IMPROVEMENT OF UNCERTAINTY TREATMENT OF SUB-RESPONSE FACTOR RELATED TO IN-PUT SEISMIC MOTION ON FRAGILITY EVALUATION OF SEISMIC PRA

Katsumi Ebisawa[1], Hiroyuki Yamada[2], Kazuhiro Kikuchi[3], Takeshi Ugata[4] Yoshinobu Mihara[5], Kohei Tanaka[6], Tsuyoshi Takada[7], Ryusuke Haraguchi[8]

[1]Nuclear Risk Research Center (NRRC), Central Research Institute of Electric Power Industry (CRIEPI): 1-6-1 Ootemachi, Chiyoda-ku,Tokyo, 100-8126, ebisawa@criepi.denken.or.jp
[2] Nuclear Risk Research Center (NRRC), Central Research Institute of Electric Power Industry (CRIEPI): 2-11-1 Iwadokita, Komae-shi, Tokyo, 201-8511, yamada@criepi.denken.or.jp
[3] Nuclear Research & Training Center, Shikoku Electric Power Co., Inc.: 6-1-2 Minatomachi, Matsuyama-shi, Ehime, 790-0012, kikuchi13981@yonden.co.jp
[4] Nuclear Facilities Division, Taisei Corporation: 1-25-1 Nishi Shinjyuku, Shinjyuku-ku, Tokyo, 163-0606, ugata@eng.taisei.co.jp
[5] Nuclear Power Department, Kajima Corporation.: 6-5-11 Akasaka, Minato-ku, Tokyo, 107-88348, y-mihara@kajima.com
[6] Center for Railway Earthquake Engineering Research, Railway Technical Research Institute.: 2-8-38 Hikari-cho, Kokubunji-shi, Tokyo, 185-8540, khtnk@rtri.or.jp
[7] Department of architecture graduate school of engineering, The University of Tokyo: 7-3-1 Hongo, Bunkyo-ku, Tokyo, 185-8540, takada@load.arch.t.u.-tokyo.ac.jp
[8] Nuclear Energy System Division, Energy & Environment, Mitsubishi Heavy Industries, Ltd.: 1-1-1 Wadasaki-cho, Hyogo-ku, Kobe, Hyogo, 652-8585, ryusuke_haraguchi@mhi.co.jp

Fragility of structure and component (SC) on seismic PRA is evaluated as conditional failure probability that realistic response of SC exceeds their capacity. Both realistic response and capacity are assumed to follow logarithmic standard distribution that is represented by median and logarithmic standard deviation (LSD). Authors improve about the following issues (1)-(3) and propose new methodology. (1) to clarify the rationality regarding treatment of zero-value of LSD (aleatry uncertainty: βr, Epistemic uncertainty: βu) related to sub-response factor, (2) To clarify the treatment of uncertainty factor of input seismic motion, (3) To clarify the rationality regarding βr and βu values of sub-response factor *of component. Through these examination, it was found that the above improvement is reasonable and practical.*

I. INTRODUCTION

Fragility of structure and component (SC) on seismic PRA is evaluated as conditional failure probability that realistic response of SC exceeds their capacity. In fragility evaluation, simple and detailed methodologies are proposed (Ref. 1 and 2)

Center Research Institute of Electric Power Industry established Nuclear Risk Research Center (NRRC) and Technical Adviser Committee (TAC) in NRRC on October 2014. TAC consists of experts of home and abroad. NRRC has been discussing with TAC about various issues related to seismic PRA.

The issues related to fragility evaluation are as follows.

(1) General consideration regarding fragility evaluation, especially consideration of uncertainty factors should be clarified.
(2) Rationality regarding utilization of zero-value of logarithmic standard deviation (aleatry uncertainty: βr, Epistemic uncertainty: βu) regarding sub-response factor should be clarified if necessary.
(3) Treatment of uncertainty factor of input seismic motion should be clarified.
(4) Seismic response of component should be considered appropriately considering non-linear characteristics of buildings.
(5) βr and βu values of component seem smaller than those in the US study. These values should be clarified.

Basic policy of examination of NRRC against these issues is as follows.

(i) To analyze and examine relevant US reports, such as EPRI reports, and grasp the current standing of fragility evaluation in Japan and the U.S.,
(ii) In US reports, To include the latest information on Diablo Canyon NPP,

(iii) To reflect to Japanese fragility evaluation steps as necessary.

