# PSHA, Site Response, and Site Spectra

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## TOPIC 4: Site Spectra


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## Topic 4: Site Spectra

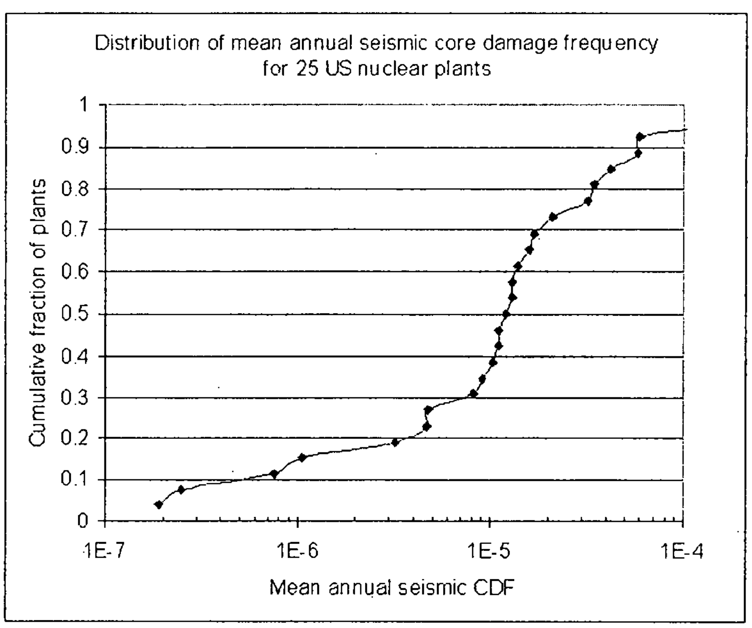
- Performance-based spectra: concept and goal
- Review of performance-based results
- Converting horizontal spectra to vertical spectra

# Seismic Hazard and SSE Spectra

Based on ASCE 43-05:

Target performance goal of mean $10^{-5}$ FOSID (Frequency of Onset of Significant Inelastic Deformation) to nuclear structures, systems and components

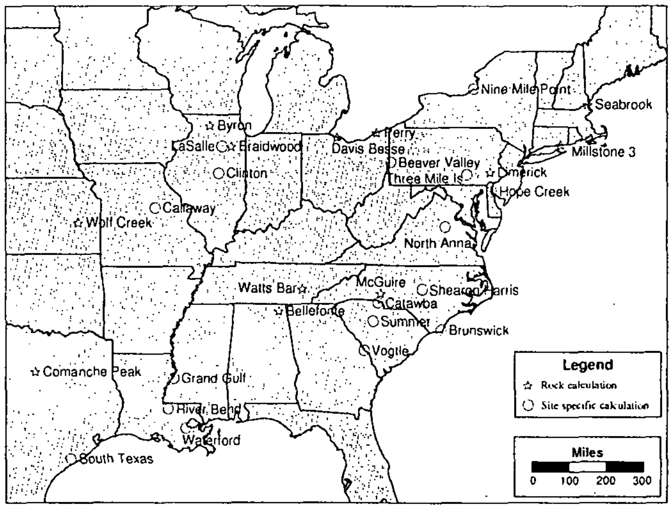





Cumulative distribution of SCDFs from 25 seismic PRAs (NUREG-1742)

Source: REI 2005 EPRI Report

## 28 sites used for hazard comparison




Source: 2005 EPRI Report

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## Calculations:

- Focus on 5 and 10 Hz spectral response (following reference probability approach in Reg. Guide 1.165)
- Develop recommended design response spectra following ASCE (2005):

$$DRS = DF \cdot UHRS$$

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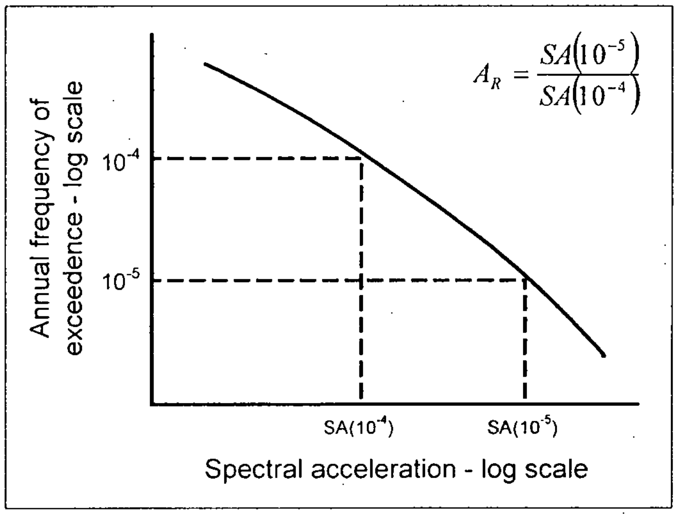
## ① Calculate ground motion ratio $A_R$



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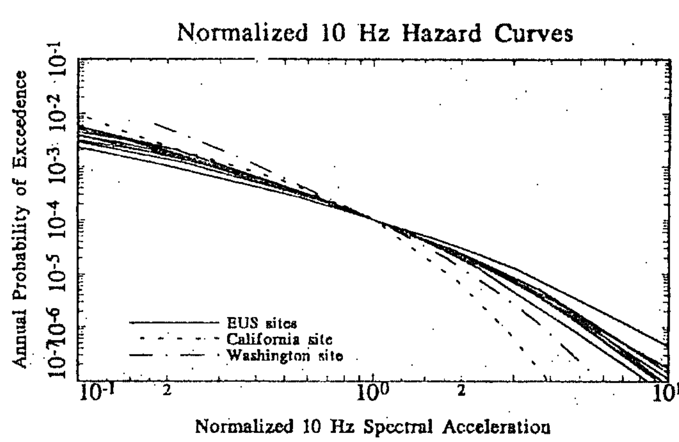
## Hazard curve slopes in US, 10 Hz




