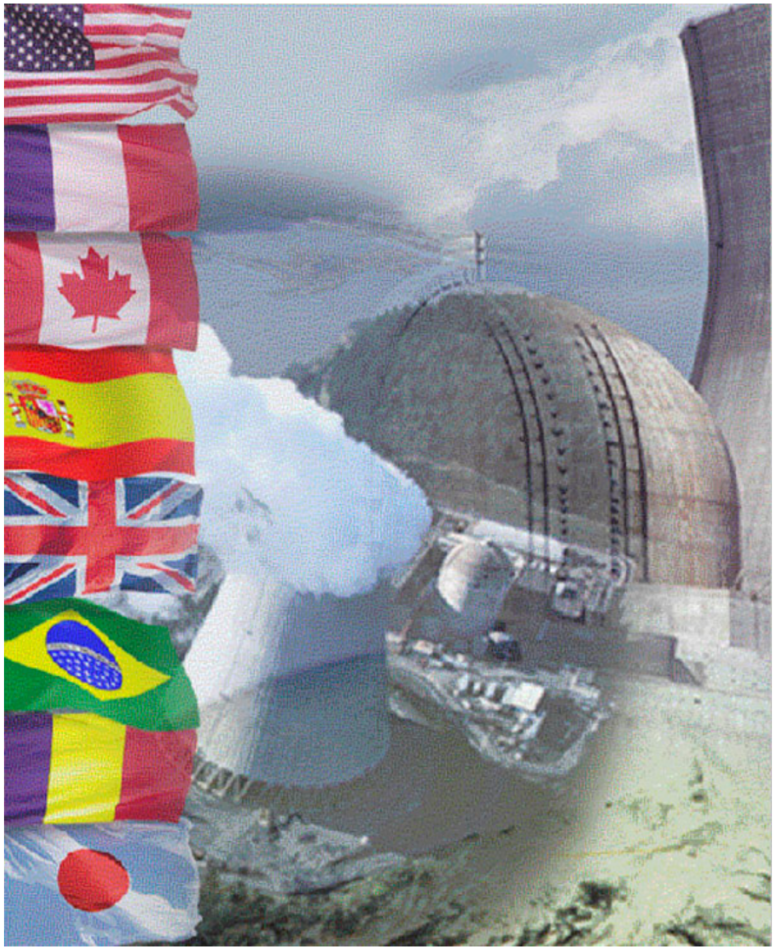


ELECTRIC POWER RESEARCH INSTITUTE

New Plant Seismic Issues Resolution Program

Status Summary of Task S2.2

by

Greg Hardy

Kelly Merz

ARES Corporation

October 20, 2005

Damage Effectiveness of High Frequency Accelerations

- **Several EPRI studies have dealt with this issue:**
  - NP-5930, "A Criterion for Determining Exceedance of the Operating Basis Earthquake", 1988
  - NP-7498, "Industry Approach to Seismic Severe Accident Policy Implementation", 1991
- **These studies document the damage thresholds to structures and equipment as determined by high frequency events such as blasting, shock testing, and operational vibration**
- **One study, TR-102470, "Analysis of High-Frequency Seismic Events", 1993, investigated an analytical basis for reduction of high frequency response of building mounted equipment by considering the effects of in-elastic deformation**

ESP Structural Task 2.2

Primary Purpose

To develop reduction (KD) factors to apply to the high frequency portion of ground response spectra to conservatively account for the fact that typical power plant equipment and structures are not damaged by high frequency motions (i.e. due to extremely limited displacement demand)

S2.2 Key Project Tasks

- Strengthen Key Assumptions
  - In structure Amplification Factor
  - Develop Simple Nonlinear Response Examples
  - Limiting Displacements (0.01”)
- Develop an Improved Procedure for Knock Down Factor Implementation
- Recommendations for Equipment with Functional Failure Modes
- Documentation of Results of S2.2 in a Report

Strengthen Key Assumptions

Develop examples to demonstrate the dynamics involved in high frequency response & capacity

- Simple sliding/rocking models
- Non linear inelastic response
- The simplified models (1 & 2 DOF) used in the TR-102470 study need to be justified as conservative representations of actual equipment response

Justify floor spectra amplification assumption

- Utilize shear/flexure/Timoshenko beam models

Justify bounding example fillet weld assumptions

- Review 0.01 inch limit displacement
- Review weld performance under cyclic loading

ESP Task S2.2

Schedule

- NRC/TRAG Technical Working Meetings
  - June 22/23 at ARES
  - August 23-24 at ARES
  - Meeting Minutes Provide Summary of Tasks Completed, Preliminary Results and Remaining Items
- NEI/NRC Meeting in October in Washington DC
- Final Report to NRC January, 2006
- NRC Review as Part of I1.1 Task (Jan-June 2006)

