New Plant Seismic Issues Resolution Program

Structural Tasks Working Meetings
Task S2.2 – Characterization of Negligible Inelastic Behavior of High Frequency Input

by
K. L. Merz, ARES

June 22, 2005

S2.2 Project Tasks

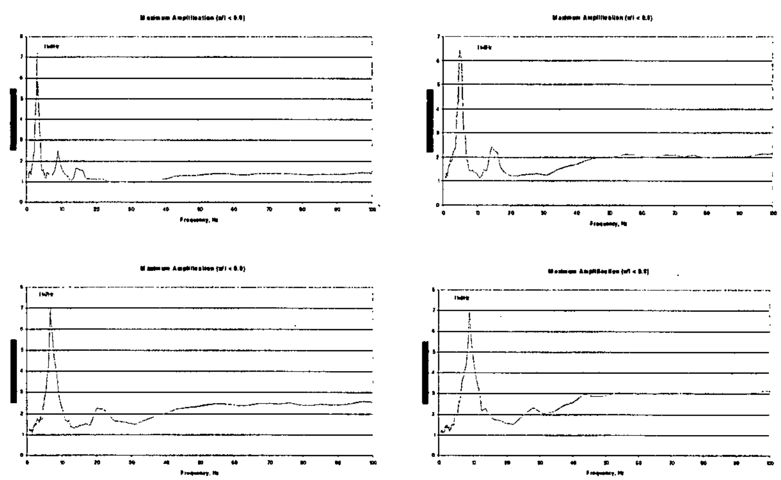
- **Task 1 – Strengthen Key Assumptions**
- **Task 2 – Develop an improved procedure for knock down factor implementation**
- **Task 3 – Define limiting failure modes for nuclear plant equipment**
- **Task 4 – Recommendations for equipment with functional failure modes**
- **Task 5 – documentation of results of S2.2 in a report**

B-1

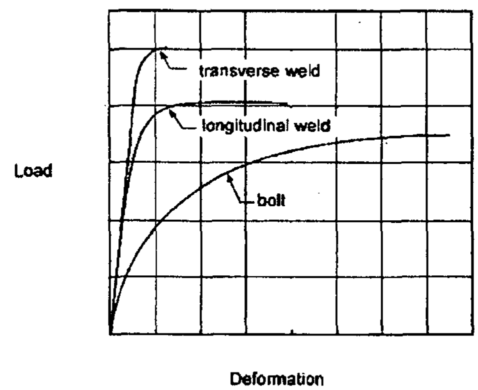
Task 1 – Strengthen Key Assumptions

- **Task 1-1 Develop Examples to demonstrate the dynamics involved in high frequency response and 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
  - Perform sensitivity analyses to determine the effect of spectral shape differences between rock and soil sites
- **Task 1-2 Justify floor spectra amplification assumption**
  - Utilize shear beam models
  - Model properties representative of New Plant designs
- **Task 1-3 Justify bounding example fillet weld assumptions**
  - Review 0.01 inch limit displacement
  - Review weld performance under cyclic loading
  - Review weld failures during Northridge earthquake

Structure Amplification (Shear Beam)



Anchorage Load-Displacement



Representative load vs. deformation characteristics.

Task 2 – Develop an Improved Procedure for Knock Down Factor Implementation

- **Reevaluate Simplified Method within TR-102470**
  - Purpose of Task 2 is to reevaluate the assumptions
  - Conservatisms relate to higher frequencies (> 30 Hz)
  - ESP response potentially high in the > 30 Hz region
  - Use of more rigorous methods in lieu of conservative assumptions
- **Evaluate the potential to simplify the high frequency response reduction method by developing a low pass filter**
  - Applied to Fourier amplitude spectra over the specified frequency ranges

Task 3 – Define limiting failure modes for nuclear plant equipment

- **Small fillet weld selected as the bounding case**
  - Welds often considered relatively non-ductile
  - Original study characterized welds as bounding (less ductile) than all other equipment and structure failure modes with the exception of some functional failure modes
- **Research Limiting Failure Modes to Strengthen Assumption**
  - SPRA and SMA fragility and HCLPF results
  - Research studies (e.g. NRC research by LANL on shear walls)
  - Document a better basis for defining the fillet welds as the appropriate bounding configuration

