components.

3. A New Approach based on Earthquake Data

Although there have been many theoretical and analytical methods which consider seismic fragility correlation as introduced in chapter 2, it is necessary to develop a data based method for estimating probability of failure practically. The database has been built by seismic qualification utility group (SQUG) organized by EPRI in the early 1980s. They gathered the earthquake data occurring in general power plants as well as NPPs because few accidents happened in NPPs. While there are increasing data, many assumptions are needed to develop the data based model because there are limitations to access some information. In this chapter, a new conceptual approach based on earthquake data is proposed.

3.1 Approach

In order to apply seismic fragility correlation in SPSA, it is needed to propose some factors such as CCF factors. The factors are called seismic alpha factors. We modified the method for calculating CCF alpha factor in accordance with NUREG report [8] to consider seismic factors. Four steps are needed to estimate seismic alpha factors as shown in Fig. 2.

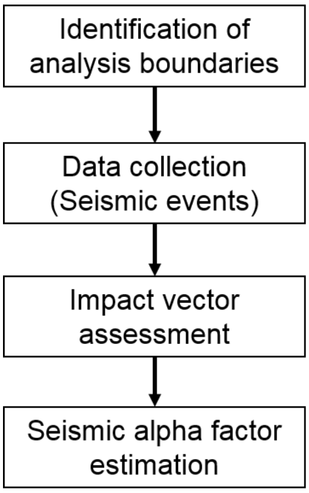

Fig. 2. Flowchart for seismic alpha factor estimation

For simplicity of the analysis, identical components with identical anchorage and materials were only considered.

- Identification of analysis boundaries: The components that you want to analyze are identified.
- Data collection: A data table is made by using collected event data which is relevant to the component identified in the previous step. The essential effective factors to be filled up in the table are as follows.
  - Degradation factor (p): Partial degradation
  - Timing factor (q): Simultaneity
  - Shared cause factor (c): Common cause
  - Location factor (Elevation factor (h), Distance factor (L)): Installation height and distance
  - Orientation factor (i): Installed orientation of components
  - Natural frequency of buildings (f)
  - Damping factor (d)

  Upper three effective factors were only used when estimating general CCF alpha factor. In here, additional five factors were considered to include seismic behaviors. They were selected by referring some documents [2, 4]. Also, they could be estimated quantitatively based on various states of components by referring the values of the upper three effective factors determined in NUREG report [8]. It is explained in Table II. It is necessary to modify this table certainly, because there are some uncertainties in both component conditions and the values.

Table II. Quantitative representation of effective factors

Effective Factors		Quantitative Representation	Note
Degradation factor (*p*)		Failed, p=1.00 // Highly degraded, p=0.50 // Degraded, p=0.10 // Incipient, p=0.01 // No Failure, p=0.00	NUREG-6268
Timing factor (*q*)		For operating components, Failure<one PRA mission time, q=1.00 // one PRA mission time < Failure <1 month, q=0.50 // 1 month < Failure, q=0.10 // one test interval < Failure, q=0.00	NUREG-6268 q=1 for earthquake
Shared cause factor (*c*)		Very high, c=1.0 // High, c=0.50 // Moderate, c=0.10 // Low, c=0.01 // No coupling, c=0.00	NUREG-6268 c=1 for earthquake
Location factor	Elevation factor (*h*)	Same floor, h=1.0 // 1 floor difference, h=0.50 // 2 floors difference, h=0.10 // 3 floors difference, h=0.01 // 4 floors or more difference, h=0.00	
	Distance factor (*L*)	Same building, L=1.0 // Adjoining buildings, L=0.50 // The buildings with one-building interval, L=0.10 // The buildings with two-buildings interval, L=0.01 // The buildings with three or more-buildings interval, L=0.00	
Orientation factor (*i*)		Same orientation, i=1.0, Different orientation, i=0.50	
Natural frequency of buildings (*f*)		Difference of natural frequencies < 1Hz, f=1.0 // 1Hz < Difference of natural frequencies < 3Hz, f=0.50 // 3Hz < Difference of natural frequencies < 5Hz, f=0.10 // 5Hz < Difference of natural frequencies, f=0	
Damping factor (*d*)		Difference of damping factors < 1%, d=1.0 // 1% < Difference of damping factors < 3%, d=0.50 // 3% < Difference of damping factors < 5%, d=0.10 // 5% < Difference of damping factors, d=0	