New Plant Seismic Issues Resolution Program

Task S2.2: Effect of Negligible Inelastic Behavior on High Frequency Response

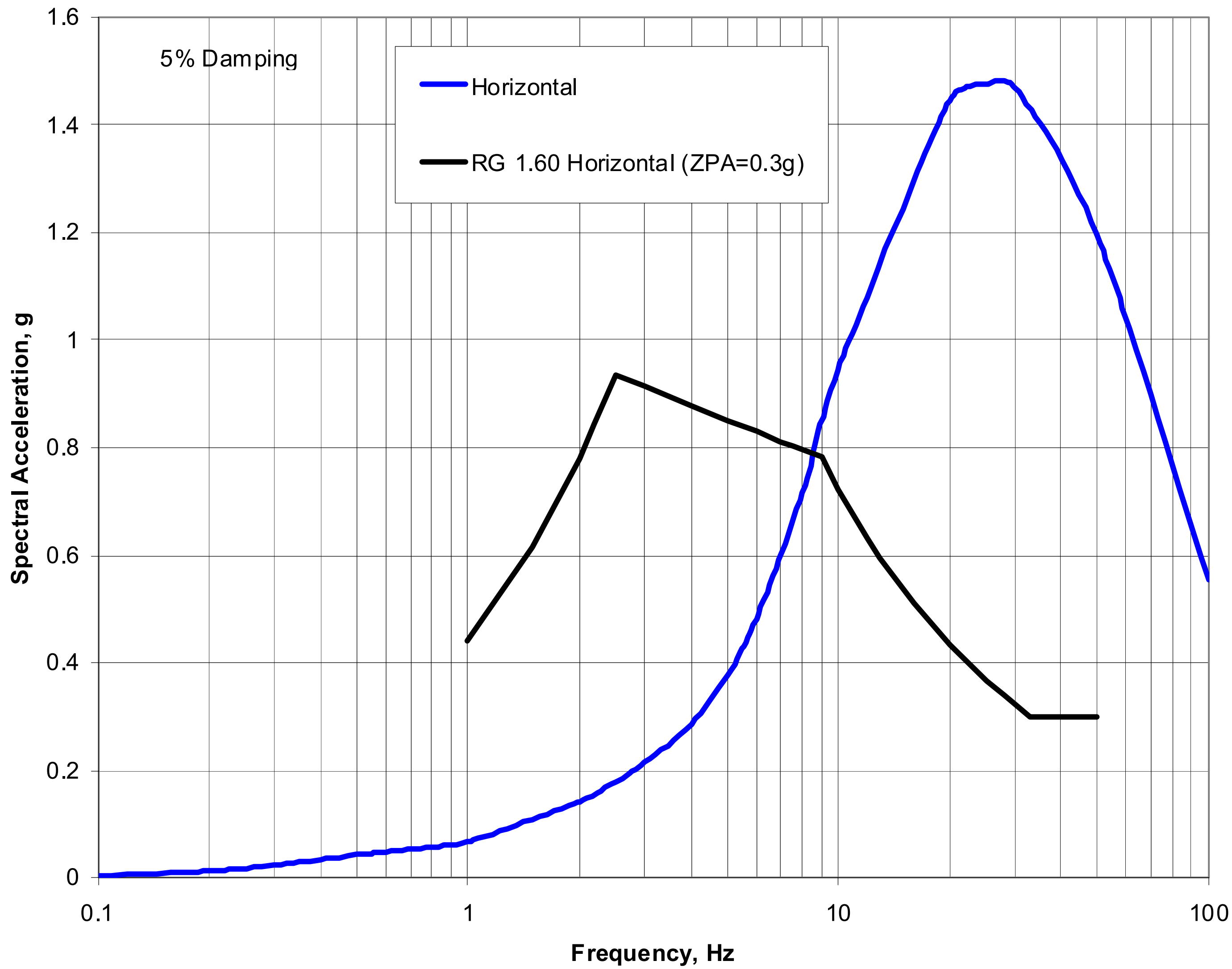
by

Kelly Merz

ARES Corporation

October 20, 2005

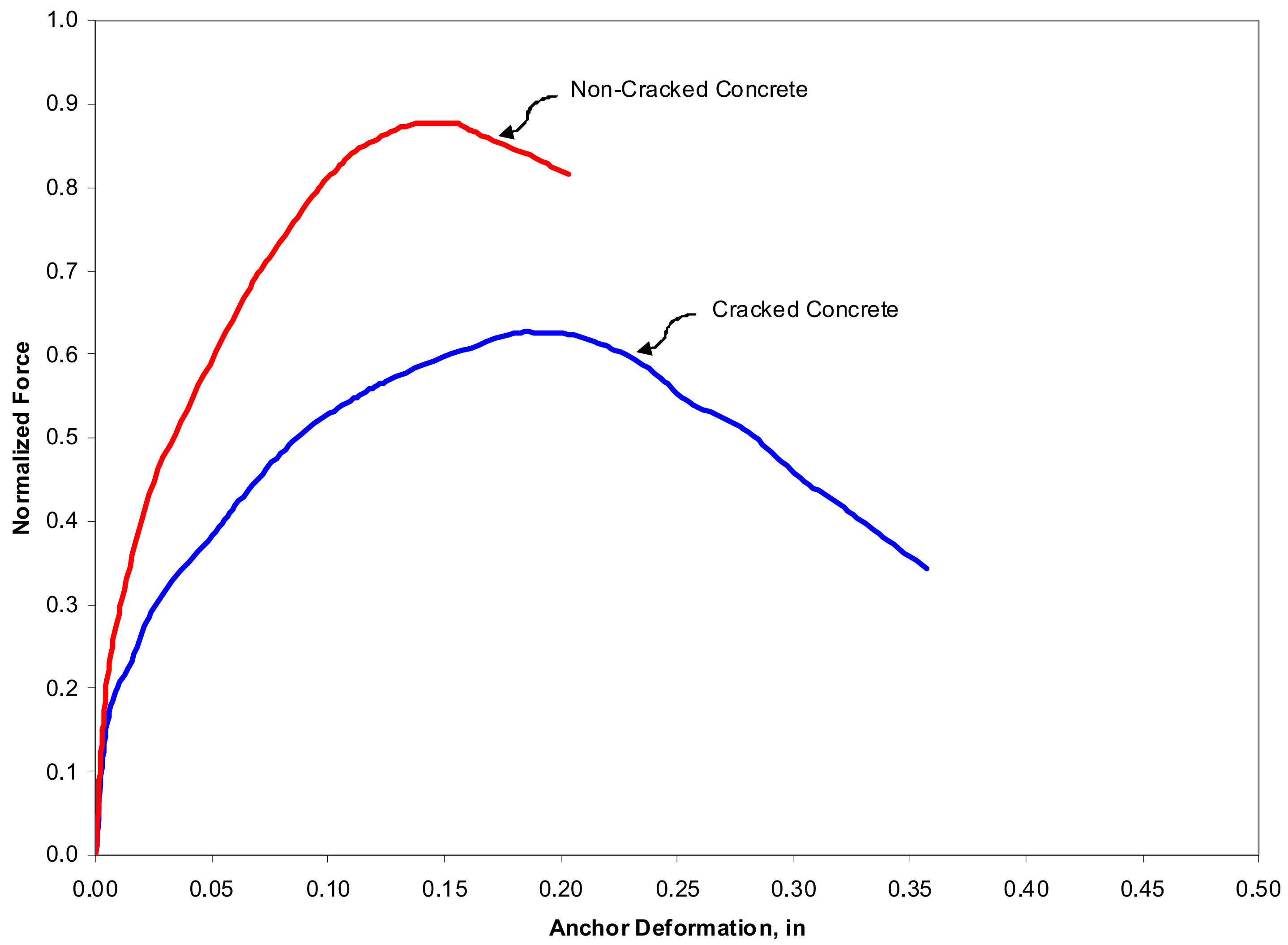
CEUS Rock Free-Field Design Motion



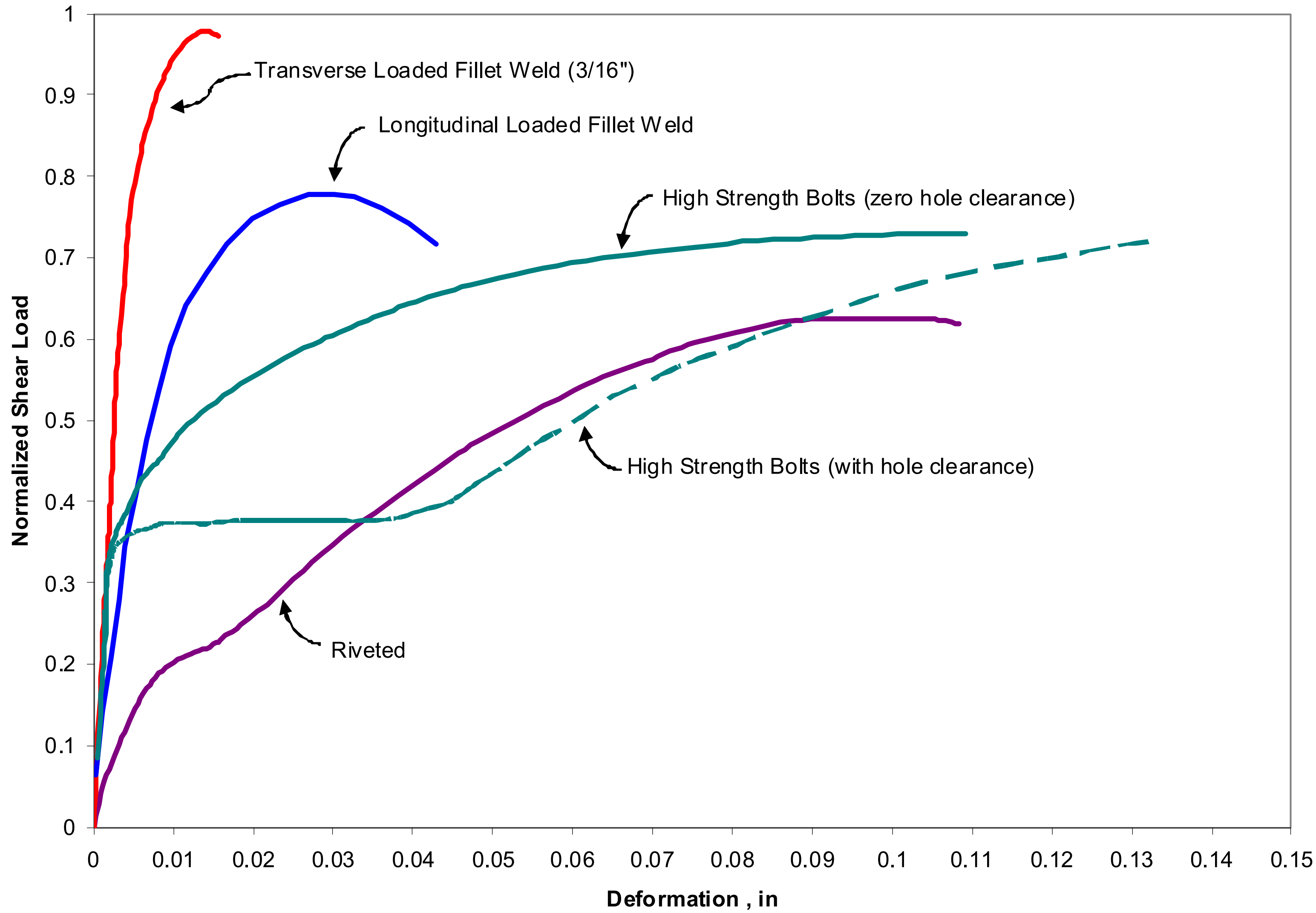
High Frequency In-Elastic Deformation Effects

- High frequency accelerations are associated with very small displacements which may be classified, from an engineering standpoint, as negligible.
- For example, a 1g response at 30 Hz will be associated with a displacement of ~0.01 inch while a 1g response at 5 Hz will involve a displacement of ~0.40 inch.
- EPRI TR-102470 (1993) developed a simplified analysis procedure to reduce the *ground level spectrum* to account for the negligible level of inelastic response which results from high frequency input motion. The goal of the current work is to re-assess the key assumptions used in TR-102470.
- The basic premise of TR-102470 is that the ground level spectrum can be modified and can then be used to generate floor spectra which implicitly incorporate reductions in the high frequency response. The effect of amplified building response is included in the procedure as an amplification factor applied to the ground motion.
- For equipment anchorage, code-based capacity is used to meet the demand computed using effective linear equipment and structural models. The inherent non-linear behavior of anchorage components is ignored in normal design since the deformation is small. However, when the anchor deformation is of the same order as the equipment response level, the equipment response will be affected.

Load-Deformation Characteristics of Concrete Expansion Anchors

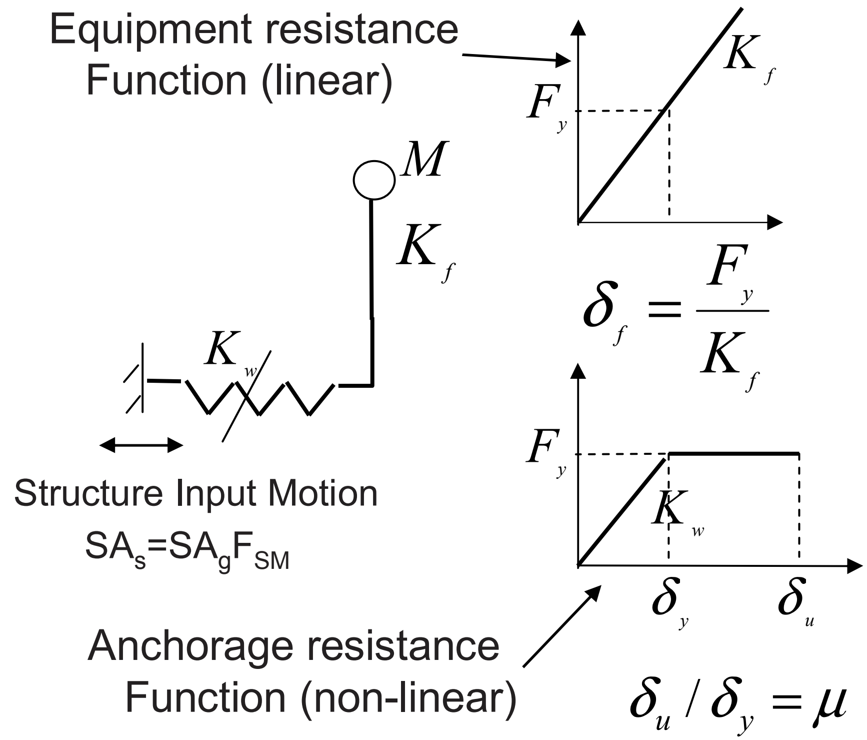


Load-Deformation Characteristics of Anchorage Load Path Connections in Shear



EPRI TR-102470 Approach

- TR-102470, “Analysis of High-Frequency Seismic Effects”, proposed a simple evaluation model with the structure and equipment response remaining linear.
- Using a SDOF representation, the Equipment Resistance Function was assumed to be linear
- The Anchorage Resistance Function was assumed to be non-linear
- The structure input motion was assumed to be represented by an amplification factor applied to the ground motion.

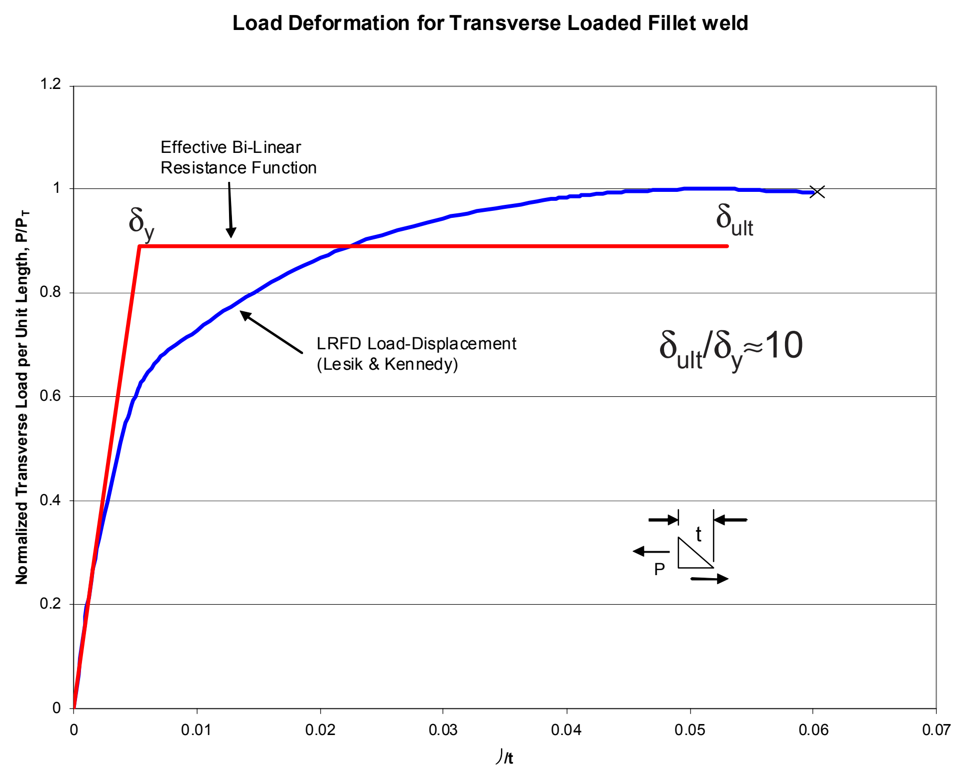


Series Stiffness

$$K^* = \frac{K_f \, K_w}{K_f + K_w} = K_f \frac{1}{1 + K_f / K_w}$$

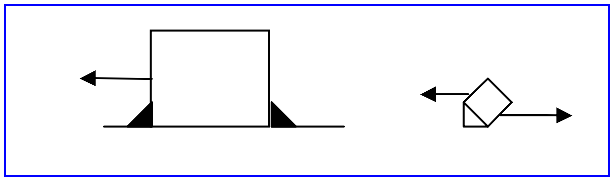
Anchorage Resistance Function

- A small fillet weld, loaded transversely in shear was selected as the surrogate anchorage component since such components are commonly used to anchor electrical cabinets and since they have the least deformation capacity
- Test based weld deformation functions (now incorporated in the AISC LRFD code) were used to idealize the resistance function
- A small minimum 3/16” fillet weld with transverse loading has an equivalent yield displacement on the order of 0.001 inch and the displacement at weld failure being approximately 0.01 inch