NRRC has been conducting the various examination based on the above policy and proposing new methodologies regarding fragility evaluation.

This paper describes chapter III about the above (1) and (2), chapter IV about (3) and chapter V about (5). The (4) describes in the other paper in PSAM 13

II. FORMULA OF FRAGILITY EVALUATION

Fragility $F(\alpha)$ of SC is evaluated as conditional failure probability that realistic response of SC exceeds their capacity. Both realistic response and capacity are assumed to follow logarithmic standard distribution that consists of median and logarithmic standard deviation (LSD). $F(\alpha)$ is represented by the following Eq. (1)

$$F(\alpha)=\int_0^\infty f_R(\alpha,x_R)\left(\int_0^{x_R} f_S(x)dx\right)dx_R \tag{1}$$

Where $f_R(\alpha,x)$ is realistic response of SC, $f_S(x)$ their capacity and α PGA at bed rock.

$f_R(\alpha,x)$ is represented by Eq. (2).

$$f_R(\alpha,x)=\frac{1}{\sqrt{2\pi}\beta_R(\alpha)\cdot x}\exp\left\{-\frac{1}{2}\left(\frac{\ln(x/R_m(\alpha))}{\beta_R(\alpha)}\right)^2\right\} \tag{2}$$

Where $R_m(\alpha)$ is median and $\beta_R(\alpha)$ LSD.

Meanwhile, $f_S(x)$ is represented by Eq. (3).

$$f_S(x)=\frac{1}{\sqrt{2\pi}\beta_S\cdot x}\exp\left\{-\frac{1}{2}\left(\frac{\ln(x/S_m)}{\beta_S}\right)^2\right\} \tag{3}$$

Where S_m is median and β_S LSD.

In seismic PRA implementation standard of the Atomic Energy Society of Japan (AESJ), simple method that is called the JAERI method is described as shown in Fig.1 (Ref.2). In this method, assume that $f_R(\alpha,x)$ is in proportion to design response q^D against design seismic motion α_D at bed rock, $f_R(\alpha,x)$ is represented by Eq. (4). Uncertainty of q^D is represented as response factor that follows logarithmic standard distribution (median and LSD). Median F_{Rm} and LSD β_R of response factor are represented by Eq. (5) and Eq. (6), respectively. Non-linearity of $f_R(\alpha,x)$ is represented as energy absorption factor F_μ that is similar to the Zion Method.

$$f_R(\alpha,x)=\frac{1}{\sqrt{2\pi}\beta_R x}\exp\left[-\frac{1}{2}\left\{\frac{\ln\left(x/(\frac{q^D}{F_{Rm}}\cdot\frac{\alpha}{\alpha^D}\cdot\frac{1}{F_\mu})\right)}{\beta_R}\right\}^2\right] \tag{4}$$

$$\overline{F_{R_m}}=\prod_{i=1}^{4}\overline{F_i} \tag{5}$$

$$\beta_R=\sqrt{\sum_{i=1}^{4}\beta_i^2} \tag{6}$$

Where suffix i is uncertainty factors of realistic response and F1 – F4 described in chapter III.A.

Meanwhile, $f_S(x)$ is represented as the above Eq. (3).

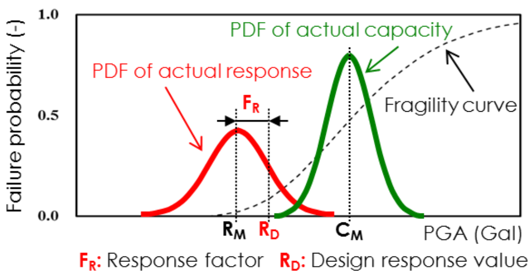

Fig.1 – PDF of conventional simple method

III. CLARIFICATION OF UNCERTAINTIES IN REALISTIC RESPONSE AND EXAMINATION REGARDING ZERO-VALUE OF LOGARITHMIC STANDARD DEVIATION

III.A. CLARIFICATION OF UNCERTAINTY FACTORS RELATED TO REALISTIC RESPONSE

In Japan, fragility evaluation method is described in the seismic PRA implementation standards of the AESJ (Ref.2). Authors have analyzed U.S. reports regarding fragility evaluation (Ref.1 and 3-11). The treatment of uncertainty factors regarding realistic response and capacity was basically the same in both Japan and the US. Uncertainty factors related to realistic response were very similar in both countries as shown in Table 1. The suffix of sub-factors in Table 1 is the normal notes that are represented in Japan and the US, respectively.

