Regulatory Development of a Risk-Informed Approach to Determine Site-Specific Safe Shutdown Earthquake

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Regulatory Guide 1.165

- To establish a Reference Probability (RP) based Approach to determine SSE
- RP is a hazard consistent measure, based on the annual probability of exceedance of SSE at 29 operating reactor sites
- Since RP depends on specific hazard curves being used, periodic update is needed
- Published in 1997, and used in two ESP applications and new studies need to be incorporated

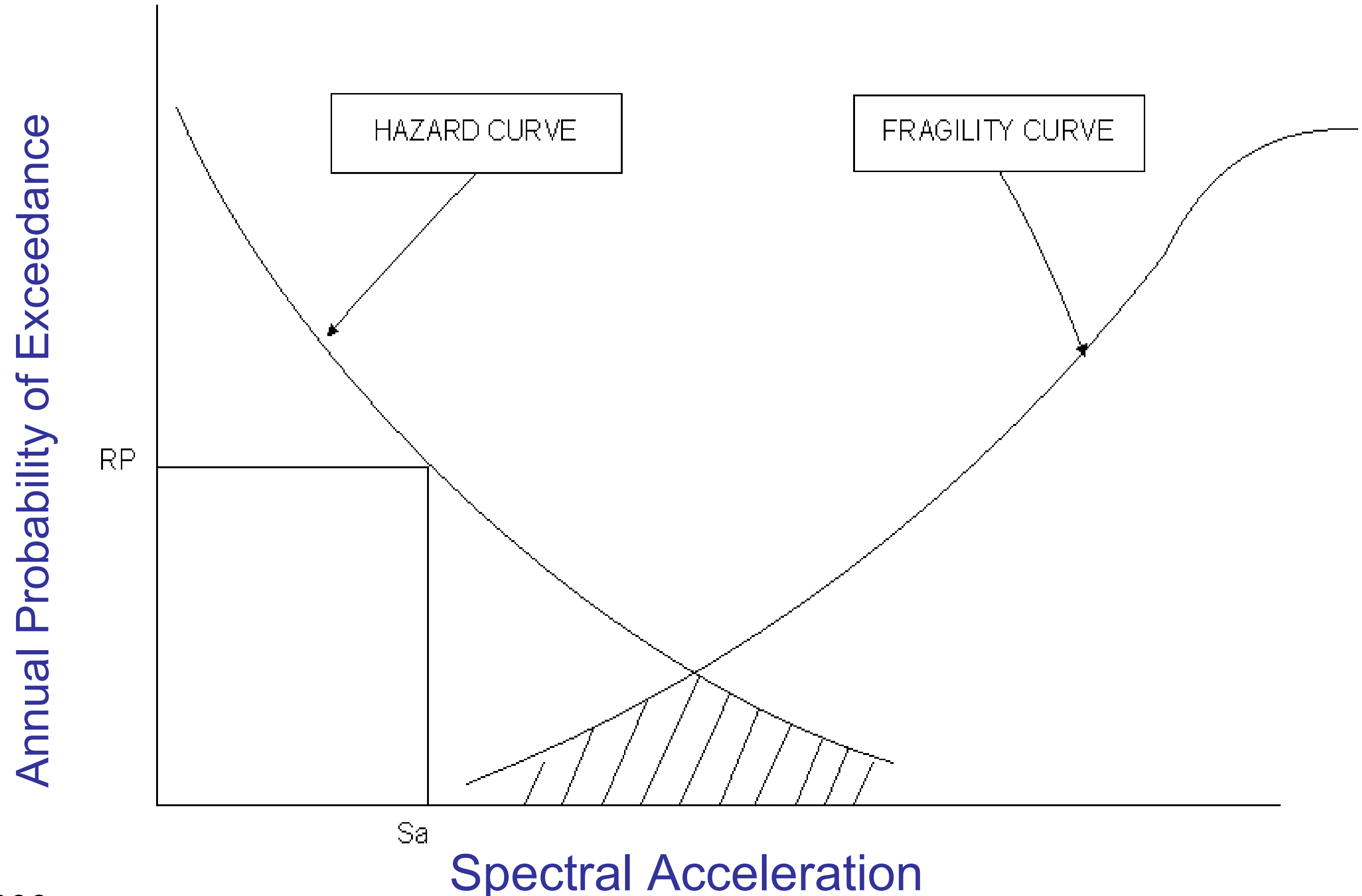
New Regulatory Guide – DG 1146

- Recommend to use Performance-Based approach to determine SSE and PB approach is a risk consistent method
- To reflect the improvement in hazard methodology, such as applying Cumulative Absolute Velocity (CAV) method to eliminate non-damaging earthquakes
- Enhanced probabilistic site response guidance

Performance-Based Approach

- Develops a risk-consistent SSE
- Achieves both high and consistent level of seismic safety in the design of future NPPs
- Has been used in DOE practice for 10 years

Comparison Between Reference Probability and Performance-Based Approaches



Performance-Based Approach to Determine SSE

$$PB\ SSE = DF \times UHRS_{10^{-4}}$$

$$DF = \text{Max}\ (0.6 A_R{}^{0.8}, 1.0)$$

$$A_R = \frac{UHRS_{10^{-5}}}{UHRS_{10^{-4}}}$$

DF: Design Factor
AR: Hazard curve slope
$UHRS_{10-5}$ and $UHRS_{10-4}$: mean Uniform hazard response spectra with annual probability of exceedance of 10^{-5} and 10^{-4}

Performance Target

- Performance Target (P_{FT}) is $1x10^{-5}$ per year
  - IPEEE Seismic PRAs conducted for 25 NPPs during mid/late 1990s determined annual seismic CDF values
  - Median SCDF is $1.2x10^{-5}$/yr
- Performance is measured in terms of Frequency of Onset of Significant Inelastic Deformation (FOSID), essentially elastic behavior
- Therefore, P_{FT} corresponds to a damage state which is more conservative than the SCDF actual