Evaluation Models

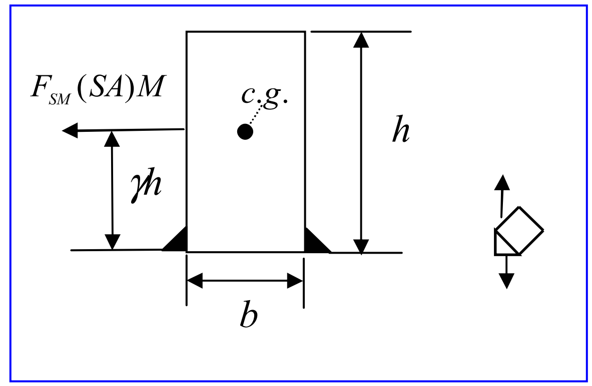
Shear Resistance Model



- F_{SM} is a scale factor which accounts for both the ratio of design to actual weld capacity and structure amplification of ground motion (floor motion) if the equipment is placed at elevation in a structure. If the ratio of weld capacity to LRFD design strength is approximately 1.6 and the maximum structural amplification in the > 10 Hz range is 2.5, then F_{SM} is within the range 1.6-4
- A sequence of equations was developed for the series resistance function to obtain the non-linear reduction factor F_{μ}
- The reduced acceleration is then

$$SA_r = \frac{SA\left(f_f, \beta_f\right)}{F_\mu}$$

Overturning Resistance Model

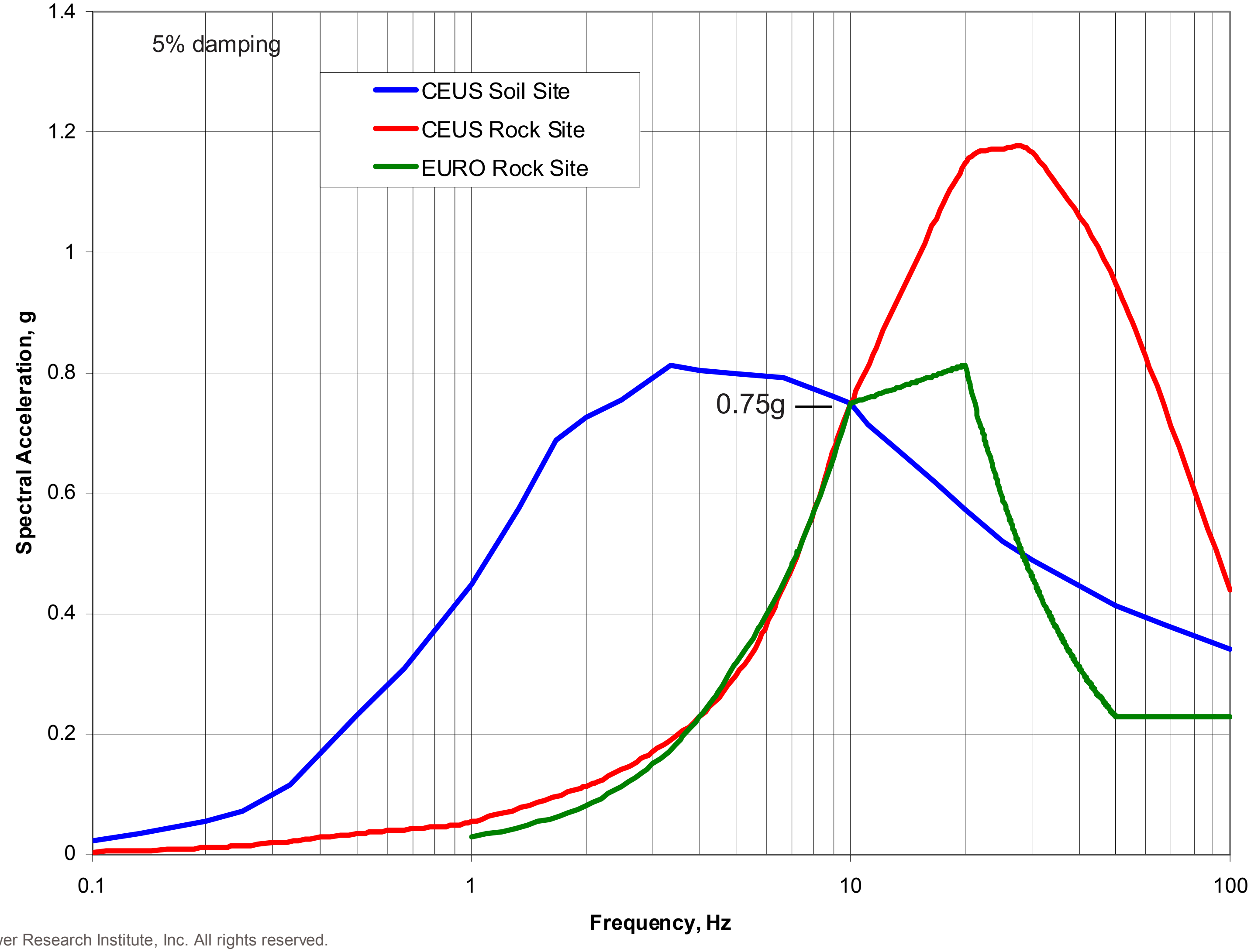


- Considering the overturning kinematics/mechanics, the equations for the overturning model can be placed in the same solution form as the shear resistance model, except that F_{SM} is replaced by F_{SM}/e
- For a typical high aspect ratio equipment item, $e \approx 2.5$, thus F_{SM}/e is with the range 0.4-1.6

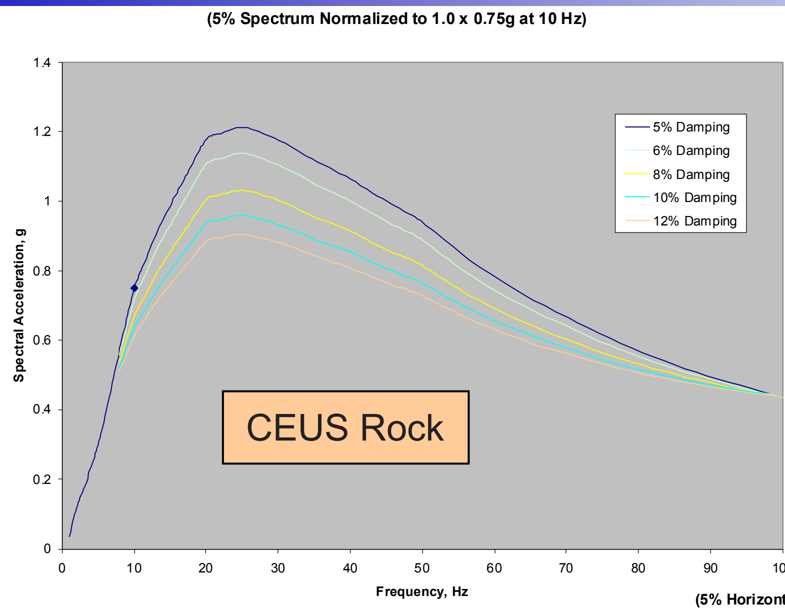
Example Reduction of Spectra for Non-Linear Behavior

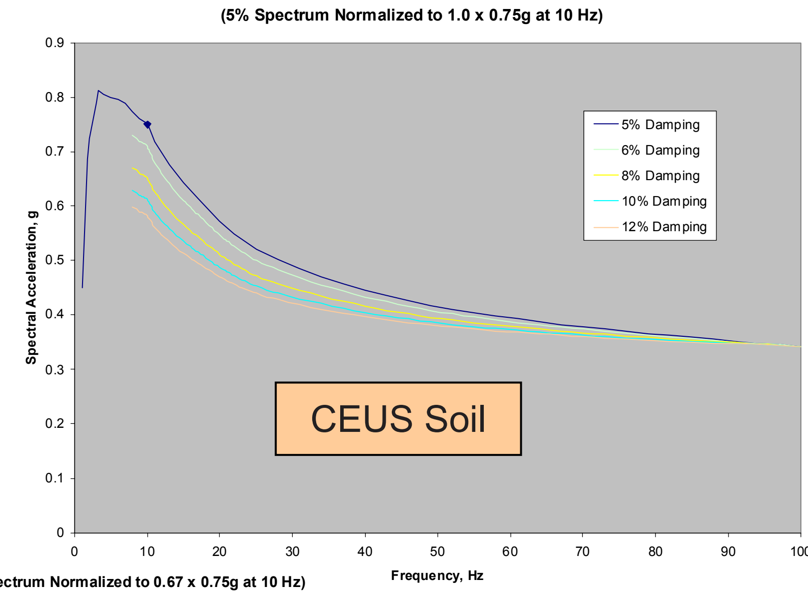
- A representative CEUS rock spectral shape, a representative CEUS soil spectral shape, and a hard rock spectrum used in Europe were chosen to demonstrate the reduction procedure
- All spectra (5% damping) were initially scaled to 0.75g at 10 Hz and the reduction procedure applied. (0.75g is the approximate spectral value of a RG 1.60 spectrum at 10 Hz)
- Next, additional reduction cases with the same spectra scaled to 1.5 x 0.75g and 0.67 x 0.75g at 10 Hz were to be developed.
- The reduced spectra are plotted for the range of (F_{SM}, F_{SM}/e) = 4.0 to 0.4
- The bounding values of the reduced spectrum are determined by:
  - $Sa(f_f,\beta_f)$, $f_f < 10$ Hz
  - $Max\{Sa_r(F_{SM}, F_{SM}/e)\}$, 10 Hz $\leq f_f \leq f_f^*$
  - $Sa(f_f,\beta_f)$, $f_f > f_f$