(1) Uncertainty factors regarding input seismic motion (F1)
(2) Uncertainty factor regarding soil response (F2)
(3) Uncertainty factors regarding building response (F3)
(4) Uncertainty factor regarding component response (F4)

The difference in both countries is caused by the type of foundation soil. The facilities in the US are built on soil foundation. On the other hand, Japanese important facilities are built on bed rock according to the regulation.

Table 1 Uncertainty factors related to realistic response

Uncertainty factors for realistic response	
(1) Uncertainty factor regarding input motion (F1) ① Seismic motion factor (F11)/ Ground motion (Fss)	(3) Uncertainty factors regarding building response (F3) 3-1) Modal analysis method <non consideration in Japan ①Ground motion incoherence factor (F31/Fgmi) ② SSI factor (including uplift) (F32)/SSI analysis (Fssi) ③ Building damping factor (F33/Fd) ④Building modeling factor (F34/Fm) ⑤ Building mode combination factor (F35/Fmc) ⑥ Building earthquake component combination(36/cc) ⑦ Building inelastic energy absorption factor (F37/Fμ) 3-2) Direct integration method <Consideration in Japan> ①Ground motion incoherence factor (F31/Fgmi) ② SSI factor (including uplift) (F32)/SSI analysis (Fssi) ③ Building damping factor (F33/Fδ) ④ Building modeling factor (F34/Fm) ⑤ Building non linear factor (Including Uplift) (F35/Fnl)
(2) Uncertainty factor regarding soil response(F2) ①Soil amplification factor (F21)/ Vertical spatial variation of ground motion (Fs)	
(4) Uncertainty factor regarding component response (F4) ① Equipment spectral shape factor (F41/Fess) ② Equipment damping factor (F42/Fed) ③Equipment modeling factor (F43/Fem) ④ Equipment mode combination factor (F44/Femc) ⑤ Equipment earthquake component combination(45/Fecc) ⑥ Equipment inelastic energy absorption factor (F46/Feμ)	

III.B. EXAMINATION REGARDING ZERO-VALUE OF LOGARITHMIC STANDARD DEVIATION

Authors have analyzed EPRI reports regarding βr and βu (Ref.5-7 and 9-10). The smaller uncertainties among βr and βu for each component are described as "-" and larger one contains smaller β value in the US as shown in Table 2 (Ref.6). However regarding βu of Fss in Table 2, after the Kennedy letter was issued, only βr was considered (Ref.7).

On the other hand, Japanese reports used "0" instead of "-" in the US. Other than this difference, treatment of uncertainty factor in Japan is almost equivalent to that in the US. Authors follow the US style "-"for that situation.

Table 2 Response and capacity factors of service water pump (Ref.6)

	Response factor of building				Response factor of component				
	Fss	Fδ	Fm	Fmc	Fess	Fed	Fem	Femc	Fecc
Median	0.63	1.0	1.0	1.0	0.86	1.0	1.16	1.0	0.93
βr	0.20	-	-	0.05	-	-	-	0.05	0.09
βu	0.21	0.15	0.11	-	0.04	0.23	0.12	-	-

IV. EXAMINATION REGARDING UNCERTAINTY FACTOR F1 OF INPUT SEISMIC MOTION

IV.A. NEW METHOD AND PROCEDURE FOR EVALUATING F1 USING SEISMIC WAVE INVENTORY

Authors have analyzed EPRI reports regarding uncertainty factor of input seismic motion (F1/Fss) (Ref.5-7 and 9-10). Fss has been treating as spectrum shape and considering as a factor of both βr and βu in the reports (Ref.5-6). As mentioned above, after the Kennedy letter was issued, only βr was considered (Ref.7).

Authors developed a new different evaluation method. This method considers as uncertainty of spectrum shape for each PGA level as shown in Fig. 2 and is defined as aleartory uncertainty βr based on Eq. (7).

$$F1\ (\alpha,\ T) = (\text{Design spectrum shape}) / (\text{Realistic spectrum shape by time history waves based on fault rupture model}) \quad (7)$$

Where α is PGA (Gal) at bed rock and T (second) natural period of structure and component.