Source. NUREG/CR-6728



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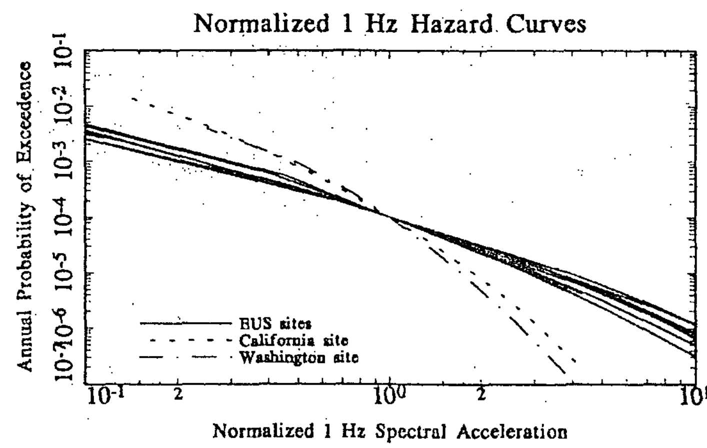
# Hazard curve slopes in US, 1 Hz




Source: NUREG/CR-6728



# ② Establish design basis earthquake response spectrum GMRS:

$SA(10^{-4})$ = mean $10^{-4}$ spectrum

$AR = SA(10^{-5}) / SA(10^{-4})$

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

$GMRS = \max[DF * SA(10^{-4}), 0.45 \times SA(10^{-5})]$

# Range of AR, DF, and P[exceedance] for 28 sites in study

| | Min | 16th | 50th | 84th | Max |
|---|---|---|---|---|---|
| 10 Hz, AR | 1.50 | 2.26 | 3.01 | 3.67 | 4.36 |
| 10 Hz, DF | 1 | 1.15 | 1.45 | 1.70 | 1.95 |
| 10 Hz, PE/1E-4 | 0.37 | 0.40 | 0.48 | 0.68 | 1 |
| 5 Hz, AR | 1.64 | 2.17 | 2.63 | 3.33 | 4.05 |
| 5 Hz, DF | 1 | 1.11 | 1.30 | 1.57 | 1.84 |
| 5 Hz, PE/1E-4 | 0.38 | 0.43 | 0.54 | 0.75 | 1 |
| 2.5 Hz, AR | 1.54 | 2.19 | 2.42 | 3.23 | 3.81 |
| 2.5 Hz, DF | 1 | 1.13 | 1.22 | 1.53 | 1.75 |
| 2.5 Hz, PE/1E-4 | 0.4 | 0.45 | 0.62 | 0.76 | 1 |
| 1 Hz, AR | 1.58 | 2.24 | 2.49 | 3.40 | 3.77 |
| 1 Hz, DF | 1 | 1.14 | 1.24 | 1.60 | 1.74 |
| 1 Hz, PE/1E-4 | 0.39 | 0.44 | 0.61 | 0.73 | 1 |



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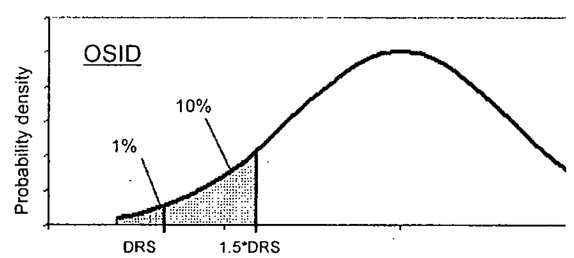
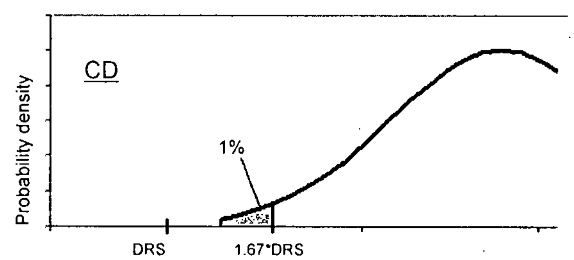
# ③ Estimate plant resistance to:




A. Onset of significant inelastic deformation




B. Core damage



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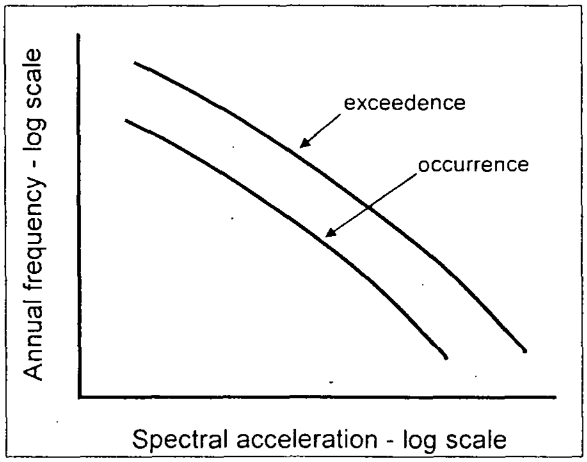
## ④ Derive P[occurrence] from P[exceedence]



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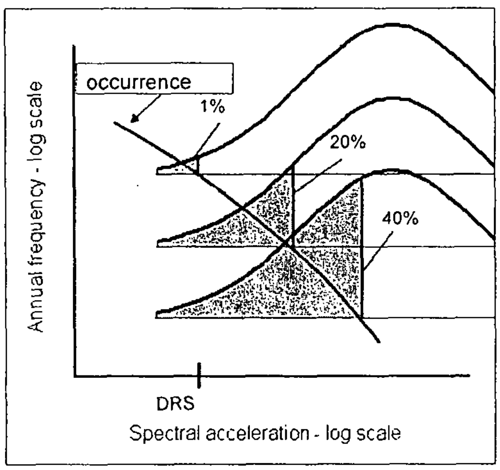
## ⑤ Convolution




$$FOSID = \sum_{SA} f(SA) * P[OSID|SA]$$

$$SCDF = \sum_{SA} f(SA) * P[CD|SA]$$



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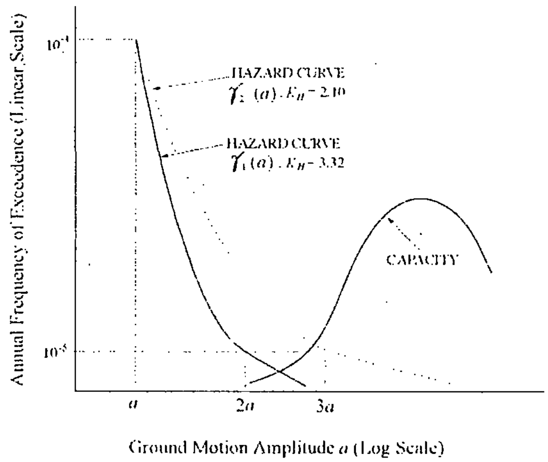
# Hazard curves and capacity curve