- Impact vector assessment: The seismic impact vector ($\overline{I_s}$) is calculated by using Eq. (1) which is slightly modified from the equation in the NUREG report [8]. The term $\bar{F}_{sn}$ meaning the n components failure out of k components is expressed in Table III. In here, the term *Es* is the multiplication of seismic effective factors (*hLifd*), meaning an overall measure of dependency. The terms F_0, F_1, …, F_k are found in the NUREG report [8].

$$\overline{I_s} = I_{s,CCF} + I_{s,C1} + I_{s,C2} + \cdots + I_{s,Ck} = [\bar{F}_{s0}, \bar{F}_{s1}, \bar{F}_{s2}, \ldots, \bar{F}_{sk}] \qquad (1)$$

Table III. The elements of seismic impact vector

Elements	Expression
$\bar{F}_{s0}$	$E_sF_0+(1-E_s)(1-p_1)+\cdots+(1-E_s)(1-p_k)$
$\bar{F}_{s1}$	$E_sF_1+(1-E_s)p_1+\cdots+(1-E_s)p_k$
$\bar{F}_{s2}$	E_sF_2
$\vdots$	$\vdots$
$\bar{F}_{sk}$	E_sF_k

- Seismic alpha factor estimation: Seismic alpha factors is calculated through Eq. (2).

$$\alpha_{sk} = \frac{\bar{F}_{sk}}{\sum_{j=1}^{n} \bar{F}_{sj}} \qquad (2)$$

3.2 Case study

- Identification of analysis boundaries: Failure of four feed-water (FW) pumps in two units. Failure of two FW pumps in unit 4 and failure of two FW pumps in unit 5.
- Data collection: Data table was made, as shown in Table IV. The information which were not confirmed in SQUG database were assumed appropriately. The assumed information are marked with *. All feed-water pumps were located on ground level. The FW pumps 1, 2 and 3 were assumed to be highly degraded (p=0.5), and a FW pump 4 was assumed to be degraded (p=0.1). Also, the FW pumps in unit 4 were located with different orientation comparing with the FW pumps in unit 5. Natural frequencies of unit 4 and 5 are same, whereas damping factors of unit 4 and 5 are 2% and 5% respectively.
- Impact vector assessment: The impact vector was obtained by Eq. (1).
  $\overline{I_s}$=[1.19, 1.26, 0.156, 0.0313, 0.00781]
- Seismic alpha factor estimation: Seismic alpha factor was calculated by Eq. (2).
  α_{s1}=0.8668, α_{s2}=0.1066, α_{s3}=2.131E-02, α_{s4}=5.329E-03.

4. Conclusion and Future Work

There have been many researches to estimate the seismic correlation between components, however, it is necessary to develop an evaluating method based on earthquake data. An approach based on earthquake data was established by modifying the procedure which is used to obtain general CCF alpha factor in accordance with NUREG report [8]. It is not developed perfectly and is needed to be modified seriously because there are many kinds of uncertainty and assumption caused by absence of information. It is needed to reduce those uncertainties and to verify assumptions by performing computational mechanical analysis. The seismic effective factors which determine a degree of dependency can be modified through the sensitivity studies.

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Table IV. Earthquake data table

Earthquake Data Sheet							
Plant		Plant A		Year		1993	
Earthquake		Guam Earthquake		Magnitude		8.0	
Component		Feed-water Pumps		Total number		4	
				Damaged number		4	
Location		Ground floor of turbine building					
Cause		Misalignments between motor and pump					
Elevation factor (h)		1.0		Distance factor (L)		1.0/0.5*	
Orientation factor (i)		1.0/0.5*					
Natural frequency (f)		1.0*		Damping factor (d)		1.0/0.5*	
Component Degradation Values (p)							
	p	Date	Time		p	Date	Time
1	0.5*	8/10/93	14:00	3	0.5*	8/10/93	16:00
2	0.5*	8/10/93	14:30	4	0.1*	8/10/93	16:30