PSHA, Site Response, and Site Spectra

Topic 2: Site Response

Technical Presentation

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Topic 2: SITE RESPONSE

Site Response

- Background
- Inputs
- Randomization of site parameters
- Site-response calculations
- Typical results

BACKGROUND

- EPRI (2004) defined "hard rock" equation for $V_s \geq 2.8$ km/s $\approx$ 9200 ft/s
- Most sites have $V_s < 9200$ ft/s, requiring site-response calculations, even for sites typically considered as rock
- Modeling: only viable approach in CEUS.
  1. Characterization
  2. Randomization
  3. Site response calculations (equiv. linear)

INPUTS: 1. rock hazard

One or more sets* of ground motions, each characterized by

→Rock spectrum Sa(f)
- 5% damping
- frequencies: 0.1-100 Hz

→Associated magnitude and distance (from deaggregation)

*Typical sets: 10^{-4} HF, 10^{-4} LF, 10^{-5} HF, 10^{-5} LF (each set run separately through site-response calcs)

Inputs: 2. Local Geotechnical properties

1. Shear-wave Velocity (Vs) vs. Depth

- Natural near-surface deposits: local borehole data (suspension logger, CPT, cross-hole, downhole, etc.)
- Engineered backfill: empirical relations for Gmax in terms of blow counts, relative density, etc.
- Deeper sites: other local geophysical data (P-wave, etc.), regional data

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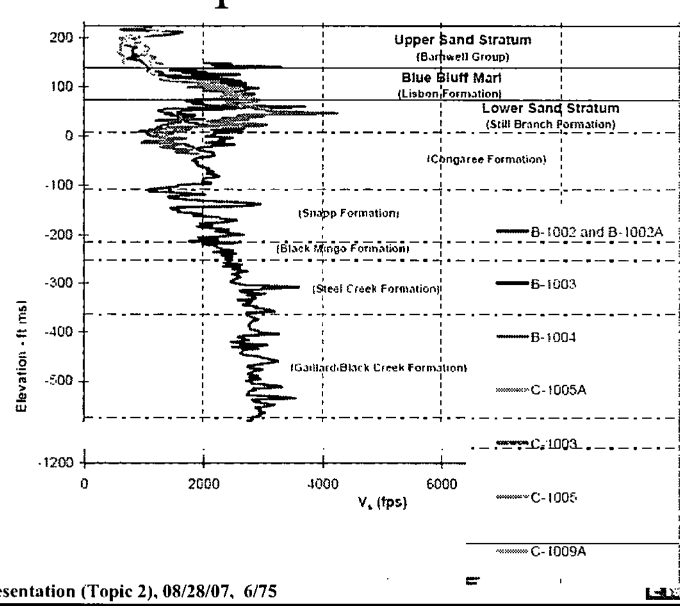
Example: borehole data



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Inputs: Local Geotechnical properties (cont'd)

2. Soil characterization vs. depth (affects choice of degradation properties)
   → Classification (sand, clay, etc.)
   → Further information (PI, fines content, etc)
3. Density vs. depth
4. Depth to bedrock (if applicable)
5. Local G/Gmax and damping degradation curves (if available)

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Inputs: 3. Generic Properties

1. Generic G/Gmax and Damping curves (choice depends on depth, PI, etc.). Available curves:
   - EPRI (1993; depend on depth)
   - Vucetic & Dobry (1991; depend on PI)
   - etc
   - Rock: use G/Gmax=1, damping=1% (Bechtel)

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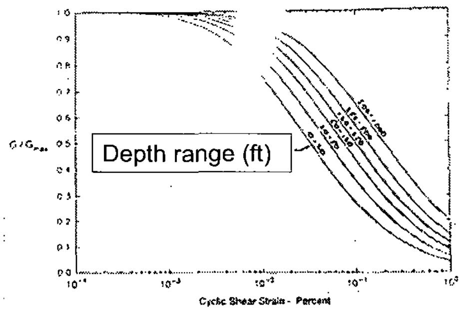
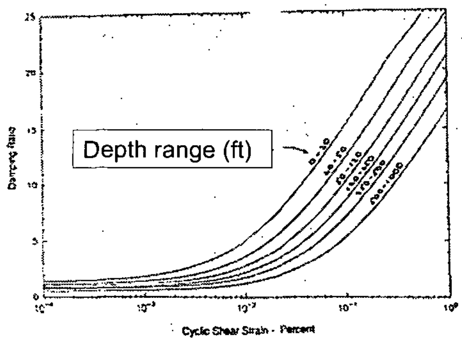
Example: EPRI(1993) Generic G/Gmax and Damping for ENA sites (depth-dependent)





Inputs: 3. Generic Properties (cont'd)

2. Generic parameters for randomization model (to be discussed later)
   → Vs randomization
   - Section 6 & Appendix 6A of EPRI (1993)
   - Toro (1996). Appendix of Silva et al. (1996, BNL)

   → G/Gmax and damping degradation
   - Section 6 of EPRI (1993)
   - Costantino (1996). Appendix of Silva et al. (1996, BNL)

RANDOMIZATION OF SITE PARAMETERS

Objective:

- Capture uncertainty in Vs and degradation properties and its effect on Amplification factors
  - → variation among sites in the same soil category
  - → variation among profiles on the building footprint
  - → Epistemic uncertainty (data limitations)
  - → vertical variation in each profile (profile roughness)

Randomization (cont'd)

Application:

1. Generate multiple artificial profiles (60 typically), which are "statistically similar" to profile data
2. Calculate site response separately for each profile
3. Calculate summary statistics (logarithmic mean and sigma) of Amplification Factor AF(f)

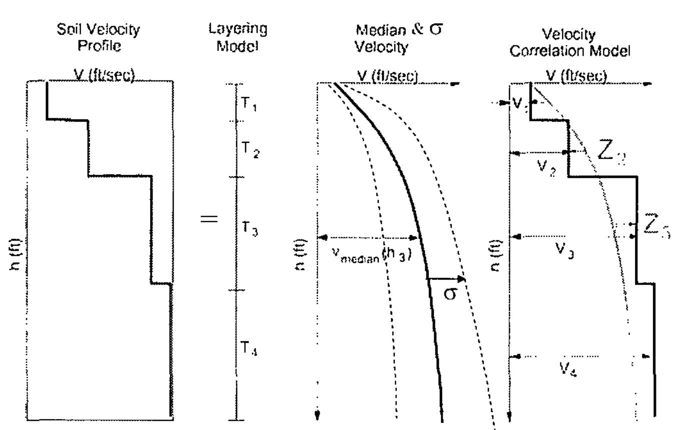
Randomization (cont'd)

Practical Effects

- Quantification of uncertainty in site response resulting from variation in properties within footprint and from epistemic uncertainty [i.e., σ(AF)]

- Mean AF(f) is a smoother function of frequency
  - → A natural consequence of uncertain properties
  - → Compensates for horizontal-layer model suspected tendency to overestimate resonances

Elements of Probabilistic Model for Randomization of Vs



Actually, model works with ln(Velocity), not with velocity as shown here

Inputs to Vs Randomization

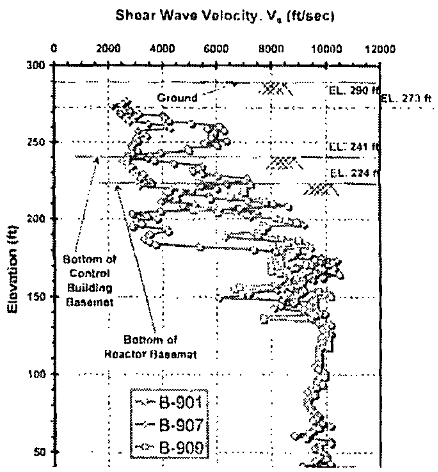
Vs Model
- Median Vs
- Standard deviation of ln[Vs]
- Correlation Coefficient ρ between ln[Vs] in adjacent layers
- Layer thickness model

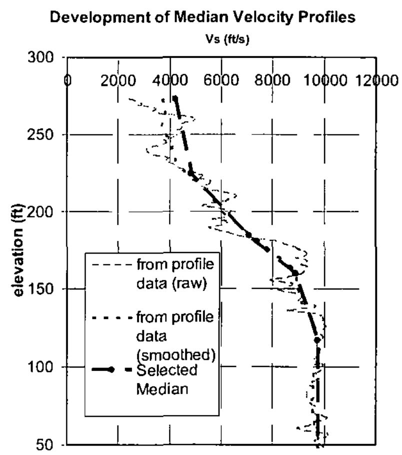
G/Gmax and Damping Model
- Median curves
- Standard deviation of ln[G/Gmax] & ln[Damping]
- Correlation Coefficient between ln[G/Gmax] & ln[Damping]
- Max. Damping

Inputs to Vs Randomization: Median Vs

- Derive from mean of ln[Vs(h)] of data
  - Vs (h) may be smoothed prior to calculation of mean
    - 5-30 ft smoothing window (typically 10 ft), or
    - Average by formation
- or, Use "base-case" profile defined by Geotech's

Example 1: Rock site with smooth median profile





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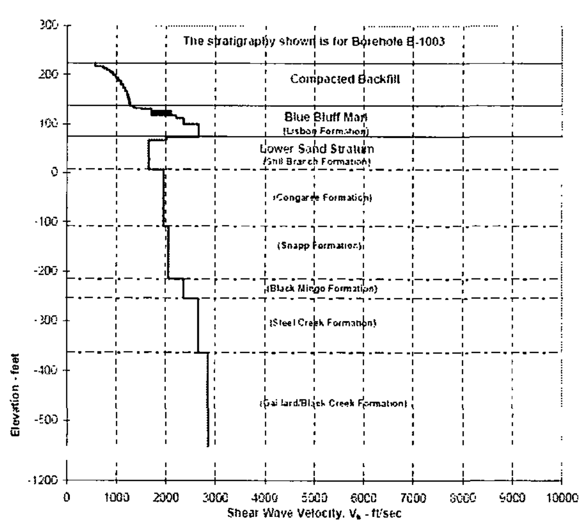
Example 2: soil site with rough median profile