Task 4 – Recommendations for equipment with functional failure modes

- **Knock down factors not appropriate for functional failure modes which are high frequency sensitive**
  - **Relay chatter**
  - **Breaker trip**
- **Goal - develop seismic qualification requirements that do not require calculation of floor spectra including large high frequency input**
  - **Floor response in high frequency region not reliable**
  - **Alternate options potentially exist**
    - **Requirements for military shock and vibration applications**
    - **Stress screening for modern electrical components**

New Plant Seismic Issues Resolution Program

Structural Tasks Working Meetings
Task S2.2 – EPRI TR-102470 Review

by
K. L. Merz, ARES

June 22, 2005

Summary of EPRI TR-102470

- **EPRI TR-102470, "Analysis of High-Frequency Seismic Effects", October 1993**
  - **Research conducted in 1989-1992 period as alternate approach for IPEEE**
  - **Basic Premise: structures and equipment have additional capacity above yield level to absorb the small displacement response associated with high-frequency earthquake ground motion**
- **"High-frequency earthquake ground motion"**
  - **> 10 Hz frequency content**
- **"Small displacements"**
  - **$SA = (2\pi f)^2 SD$, if SA = 0.5 g :**

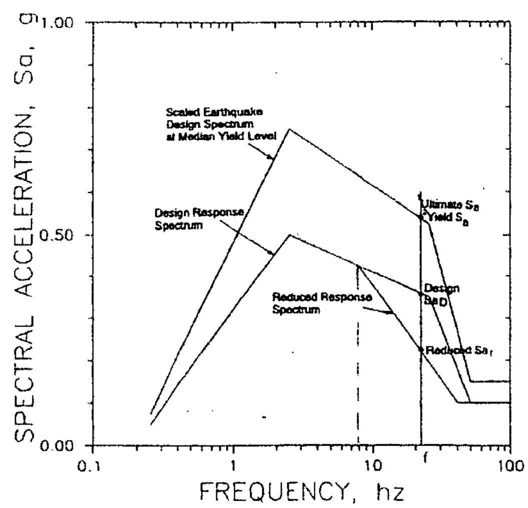
f, Hz	SD, in.
5	0.20
10	0.05
25	0.01

Note: 1/32 = 0.031

Bolt holes are oversized by 1/16

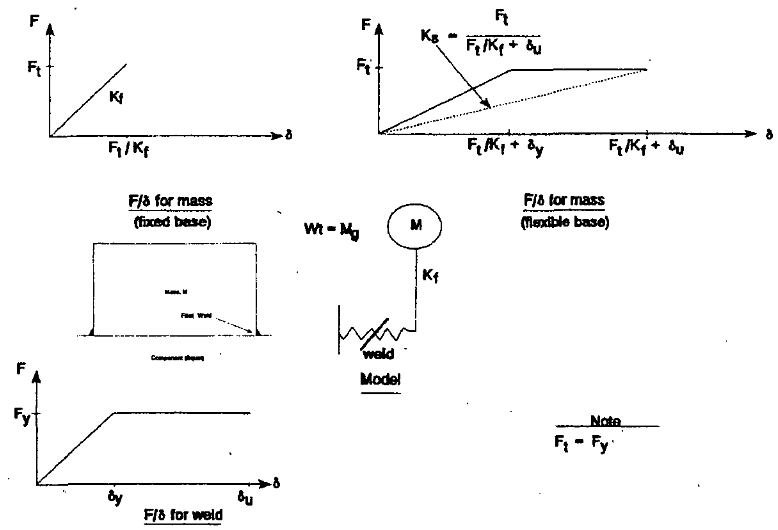
Reduction of High Frequency Response

- A design response spectrum can be reduced for frequencies > ~ 8 Hz
- $Sa_r = Sa_D/F_\mu$
- F_μ = Inelastic Reduction factor
- $Sa_c = F_{SM}\, Sa_r$
- F_{SM} = Design Margin