Source: McGuire (2004)



Risk equation (approximation to direct convolution)

$$P[\text{failure}] = \gamma(a^*)\, f_s^{-K_H} \exp[-x_p K_H \beta_C + 0.5(K_H \beta_C)^2]$$

where $\gamma(a^*)$ is hazard at design value $a^*$

$f_s$ is factor of safety on design (=1 for individual components)

$K_H$ is log-log slope of hazard curve

$\beta_C$ is $\sigma_{\ln \text{CAPACITY}}$

$x_p = 2.326$ (for HCLPF of 1%)

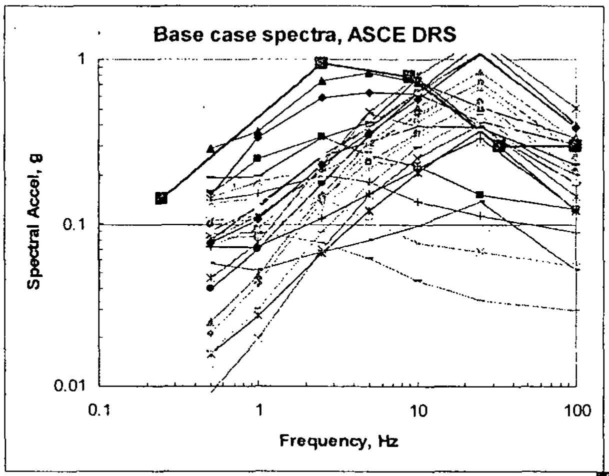
# Calculations:

Comparison 1:

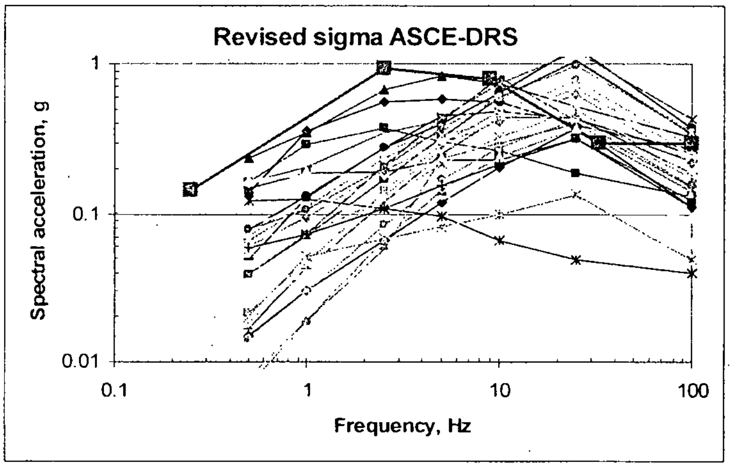
Recommended design response spectra vs. SSE spectra used for existing plants:

- average of DRS/SSE at 5 and 10 Hz
- minimum DRS is RG 1.60 spectrum anchored to 0.1g (ASCE, 2005)






Source: 2006 EPRI Report




Source: 2006 EPRI Report



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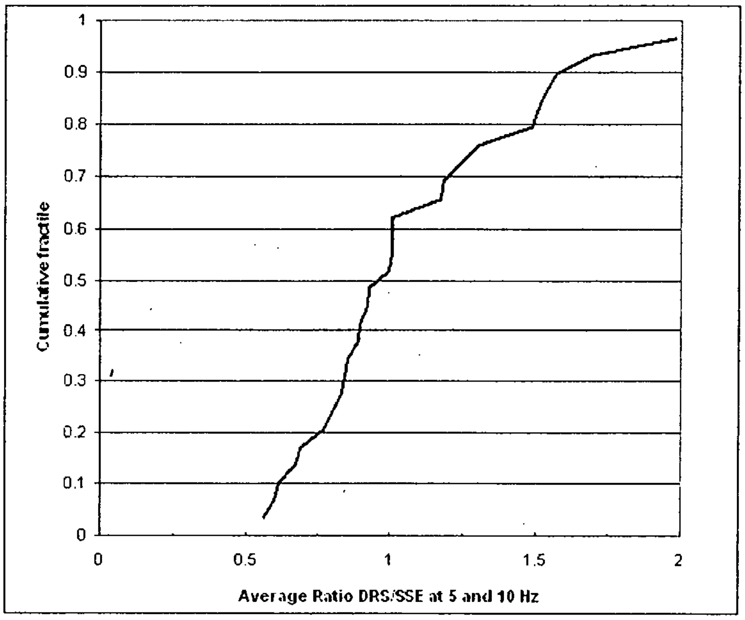


**Figure 3.1 Cumulative Distribution of DRS/SSE Ratio at 5 and 10 Hz**

Source. REI 2005 EPRI Report



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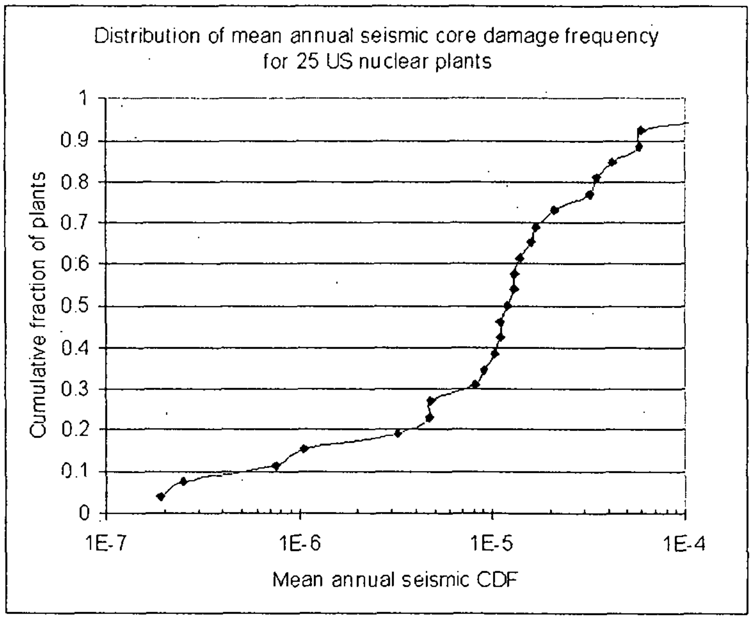
# Calculations:

<u>Comparison 2:</u>

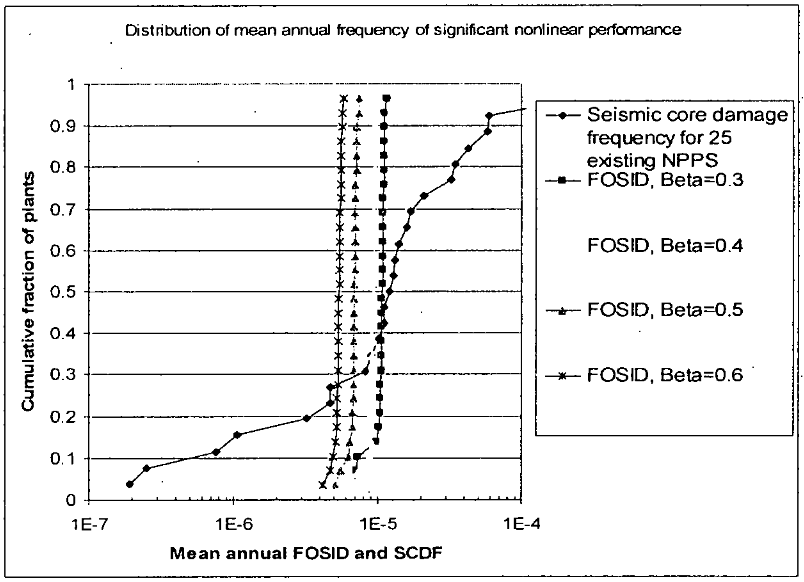
Component-level behavior:

- calculate Frequency of Onset of Significant Inelastic Deformation (FOSID), compare to distribution of Seismic Core Damage Frequency (SCDF) from 25 seismic PRAs






Cumulative distribution of SCDFs from 25 seismic PRAs (NUREG-1742)




Cumulative distribution of FOSIDs for components, compared to SCDF

Source: REI 2005 EPRI Report



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# Example of risk contributions

- "Typical" hard rock site
- 10 Hz spectral acceleration
- Look at Base Case (with original EPRI σ's) and CAV case (with revised σ's)
- Design SA: for Base case = 0.358g
  for CAV case = 0.298g
- For β=0.4, P[failure] ≃ 9.6 x $10^{-6}$ (base & CAV)
  For β=0.5, P[failure] ≃ 7.2 x $10^{-6}$ (base & CAV)



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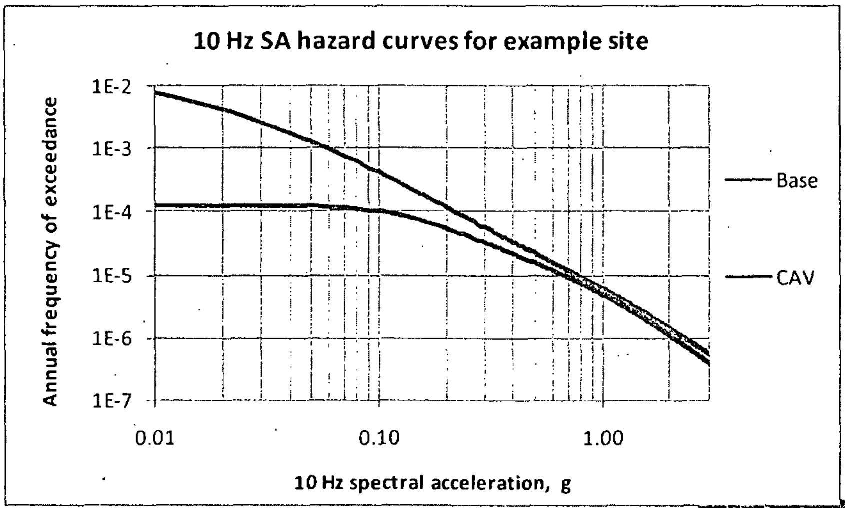
# Hazard curves, Base and CAV



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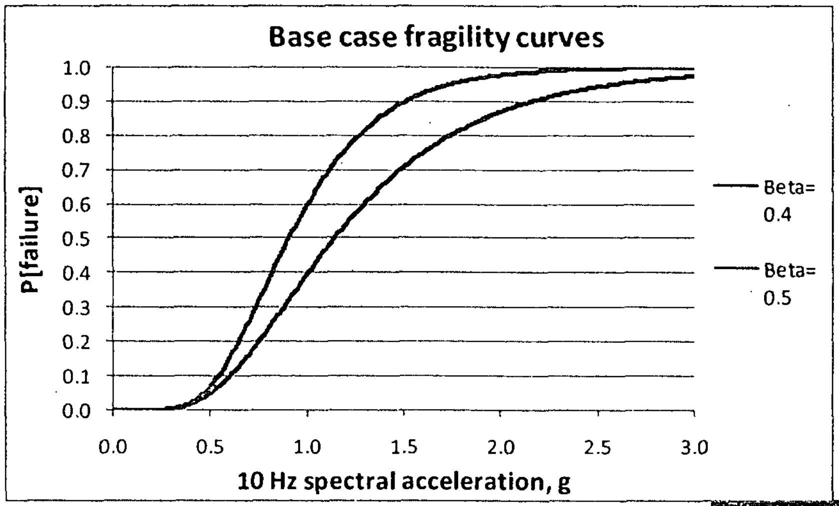
# Fragility cures for Base case