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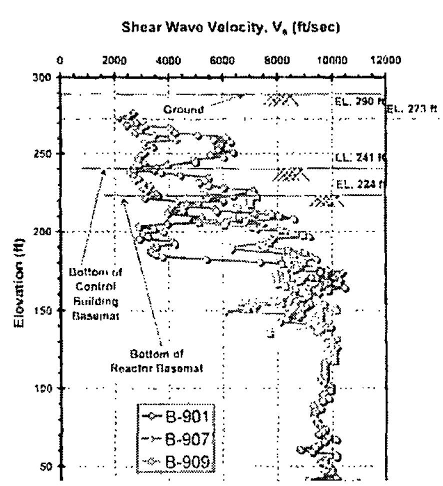
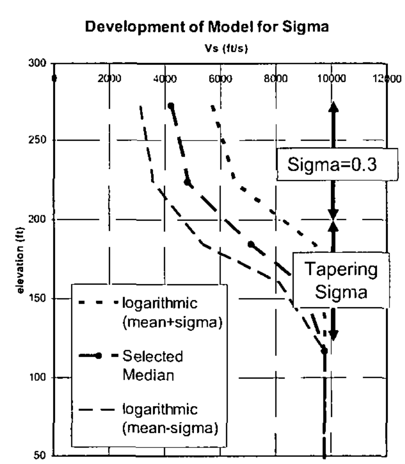
Inputs to Vs Randomization: $\sigma_{\ln[Vs]}$

- Typically depth-dependent (constant in EPRI, 1993)
- Data Sources
  - →Compute from site data (multiply result by $[1+1/n]^{1/2}$ to account for epistemic uncertainty in median)
  - →Generic results from other studies (0.27-0.41 for various soil categories)

Example: Same rock site seen earlier



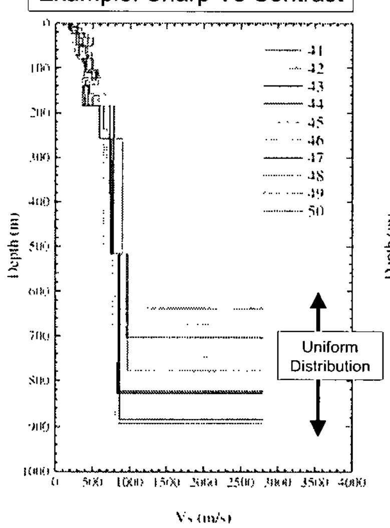


Inputs to Vs Randomization: bedrock characterization

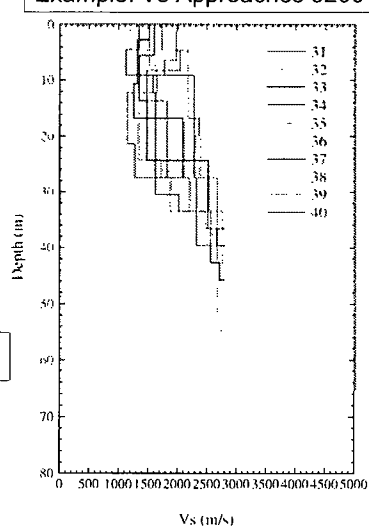
- Vs=9,200 fps (defined by EPRI, 2004)
- No uncertainty in Vs (uncertainty in bedrock Vs already captured by EPRI, 2004 attenuation equations)
- Depth to bedrock (site-specific); 2 situations:
  - → Sharp Vs contrast between soil and bedrock
    - Treat as uniformly distributed, specify min. & max. values
  - → Median Vs approaches 9,200 fps gradually
    - Define bedrock where standard Vs randomization reaches 9,200 fps

Examples of Bedrock

Example: Sharp Vs Contrast



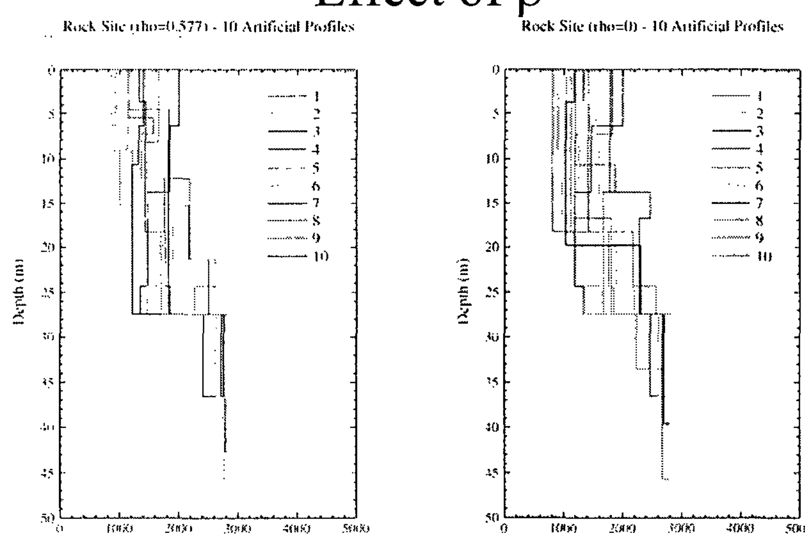
Example: Vs Approaches 9200 fps gradually