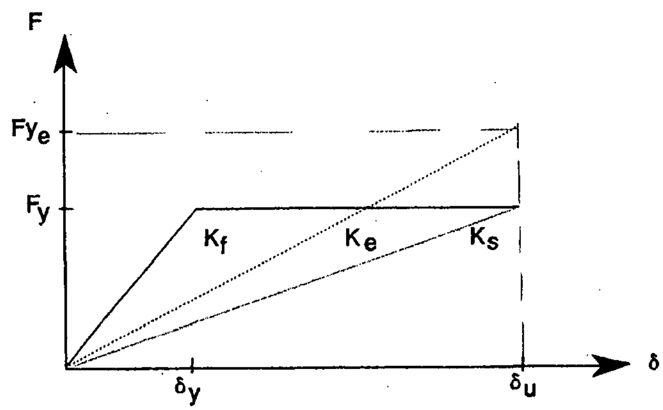
Basic Assumptions

- The least ductile component can accommodate displacements > 0.01 in. (negligible distortion)
- Equipment items anchored with minimum 3/16 in. fillet welds loaded in the transverse shear represent the limiting case of negligible distortion
  - yield level ~ 0.001 inch
  - capacity level ~ 0:01 inch
- Simple elasto-plastic models can be used to demonstrate the response of systems with negligible non-linear behavior



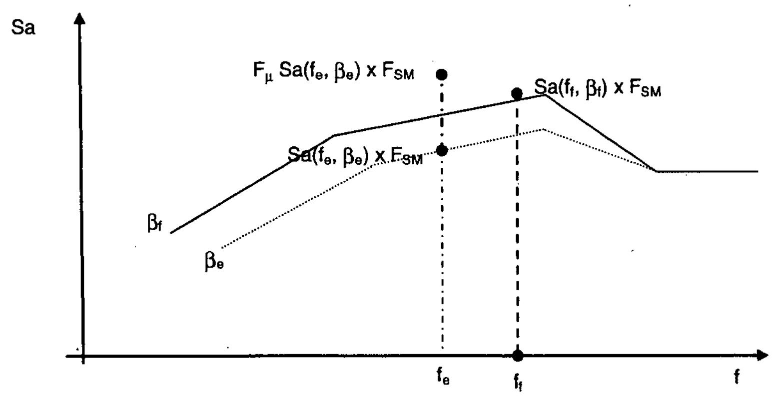
Model and Force-Displacement (F/δ) Diagrams

Effective Linear Model



Force-Displacement (F/δ) Diagram

Effective Linear Model



f = initial elastic response

e = effective system response

Effective Linear Model

- $\delta_\mu = F_\mu \, S_a(f_e,\beta_e) x F_{SM}/(2\pi f_e)^2$
- Displacement of mass at ultimate capacity is equal to the yield reduction factor times the pseudo-linear-elastic model displacement evaluated at the effective frequency and damping
- $\delta_\mu = K_f/K_s \, \delta_y = (K_f/M)/(K_s/M) = (f_f^2/f_s^2) \, \delta_y = 1/(f_s^2/f_f^2) \, \delta_y$
- $X = (f_s^2/f_f^2)$, $\delta_y = S_a(f_f,\beta_f) x F_{SM}/(2\pi f_f)^2$, $X_e = (f_e^2/f_f^2)$
- $F_\mu = (X/X_e) \, [S_a(f_f,\beta_f)/S_a(f_e,\beta_e)]$

Secant Frequency

1. $X = (f_s/f_f)^2$

2. $X = K_s/K_f$

3. $X = \dfrac{F_t/K_f}{F_t/K_f + \delta_u}$

4. $X = \dfrac{1}{1 + \dfrac{K_f \delta_u}{F_t}}$

5. $X = \dfrac{1}{1 + \dfrac{(2\pi f_f)^2 \delta_u/g}{F_t/Wt}}$

Equations for Obtaining X

Derivation For Normalized Secant Frequency Squared, X, for One-Degree-of-Freedom Sliding Model

Response Correlation

- F_μ is the EQ scale factor required for an elasto-plastic model to reach the ultimate deformation, $\delta_\mu = \mu\ \delta_y$

- Non-linear time history analyses yield empirical response relations:

- $(1-X_e) = (1-X)^a$, $a = 1.6$
- $\beta_e = (X/Xe)\ [X^{1/2}\beta_f) + b\beta_H)$, $b = 0.3$
- $\beta_H = (2/\pi)\ (1-X)(1-1/\mu_w)$
- $\mu_w = \delta_\mu/\delta_y$

