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A MODIFIED HYBRID METHOD FOR DEVELOPING SEISMIC FRAGILITIES

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ABSTRACT

A seismic probabilistic risk assessment (SPRA) is an important tool in evaluating the safety of nuclear power plants worldwide. The effort involved in performing a new SPRA typically spans multiple years, requiring significant engineering resources. The scope of fragility evaluations in an SPRA, typically extending to several hundreds of structures, systems, and components (SSCs), requires that their complexity be appropriately managed. Seismic fragilities are typically developed using one of the two methods described in EPRI (2018): the separation of variables (SOV) method and the hybrid method. The SOV method is more rigorous and highly detailed, requiring considerably more effort. The hybrid method is more streamlined, closer to conventional civil engineering design evaluations familiar to engineers with little or no exposure to probability and reliability, and allows for rapid development of seismic fragilities for a large number of SSCs. As a practical matter, the majority of SSC seismic fragilities in typical SPRAs are developed using the hybrid method, with the more detailed SOV method reserved for SSCs with dominant risk contributions. This represents an efficient and cost-effective strategy for seismic fragility development in typical SPRAs.

It is generally believed that the hybrid method introduces some conservatism in the fragility evaluation. This has been considered an acceptable trade-off for the reduction in complexity and engineering effort required for otherwise detailed fragility evaluations. However, while the introduced conservatism in a single fragility developed using the hybrid method for a non-dominant risk contributor has a negligible effect on the overall risk estimate, the aggregate conservatism across all non-dominant risk contributors evaluated using the hybrid method may have a meaningful influence on the calculated risk and risk insights. Furthermore, in certain cases where the variability in the seismic demand is significantly greater than the variability in the SSC capacity, this study demonstrates that the hybrid method can result in unconservative outcome contrary to common belief.

This paper presents a modified hybrid method that results in more realistic fragility characterizations than the hybrid method with only a marginal increase in the analysis effort. In the modified hybrid method, the Conservative Deterministic Failure Margin (CDFM) seismic capacity is computed following the hybrid method, and the median seismic capacity is estimated following the SOV method in EPRI (2018). The aleatory and epistemic variabilities are computed from the median and the CDFM seismic capacities. A minimum variability check for consistency is performed to preclude cases where the hybrid method may yield unconservative results.

INTRODUCTION

SPRAs serve an important role in the safety evaluation of nuclear power plants (NPPs) worldwide. However, SPRAs typically require multi-year studies involving engineering resources across multiple disciplines. The complexity and scope of fragility evaluations in an SPRA is usually a major cost driver: it is often the case that seismic fragilities need to be developed for several hundreds of SSCs in an SPRA. These seismic fragilities are commonly developed using one of the two methods described in EPRI (2018): the SOV method and the hybrid method. The SOV method is rigorous and requires considerably more engineering effort. The hybrid method is similar to conventional civil engineering design evaluations familiar to engineers with little or no exposure to probability and structural reliability concepts; it is a more streamlined method that allows for rapid development of seismic fragilities for a large number of SSCs. Consequently, the SOV method is generally reserved for fragility evaluations of dominant risk contributors in SPRAs while the remaining SSC fragilities are developed using the simpler hybrid method. This division of effort presents an efficient and cost-effective strategy for seismic fragility development in SPRAs.

The hybrid method is generally believed to produce conservatively biased fragilities. This has been considered an acceptable trade-off for the reduction in complexity and engineering effort required for the otherwise detailed SOV fragility evaluations. However, while conservatism in a given hybrid method fragility for a non-dominant risk contributor has a negligible effect on the overall risk estimate, the aggregate conservatism across all non-dominant risk contributors evaluated using the hybrid method may have a meaningful influence on the calculated risk and risk insights.

This paper presents a modified hybrid method that results in more realistic fragility characterizations than the common implementation of the hybrid method with only a marginal increase in the analysis effort. Before presenting this improved method, the hybrid method, as commonly implemented following the guidance in EPRI (2018), is reviewed in the next section.