Ground Motions Considered

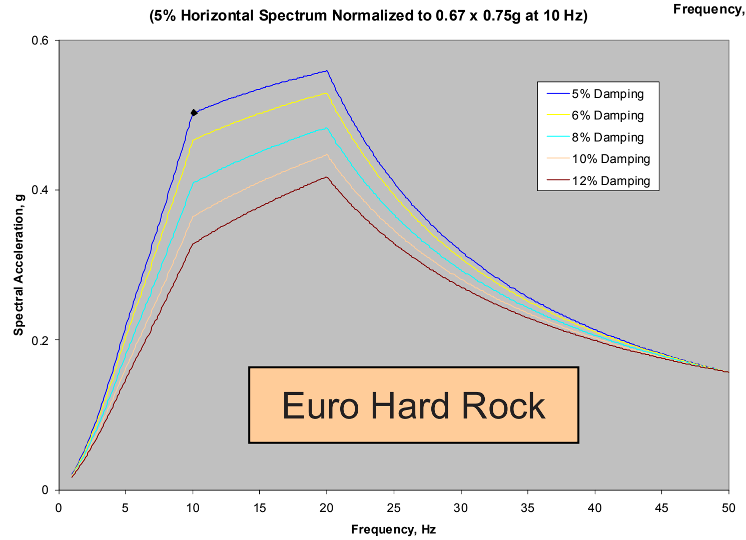


Response Spectra as a Function of Damping

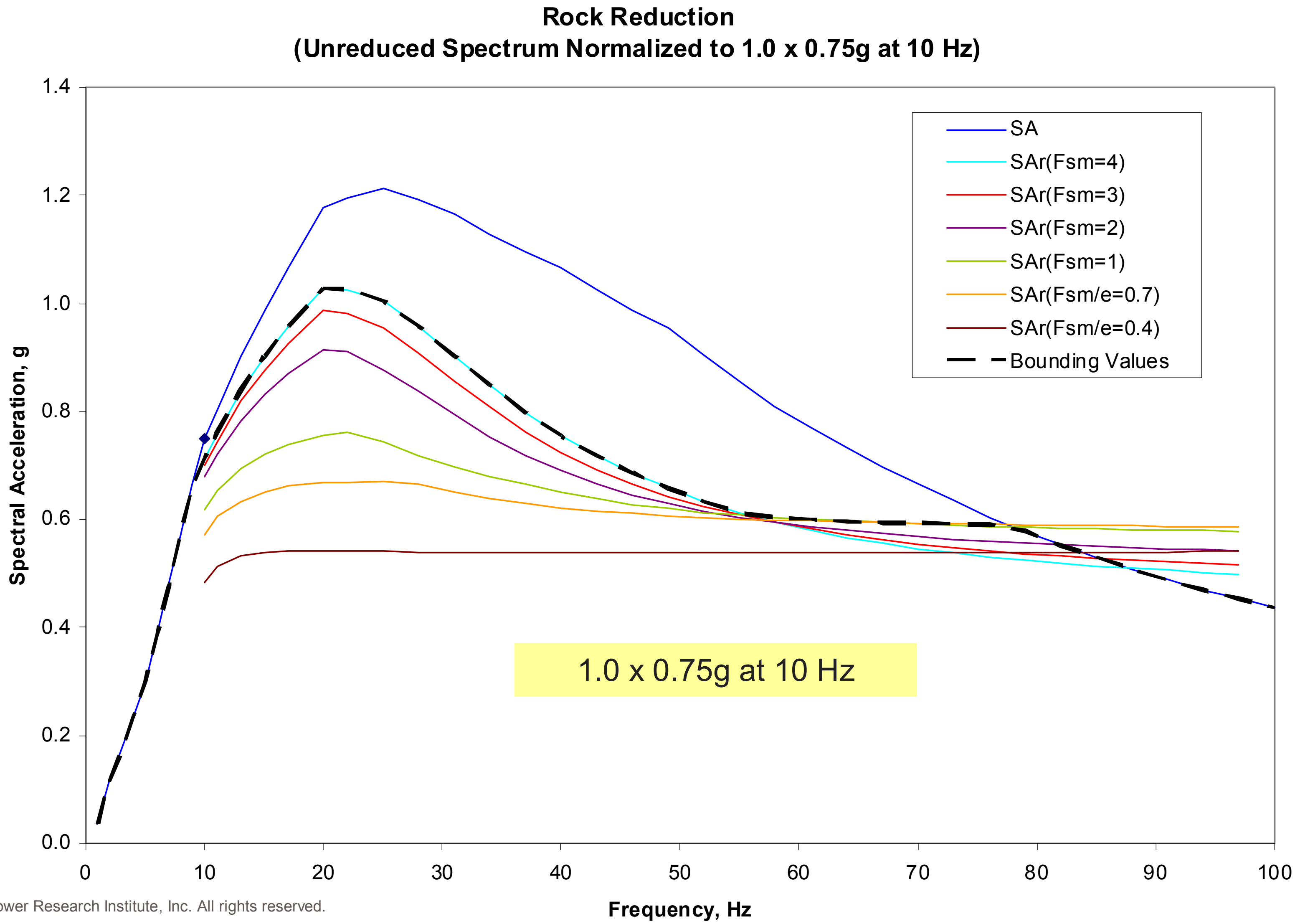




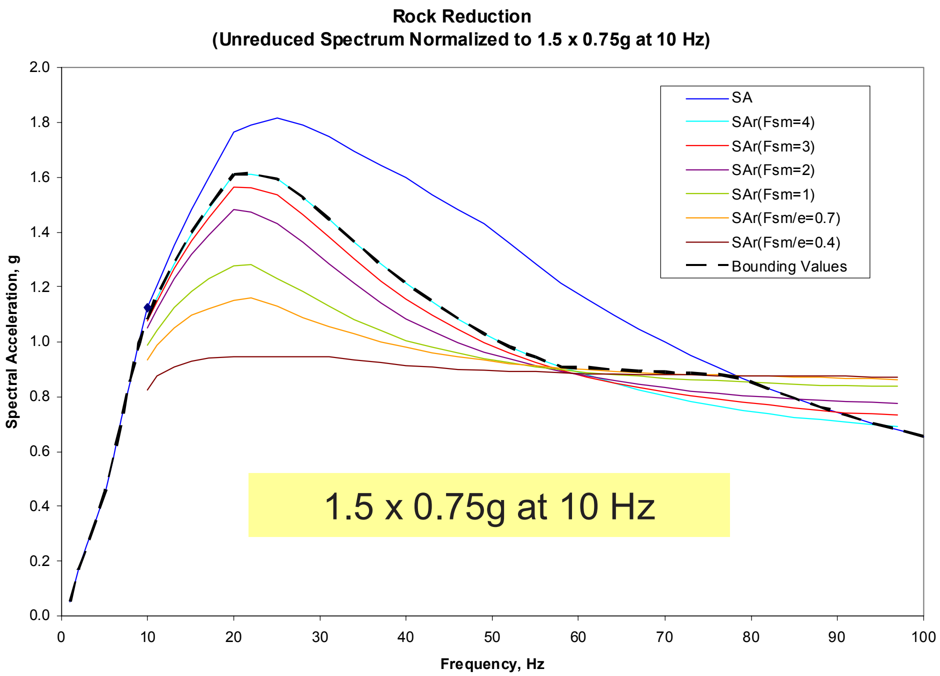
- Damping Variation of CEUS Rock and Soil Spectra Using NUREG/CR-6728 Recommendation
- Damping Variation of EURO Rock using Interpolation