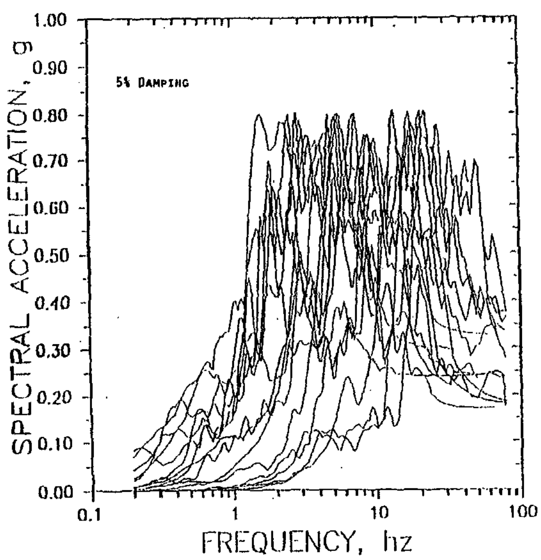
- Mean $\{F_{\mu TH} / F_{\mu\ predicted}\} \sim 1.0$, COV ≈ 0.16

EARTHQUAKE RECORDS USED IN HIGH-FREQUENCY STUDY

No.	Earthquake	Date	Station Name	Direction	Magnitude M_S	Site Intensity MMI
1	R.G. 1.60 (Artificial)	—	—	—	—	—
2	Olympia, WA	04/13/1949	Highway Test Labs	N86E	7.0	VIII
3	Parkfield, CA	06/27/1966	Cholame No. 2	N65E	6.4	VII
4	Tabas, Iran	09/16/1978	Tabas	Trans.	7.7	X
5	Imperial Valley, CA	10/15/1979	E.C. Array No. 5	140	6.9	VII
6	Nahanni, Canada	12/23/1985	Site 1	Long.	6.9	IX
7	Saguenay, Canada	11/25/1988	Site 20	Long.	6.0	—
8	Gazli, USSR	05/17/1976	Karakyr Point	East	7.0	IX
9	Bear Valley, CA	09/04/1972	Melendy Ranch	N29W	4.3	VI
10	Gazli, USSR	05/17/1976	Karakyr Point	North	7.0	IX
11	Saguenay, Canada	11/25/1988	Site 16	Long.	6.0	—
12	Leroy Modified	—	—	—	—	—
13	Leroy, Ohio	01/31/1986	Perry NPP Basemat	South	4.8*	V
14	New Brunswick, Canada	03/31/1982	Mitchell Lake	28	4.0*	IV
15	Artificial	—	—	—	—	—

M_S - Surface wave magnitude

* Moment magnitude



Response Spectra for Earthquake Time Histories Used in Study Normalized to 0.8g Peak 5-Percent Damped Spectral Acceleration

Response Estimation

- Given Sa_{ri}, F_{SM}, f_f, β_f, δ_μ, μ_w
- $Sa_C = F_{SM}\, Sa_{ri}$
- $A = (2\pi f_f)^2\, \delta_\mu / Sa_C$
- $X = 1/(1+A)$
- $X_e = 1-(1-X)^{1.6}$
- $\beta_e = (X/Xe)\, [X^{1/2}\beta_f) + (0.6/\pi)\, (1-X)(1-1/\mu_w))$
- $F_\mu = (X/X_e)\, [S_a(f_f,\beta_f)/S_a(f_e,\beta_e)]$
- $Sa_{ri+1} = S_a(f_f,\beta_f)/F_\mu$

EXAMPLE SLIDING MODEL ANALYSIS

Trial	Sa_r(g)	Sa_c(g)	A	X	X_e	f_e (Hz)	β_e	$Sa(f_e, \beta_e)$ (g)	F_μ	Sa_i/F_μ (g)
1	0.507	0.761	0.302	0.768	0.903	14.257	0.071	0.449	1.327	0.382
2	0.382	0.573	0.401	0.714	0.865	13.950	0.075	0.439	1.400	0.362
3	0.362	0.543	0.423	0.703	0.856	13.881	0.076	0.436	1.415	0.358