Inputs to Vs Randomization: Correlation ρ Between ln[Vs] of Adjacent Layers

- Controls "roughness" of profiles
- Estimated from profiles that have been "interpreted" into layers with constant velocity
  - →Not easy to estimate from existing site-specific data
  - →Use generic data

Effect of ρ



Model for ρ in Toro (1996)

ρ (correlation coefficient): may depend on both depth and thickness.

$$\rho(h,t) = \left(1 - \rho_d(h)\right)\rho_t(t) + \rho_d(h) \quad (7)$$

Depth-and thickness-dependent dependent terms:

$$\rho_d(h) = \begin{cases} \rho_{200}\left[\dfrac{h+h_0}{200+h_0}\right]^b & \text{for } h \le 200 \text{ m} \\ \rho_{200} & \text{for } h > 200 \text{ m} \end{cases} \quad (8)$$

$$\rho_t(t) = \rho_0 \exp\left[-\frac{t}{\Delta}\right] \quad (9)$$

EPRI (1993) used rho=const.=0.577

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Generic ρ Values from Toro (1996)

CALCULATED PARAMETER VALUES: GENERIC MODEL

	Category							
Parameter	**Geomatrix A+B**	**Geomatrix C+D**	**USGS A+B**	**USGS C+D**	**USGS A**	**USGS B**	**USGS C**	**USGS D**
sigma	0.46	0.38	0.35	0.36	0.36	0.27	0.31	0.37
rho0	0.96	0.99	0.95	0.99	0.95	0.97	0.99	0.00
Delta	13.1	8.0	4.2	3.9	3.4	3.8	3.9	5.0
rho200	0.96	1.00	1.00	1.00	0.42	1.00	0.98	0.50
h0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
b	0.095	0.160	0.138	0.293	0.063	0.293	0.344	0.744

NEHRP NOMENCLATURE: B+C D+E B C D E

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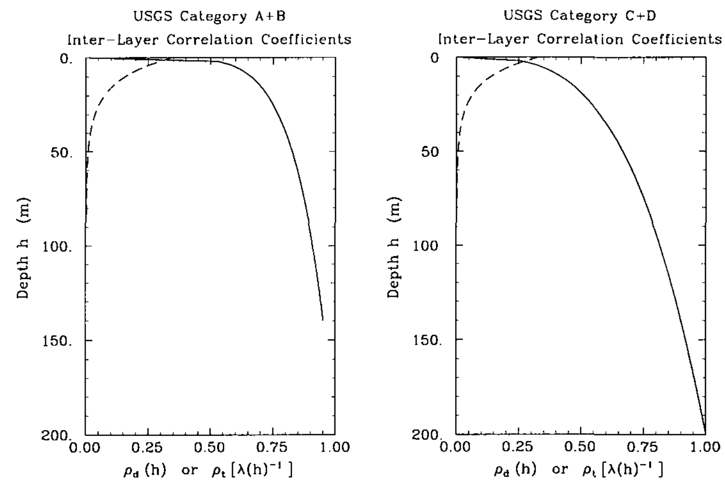
ρ Examples (Toro, 1996)



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Inputs to Vs Randomization: Layering Model

Model: Non-homogeneous Poisson with rate of layer boundaries $\lambda(h)$, which may be interpreted as

$$\frac{1}{\text{mean layer thickness(h)}}$$

- Not easy to estimate from available site-specific data
- Use Toro (1996) generic values + recent refinements

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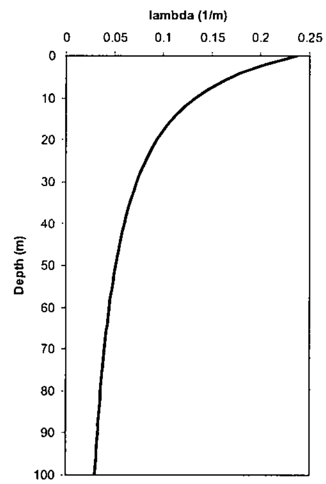
Layer thickness model



$$\lambda(h) = 0 \quad \text{for } 0 < h \le h_c$$
$$c_3[h + c_1^{\,2}]^{-c_2} \quad \text{for } h > h_c$$

$c_1 = 3.3m^{1/2}$

$c_2 = 0.89$

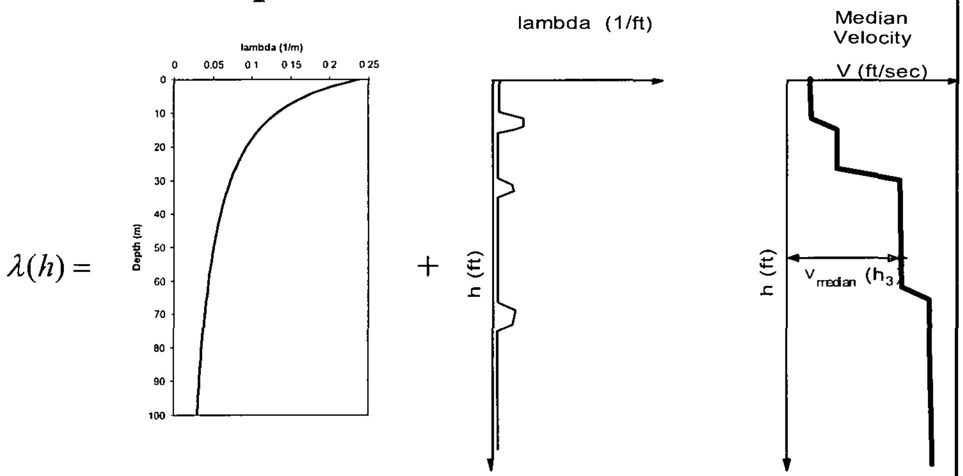
$c_3 = 1.98m^{-1}$

$c_4 = h_c = 0$

Recent refinements to Thickness Model (YM, SRS, etc.)