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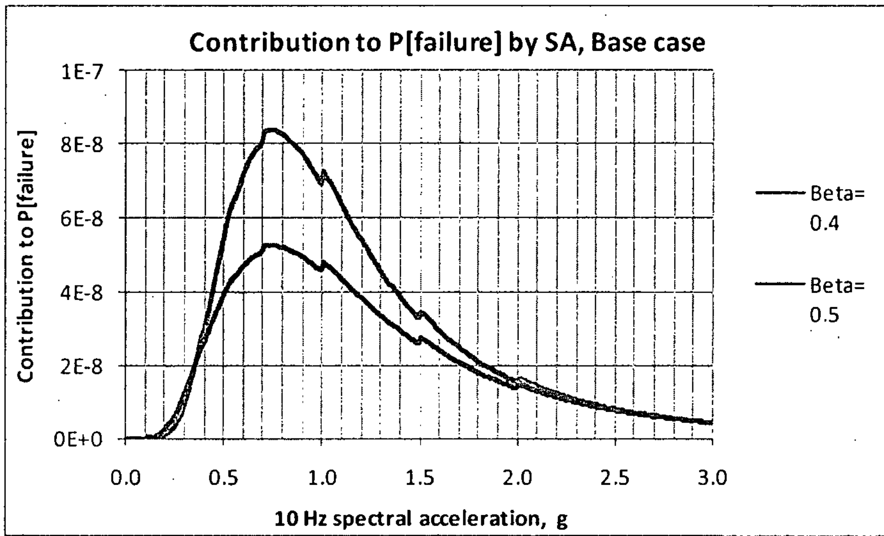
# Base case risk contribution by spectral amplitude

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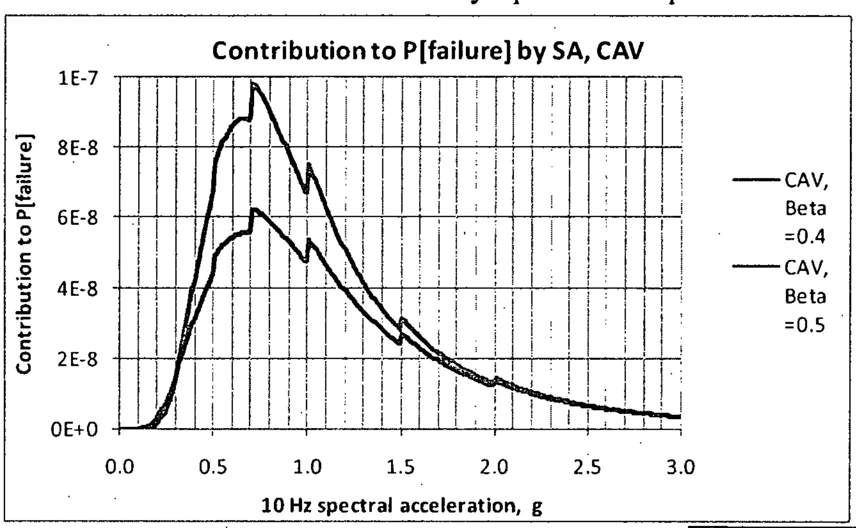
# CAV case risk contribution by spectral amplitude

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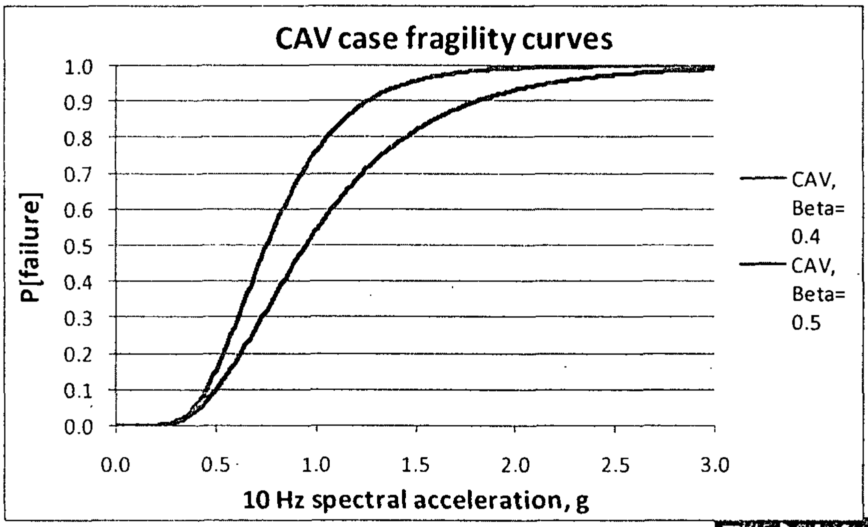
# Fragility curves for CAV case



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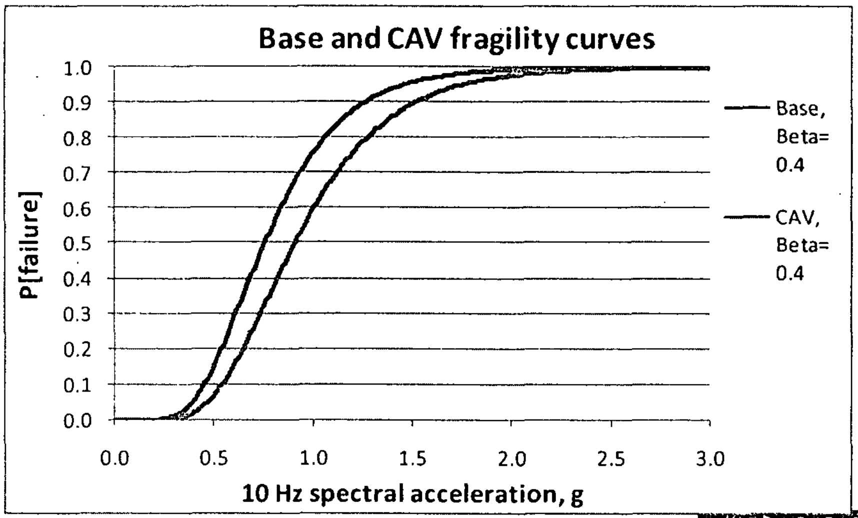
# Fragility curves for Base and CAV cases