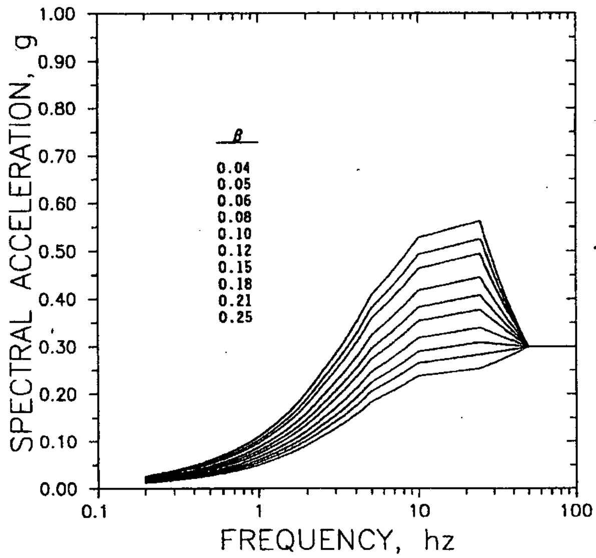
Model Parameters (Permissible inelastic anchor displacement = 0.01 inch)

F_{SM} = 1.5 Sa_i = $Sa(f_f, \beta_f)$ = 0.507g

δ_u = 0.01 inch μ_w = 10

f_f = 15 Hz

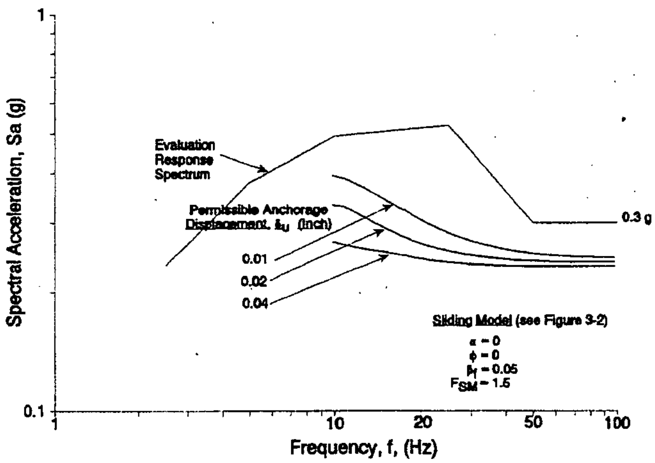
β_f = 0.05



Evaluation Response Spectra at Different Damping Values

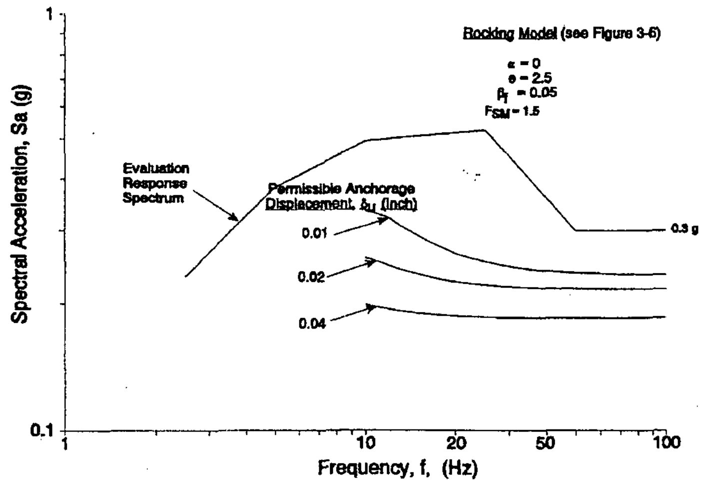
Response Spectra Used in the Example Calculation

Sliding Model



Example Reduced Response Spectra for Uniform Hazard Evaluation Spectrum Based on Sliding Model for Different Permissible Ultimate Weld Displacement