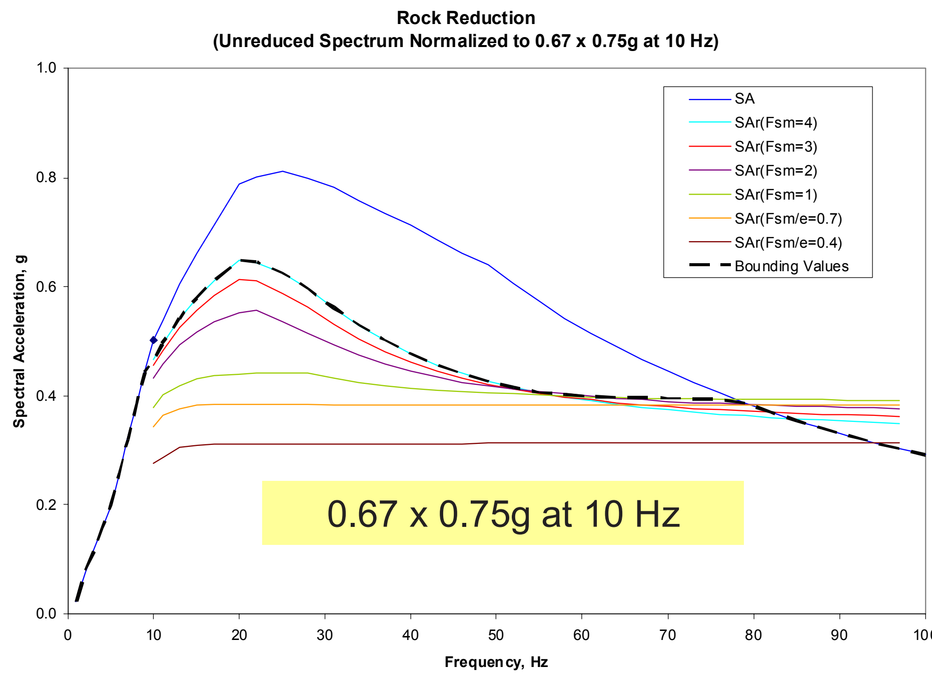


Rock Spectra Reduction

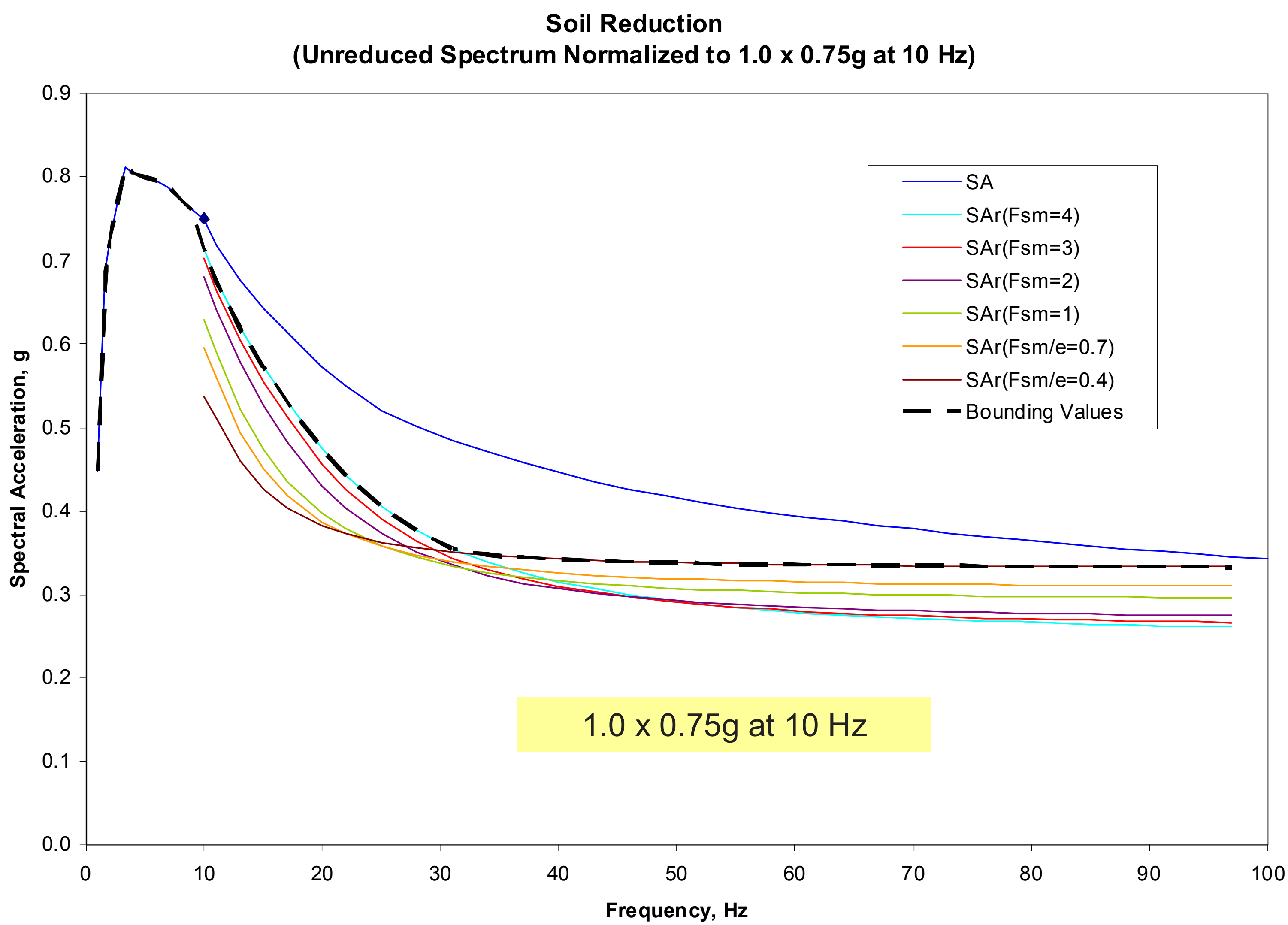


Effect of Scaling on Rock Spectra

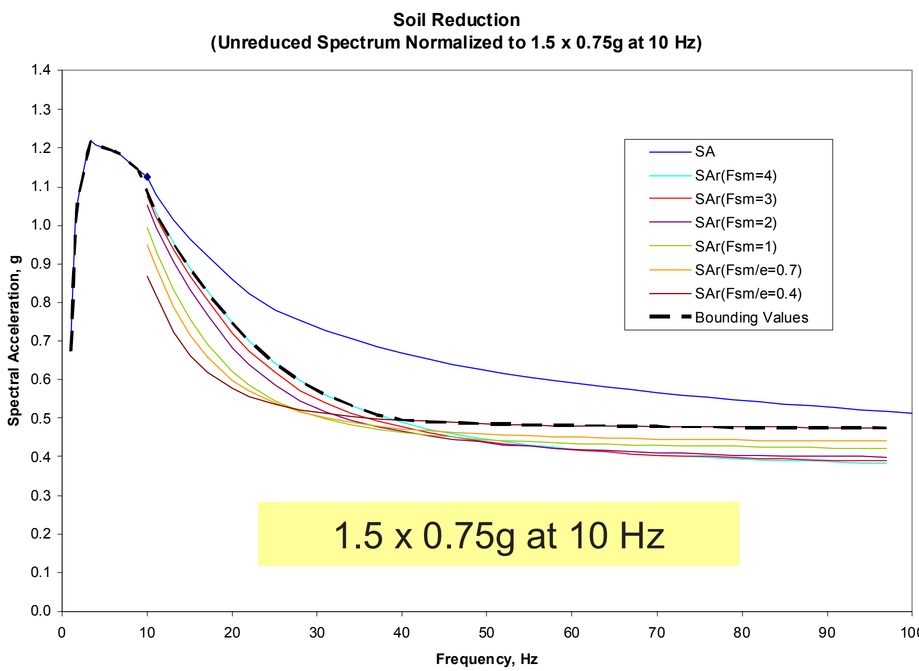


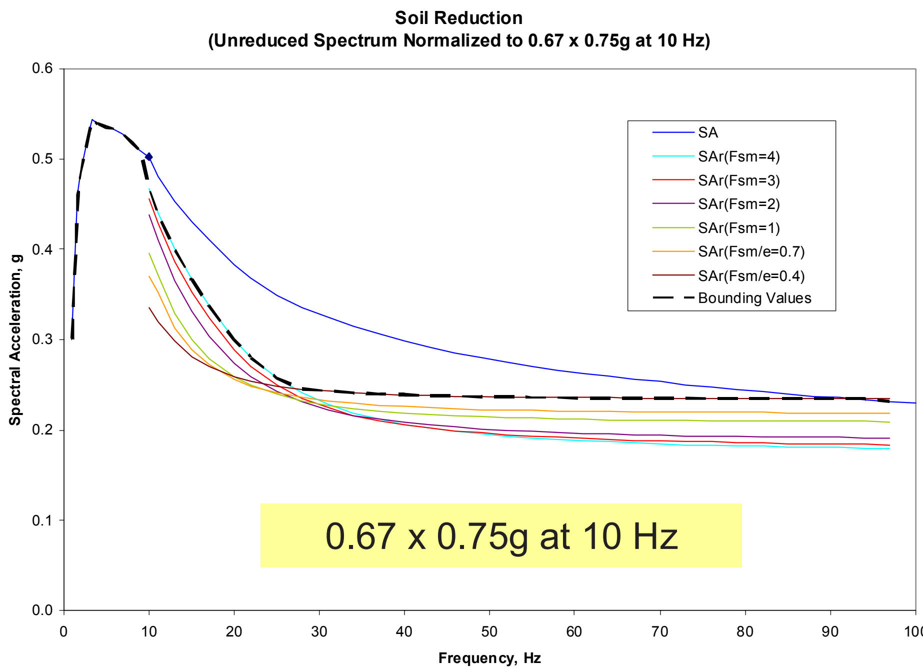


Soil Spectra Reduction

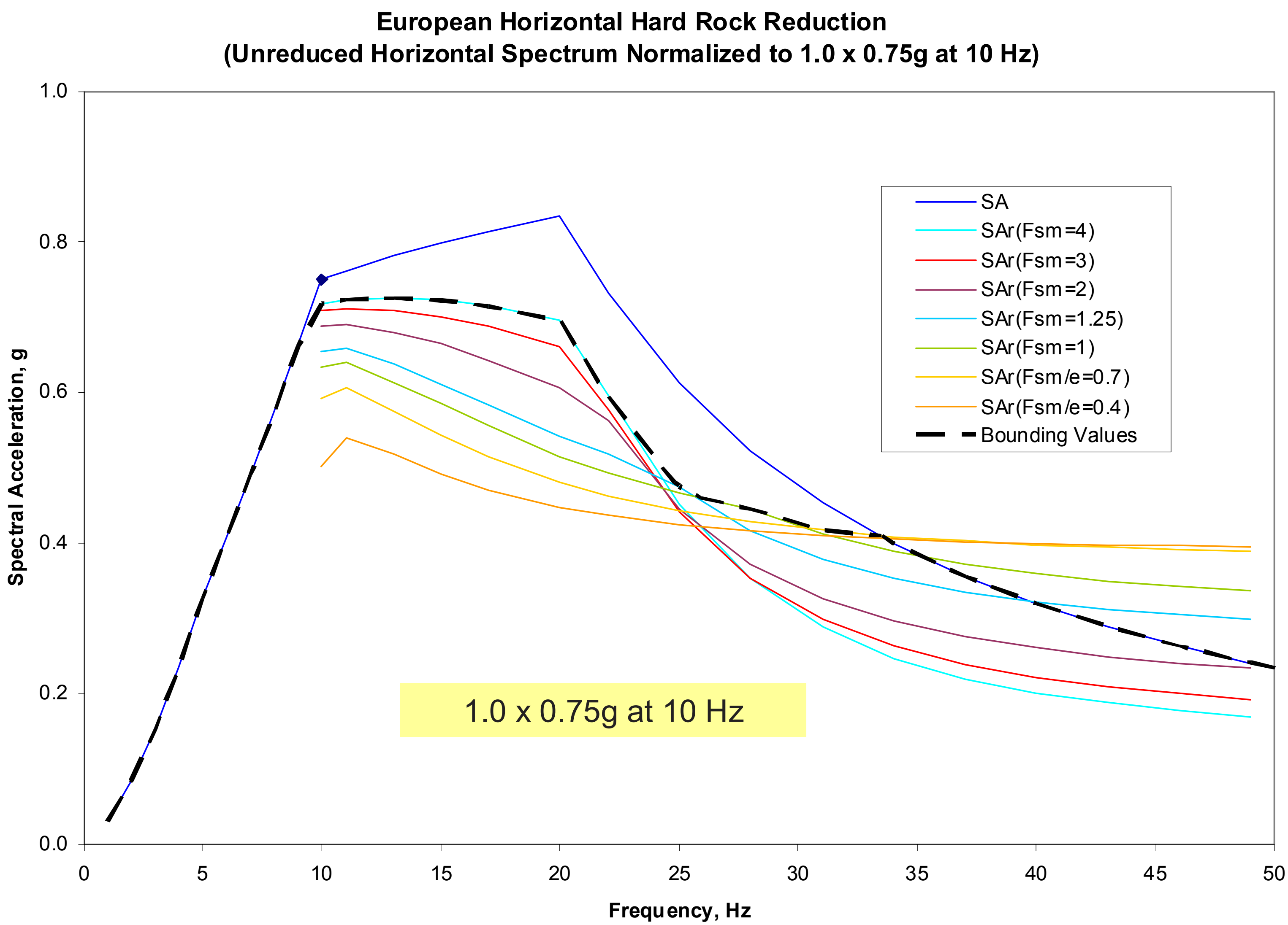


Effect of Scaling on Soil Spectra

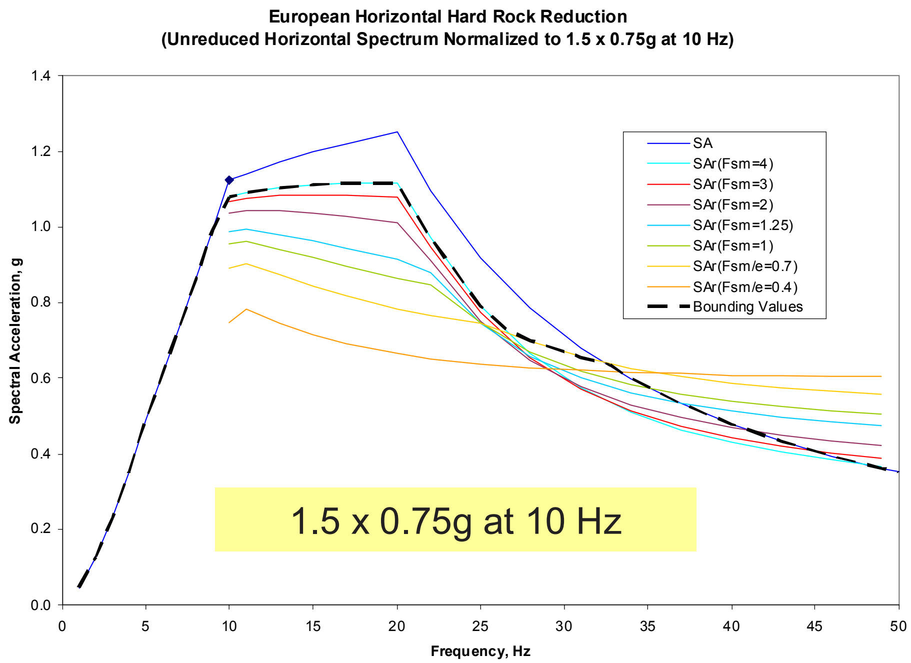


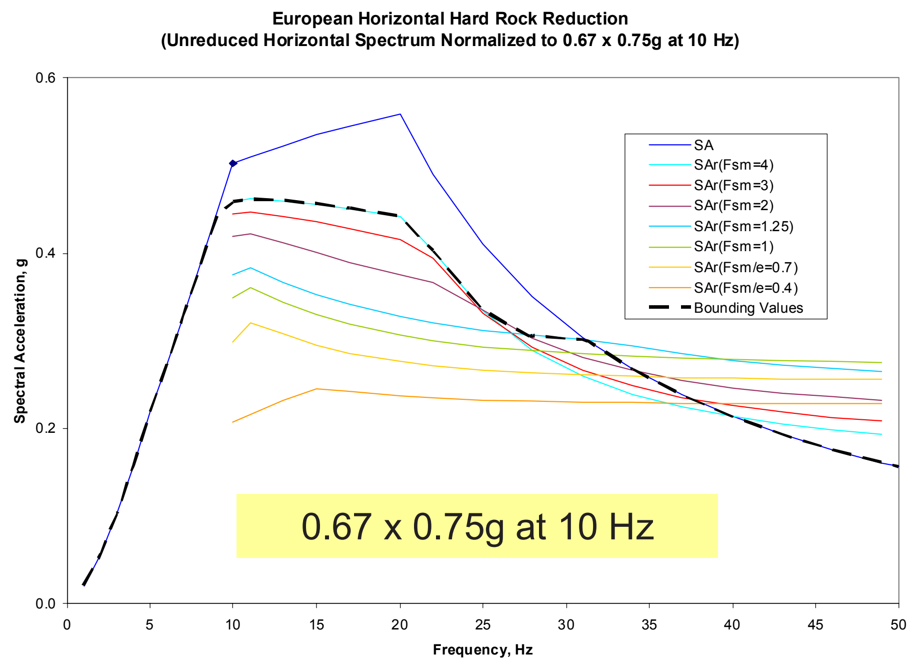


European Rock Spectra Reduction



Effect of Scaling on European Rock Spectra



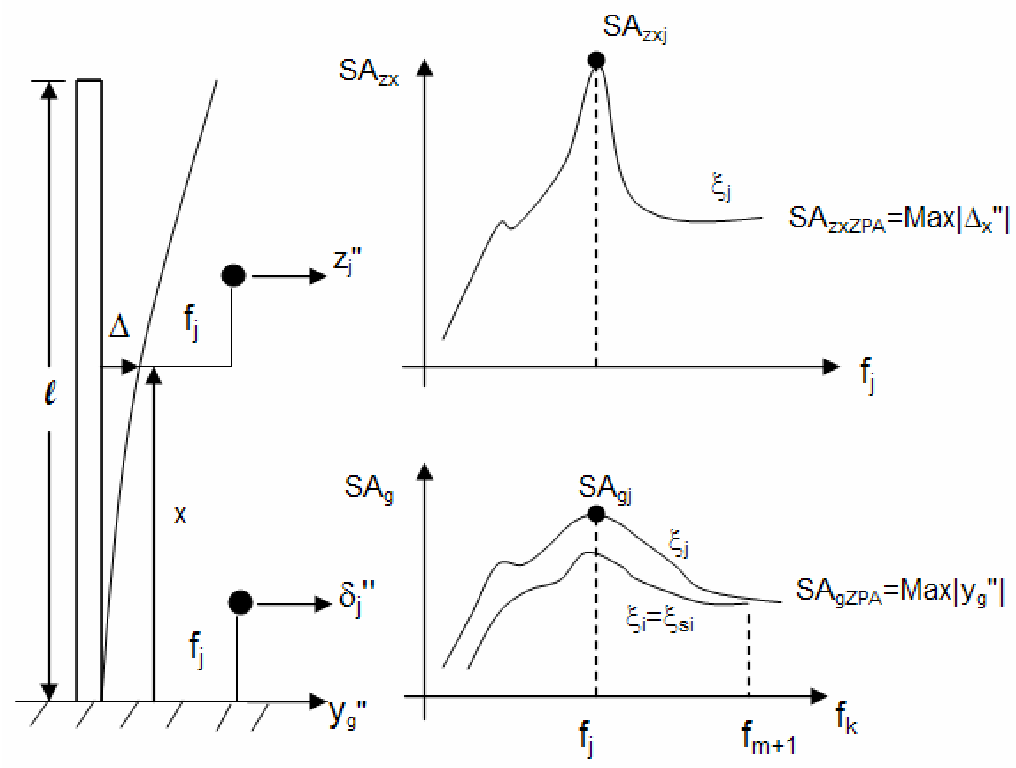


Structure Amplification in the > 10 Hz Range

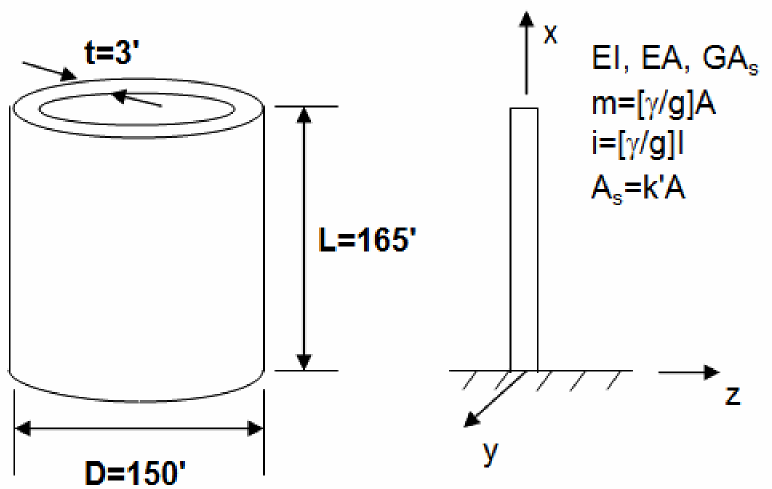
- The goal of the foregoing development is to modify the ground motion spectrum and then use the modified ground spectrum to define a time history to be used to generate floor spectra which implicitly incorporate reductions in the high frequency response.
- The motivation for this approach is that structural models have inherent limitations for computing high frequency response thus the high frequency content of the floor motion is removed at the input level rather than the structure response level
- One of the key assumptions in the foregoing development is that the structure amplification, as measured by the ratio of a in-structure spectrum to ground spectrum, is at most about a factor of 2.5 in the greater than 10 Hz range

Response of Building Mounted Components

- $SA_{gj} = Max|A_{gj}|$