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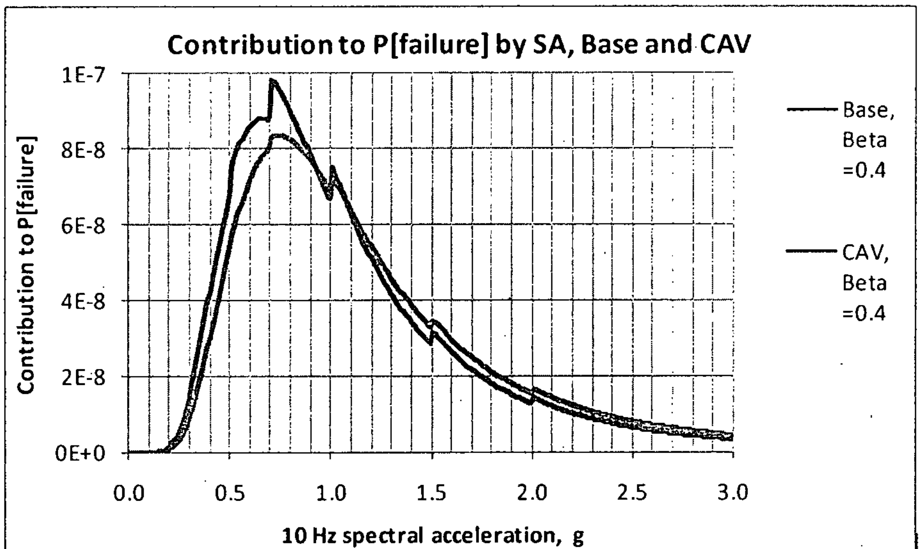
# Risk contributions for Base and CAV cases



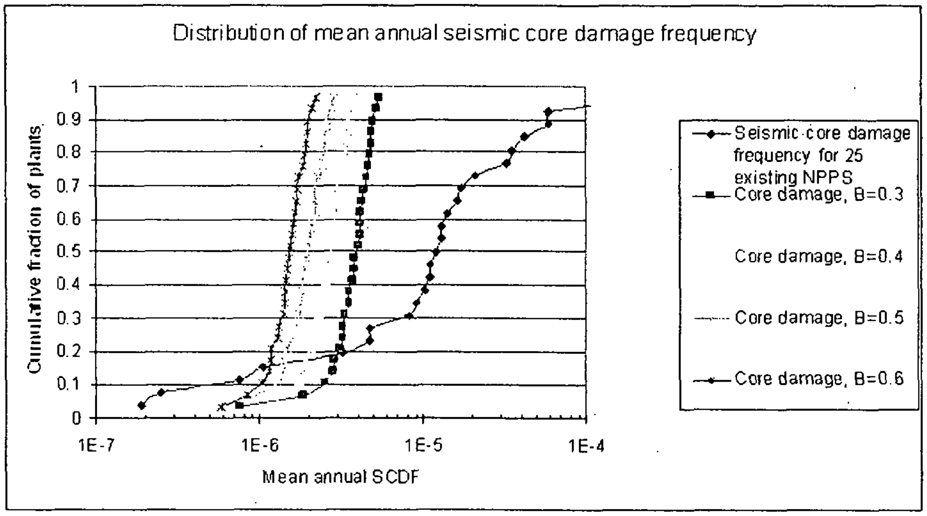



# Calculations:

Comparison 3:

Plant-level behavior:

- calculate frequency of plant-level damage, compare to distribution of Seismic Core Damage Frequency (SCDF) from 25 seismic PRAs




Cumulative distribution of plant-level performance, compared to SCDF

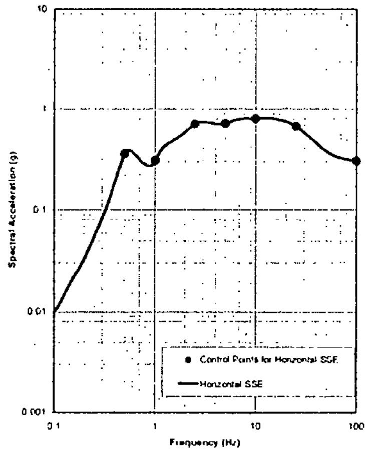
Source: REI 2005 EPRI Report



# Conclusions:

- ASCE DRS method leads to recommended design response spectra at 5 and 10 Hz that, as a whole, are equivalent to those used at 28 existing NPPs
- ASCE DRS method leads to recommended design response spectra that achieve a performance goal of 1 x $10^{-5}$ per year, for individual components at 5 and 10 Hz
- ASCE DRS method leads to plant-level performance estimates that are safer against seismic initiated core damage than 80% of existing nuclear plants (based on 5 and 10 Hz)

- Soil sites may have reduced peaks at high frequencies




Source: Vogtle ESP (2006)



# Recommended SSE spectra

- Keep performance-based spectral amplitudes at 7 frequencies
- Smooth spectra in between based on spectral shape

# Vertical SSE Spectrum

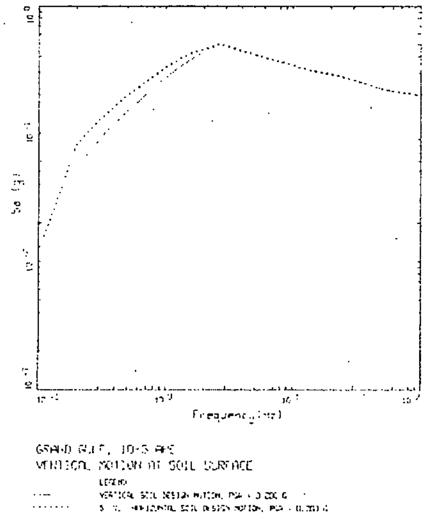
- Multiply horizontal SSE spectrum by V/H to derive vertical SSE spectrum
- Precedents:
  - →Grand Gulf (simplest)
  - →Clinton
  - →North Anna
  - →Vogtle



# Grand Gulf

- Calculated horizontal SSE spectrum
- Used V/H ratio from RG 1.60
  (maximum = 1.0 at frequencies $\geq$ 3.5 Hz)