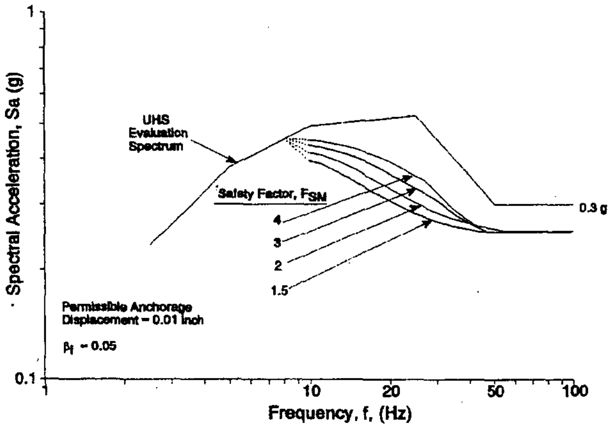
Rocking Model



Instructure Spectra

- Thus far, have only considered component mounted on the ground
- TR-102470 considered the effect of an instructure mounted component by increasing the margin factor, F_{SM}, by the expected amplification factor (AF) for instructurespectra in the > 10 Hz range
- AF = 2
- FM* = FM x AF
- The basic concept is to reduce the ground input spectra prior to generation of floor spectra

Effect of Design Margin/ Structure Amplification



Example Reduced Response Spectra for UHS Anchored to 0.3 g PGA.

New Plant Seismic Issues Resolution Program

Structural Tasks Working Meetings

by
Greg Hardy, ARES

June 22, 2005

ARES CORPORATION Applied Research & Engineering Sciences EPRI

Purpose of Working Meetings

Discuss:

- Status of Task S2.1 on Ground Motion Incoherence Effects to Foundation and Building Response
- Status of Task S2.2 on High Frequency Negligible Inelastic Behavior
- Status of Task G1.2 on Characterization of Lower Bound on Earthquake Magnitude (Time Permitting)

Provide Forum for Suggestions and Comments:

- Technical Review and Advisory Group
- NRC

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June 22nd – S2.2 Meeting Agenda

• Welcome and Introductions	Hardy
• NRC Participation in S Tasks	Murphy
• Overview of Industry Program	Hardy
• ESP Task S2.2 Description & Goals	Hardy
• Summary of EPRI TR-102470	Merz
• S2.2 Project Activities – In-Structure Amplification Factor – Selection of Bounding Case for Negligible Inelastic Behavior – Fillet Weld Inelastic Behavior (Static and Dynamic) – Simple Equivalent Linear Models – New Procedure for Spectrum Reductions in High Frequency Range	Merz
• Suggestions and Directions – TRAG – NRC	

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June 23rd – S2.1 and G1.2 Meeting Agenda

• ESP Task S2.1 Description & Goals	Hardy
• Abrahamson Coherency Function	Abrahamson
• ARES Approach for Considering Coherency	Short/Johnson
• Bechtel Approach for Considering Coherency	Ostadan
• Benchmark Problem Comparison	Short/Johnson/Ostadan
• S2.1 Results, Schedule & Milestones	Short/Johnson
• G1.2 Task Descriptions	Hardy
• G1.2 Status	Abrahamson

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New Plant Seismic Issues Resolution Program

Overview of Industry Program

by
Greg Hardy, ARES

June 22, 2005

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Background: New Plant Seismic Issues

- **Eastern U.S. ground motion spectra include a high frequency component that is non-damaging but can exceed certified design spectra in the high frequency region**
- **Experience/concerns with RG1.165**
  - Method is based on a reference relative hazard probability, not a performance-based (safety-based) approach
  - Potential for regulatory and technical instability
- **Process has strong potential to deter many utilities from applying for ESP or COL**

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Industry Resolution Plan

ASCE

- Evaluate alternate performance-based methods for determination of site spectra
- Incorporate other technology advances in PSHA implementation
- Resolve the high frequency issue
- Propose revision to R.G. 1.165 and SRP 2.5.2 (NUREG 0800)

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Industry Program

- Demonstrate generic applicability of ASCE/SEI 43-05 - Task G1.1
- Improve seismic hazard estimation methodology to reflect technology advances - Tasks G1.2, G1.3
- Update and improve methods for addressing non-damaging high frequency portion of ground motion spectra - Tasks S2.1, S2.2 ✓ June 22-23 Topics
- Develop proposed revisions to RG1.165 and NUREG 0800 - Task I1.1