This method is evaluated as uncertainty of spectrum shape for each PGA level by using fault rapture model and composed from the following seventh steps as shown in Fig.3.

1) To select target site considering soil hardness of bedrock and earthquake type,
2) To evaluate hazard-consistent magnitude ($\overline{M}$) and distance ($\overline{\Delta}$) (Ref.12) at target site,
3) To set fault parameters of fault rupture model corresponding to ($\overline{M}$) and ($\overline{\Delta}$),
4) To generate seismic time history waves based on fault rapture model,
5) To prepare seismic wave inventory (Ref.13) by storing the above seismic waves,
6) To select seismic waves every PGA from the above seismic wave inventory,
7) To evaluate F1(α,T) (median and βr as aleartory uncertainty) considering correlation between frequency characteristics of seismic wave by using the above seismic waves

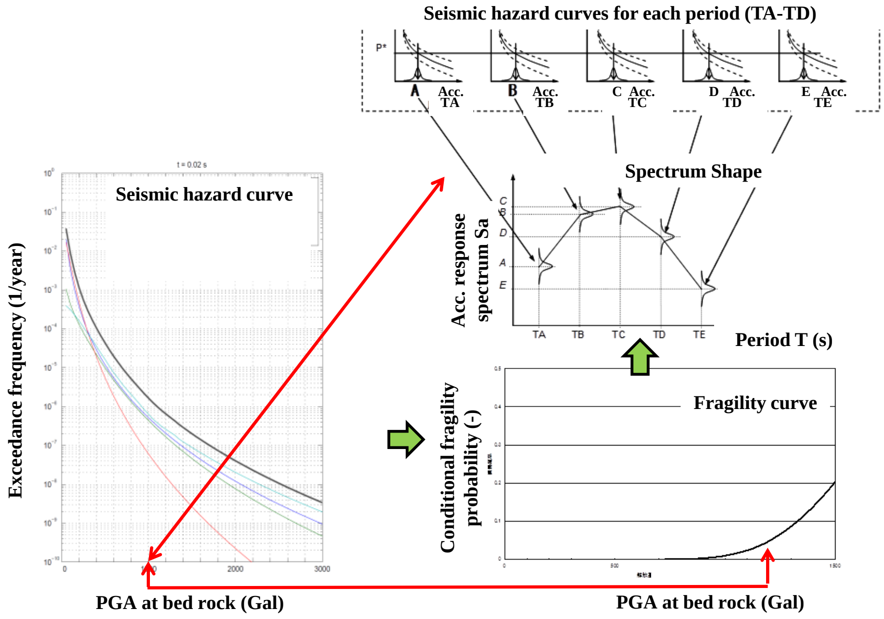

Fig.2 - Illustration of relationship between seismic hazard curve and fragility curve

