AN IMPROVED HYBRID METHOD TO DEVELOP SEISMIC FRAGILITIES FOR SEISMIC PROBABILISTIC RISK ASSESSMENTS

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October 22, 2020

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Motivation

- Seismic Probabilistic Risk Assessment (SPRA) is an important evaluation method for DOE facilities and commercial NPPs
- The complexity and scope of fragility analysis is a major cost driver
- Widely used methods in detailed fragility evaluations (EPRI 3002012994):
  - Separation of Variables
  - Hybrid Method

Motivation

- Separation of Variables (SOV)
  - Rigorous, highly detailed
  - Higher engineering effort
  - Typically reserved for dominant risk contributors in SPRAs

- Hybrid Method
  - More streamlined, similar to conventional civil/structural design calculations
  - Can be easily performed by engineers with little to no exposure to probability and reliability
  - Enables efficient development of seismic fragilities for a large number of SSCs

Motivation

- Performance of a facility is typically governed by a subset of SSCs
- The more detailed SOV approach is typically reserved for dominant and/or significant risk contributors, while the remaining vast majority of SSC fragilities are developed using the Hybrid Method
  - Efficient and cost-effective strategy for seismic fragility development in SPRAs

Motivation

- It is believed that the Hybrid Method introduces some conservatism

- The proposed Improved Hybrid Method performs better
  - More realistic fragilities with only marginally higher fragility analysis effort
  - Makes a systemic non-trivial difference in risk (recent project observation)
  - Saves cost on multiple risk-importance iterations
    - List of significant risk contributors more stable across iterations

Review: Separation of Variables Method

- Start by computing the median seismic capacity, A_m, which has 50% probability of being exceeded, using best-estimate demands, etc.

- Perform separate analyses for applicable sources of randomness and uncertainty in the variables influencing seismic capacity to compute corresponding log. std. dev., β_R and β_U, and combine them across all sources

Review: Hybrid Method

- Intent is to compute the 1% probability of failure seismic capacity, $C_{1\%}$.
- With known A_m and β's

$$\boldsymbol{C_{1\%} = A_m\, exp(-2.33\beta_{CMP})}$$

$$\boldsymbol{\beta_{CMP} = \sqrt{{\beta_R}^2 + {\beta_U}^2}}$$

- Instead of A_m and β's from SOV, use a set of deterministic rules
  - This set of deterministic rules encompasses the Conservative Deterministic Failure Margin (CDFM) Method
  - The rules are calibrated so that the CDFM seismic capacity, C_{CDFM}, is approximately equal to $C_{1\%}$

Review: Hybrid Method

- High Confidence of Low Probability of Failure (HCLPF) seismic capacity
  - 95% confidence of 5% probability of failure

$$\boldsymbol{HCLPF = A_m\, exp[-1.65(\beta_R + \beta_U)]}$$

  - It can be shown that $C_{1\%}$ is a lower-bound estimate of the HCLPF seismic capacity (EPRI 3002012994)
  - In the EPRI 3002012994 Hybrid Method, HCLPF is conservatively set to $C_{1\%}$, which is approximated by C_{CDFM}