- Given m modes: f_i, ξ_i, $\Gamma_i\phi_i(x)$
- $A_x = \sum_{1}^{m} \Gamma_i\phi_i(x)A_i + [1-\sum_{1}^{m}\Gamma_i\phi_i(x)]y_g''$
- $SA_{zxj} = Max|A_{zxj}|$
- $AF_x(f_j) = SA_{zxj}/SA_{gj}$



Representative Plant Structure



Timoshenko Beam

			x/L=1	x/L=0.5
Horz Mode	f, Hz	f/f1	Gamma Phi	Gamma Phi
1	6.050	1.000	1.34663	0.75020
2	15.837	2.618	-0.37953	0.36187
3	25.452	4.207	-0.10529	0.07537
4	35.523	5.872	0.25404	-0.18077
5	49.415	8.168	-0.07816	-0.07773
6	51.543	8.520	-0.11898	-0.05413
7	65.820	10.879	0.14110	0.11008
8	79.050	13.066	-0.08312	0.07926
9	81.945	13.545	-0.04635	0.02166
10	95.187	15.733	0.09773	-0.08147
11	109.866	18.160	-0.08126	-0.04344
12	111.709	18.464	-0.00522	-0.00197

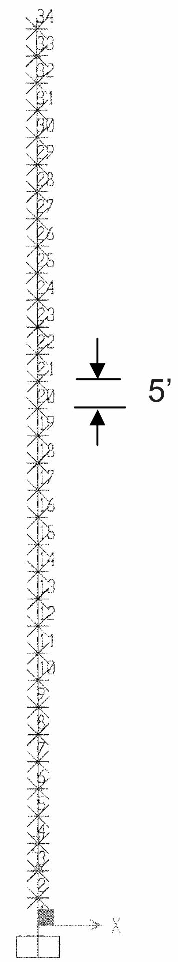
$I/(AL^2) = 0.1$ $E/(k'G) = 4.6$

$E = 35 \times 10^5$ psi, $\nu = 0.2$, and weight density γ = 150 lb/ft^3

High Resolution Model Discretization

Case 2

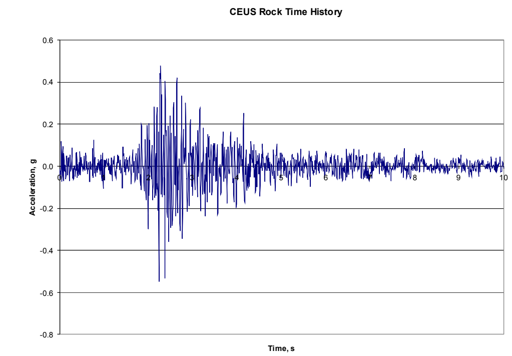
Horz. Mode	f, Hz	f/f1	x/L=1 Gamma Phi	x/L=0.5 Gamma Phi
1	6.047	1.000	1.34635	0.71128
2	15.795	2.612	-0.37840	0.37204
3	25.582	4.230	-0.12738	0.11803
4	35.353	5.846	0.26696	-0.15215
5	49.351	8.161	-0.06923	-0.08107
6	51.303	8.484	-0.11610	-0.07109
7	65.343	10.805	0.13957	0.07180
8	78.316	12.951	-0.07298	0.07024
9	81.511	13.479	-0.04020	0.03009
10	93.656	15.487	0.09554	-0.04372
11	107.600	17.793	-0.08061	-0.07322
12	111.050	18.364	-0.00093	-0.00145
Sum Gamma Phi			0.96257	0.95077