- Non-Homogeneous Poisson → Non-Homogeneous Renewal
  - →Changes distribution of normalized layer thickness from exponential to lognormal (with COV~ 0.6)
  - →Avoids unrealistically thin layers
- Model for λ(h) for cases when median profile is not smooth

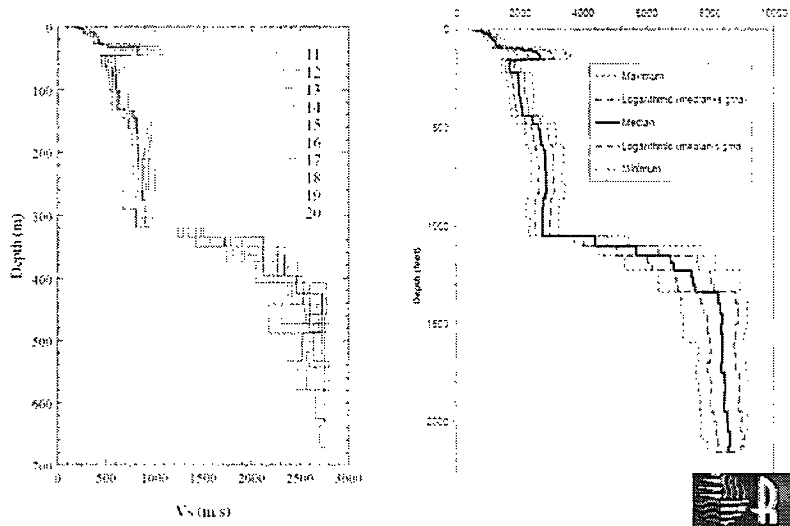
Model for l(h): cases where median profile is not smooth



Velocity Correlation Model (summary)

- Works with ln[Velocity]
- Deviations from median profile are correlated lognormal quantities
- Correlation is characterized by one parameter (ρ)
- The median velocity, $\sigma_{\ln V_S}$, and ρ may vary as a function of depth
- Thickness model λ(h) may include a smooth portion and a rough portion associated with jumps in median profile

Example: artificial profiles & summary results



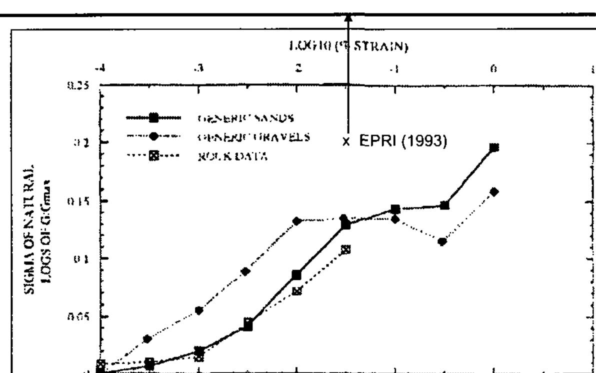
Inputs for Randomization of G/Gmax and Damping Curves

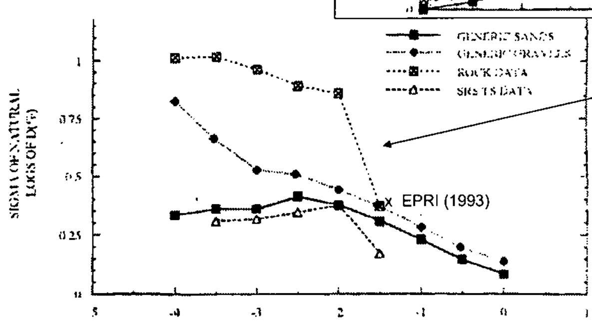
- Median G/Gmax and Damping Curves (discussed earlier)
- Uncertainty in ln[G/Gmax] and ln[Damping]
  - →Use Generic results from Costantino (1996) or EPRI (1993)
- Correlation between ln[G/Gmax] and ln[Damping]: use -0.75
- Max. Damping: 15%

Notes on Inputs

- Uncertainties are specified at one strain level; software extends it to other strains and tapers it at the end points
- G/Gmax, Damping, their uncertainties, etc. are specified as a function of depth
  - →Independent of Vs randomization
  - →Independent of layering randomization