Establish Seismic Hazard Exceedance Frequency

- DF is a function of probability Ratio R_p of Seismic Hazard Curve

  $H(a) = R_p * P_{FT}$

  R_p = Probability Ratio

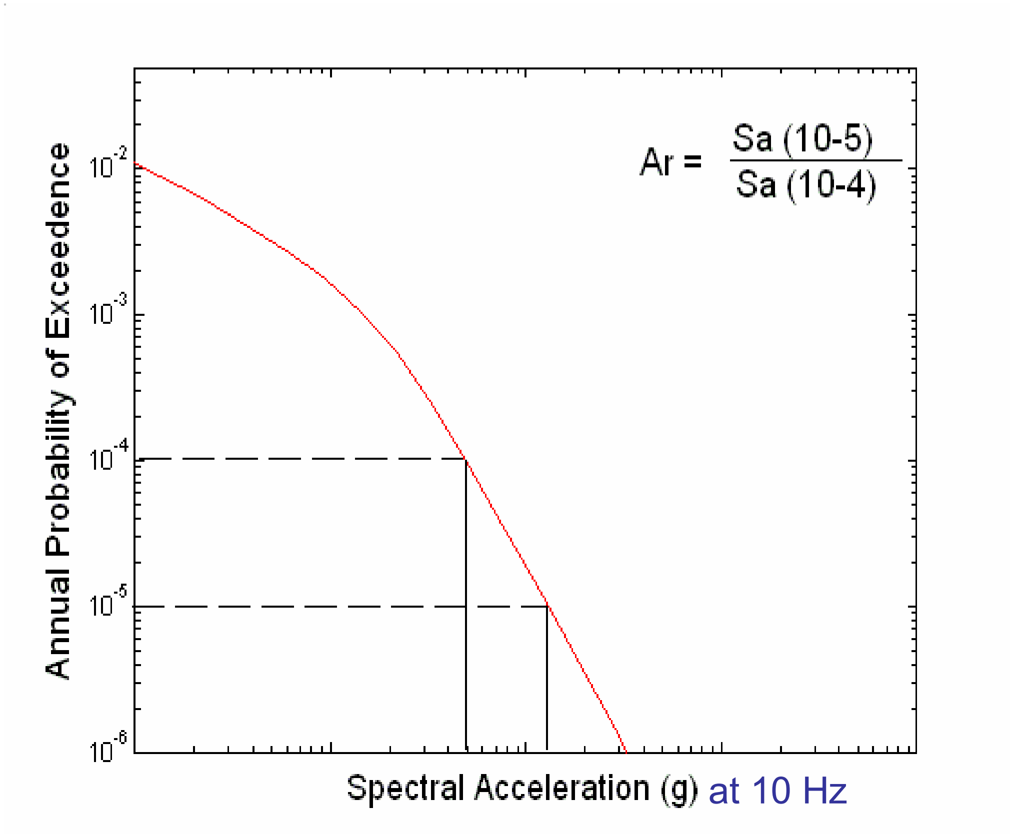
  $2 \leq R_p \geq 20$

  $R_p = 10$

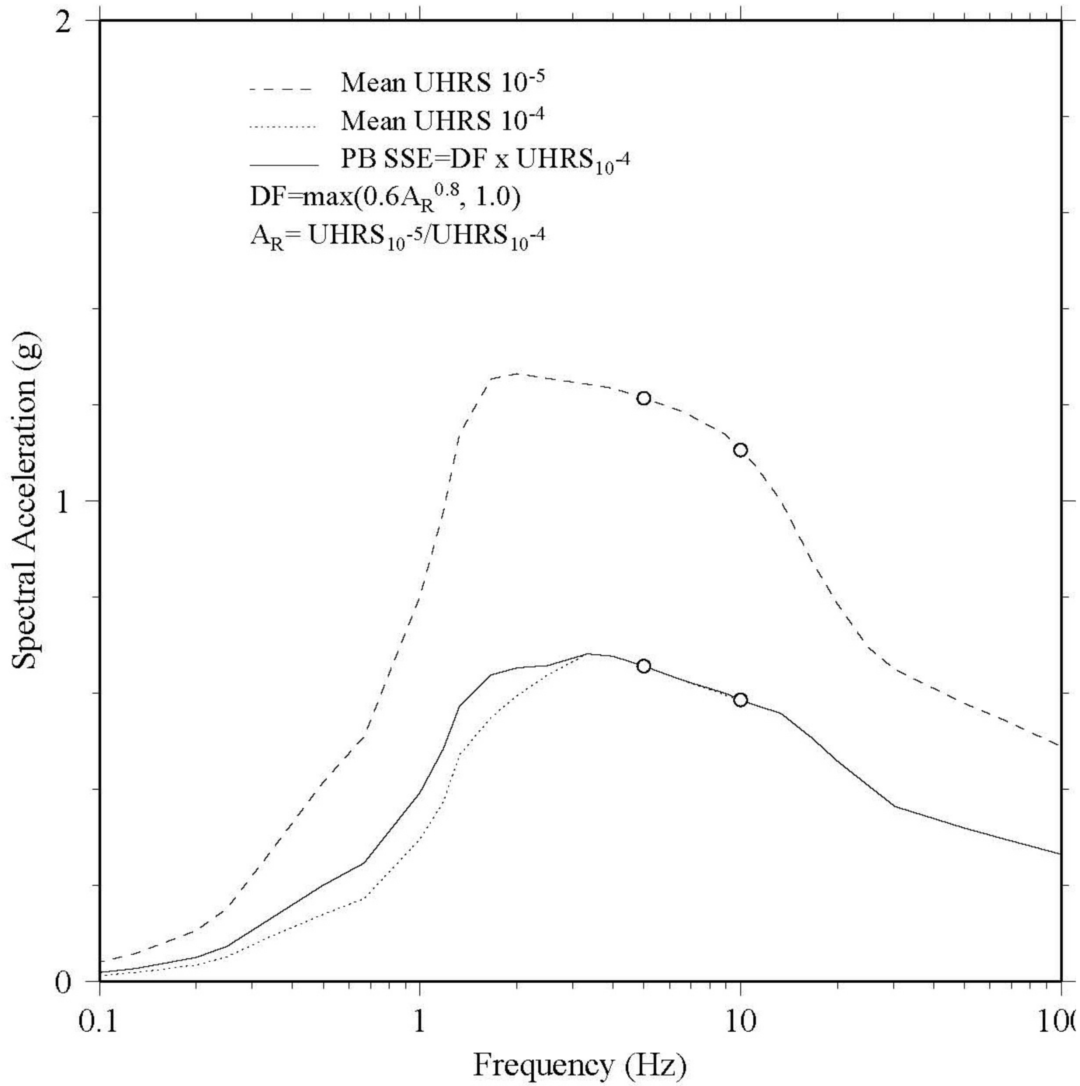
  $H(a)$ = Mean $1x\ 10^{-4}$

Seismic Hazard Slope

- DF is also the function of Seismic Hazard Curve
  - Normally linear hazard curve between 10^{-4} and 10^{-5} before applying CAV filter
  - Slight downward curvature of hazard curve



Performance-Based Approach to Determine the SSE



Derivation of Design Factor

- Seismic Risk Equation

$$P_f = \int_0^\infty H(a) \frac{\mathrm{d}P_f(a)}{\mathrm{d}a} \mathrm{d}a$$