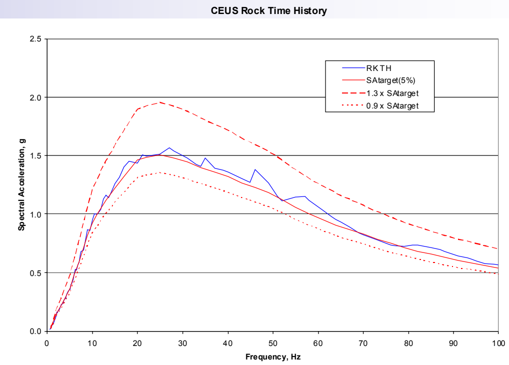


Amplification Study

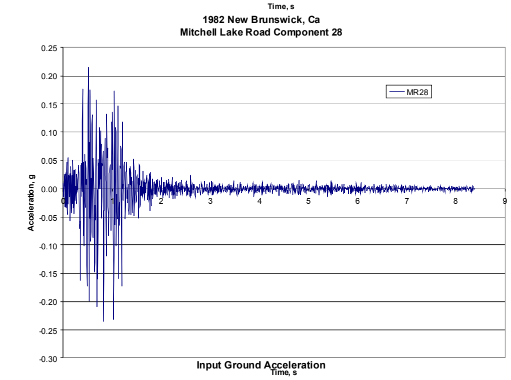
- Consider uniform Shear Beam, Timoshenko Beam, and Flexure Beam
- Use theoretical frequencies, mode shapes, and participation factors
- Choose fundamental frequencies of 3, 5, 7, and 9 Hz for each beam type
- Consider all modes to 100 Hz
- All modes with 7% damping
- Use three time histories:
  1) CEUS Rock compatible,
  2) ENA actual record,
  3) TH compatible with European Hard Rock Spectra

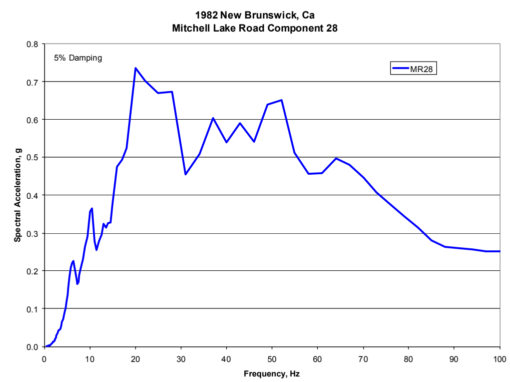
Amplification Study Time Histories



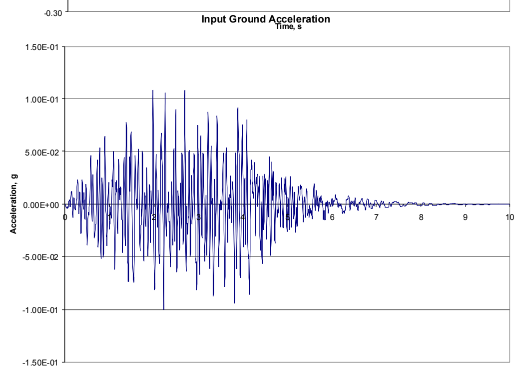


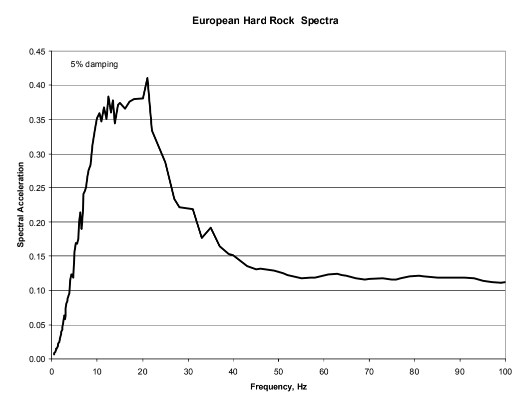
Compatible CEUS Rock Time History





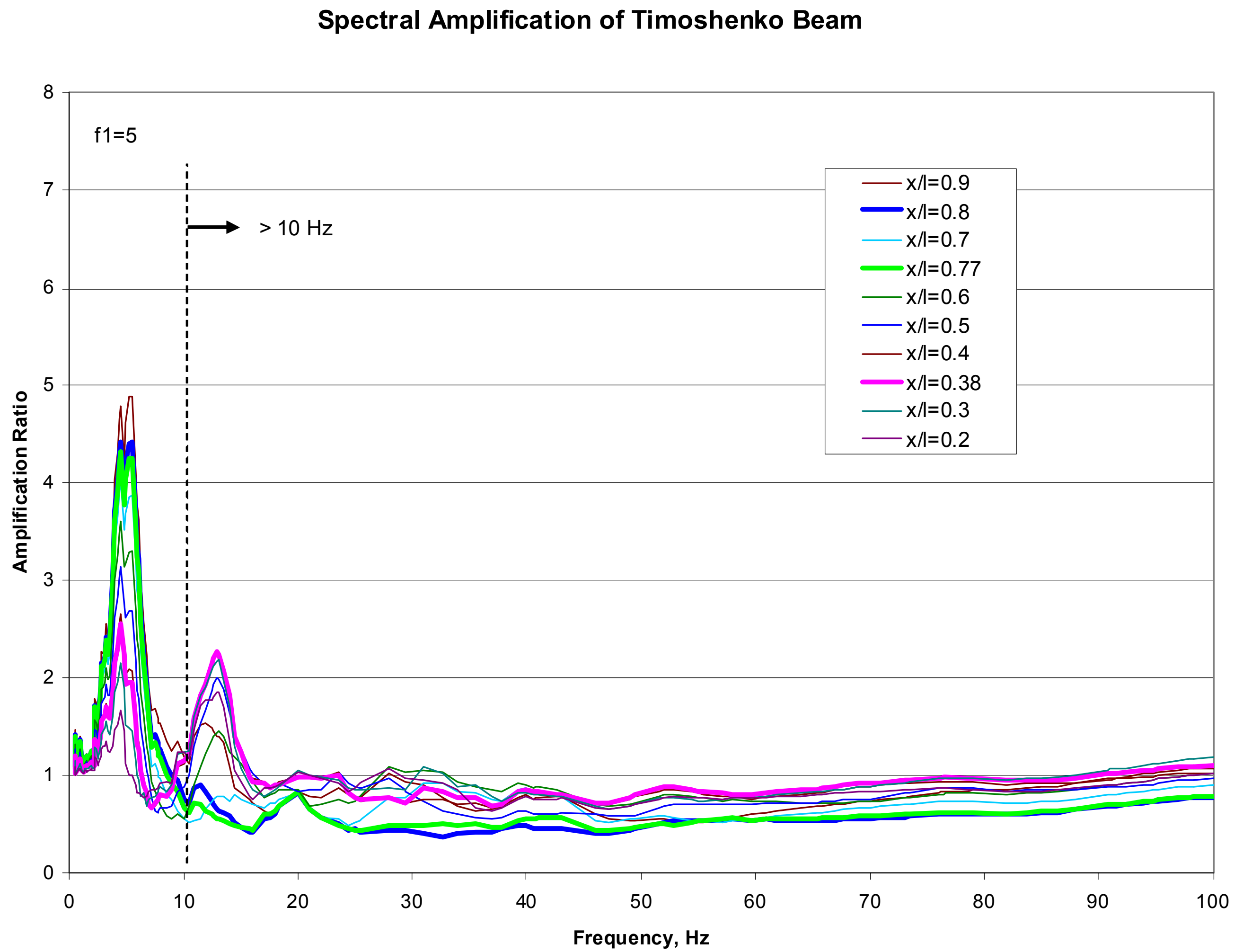
ENA Record (Mitchell Lake Road Component 28, 1982 New Brunswick, Ca EQ)



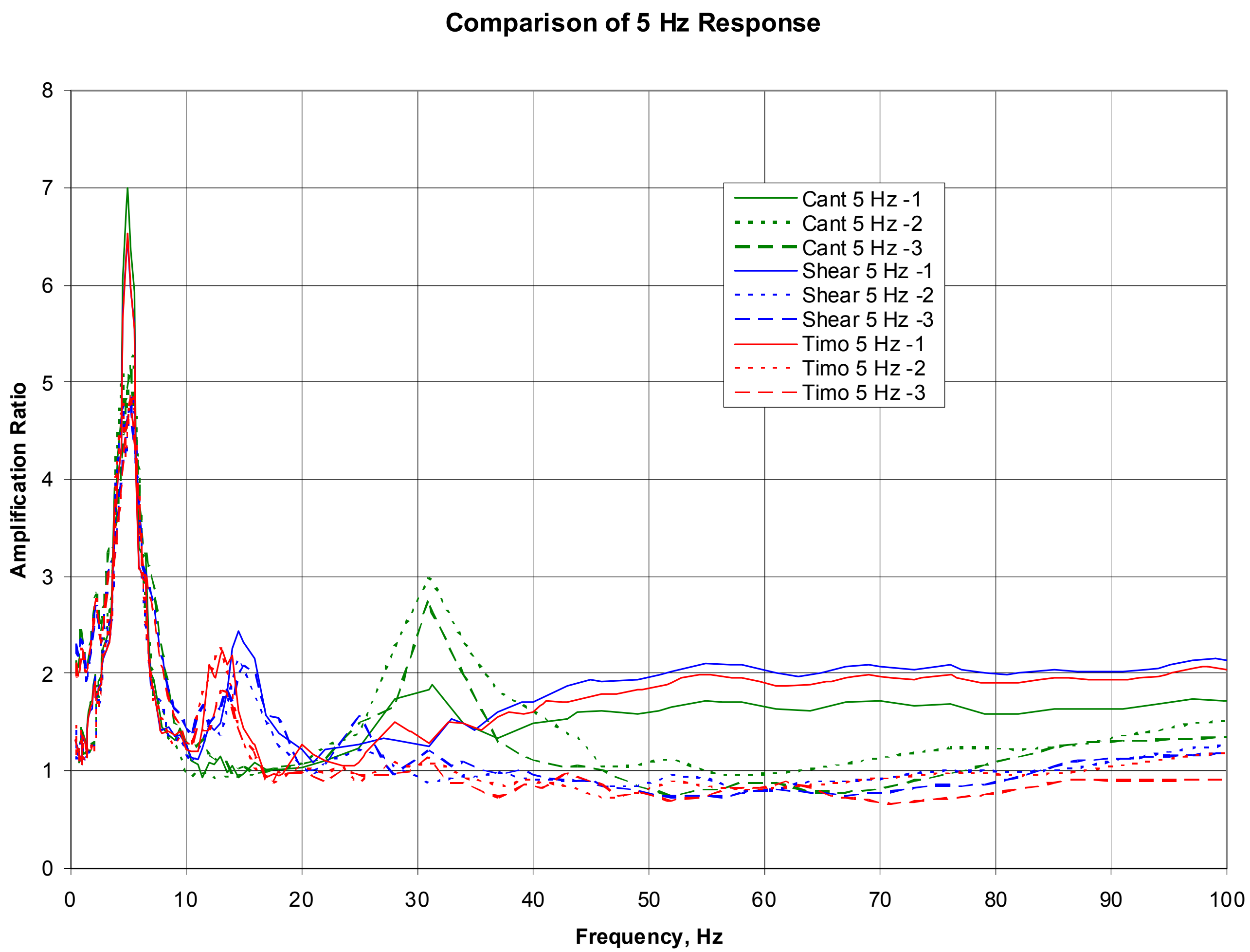


European Hard Rock Compatible TH

Example In-Structure Amplification
(Mitchell Lake Road Input)