HYBRID METHOD: A REVIEW

The first step in the hybrid method is to compute the CDFM seismic capacity, A_{CDFM}, using seismic demands and capacities defined at the following prescribed confidence levels, similar to design standards:

- The 84% non-exceedance probability SSC demand, $D_{84\%}$
- The 1% non-exceedance probability SSC capacity, $C_{1\%}$

The CDFM seismic capacity, A_{CDFM}, is given by:

$$A_{CDFM} = \frac{C_{1\%}}{D_{84\%}} A_{ref} \tag{1}$$

Where A_{ref} is the reference ground motion parameter used in the SPRA, usually the peak ground acceleration (PGA). The CDFM method is based on prescriptive evaluation rules to estimate $D_{84\%}$ and $C_{1\%}$, which are calibrated such that (EPRI, 2018):

$$\mathrm{A}_{1\%} \approx A_{CDFM} \tag{2}$$

Where $A_{1\%}$ is the 1% probability of failure seismic capacity. The median seismic capacity, A_m, is then estimated using generic values or estimates of β_R and β_U as:

$$\mathrm{A_m} = A_{1\%} \exp\,(2.33\beta_C) \tag{3}$$

$$\beta_C = \sqrt{{\beta_R}^2 + {\beta_U}^2} \tag{4}$$

EPRI (2018) recommends generic β_R and β_U values that are biased toward the low end of industry experience with previous SPRAs.[1] This bias is intentionally meant to produce a conservative estimate of A_m. This common implementation of the hybrid method is intended to estimate a reasonably accurate $A_{1\%}$ based on Equation (2) and a conservative estimate of A_m using the generic values of β_R and β_U to describe the mean fragility curve. The mean fragility curve is of most interest to the SPRA since it is used along with the mean hazard curve to compute the point-estimate mean seismic core damage frequency (SCDF) and/or large early release frequency (LERF) of NPPs in current SPRAs and determine corresponding risk insights.

The EPRI (2018) hybrid method contrasts with the SOV method wherein A_m is computed first using median-centred demands and capacities, followed by a rigorous computation of β_R and β_U from a variability analysis of significant random variables contributing to the demands and capacities. The variability analysis is the main reason for the increased complexity of the SOV method; the engineering effort required in the computation of A_m using median-centred demands and capacities in the SOV method is comparable to the computation of A_{CDFM} in the hybrid method if the best-estimate material properties, strengths, and other analysis variables are available.

MODIFIED HYBRID METHOD

So long as the approximation in Equation (2) is valid, the conservatism in the A_m estimated using the hybrid method ensures that the resulting mean fragilities are conservative. This conservatism can be significant if the true composite variability, β_C is significantly higher than the generic value. This is not an uncommon case in modern SPRAs, particularly when state-of-the-art soil-structure interaction (SSI) analyses are used to compute the in-structure response spectra for the calculation of seismic demands on the SSCs. We propose the following modified hybrid method that reduces this conservatism:

Step 1: Compute A_{CDFM} following the CDFM method.
Step 2: Compute A_m following the SOV method, i.e., using median-centred SSC demands and capacities.
Step 3: Estimate β_C using Equation (3) assuming Equation (2) is valid, i.e., $A_{1\%} \approx A_{CDFM}$; constrain this value against the validity of the CDFM method assumption represented by Equation (2) as explained in the next section.
Step 4: Split β_C into β_R and β_U using Equation (4) and the generic β_R values recommended in EPRI (2018); this step is optional and is not needed if only a mean fragility curve is required.

As noted earlier, the engineering effort involved in the computation of A_{CDFM} using the conservative demands and capacities is comparable to that involved in the computation of A_m using median-centred quantities. The additional effort is due to two factors: (1) two sets of demand and capacity computations need to be performed and (2) establishing best-estimate material properties and other parameters for input to the median-centred evaluation may involve utilizing data that is not as readily available as code-prescribed specific values. In practice, if seismic demand results are available from probability analyses and best-estimate capacity quantities are available, the explicit computation of both A_{CDFM} and A_m according to the proposed steps requires only a marginally increased effort than computing just A_{CDFM}. Since the proposed method is meant to be replace the hybrid method to develop non-dominant risk contributor SSC fragilities, the fragility analyst can choose to make conservatively biased approximations in the best-estimate parameter input to the computation of median demands and capacities to streamline the

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[1] The EPRI (2018) guidance permits the estimation of non-generic values of β_R and β_U, but this is seldom used in current SPRA practice.

evaluations when data is not readily available. Such as-needed approximation maintains cost-effectiveness and achieves less conservatism in the estimated A_m compared to the hybrid method.