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Schedule

- **Completion of Task G1.1 by July 2005** — to NRC ~ August
- **Completion of other G and S tasks by end of 2005**
- **Completion of Task I1.1 (Industry input to NRC) in 2006**

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Task G1.2 - Lower Bound Magnitude

- **Choice of lower bound magnitude (LBM) has major impact on computed hazard levels, especially for higher frequencies**
- **Task will study**
  - New observations of damage to industrial facilities and nuclear plant assessments to support a revised LBM
  - New data on Cumulative Absolute Velocity (CAV) to provide the basis for the LBM distribution
- **A realistic LBM distribution would reduce hazard consistent with realistic damage potential of small earthquakes**

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Tasks S2.1 and S2.2 - Treatment of High Frequency (HF) Motions

- **Analytical and observational data show that ground motion spectra for CEUS sites will contain high spectral accelerations at high frequencies (i.e.- over ~ 10 hz), but the HF content has negligible damage potential**
- **Objectives of tasks S2.1 and S2.2 are to develop generic methods for accommodating HF motions considering**
  - Effect of seismic wave incoherence (S2.1), and
  - Effect of limited inelastic behavior on response to HF input motions (S2.2)

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New Plant Seismic Issues Resolution Program

Structural Tasks Working Meetings
Task S2.2 – Characterization of Negligible Inelastic Behavior of High Frequency Input

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Background: CEUS Ground Motion

- **Observations of strong ground motion due to small magnitude earthquakes occurring in eastern North America**
  - Did not cause damage to engineered structures – need to be fully documented OBE (Reed)
  - Exhibit considerably higher PGAs than would have been expected based on WUS experience
  - Response spectral ordinates appear to be richer in high frequency energy, particularly for frequencies greater than about 10 Hz
- **New SSE Spectra present issues**
  - SSE high frequency beyond Advanced Reactor Design qualification level

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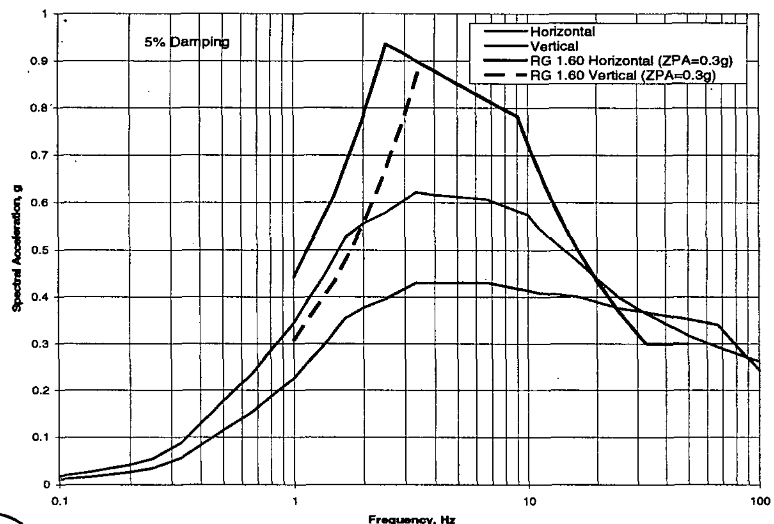
Hypothetical Site Specific Response Spectra for Soil Site



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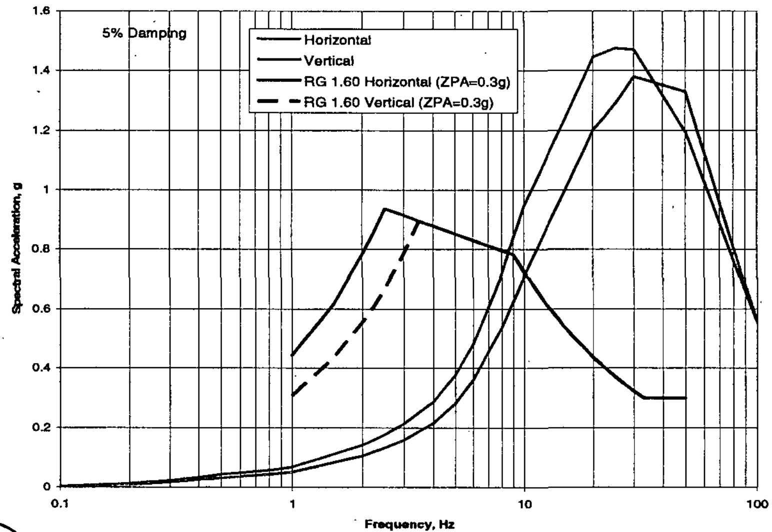
Hypothetical Site Specific Response Spectra for Rock Site