5 Hz Structure Amplification



In-Structure Amplification Observations

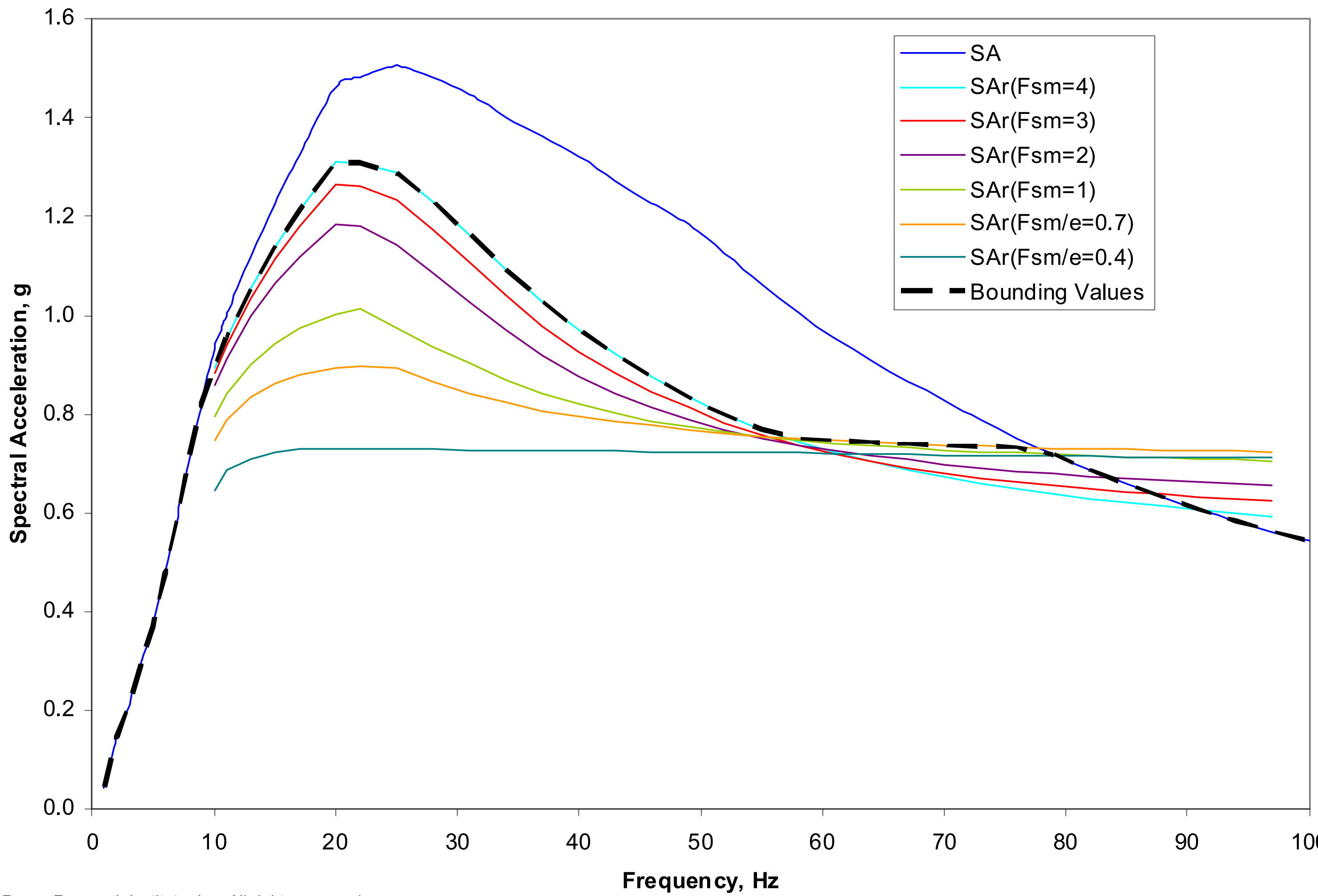
- Both the shear beam and Timoshenko beam have amplification less than 2.5 for higher modes greater than 10 HZ
- The flexural beam is not considered as representative of nuclear plant structural configurations
- If the ground input has a ZPA at frequency less than 100 Hz, the amplification ratio is simply the ratio of the in-structure ZPA to the ground ZPA and is not an oscillator amplification.

Overall Ground Level Spectra Reduction

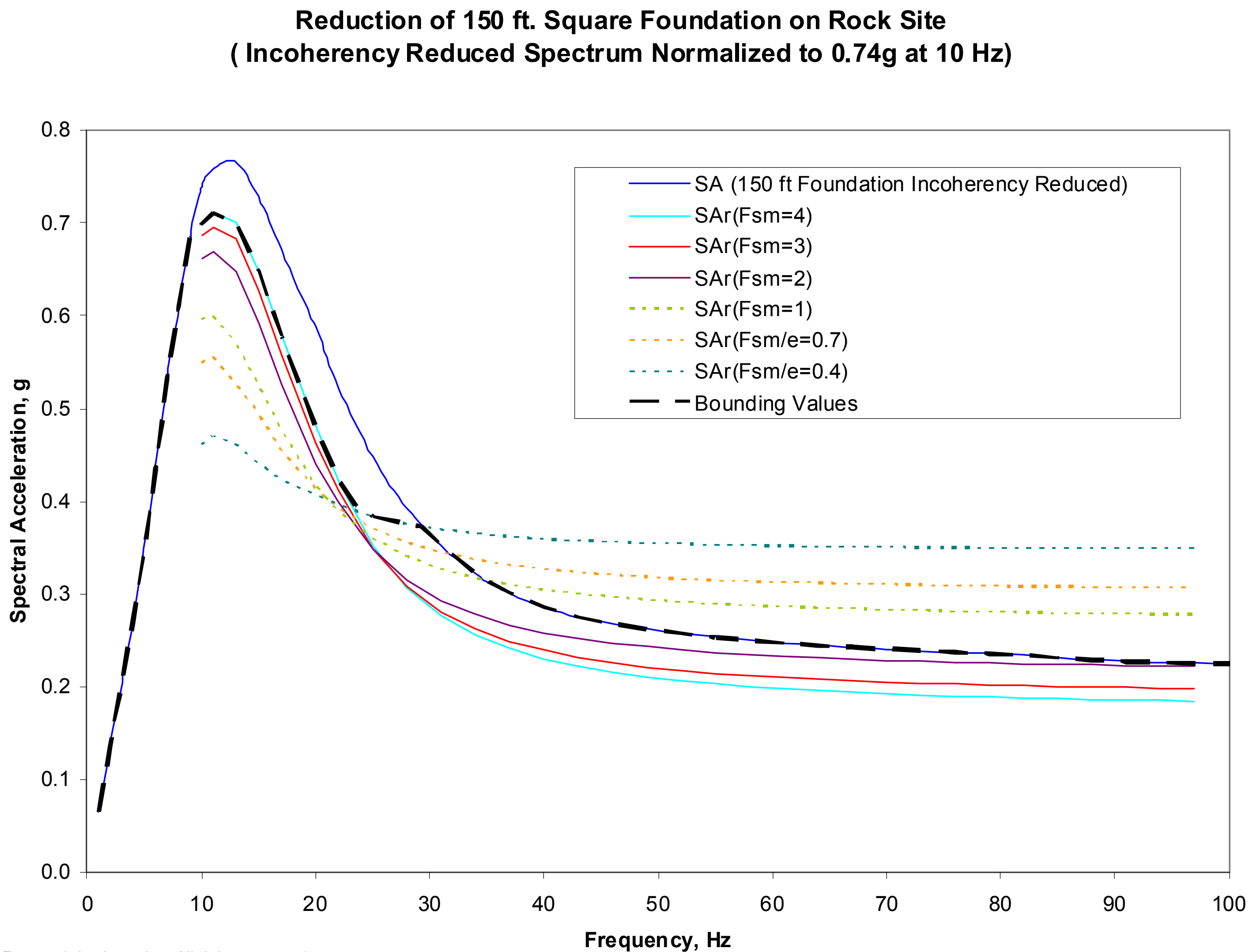
- Equipment response is reduced by the presence of negligible non-linear deformations in the anchorage load path.
- The reduction of ground level spectra for in-elastic response behavior should be performed using the spatial incoherence reduced spectra associated with the foundation motion.

CEUS Rock In-Elastic Reduction

(Unreduced Spectrum Normalized to 0.931g at 10 Hz)



CEUS Rock Overall Reduction



Observation on Equipment Qualification

- If the reduction of high frequency motion content due to spatial incoherence is accomplished, the resulting in-structure spectra can be used with current qualification test procedures.
- EPRI TR-102470 recommended that reduction due to non-linear load path behavior should be used only for structural integrity and not used to generate spectra for functional qualification.
- For those cases, where the incoherence reduction cannot be applied, a screening level test with wide band random input motion defined over the 10-100 Hz band is recommended

Fillet Weld Bounding Example

- **Limit Displacement of 0.01 Inch**
  - Proposed in EPRI TR-102470
  - Based on Assumed Minimum Weld Size
  - Empirical Capacity and Deformation Established by Test
  - Adopted in AISC LFRD Code
  - Recent Test Programs Indicate 0.01 Inch Conservative (AISC Program 2000-2005)
- **Fillet Weld Performance Under Cyclic Loading**
  - Limited Ultra-Low-Cycle (<50) Test Data Available
  - Subject of Recent Research Programs
  - Unpublished Data May Be Available Through Survey
    - Professor Abolhassen Asteneh-Asl

Task S2.1 Status

- Demonstrated Small Transverse Fillet Weld to be Bounding Inelastic Response
- Demonstrated Key Assumption on Amplification Factor/Margin of 4 is Appropriate
  - Fundamental Frequency of Structures < 10 Hz
  - Amplifications for High Frequencies > 10 Hz
- Verified Static Weld Capacity of 0.01” (for 3/16” Weld) to be conservative
  - Ultra Low Cycle Fatigue Effect Requires Applicable Test Data

Task S2.1 Status (Continued)

- Developed Excel Spreadsheet Application to Simplify Computation Procedure
- Use of the Application Tool Allowed Reduced Spectrum Method
  - Envelope of Several Cases Efficiently Computed
  - Addresses High Frequencies of Current CEUS UHS
- Generated Example Reduced Spectra Results for Diverse Set of Spectra
  - Three Characteristic Shapes
  - Three Acceleration Amplitudes