Table 1 presents a comparison of the fragilities computed using the EPRI (2018) hybrid method, SOV method, and the modified hybrid method for an SSC the authors evaluated in a recent SPRA for an NPP, henceforth referred to as Plant X. This SSC was an air handling unit located on the top-most floor of a structure whose seismic response was strongly influenced by SSI effects. Figure 1 compares the corresponding fragility curves. The modified hybrid method results in a fragility curve that is very close to the one developed using the SOV method, which is considered the most realistic. In comparison to the SOV method fragility, the fragility from the hybrid method is somewhat unconservative in the lower tail of the curve (up to about 8% probability of failure) and then becomes increasingly conservative at higher probabilities of failure. This has offsetting effects on the SSC's seismic risk contribution, which is computed by the convolution of the entire fragility curve with the hazard curve. While the net effect depends on the hazard curve being convolved, it is believed to usually be conservative due to the significant conservatism in the hybrid method at higher probabilities of failure.

Application of the modified hybrid method in the Plant X SPRA indicated non-trivial reductions in the computed SCDF and LERF risk metrics. More importantly, because the fragilities estimated using the modified hybrid method were more realistic, the list of significant risk contributors remained relatively stable when selected fragilities were refined using the SOV method following successive risk quantification iterations. As such, fewer iterations were required to achieve a stable list of significant risk contributors, which translated into reduced overall engineering and analysis cost of the SPRA. The application of this modified hybrid method to the Plant X SPRA was accepted by the U.S. Nuclear Regulatory Commission.

Table 1 also lists the high confidence of low probability of failure (HCLPF) seismic capacities for the different fragility curves. This is a useful parameter commonly computed to characterize the seismic robustness of an SSC. It represents the 95% confidence of 5% probability of failure capacity defined as:

$$HCLPF = \mathrm{A_m} \exp\left(-1.65(\beta_R + \beta_U)\right) \tag{5}$$

Table 1 indicates that the HCLPF capacity estimated using the modified hybrid method is close to the HCLPF capacity determined using the SOV method. Another noteworthy observation is that the HCLPF capacity estimated using the hybrid method is somewhat unconservative with respect to the SOV method. Consequently, it should not be assumed unconditionally that the hybrid method HCLPF is always conservative. However, in most such cases, the potential lack of conservatism in the hybrid method HCLPF capacity is likely to be adequately offset by the conservatism in the estimated median capacity, A_m.

Table 1: Seismic fragility for example SSC.

Fragility Parameter	Hybrid Method	SOV Method	Modified Hybrid Method
A_m (g)	0.52	0.86	0.81
β_C	0.45	0.82	0.94
β_R	0.24	0.26	0.24
β_U	0.38	0.78	0.91
HCLPF (g)	0.18	0.15	0.12

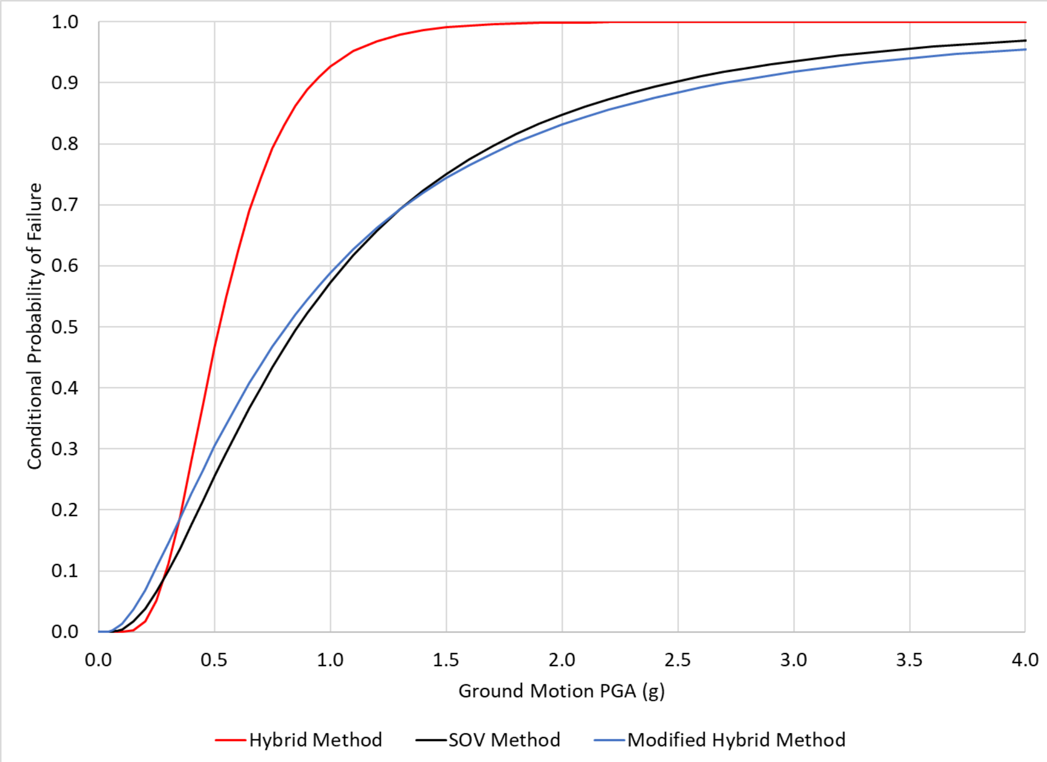

Figure 1. Mean seismic fragility curves for example SSC.