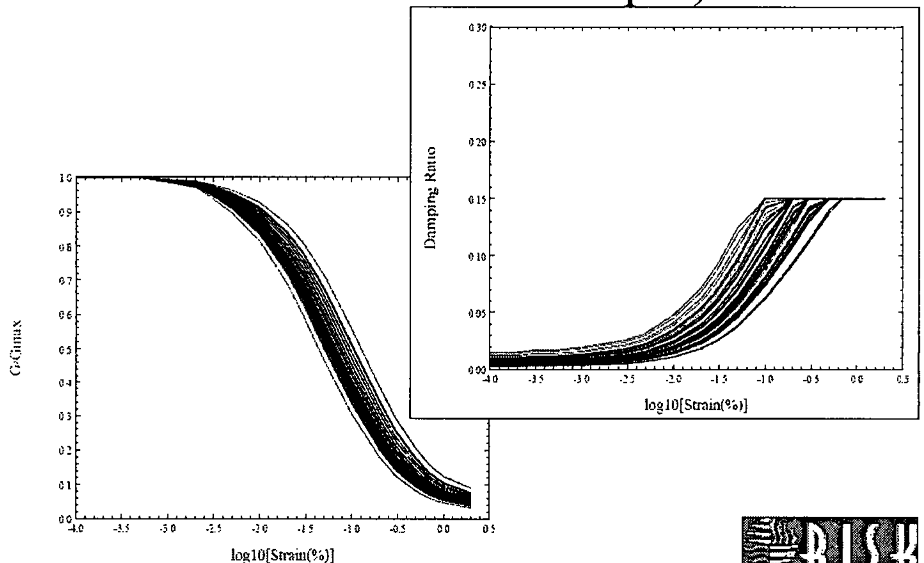
Costantino (1996) & EPRI (1993)



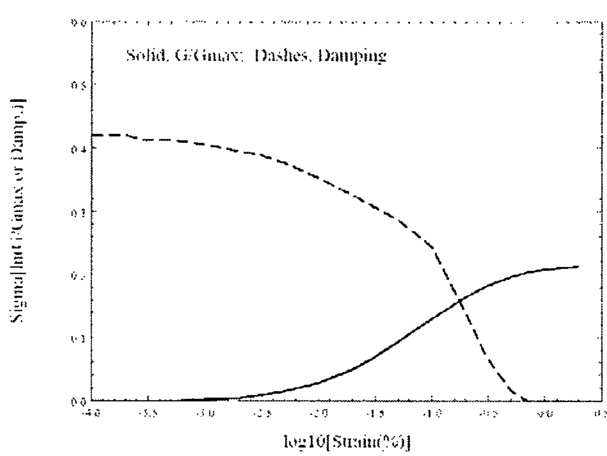


Note: rock results apply to a very wide range of rock types (Vs=900-8,000 fps)

Example: randomized EPRI (1993 curves for 200 ft depth)



Example (cont'd): summary statistics



SITE RESPONSE CALCULATIONS

Standard Engineering Methodology:

- Horizontally layered strata
- Vertically-propagating shear waves
- Material non-linearity modeled using equivalent-linear formulation

(approach initially implemented in SHAKE)

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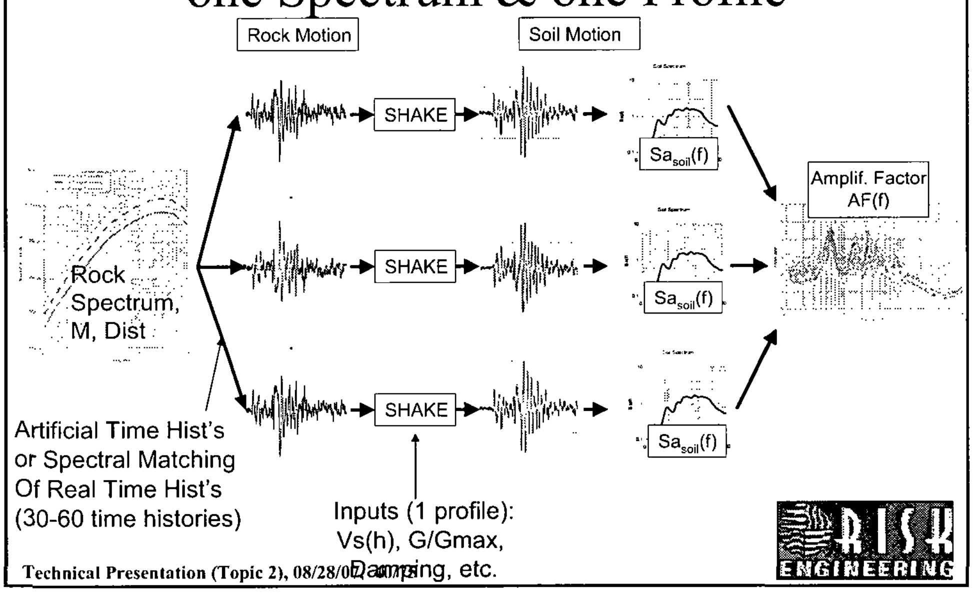
Conventional Approach (SHAKE) for one Spectrum & one Profile