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Background: Development of Engineering Design SSE Response Spectrum

- **Development of Site Specific UHS**
  - Utilize ground motion relationships for CEUS conditions
  - Characteristic high frequency content in the region greater than 10 Hz
- **Convert to Risk-Consistent Site-Specific Spectrum (ASCE 43-5)**
- **Generate Engineering Design SSE**
  - Consideration of Incoherency Effects
  - Consideration of High Frequency Inelastic Deformation Effects

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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**
- **Kelly to provide summary of TR-102470 methodology**

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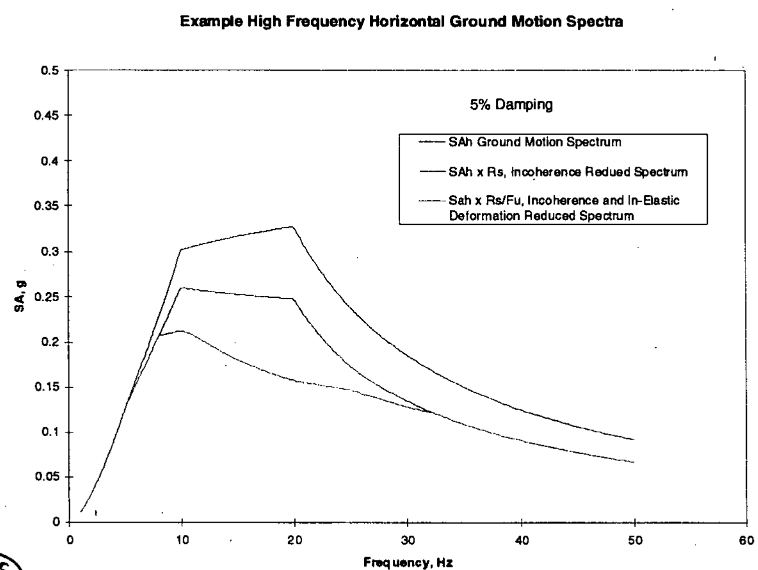
Example Reductions for Incoherence and Inelastic Deformation



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New Plant 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)

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S2.2 Task Objectives

- **Reassess Key Assumptions in TR-102470 Report**
- **Simplify the Process of Performing Reductions**
- * **Propose Qualification Requirements for High Frequency-Sensitive Devices**
- **Provide Clear Documentation of Results in an EPRI Report**

check on BNL comments

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S2.2 Project Tasks

- Task 1 - **Strengthen Key Assumptions**
- Task 2 - **Develop an Improved Procedure for Knock Down Factor Implementation**
- Task 3 - **Define Limiting Failure Modes for Nuclear Plant Equipment**
- Task 4 - **Recommendations for Equipment with Functional Failure Modes**
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Task 1 – Strengthen Key Assumptions

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  - Review 0.01 inch limit displacement
  - Review weld performance under cyclic loading
  - Review weld failures during Loma Prieta earthquake

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Task 2 – Develop an Improved Procedure for Knock Down Factor Implementation

- **Reevaluate simplified method within TR-102470**
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Task 4 – Recommendations for Equipment with Functional Failure Modes

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Status of Task S2.2

Status

- **Project Plan Developed and Reviewed April/May 2005**
- **Tasks Initiated May 2005**
- **NRC Meeting May 25**
  - Presented approach
  - Initiate NRC task participation
    - Identified NRC participants (Andy and Goutam)
- **Project Meeting with Bob Kennedy Early June**
- **NRC/TRAG Technical Meetings in So Cal (June 22 and August 2005)**
- **Full NEI/NRC Meeting in October in Washington DC**
- **Draft Report November 2005**

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