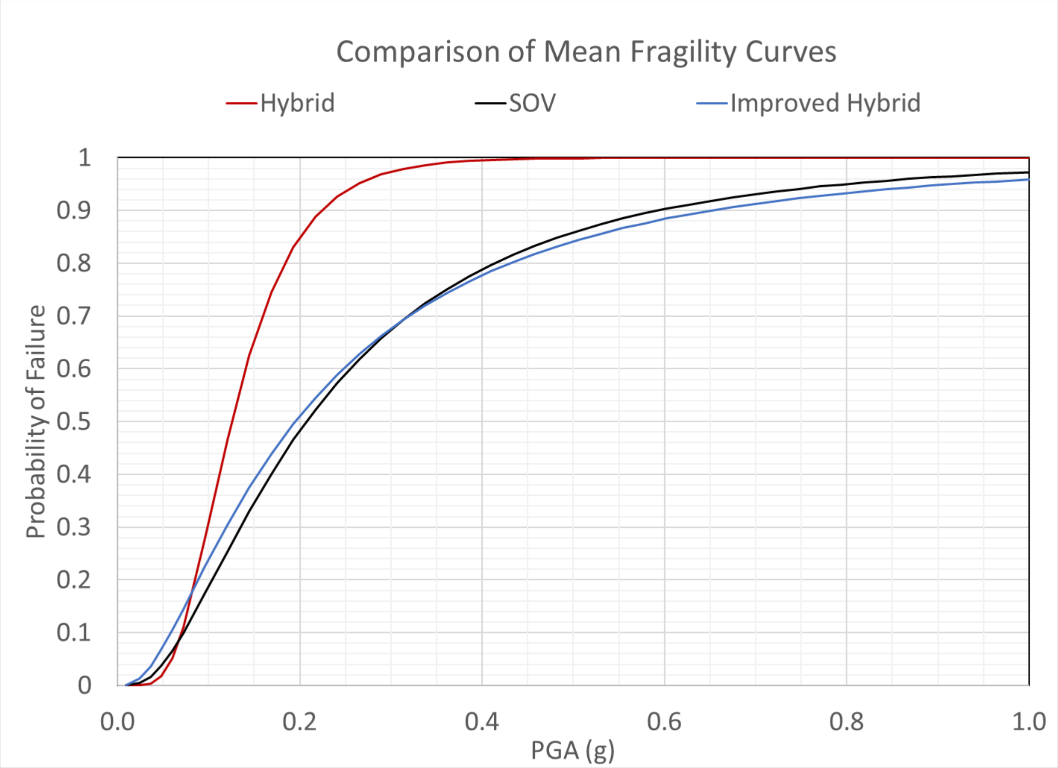
- A conservative A_m is then estimated using generic β_R and β_U, per values recommended in EPRI 3002012994
  - EPRI 3002012994 permits more realistic estimates of A_m, β_R, and β_U - seldom practiced

Improved Hybrid Method

- **Step 1:** Calculate C_{CDFM} following the Hybrid Method
- **Step 2:** Calculate A_m following the SOV Method (best-estimate demand and capacities)
  - May make conservatively-biased simplifications to streamline
- **Step 3:** Estimate β_{CMP} from C_{CDFM} ($\approx$ $C_{1\%}$) and A_m
  - Constrain β_{CMP} against CDFM Method assumptions **(important, discussed later)**
- **Step 4:** Split β_{CMP} into components for randomness and uncertainty

How Much Difference Can it Make?

- Example from a recent SPRA project
  - Special case of significantly high SSI response variability
- AHU governed by anchorage failure



Fragility Parameter	Original Hybrid	SOV Method	Improved Hybrid
Median (g)	0.52	0.86	0.81
β_{CMP}	0.45	0.93	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

Constraining β_{CMP}

- The CDFM Method recommends deterministic rules for estimating
  - CAP_1, 1% non-exceedance probability of component capacity
  - DEM_{84}, 84% non-exceedance probability of component demand

- Then in principle,

$$C_{CDFM} = \frac{CAP_1}{DEM_{84}} PGA_{ref}$$

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CDFM Seismic Capacity Assumptions

$$C_{CDFM} = \frac{CAP_1}{DEM_{84}} PGA_{ref}$$

$$= \frac{CAP_{50} \exp(-2.33\beta_{CAP})}{DEM_{50} \exp(\beta_{DEM})} PGA_{ref}$$

$$= \boldsymbol{A_m \exp[-(2.33\beta_{CAP} + \beta_{DEM})]}$$ **is taken to represent** $$\boldsymbol{C_{1\%} = A_m\, exp(-2.33\beta_{CMP})}$$

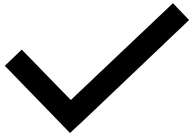
- Let's evaluate three cases
  - $\beta_{CAP} \gg \beta_{DEM}$ Fragility variability dominated by capacity variables
  - $\beta_{CAP} = \beta_{DEM}$
  - $\beta_{CAP} \ll \beta_{DEM}$ Fragility variability dominated by demand variables

$\boldsymbol{\beta_{CAP} \gg \beta_{DEM}}$

- Seismic fragility variability is dominated by capacity variables

$$\beta_{CMP} = \text{SRSS}(\beta_{CAP}, \beta_{DEM}) \approx \beta_{CAP}$$

$$C_{CDFM} = A_m \exp[-(2.33\beta_{CAP} + \beta_{DEM})] \approx A_m \exp(-2.33\beta_{CAP}) \approx A_m \exp(-2.33\beta_{CMP}) \approx C_{1\%}$$