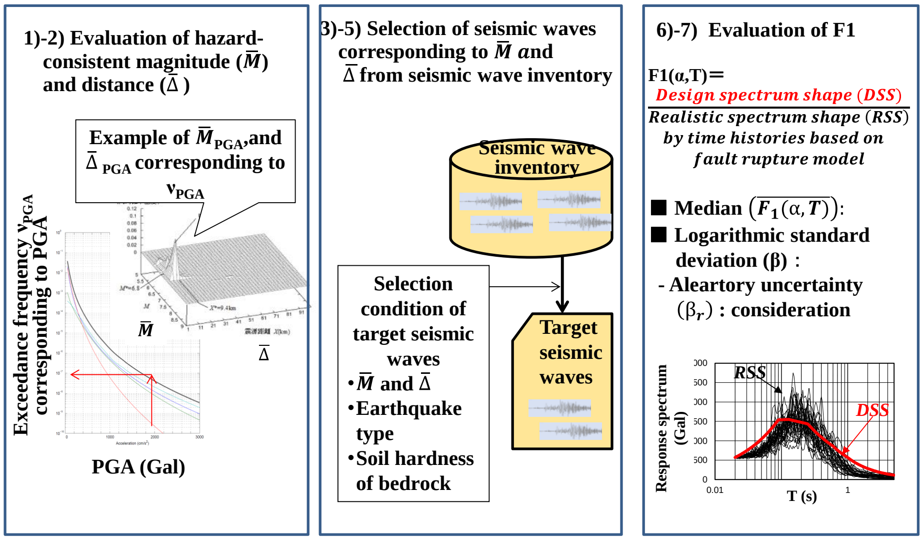

Fig. 3 - Procedure for evaluating F1 using seismic motion inventory

IV.B. EXAMINATION OF EVALUATION FOR CONFIRMING FEASIBILITY OF PROPOSED METHOD

Since authors have confirmed the feasibility of method, this method was applied to Ikata site as shown in **Fig.4.** Main target seismic sources are active fault (Seismic magnitude 7.6) in sea area nearby site as shown in **Fig. 4.** Evaluation method of seismic motion is fault rupture model based on fault rupture recipe (Ref.14). Fault parameters are as follows.

- Mean stress drop (SD) of fault
- SD of asperity 1(Sa 1)
- SD of asperity 2 (Sa 2)
- Ratio of area of asperity (Sa2/Sa1)
- Ratio of slip of asperity
- Ratio of shear velocity of rupture propagation
- $f_{\max}$
- Ration of raise time coefficient

Regarding the treatment of uncertainty of the above fault parameters, the range (upper, median and low values) of uncertainty for each fault parameter was set and time histories for their values using fault rupture model based on recipe were calculated.

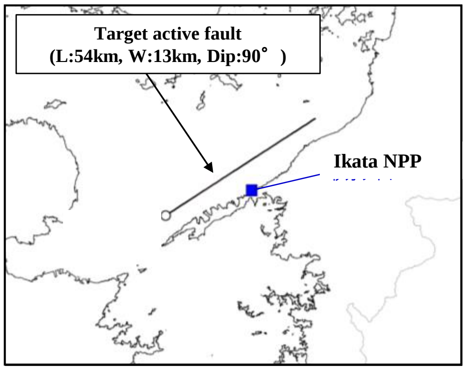

Fig. 4 - Illustration of target site and active fault

Based on fault rapture model parameters, seismic time history waves of 1000 were generated. The range of PGA of 1000 waves was from 500 Gal to 1750 Gal. The numbers of waves around 570 Gal that is PGA of design seismic motion are 45 and their spectra are illustrated as black bold lines as shown in Fig.5. The spectrum of design seismic motion is also described as red bold line in Fig.5.

Assume that spectra values for each period on seismic motion waves follow logarithmic standard distribution, median and LSD (β) were evaluated. Fig.6 illustrates the relationship among median ± β, design seismic motion spectrum (Ss-H) and uniform hazard spectrum (UHS) that obtains from probabilistic seismic hazard evaluation. In the ranges of 0.08 second under and 0.3 second over in Fig.6, both median + β is smaller than Ss-H and UHS. In the all range, median is also smaller than Ss-H and UHS.

These median and βr are those of F1 for each period (T second) at 570 PGA. Fig.7 and 8 show examples of median and βr of F1 at T of 0.08 and 0.20 s. As for example, median and βr of F1 on period of 0.08 second against PGA of 570 Gal are 1.38 and 0.24, respectively. It was found that fault rupture parameters that contribute to spectrum shape are f_{max} and stress drop etc.

Through these evaluations, it was found that the above new methodology is reasonable and practical. Authors confirmed the feasibility thought the above application to Ikata site.

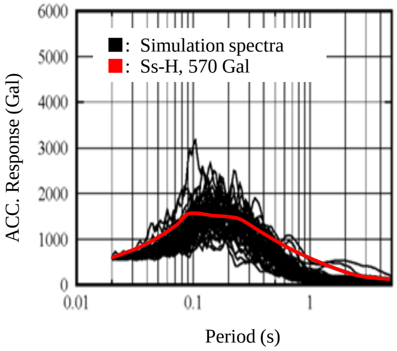

Fig.5 Relationship between simulation spectra and design seismic motion spectrum

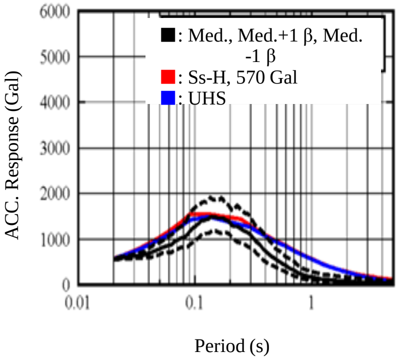

Fig.6 Relationship among median and β of simulation spectra, design seismic motion spectrum and UHS