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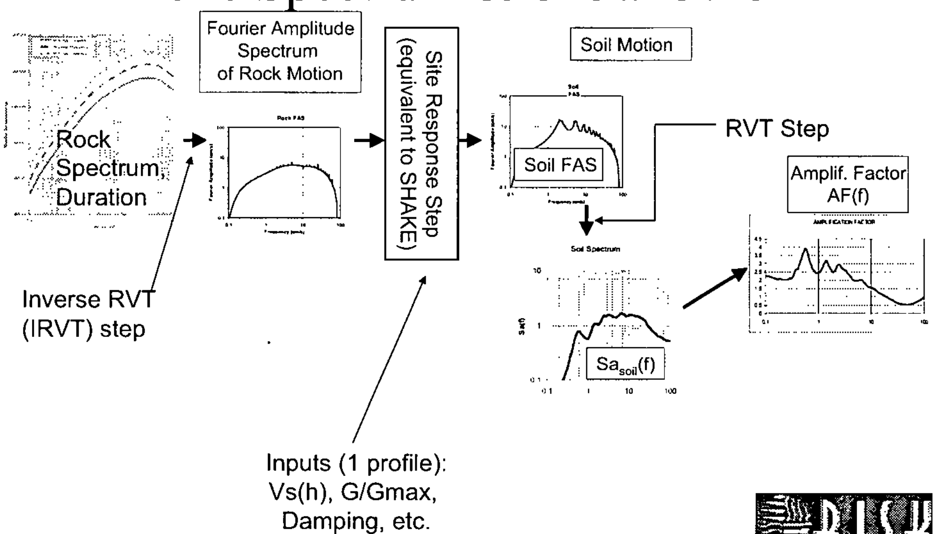
RVT Approach (RVTSITE, etc.) for one Spectrum & one Profile



Key Feature of RVT Approach

In one run, it generates the mean Amplification Factor AF(f) for the entire <u>ensemble</u> of time histories with the same Sa(f) and duration

- No need for selection & spectral matching of time histories ☺
- Reduces computational and book-keeping burdens associated with multiple SHAKE runs with different time histories ☺
- Still needs to run multiple profiles ☹ (RVTSITE does it in one run ☺)

Common Features of SHAKE and RVT Implementation

1. "Guts" of soil dynamics formulation (frequency domain) are the same

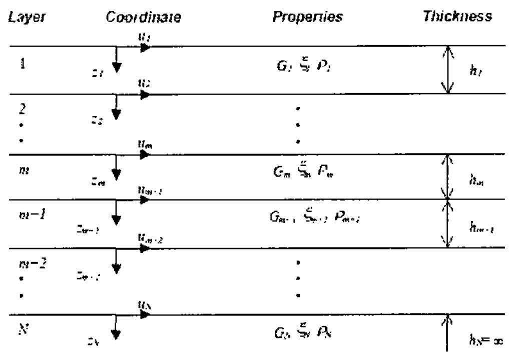


Figure 6 One-dimensional layered soil deposit system (after Schnabel et al., 1972).

Common Features (cont'd)

2. Equivalent-linear iterations are similar; only difference: calculation of peak strain
   - → SHAKE uses IFFT of strain Fourier transform
   - → RVT uses RVT (i.e., rms strain * peak factor)

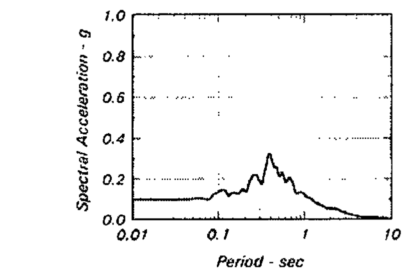
Inputs for each SHAKE run – one profile

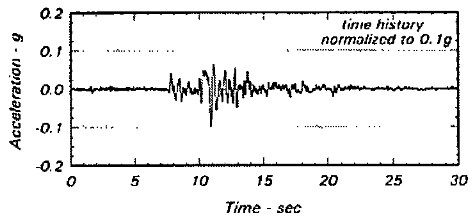
- Rock motion (time history)
- Profile properties (Vs, density, G/Gmax, Damping)
- Effective strain ratio
  - →0.5-0.65 range
  - →(M-1)/10 (Idriss & Sun, 1992)
- Desired results (depth horizons, etc.)

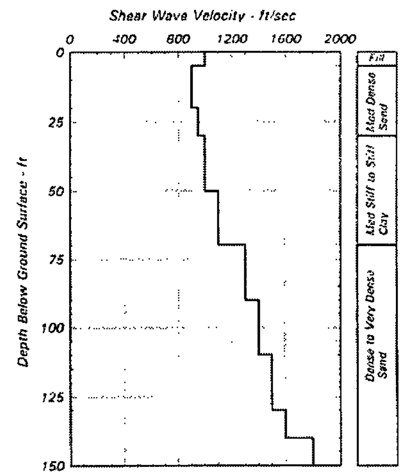
Inputs for each RVTSITE run – one profile

- Rock motion
  - → Sa(f)
  - → Duration
    - Seismological: (corner freq.)$^{-1}$ + 0.05*Duration
    - Section 5.5 of NUREG/CR-6728
- Profile properties (Vs, density, G/Gmax, Damping)
- Effective strain ratio
  - → 0.5-0.65 range
  - → (M-1)/10 (Idriss & Sun, 1992)
- Spectral integration parameters: df, fmax
- Desired results, depth horizons, etc.

