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Introduction of the Response Spectral Peak and Valley Variability in Fragility Analysis and HCLPF Capacity Estimates

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1. Introduction

The term, "seismic fragility" refers to a set of failure probabilities conditional upon a range of earthquake ground motions (e.g., peak ground acceleration, PGA). Combining the seismic demand distribution with the seismic capacity distribution, the probability of failure for the given ground motion level (e.g., 0.3g PGA) is the probability that the demand exceeds the capacity. When this comparison of seismic capacity and demand is performed over a range of ground motion levels, the result is a seismic fragility function. [1]

Fundamentally, the seismic demand in a seismic probabilistic risk assessment (SPRA) is defined by the seismic hazard at the nuclear power plant (NPP) site. The seismic hazard defines the annual exceedance probability (AEP) for a range of ground motion parameter values. All probabilistic seismic hazard assessments (PSHAs) have included the response spectral peak and valley variability $\beta_{PV.R}$ as part of the randomness when developing seismic hazard estimates as a function of the annual frequency of exceedance (AFE). [1]

This study introduces recommendation of EPRI report [1] about how to include the response spectral peak and valley variability in fragility analysis and the results of this study are expected to help the understanding of spectral peak and valley variability.

2. Methods and Results

2.1 Introduction for Existing Fragility Analysis

The seismic capacity and demand distributions each include two types of variability. The part of the variability that is potentially reducible is defined to be uncertainty. It includes those source of variability due to lack of knowledge of structural response and capacity that could be reduced by more detail studies. The part of the variability that cannot be practically reduced is called randomness. It is unlikely that any amount of testing or analysis will reduce this randomness. The response spectral peak and valley variability $\beta_{PV.R}$ is being included as part of the randomness considered in the PSHA. [1]

Until the 2000s, fragility estimates performed in accordance with the standard separation of variables (SOV) fragility analysis methodology have also included the response spectral peak and valley variability $\beta_{PV.R}$ in the fragility estimates. Thus the effect of $\beta_{PV.R}$ has been double counted when the hazard and fragility curves are convolved together to estimate the seismic risk. [1]

Prior to the Diablo Canyon SPRA, this double counting of $\beta_{PV.R}$ was not recognized. The EPRI TR-103959 [2] recommends inclusion of $\beta_{PV.R}$ in the range of 0.2 to 0.3 in the fragility estimate as had been the prior common practice. Since EPRI TR-103959 [2] was written, PSHAs have continued to include the response spectral peak and valley variability $\beta_{PV.R}$ in the randomness included in the hazard estimate. Thus, inclusion of $\beta_{PV.R}$ in the fragility estimate as recommended in EPRI TR-103959 [2] has continued to result in double counting $\beta_{PV.R}$. [1]

2.2 Modification for the Existing Fragility Analysis

The EPRI report presents [1], the input to multiple time history analyses, the $\beta_{PV.R}$ values have typically been in the 0.2 to 0.4 range.

Once the $\beta_{PV.R}$ used in the fragility analysis has been determined, the composite (mean) variability β_C that does not include $\beta_{PV.R}$ can be computed from: [1]

$$\beta_C = (\beta_{PV.C}^2 - \beta_{PV.R}^2)^{0.5} \qquad (1)$$

Where,
β_C : composite logarithmic standard deviation
$\beta_{PV.C}$: composite variability which included $\beta_{PV.R}$

The high confidence of low probability of failure (HCLPF) capacity is defined by the 1% failure probability capacity on the composite fragility curve, the corrected HCLPF capacity, HCLPF' is given by: [1]

$$\text{HCLPF}' = A_{1\%} = A_m e^{-2.326 \cdot \beta_C} \qquad (2)$$

Where,
HCLPF' : HCLPF corrected to avoid double counting of $\beta_{PV.R}$
$A_{1\%}$: 1% NEP ground acceleration capacity
A_m : median ground acceleration capacity

And the HCLPF_{PV} reported in a fragility analysis the included $\beta_{PV.R}$ in the fragility evaluation needs to be increased by a factor F_{PV} to avoid double counting of $\beta_{PV.R}$, where: [1]

$$HCLPF' = F_{PV} \cdot HCLPF_{PV} \qquad (3)$$

$$F_{PV} = e^{2.326 \cdot (\beta_{PV.C} - \beta_C)} \qquad (4)$$

Where,

$HCLPF_{PV}$: HCLPF not corrected to avoid double counting of $\beta_{PV.R}$
F_{PV} : factor to correct HCLPF to avoid double counting of $\beta_{PV.R}$