Annual probability of failure (P_f) is equal to the product of the annual probability that ground motion amplitude (seismic demand), exceeds *a* (H(a)) and the probability that the seismic capacity equals *a* ($dP_f(a)$), summed over all possible values of *a*

Derivation of Design Factor

- Seismic Fragility
  - PB approach models SSC seismic fragility using lognormal distribution

$$f_c(a) = \frac{1}{\sqrt{2\pi}\beta a}\exp\left[-\frac{1}{2}\left(\frac{\ln a - \mu}{\beta}\right)^2\right], a > 0$$

  - Fragility Parameters: Mean (μ), SD (β)
    - Mean expressed in terms of $C_{1\%}$ or HCLPF
    - HCLPF corresponds to 1% capacity level on mean fragility curve

$$\mu = \ln HCLPF + 2.32\beta$$

$$HCLPF = SSE \times M_s$$

Derivation of Design Factor

- Hazard curve is approximated as linear in logarithmic space

$$H(a) = ka^{-1/\log Ar}$$

- Based on closed form solution of risk equation and substituted with all the parameters, exact DF can be derived

$$DF = \frac{1}{Ms}\left[\frac{k \cdot UHRS_{pref}^{-1/\log Ar}}{P_f}\right] \cdot \left[\exp(-2.32\beta / \log Ar + \frac{1}{2}(\frac{\beta}{\log Ar})^2\right]$$

Impact of CAV Filter to Hazard Curve Slope and UHRS (10^{-4})

After applying CAV filter

- At some sites hazard curves no longer appear as linear on a log-log plot, and at some other sites, UHRS 10^{-4} hazard is zero
- Industry proposed a lower bound in these cases

$$PB\ SSE >= 0.45\ UHRS_{10^{-5}}$$

Direct Integration

SSE can be back-calculated using direct integration by assuming:

- Target $P_{FT} = 1x10^{-5}$/yr
- $\beta = 0.4$
- Seismic Margin = 1

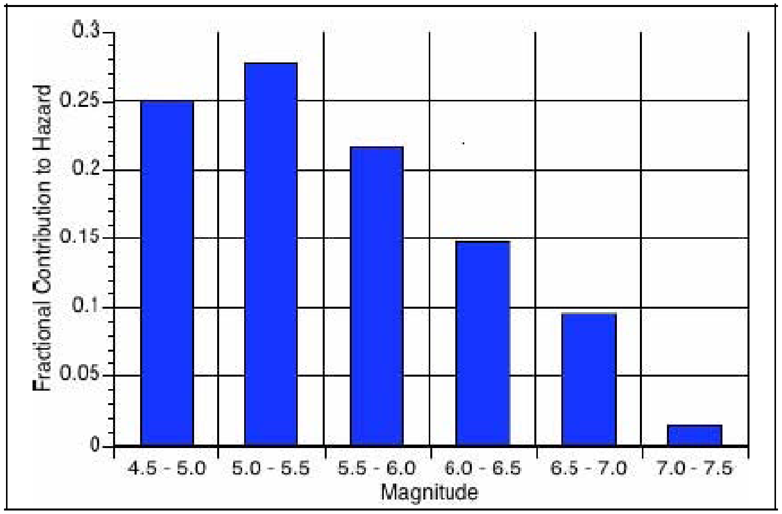
	SSE	
Frequency (Hz)	Risk Integral (g)	Risk Equation (g)
1	0.337	0.395
2.5	0.574	0.658
5	0.604	0.657
10	0.559	0.586