# Grand Gulf design spectra



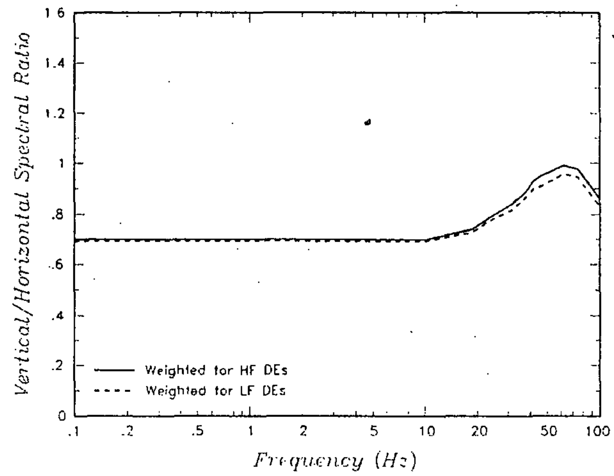
Source: Entergy Grand Gulf ESP Application (2003)



# Clinton

- Calculated horizontal SSE spectrum
- Derived V/H ratios in 4 steps
  - →Rock CEUS V/H from NUREG/CR-6728
  - →Soil WUS V/H from A&S (1997) and Campbell (1997) for M = 6.4, R = 15 km
  - →Shifting peak response from ~15 Hz to ~60 Hz
  - →Multiplying horizontal SSE by V/H ratio

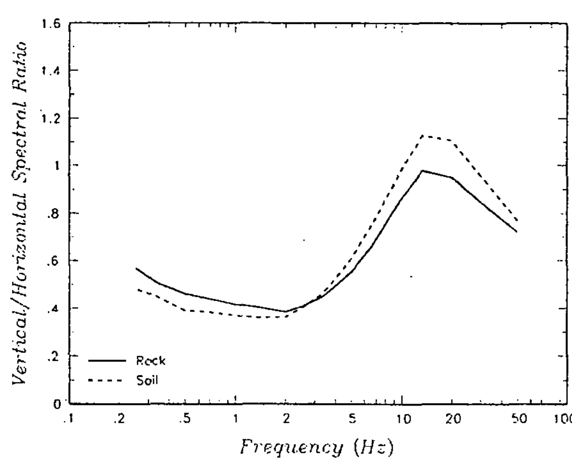
# V/H ratios, CEUS rock, Clinton (from NUREG/CR-6728)




Source: Exelon Clinton ESP Application (2004)

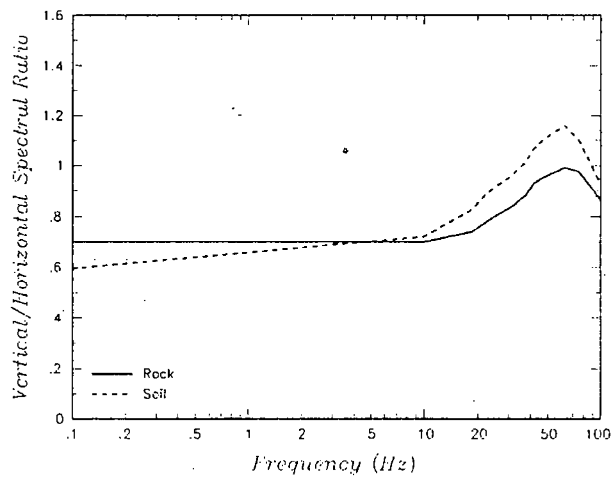


# V/H ratios, WUS, Empirical (M=6.4, R=15 km)




Source: Exelon Clinton ESP Application (2004)

# Recommended VH ratios for Clinton



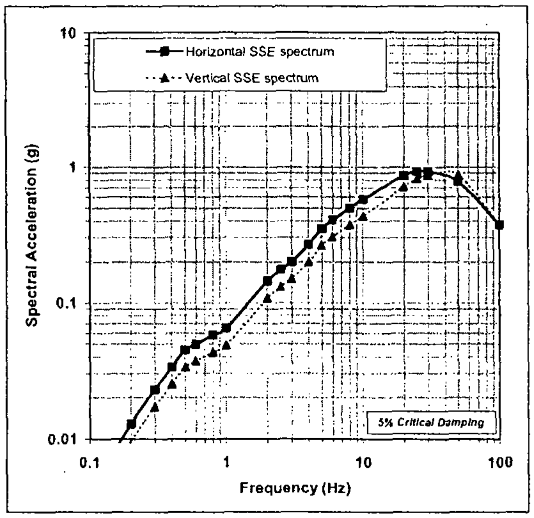

Source: Exelon Clinton ESP Application (2004)



# North Anna

- Calculated horizontal SSE spectrum
- Used V/H from NUREG/CR-6728 (CEUS rock)
  - →Applied V/H to get hard rock vertical SSE
  - →Applied V/H to get soft rock vertical SSE
  - →Checked soft rock calculation with RVT site response for vertical motions (P-SV waves)

# North Anna hard rock SSE spectra




Source: North Anna ESP (2004)



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# Vogtle

- Calculated horizontal SSE spectrum
- Used $V/H_{Soil}$ calculated by

→ 1st term: A&S (1997)

→ 2nd term: NUREG/CR-6728 Appendix J



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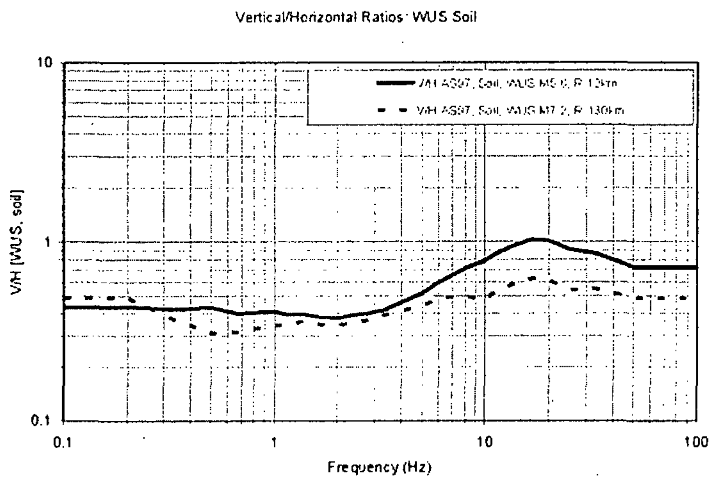
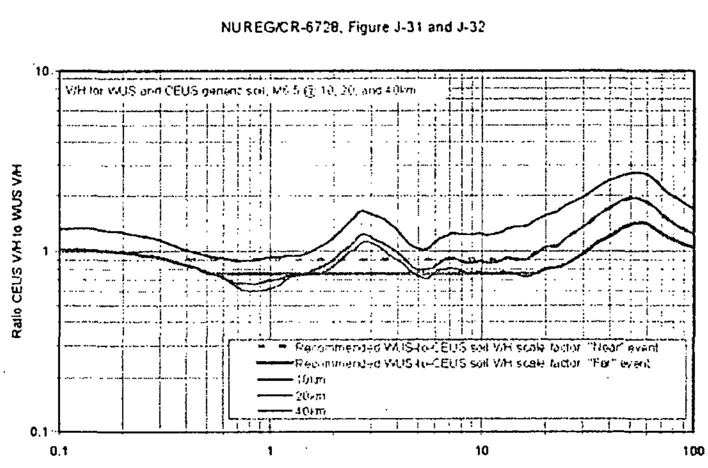
# V/H ratio, WUS, Soil, Empirical