In case of $\beta_{PV.R}$ = 0.2 and β_C = 0.3, the factor F_{PV} is:

$$\beta_{PV.C} = (\beta_C^2 + \beta_{PV.R}^2)^{0.5} = (0.3^2 + 0.2^2)^{0.5} = 0.36$$

$$F_{PV} = e^{2.326\cdot(\beta_{PV.C}-\beta_C)} = e^{2.326\cdot(0.36-0.3)} = 1.15$$

For $\beta_{PV.R}$ = 0.2, the increase factor F_{PV} for a HCLPF ranges from 1.08 to 1.15, that is the increase factor is relatively moderate. Table 1 shows the required correction factor F_{PV} for the typical range of β_C from 0.3 to 0.6 and $\beta_{PV.R}$ from 0.2 to 0.4. [1]

Table 1: HCLPF correction factor F_{PV} [1]

β_C	F_{PV}		
	$\beta_{PV.R}$ = 0.2	$\beta_{PV.R}$ = 0.3	$\beta_{PV.R}$ = 0.4
0.3	1.15	1.34	1.59
0.4	1.12	1.26	1.47
0.5	1.09	1.21	1.39
0.6	1.08	1.18	1.33

So long as $\beta_{PV.R}$ is less than 0.2, the correction is small and can be ignored with only small conservative bias being introduced. However, if $\beta_{PV.R}$ exceeds 0.2, this correction should be made in order to avoid excess conservatism. [1]

2.3 In Case of HCLPF Capacities Computed by the Conservative Deterministic Failure Margin Methodology

The conservative deterministic failure margin (CDFM) methodology is aimed at estimating the 1% failure probability ($A_{1\%}$) capacity on the composite fragility curve. However, the CDFM method determines the $A_{1\%}$ capacity assuming a smooth target input response spectrum shape with no peak and valley variability $\beta_{PV.R}$ about this target response spectrum shape. So, if the target response spectrum shape used in the CDFM evaluation is identical to the target uniform hazard response spectrum (UHRS) obtained from the PSHA that included $\beta_{PV.R}$ in the randomness, then no correction should be made to the CDFM computed HCLPF capacity, i.e.: [1]

$$HCLPF' = HCLPF_{CDFM} \quad (5)$$

Where,
$HCLPF_{CDFM}$: CDFM HCLPF capacity

2.4 Screening Components in SPRA

The screened out components be replaced by a surrogate element in the SPRA are described in EPRI NP-6041 [3] Tables 2-3 and 2-4. And the surrogate element having the following fragility parameters: [1]

$$C_{gm} = 2Sa_{SL}e^{-\beta_{PV.R}} \quad (6)$$

Where,
C_{gm} : median capacity expressed in terms of ground spectral acceleration
Sa_{SL} : peak 5% damped horizontal ground spectral acceleration

The peak and valley variability $\beta_{PV.R}$ is already included in the randomness used in the PSHA, $\beta_{PV.R}$ to be included in the fragility analysis should be set to zero. Therefore, Equation (6) becomes: [1]

$$C_{gm} = 2Sa_{SL} \quad (7)$$
$$\text{Median/HCLPF} = \exp[2.326(0.3)] = 2.0$$
$$\beta_C = 0.3$$
$$C_{g1\%} = Sa_{SL}$$

Where,
$C_{g1\%}$: 1% NEP capacity expressed in terms of ground spectral acceleration

3. Conclusions

This study introduces the recommendation of EPRI report [1] that in order to avoid excess conservatism in fragility analysis and HCLPF capacity estimates.

For the SOV method, in case of the peak and valley variability $\beta_{PV.R}$ has already been included in the randomness of the PSHA, the appropriate value for this variability is zero. And so long as $\beta_{PV.R}$ is less than 0.2, the correction factor F_{PV} is small and can be ignored with only a small conservative bias. However, if $\beta_{PV.R}$ exceeds 0.2 and increases to 0.4, the F_{PV} may increase up to 1.59, this correction should be made in order to avoid excess conservatism.

For the CDFM method, no correction should be made to the compute HCLPF capacity, if the target response spectrum shape is identical to the target UHRS obtained from the PSHA.

About using screening table, since $\beta_{PV.R}$ has already been included in PSHA hazard curves, it should not also be included in developing the median capacity of the surrogate element. Thus, the median value of the surrogate element should be set at twice the screening level.

REFERENCES

[1] EPRI, Seismic Fragility and Seismic Margin Guidance for Seismic Probabilistic Risk Assessments, EPRI-3002012994, 2018.

[2] EPRI, Methodology for Developing Seismic Fragilities, TR-103959, June, 1994.
[3] EPRI, A Methodology for Assessment of Nuclear Power Plant Seismic Margin Revision 1, NP-6041-SL, 1991.