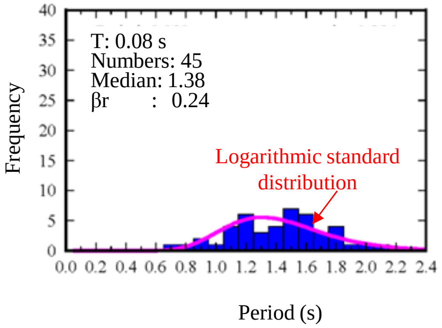

Fig.7 Example of Result of F1 (Median and βr) at T (0.08 s)

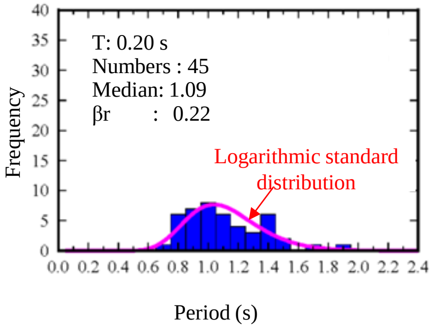

Fig.8 Example of Result of F1 (Median and βr) at T (0.20 s)

V. EXAMINATION REGARDING COMPONENT SUB-RESPONSE FACTOR F4

V.A. OUTLINE OF EXAMINATION

Authors have analyzed EPRI reports regarding fragility evaluation (Ref.5-7 and 9-10). Authors selected the target component (Ref.6) as shown in Fig.9 as the study example and analyzed the difference between Japan and the US evaluation. **Table 3** shows the specification of this component. The reason why authors selected this component was there was enough information for quantitative evaluation.

Trends of specifications between Japan and U.S are as follows. Regarding natural period, short period is prominent in Japan. Regarding damping factor both Japan and U.S., the former is smaller than The latter. The failure mode and response analysis method are same both countries.

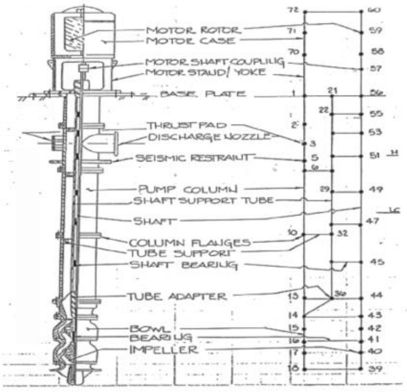

Fig.9 - Model of the service water pump of target component (Ref.6)

Table 3 Specification of target component

	U.S.	Japan
Design natural period	3.9 Hz (0.27 s)	24.7 Hz (0.04 s)
Design damping factor Realistic DF	2% 5%	1% 3%
Installation	unknown	Intake pit
Failure part	Motor stand	Volt for preventing shake
Failure mode	Structural failure	Structural failure
Response analysis method	Modal Analysis	Modal Analysis

V.B. RESULTS OF EXAMINATION

Authors examined also equations that were used in the component fragility evaluation. There are not any signification differences between Japan and the US as shown in Table 4.

In order to catch trends of all uncertainty factors of Japan related to realistic response, uncertainty factors regarding F1, F2 and F3 are also described in Table 4. Uncertainty factor values of F1 are those of chapter IV.B. Uncertainty factor values of F2 and 3 are those of reference (Ref. 2 and 15).Since the service water pump of target component is installed in intake pit but uncertainty factor values in take pit are not examined, uncertainty factors of reactor building are described. Seismic analysis method for reactor building is 3D-dynamic non- linear direct integration method. Since authors is examining about F33, values are not described in Table.

Table 4 Example of results regarding sub-response factors related to realistic response between U.S. and Japan

		Input seismic motion (F1)	Response factor of building (F2,F3)			Response factor of component (F4)				FR=F1F2F3F4	
		F1/Fss	F33/ Fδ	F34/ Fm	F35/ Fmc	①Spectral shape(Fess)	②Damping (Fed)	③Modeling (Fem)	④Mode combination (Femc)	Composite	
US	Median	0.63	1.0	1.0	1.0	0.86	1.0	1.16	1.0	0.63	
	βr	0.20	-	-	0.05	-	-	-	0.05	0.21	0.38
	βu	-	0.15	0.11		0.04	0.23	0.12	-	0.32	
Japan		F1/	F33	F34	F35	(Fess)	(Fed)	(Fem)	(Femc)	Composite	
	Median	1.38	0.99	0.99		1.18	1.21	1.0	1.0	1.93	
	βr	0.24	-	-		-	-	-	0.15	0.24	0.36
	βu	-	0.07	0.1		0.07	0.09	0.15	-	0.23	