CONSTRAINING β_C

The need for constraining β_C in Step 3 above arises when the CDFM method assumption represented by Equation (2) is not valid. Validating this assumption requires that Equation (3) be first expanded as follows using the definitions of $C_{1\%}$, $D_{84\%}$, and A_m:

$$A_{CDFM} = \frac{C_{1\%}}{D_{84\%}} A_{ref} = \frac{C_{50\%} \exp(-2.33\beta_{CAP})}{D_{50\%} \exp(\beta_D)} A_{ref} = \left(\frac{C_{50\%}}{D_{50\%}} A_{ref}\right) \exp\left(-(2.33\beta_{CAP} + \beta_D)\right)$$

or,

$$A_{CDFM} = A_m \exp\left(-(2.33\beta_{CAP} + \beta_D)\right) \tag{6}$$

Where $D_{50\%}$ is the median seismic demand on the SSC, $C_{50\%}$ is the median SSC capacity, and β_D and β_{CAP} are the logarithmic standard deviations associated with SSC demand and capacity, respectively. β_D and β_{CAP} are given by:

$$\beta_D = \ln\left(\frac{D_{84\%}}{D_{50\%}}\right) \tag{7}$$

$$\beta_{CAP} = \frac{1}{2.33} \ln\left(\frac{C_{50\%}}{C_{1\%}}\right) \tag{8}$$

Equation (6) can then be compared to Equation (3) to test the validity of Equation (2) for the following three cases:

- $\beta_{CAP} >> \beta_D$, i.e., when the fragility variability is dominated by capacity variables
- $\beta_{CAP} = \beta_D$, i.e., when the fragility variabilities due to capacity and demand variables are comparable
- $\beta_{CAP} << \beta_D$, i.e., when the fragility variability is dominated by demand variables

***Case 1*: $\beta_{CAP} >> \beta_D$**

Under this condition:

$$\beta_C = \sqrt{{\beta_{CAP}}^2 + {\beta_D}^2} \approx \beta_{CAP}$$

and, from Equations (6) and (3):

$$A_{CDFM} = A_m \exp\big(-(2.33\beta_{CAP} + \beta_D)\big) \approx A_m \exp(-2.33\beta_{CAP}) \approx A_m \exp(-2.33\beta_C) \approx A_{1\%} \quad (9)$$

Equation (9) shows that when the fragility variability is dominated by capacity variables, the CDFM method assumption in Equation (2) is valid.

***Case 2*: $\beta_{CAP} = \beta_D$**

Under this condition:

$$\beta_C = \sqrt{{\beta_{CAP}}^2 + {\beta_D}^2} = \sqrt{2}\beta_{CAP}$$

and, from Equations (6) and (3):

$$A_{CDFM} = A_m \exp\big(-(2.33\beta_{CAP} + \beta_D)\big) = A_m \exp(-3.33\beta_{CAP}) = A_m \exp\left(-\frac{2.33}{\sqrt{2}}\beta_C\right) \quad (10a)$$

or,

$$A_{CDFM} = A_m \exp\left(-\frac{2.33}{\sqrt{2}}\beta_C\right) = A_m \exp(-2.35\beta_{CAP}) \approx A_{1\%} \quad (10b)$$

Equation (10b) shows that when the SSC demand and capacity variabilities are comparable, the CDFM method assumption in Equation (4) is valid.