Source. Vogtle ESP (2006)

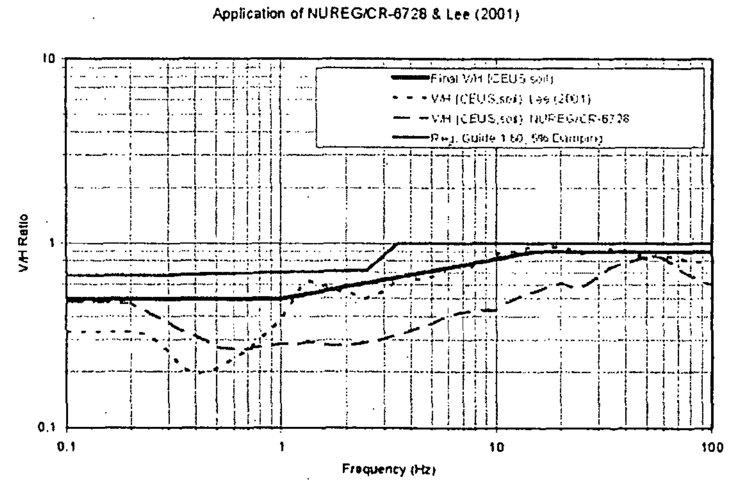


# Ratio of V/H ratios, CEUS soil model/WUS soil model




Source: Vogtle ESP (2006)

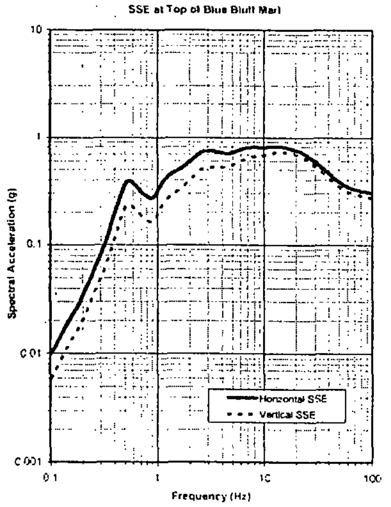
# Final recommended V/H ratios, Vogtle soil




Source: Vogtle ESP (2006)

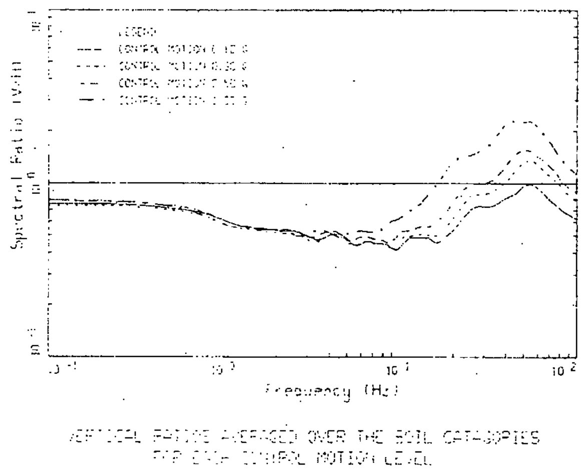


# Vogtle H and V GMRS




Source: Vogtle ESP (2006)

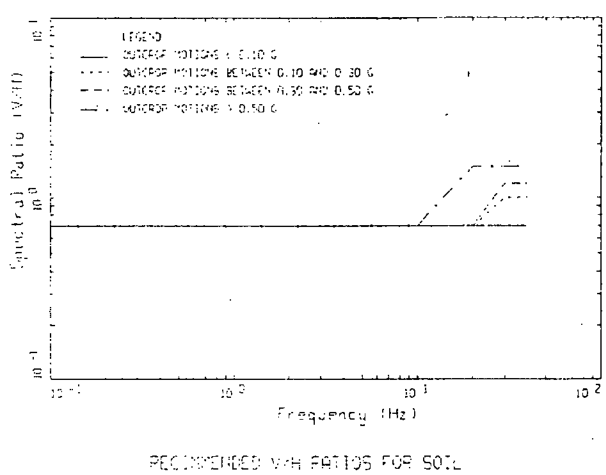
# Average V/H for 5 soil categories




Source: EPRI (1993)



# Recommended V/H for CEUS soil




Source: EPRI (1993)

# Options for Vertical SSE

1. (simple) Reg. Guide 1.60

2. Generic Soil Recommendations:
   Convert WUS soil V/H to CEUS soil V/H
   - A. Ad hoc (Clinton)
   - B. Numerical (Vogtle)

   Use published V/H ratios
   - C. Soft rock = hard rock (North Anna)
   - D. Average soil ratios (EPRI, 1993)

3. (site-specific soil) Calculate vertical amp. Factors with software (RASCAL-P). Use V/H (rock) to calculate vertical rock spectrum and amplify (Approach 2A or other (?))





# Summary

- Performance-based method of selecting GMRS achieves a FOSID of $\leq 1\times10^{-5}$ per year
- For soil sites, $10^{-4}$ and $10^{-5}$ site spectra should be calculated and GMRS determined from those
- Final spectra should be anchored to calculated GMRS at 7 frequencies and smoothed at other frequencies
- Several methods of calculating vertical spectra are available and justifiable



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