(1) Spectral shape factor (Fess)

F_{ess} is defined as the following Eq. (8) both U.S. and Japan.

$$F_{ess} = \frac{\text{Design floor response spectrum with expansion of 10\%}}{\text{Realistic floor response spectrum at realistic model without expansion}} \tag{8}$$

$\beta_{u/ess}$ of F_{ess} is evaluated by the following Eq. (9) both U.S. and Japan.

$$\beta_{u/ess} = \frac{1}{S_p} ln\left(\frac{\text{Realistic floor response spectrum at upper confidence P\% of realistic model without expansion}}{\text{Realistic floor response spectrum at median of realistic model without expansion}}\right) \tag{9}$$

$$S_p = \Phi^{-1}(p) \tag{10}$$

Where S_p is standard normal variate, Φ^{-1} inverse function of standard normal probability density function and p cumulative probability of upper confidence limit. When p is 95% and 99%, S_p is 1.65 and 2.33, respectively.

In U.S., assume that S_p is 2.33, $\beta_{u/ess}$ is 0.04. On the other hand, in Japan, assumed that S_p is 1.65, $\beta_{u/ess}$ is 0.07. Difference between Japan and U.S. is as follows.

- Evaluation method both Japan and U.S. is same and value of $\beta_{u/ess}$ is also similar.
- Median (0.86) of U.S. is un-conservative. It means that expansion of spectrum is not enveloped completely.

(2) Damping factor (F_{ed})

F_{ed} is defined asEq. (11) both U.S. and Japan.

$$F_{ed} = \frac{\text{Design floor response spectrum at design damping factor}}{\text{Relistic floor response spectrum at median of realistic damping factor}} \tag{11}$$

$\beta_{u/ed}$ of F_{ed} in U.S. is evaluated by Eq. (12).

$$\beta_{u/ed} = \frac{1}{2} ln \sqrt{\frac{Median of\ realistic\ damping\ factor}{Design damping\ factor}} \qquad (12)$$

$\beta_{u/ed}$ of F_{ed} in Japan is evaluated by Eq. (13).

$$\beta_{u/ed} = \frac{1}{2} ln \left(\frac{Realistic\ floor\ response spectrum at upper confidence\ P\ \%\ of\ realistic\ damping\ factor}{Realistic\ floor\ response spectrum at\ median of\ realistic\ damping\ factor} \right) \qquad (13)$$

$\beta_{u/ed}$ of U.S. is 0.23. In Japan, assumed that S_p is 2.33, $\beta_{u/ed}$ is 0.09. Difference between Japan and U.S. is as follows.

- Evaluation method between Japan and U.S. is different. Japan method is standard but U.S. is a simplified method.
- The former value is smaller than the latter. The value based on Japanese evaluation conditions by using U.S. method is 0.27 and is similar as U.S. value.

(3) Modeling factor (F_{em})

Median both U.S. and Japan is similar value. $\beta_{u/em}$ both U.S. and Japan is similar value based on U.S. references both U.S. and Japan.

(4) Mode combination factor (F_{emc})

Median both U.S. and Japan is same value. $\beta_{r/emc}$ of U.S. and Japan is 0.05 and 0.15, respectively. Evaluation value is different. $\beta_{r/emc}$ in U.S. is no references. $\beta_{r/emc}$ in Japan is based on shaking table testing results (Ref.16).

VI. SUMMARY AND FUTURE PLAN

Authors improved about the following main issues and proposed new methodology. (1) Consideration of uncertainty factors should be clarified (2) Rationality regarding treatment of zero-value of LSD (aleatry uncertainty: β_r, Epistemic uncertainty: β_u) related to sub-response factor should be clarified. (3) Treatment of uncertainty factor of input seismic motion should be clarified. (4) Since β_r and βu values of component seem smaller than those in the US study, these should be clarified. Through these examination, it was found that the above improvement is reasonable and practical.

NRRC will acquire information regarding Diablo Canyon Power Plant fragility. This information shall be analyzed and examined, and improvements made to fragility evaluation as needed.

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