***Case 3*: $\beta_{CAP} << \beta_D$**

Under this condition:

$$\beta_C = \sqrt{{\beta_{CAP}}^2 + {\beta_D}^2} \approx \beta_D$$

and, from Equations (6) and (1):

$$A_{CDFM} = A_m \exp\big(-(2.33\beta_{CAP} + \beta_D)\big) \approx A_m \exp(-\beta_D) \approx A_m \exp(-\beta_C) \approx A_{16\%} > A_{1\%} \quad (11)$$

Equation (11) shows that when the fragility variability is dominated by demand variables, A_{CDFM} becomes an unconservative estimator of $A_{1\%}$, and the assumption in Equation (2) is no longer valid. For example, if $\beta_D \approx \beta_C = 0.5$, then $A_{CDFM} \approx 2A_{1\%}$. While it has not been historically common in SPRA practice for the fragility variability to be significantly dominated by demand variables (i.e., closer to Case 3 than Case 2), more recent SPRAs include examples of this situation. In such a situation, setting $A_{1\%} = A_{CDFM}$ in Step 3 of the modified hybrid method would produce an unconservative estimate of the lower tail of the fragility curve and under-estimate β_C. This situation is eliminated by imposing a minimum value on β_C given by:

$$\beta_{C,min} = \sqrt{{\beta_{CAP}}^2 + {\beta_D}^2} \tag{12}$$

Computing $\beta_{C,min}$ requires the availability of $C_{1\%}$, $C_{50\%}$, $D_{84\%}$, and $D_{50\%}$ (Equations (7) and (8)). These parameters are already computed in Steps 1 and 2 of the modified hybrid method for the calculations of A_{CDFM} and A_m. The modified hybrid mean fragility curve is then defined by A_m and β_C constrained by $\beta_{C,min}$.

Decomposition of the composite variability β_C into β_R and β_U may be desired to allow developing estimates of fractile fragility curves in addition to the mean fragility. A reasonable and efficient decomposition is adequate for non-dominant risk contributors for which the modified hybrid method is intended. The randomness variability in seismic fragilities is primarily due to ground motion randomness, which is often nearly uniform within a region under the ergodic modelling of ground motion typically used in seismic hazard characterization. Accordingly, decomposing the composite variability β_C into a pre-selected value of β_R and calculating the corresponding β_U using Equation (4) is proposed. In the Plant X SPRA, the generic value of 0.24 recommended for β_R in EPRI (2018) was found to be applicable. Table 2 summarizes the modified hybrid method implementation.

Table 2: Modified hybrid method procedure.

Step 1	Compute A_{CDFM} following the CDFM method
Step 2	Compute A_m following the SOV method
Step 3	Compute β_C as the maximum of the value computed from Equation (3) assuming $A_{CDFM} \approx A_{1\%}$, and the $\beta_{C,min}$ value computed in accordance with Equation (12)
Step 4	Split β_C into β_R and β_U using a constant value of β_R (0.24 recommended) and Equation (4)

CAUTION ON APPROXIMATING HCLPF CAPACITY BY A_{CDFM}

As noted earlier, the HCLPF capacity is commonly used to characterize the seismic robustness of an SSC. It is typical practice to approximate the HCLPF capacity by A_{CDFM} when the SSC fragility is computed using the hybrid method. The basis for this practice lies in the CDFM method assumption that $A_{1\%} \approx A_{CDFM}$ according to Equation (2). It can be shown that $A_{1\%}$ is an unconditional lower-bound estimator of the HCLPF capacity (EPRI, 2018). Therefore, when Equation (2) is valid, A_{CDFM} is a reasonably conservative estimate of the HCLPF capacity.

However, as shown earlier, when the fragility variability is dominated by the demand variables, A_{CDFM} can be an unconservative estimator of $A_{1\%}$. In these cases, using A_{CDFM} as an estimate of the HCLPF capacity may be unconservative. The authors believe this is why the hybrid method HCLPF capacity in Table 1 is unconservative with respect to the SOV method HCLPF capacity. The fragility variability for this SSC was governed by demand variables (in particular, SSI response variability). While the HCLPF capacity does not directly get utilized in the risk quantification of an SPRA model, caution should be exercised when approximating the HCLPF capacity by A_{CDFM} for comparison and decision-making purposes (e.g., screening out SSCs from detailed fragility evaluations based on HCLPF capacities).

CONCLUSION

This paper presents a modified hybrid method that results in more realistic fragility characterizations than the hybrid method outlined in EPRI (2018) as commonly implemented, with only a marginal increase in the analysis effort. The modified hybrid method reduces conservatism in estimated median capacities that is typical of the hybrid method and avoids situations in which the hybrid method may produce unconservative estimates of the HCLPF capacities. Application of the modified hybrid method in a recent SPRA project accepted by the U.S. Nuclear Regulatory Commission resulted in non-trivial reductions in the computed SCDF and LERF compared to the hybrid method. Furthermore, the modified hybrid method fragilities were more realistic, which resulted in faster convergence of the risk quantification iterations and a reduction in the overall engineering and analysis cost of the SPRA.

REFERENCES

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