Cumulative Absolute Velocity vs. Minimum Magnitude Truncation

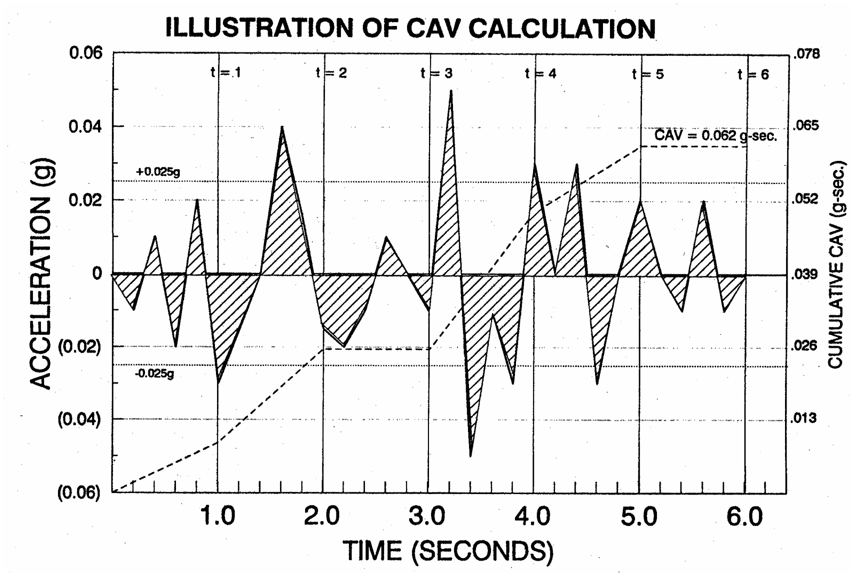
- Current PSHA uses minimum magnitude (step function) as a threshold for hazard input
- Recommend to use Cumulative Absolute Velocity (CAV) to determine ground motion cut-off

Cumulative Absolute Velocity vs. Minimum Magnitude Truncation

Magnitude Truncation



Cumulative Absolute Velocity



CAV Integration

Conventional PSHA

$$\nu(Sa > z) = \sum_{i=1}^{Nsource} Ni(M > Min)$$

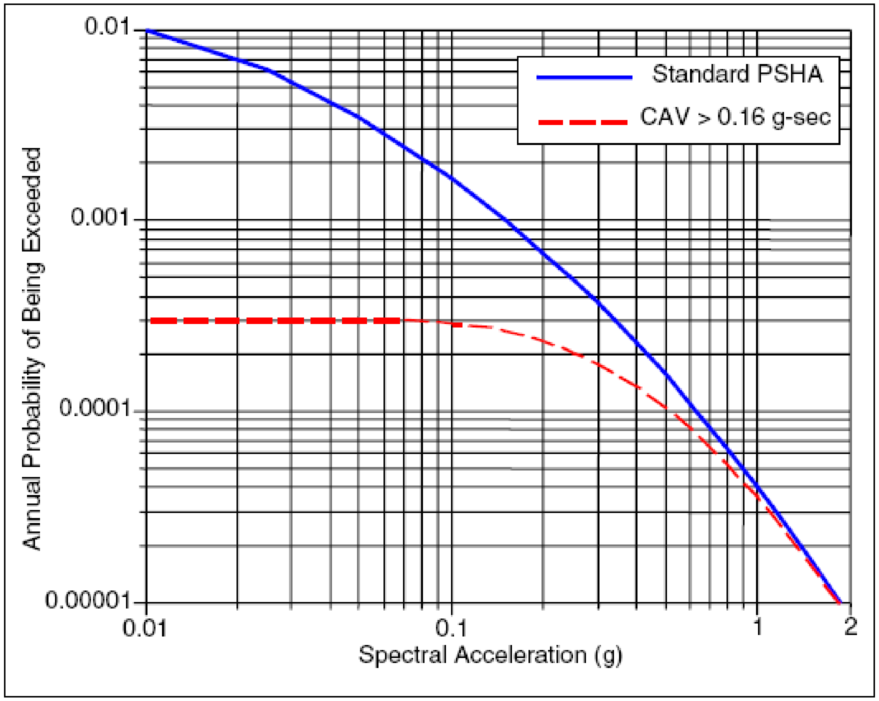
$$\int_{M\min}^{M\max}\int_{0}^{\infty} f_{mi}(M) f_{ri}(r, M) P(Sa > z \mid M, r) dr dM$$