$\boldsymbol{\beta_{CAP} = \beta_{DEM}}$

- Variabilities for demand and capacity variables are comparable

$$\beta_{CMP} = \mathrm{SRSS}(\beta_{CAP}, \beta_{DEM}) = \sqrt{2}\beta_{CAP}$$

$$C_{CDFM} = A_m \exp[-(2.33\beta_{CAP} + \beta_{DEM})] = A_m \exp(-3.33\beta_{CAP}) = A_m \exp\left(-\frac{3.33}{\sqrt{2}}\beta_{CMP}\right) = A_m \exp(-2.35\beta_{CMP}) \approx C_{1\%}$$

$\boldsymbol{\beta_{CAP} \ll \beta_{DEM}}$

- Seismic fragility variability is dominated by demand variables

$$\beta_{CMP} = \mathrm{SRSS}(\beta_{CAP}, \beta_{DEM}) \approx \beta_{DEM}$$

$$C_{CDFM} = A_m \exp[-(2.33\beta_{CAP} + \beta_{DEM})] \approx A_m \exp(-\beta_{DEM}) \approx A_m \exp(-\beta_{CMP}) \approx A_m \exp(-2.33\beta_{CMP}) \exp(1.33\beta_{CMP}) > C_{1\%}$$

e.g., for $\beta_{DEM} \approx \beta_{CMP} \approx \mathbf{0.5}$, $\boldsymbol{C_{CDFM} \approx 2C_{1\%}}$?

CDFM Seismic Capacity Assumptions: Impact

- On the CDFM Method
  - $C_{CDFM} \approx C_{1\%}$ holds when β_{CAP} is comparable to or greater than β_{DEM}
  - If β_{DEM} becomes significantly larger than β_{CAP}, C_{CDFM} becomes an unconservative estimate of $C_{1\%}$

CDFM Seismic Capacity Assumptions: Impact

- On the Hybrid Method (**when $\boldsymbol{\beta_{CAP}}$ is comparable or greater than $\boldsymbol{\beta_{DEM}}$**)
  - The method works as intended, and is conservative

- On the Hybrid Method (**when $\boldsymbol{\beta_{DEM}}$ is significantly greater than $\boldsymbol{\beta_{CAP}}$**)
  - The effect of $C_{CDFM} > C_{1\%}$ is reduced when C_{CDFM} is used as a surrogate for HCLPF capacity, since HCLPF capacity is typically higher than $C_{1\%}$
  - Additional conservatism in the Hybrid Method fragility exists when using conservatively low β values, which results in a A_m conservative estimate
  - Overall effect on convolution of fragility and hazard curves could still be conservative

Constraining β_{CMP} in Improved Hybrid Method

- Impose a minimum β_{CMP} value to correct for cases where $\beta_{CAP} \ll \beta_{DEM}$ resulting in $C_{CDFM} > C_{1\%}$
- Compute
  - $\beta_{CMP,CDFM} = \left(\frac{1}{2.33}\right) \ln\left(\frac{A_m}{C_{1\%}}\right)$
- Estimate
  - $\beta_{DEM} = \ln\left(\frac{DEM_{84}}{DEM_{50}}\right)$
  - $\beta_{CAP} = \left(\frac{1}{2.33}\right) \ln\left(\frac{CAP_{50}}{CAP_1}\right)$
- Impose
  - $\beta_{CMP,MIN} = \sqrt{\beta_{CAP}{}^2 + \beta_{DEM}{}^2}$
- $\beta_{CMP} = \max(\beta_{CMP,CDFM}, \beta_{CMP,MIN})$

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Estimating Randomness and Uncertainty

- β_{CMP} can be split into randomness and uncertainty components following the original Hybrid Method outlined in EPRI 3002012994
  - $\beta_R = 0.24$
  - $\beta_U = \sqrt{{\beta_{CMP}}^2 - {\beta_{DEM}}^2}$

- $HCLPF = A_m \exp[-1.65(\beta_R + \beta_U)]$

Conclusions

- Improved Hybrid Method provides:
  - More realistic estimates of A_m and HCLPF seismic capacities
  - More reliable estimates of risk
  - Potential efficiency in SPRA risk-importance iteration cost

- Marginally more computations than the original Hybrid Method are required to get the above benefits

- The method was used successfully and accepted by NRC in a recent SPRA project

Questions?