PSHA with CAV Filter

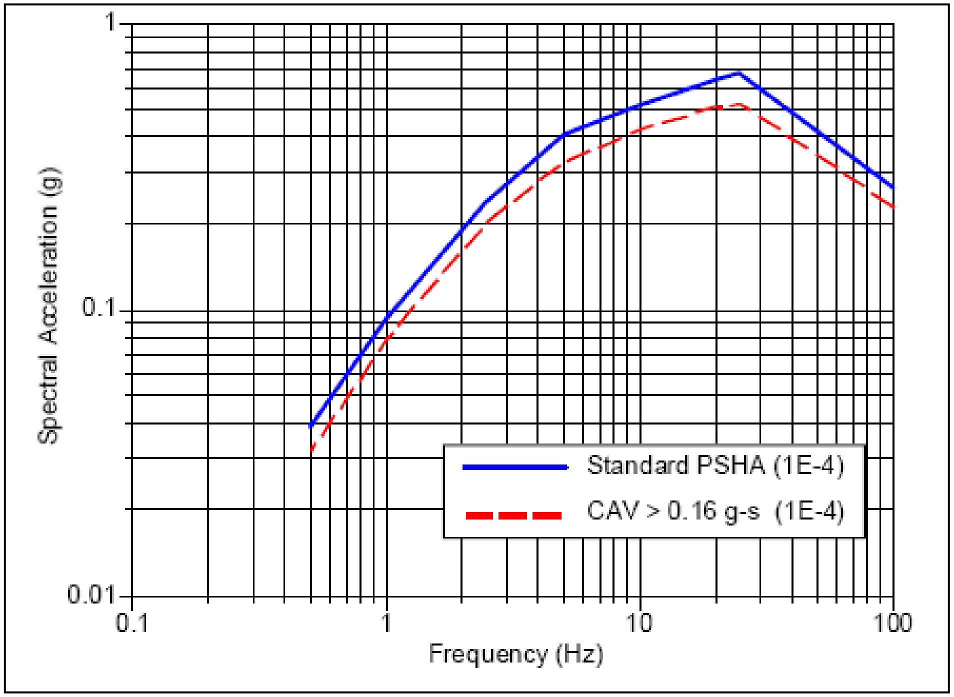
$$\nu(Sa > z) = \sum_{i=1}^{Nsource} Ni(M > Min) \int_{M\min}^{M\max}\int_{0}^{\infty}\int_{\varepsilon_{PGA}=-5}^{5} f_{mi}(M) f_{ri}(r, M) f_{\varepsilon}(\varepsilon_{PGA}) P(CAV > 0.16$$

$$\mid M, PGA(M, R, \varepsilon_{pga})) P(Sa > z \mid M, R, PGA) d\varepsilon_{pga} dr dM$$

CAV Effects



Standard PSHA
CAV > 0.16 g-sec
Annual Probability of Being Exceeded
0.01
0.001
0.0001
0.00001
0.01
0.1
1
2
Spectral Acceleration (g)



Standard PSHA (1E-4)
CAV > 0.16 g-s (1E-4)
Spectral Acceleration (g)
1
0.1
0.01
0.1
1
10
100
Frequency (Hz)