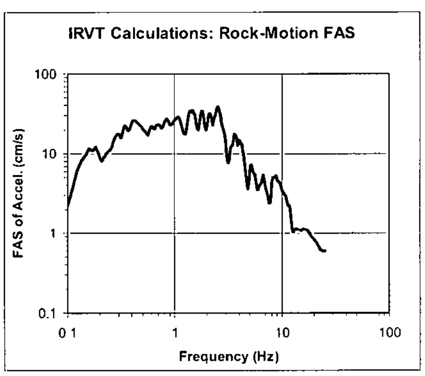
Comparison: SHAKE vs. RVTSITE (SHAKE91 example)

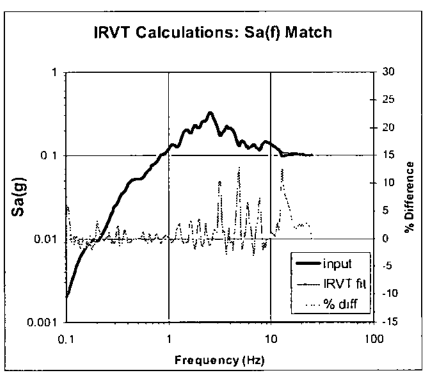




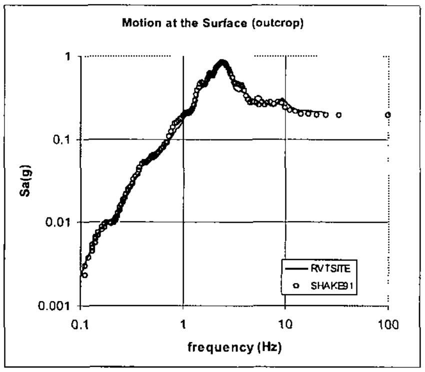


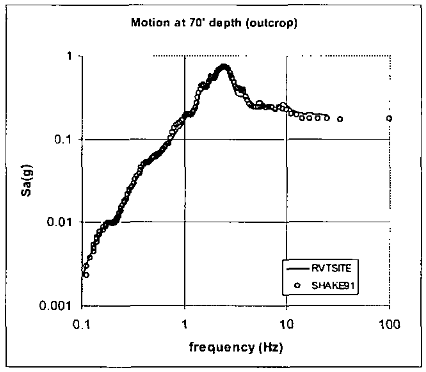
RVTSITE's IRVT Step





Comparisons: Response Spectra





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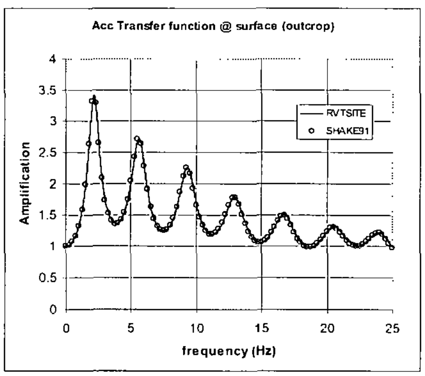
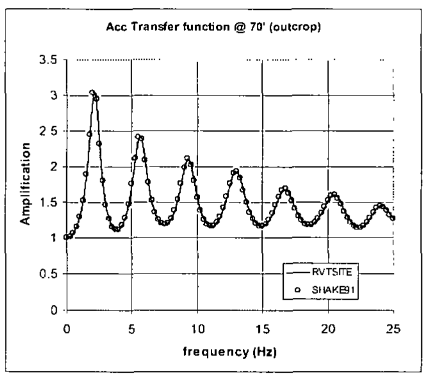
Comparisons: Accel. Transfer Functions (strain-compatible)





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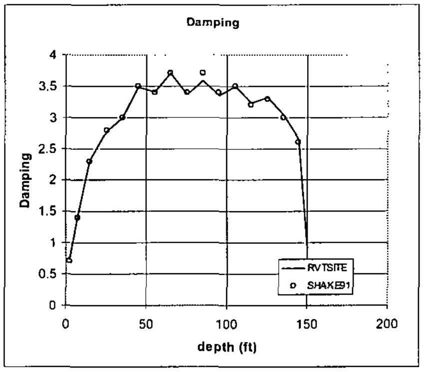
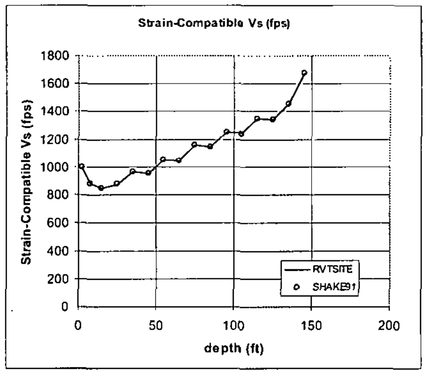
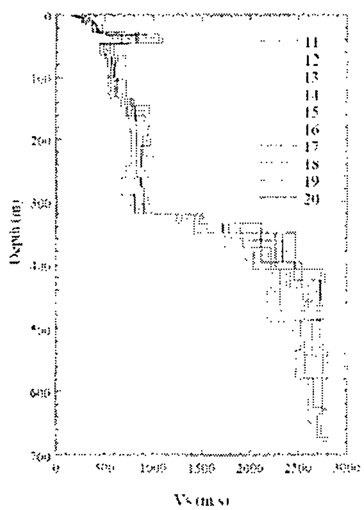
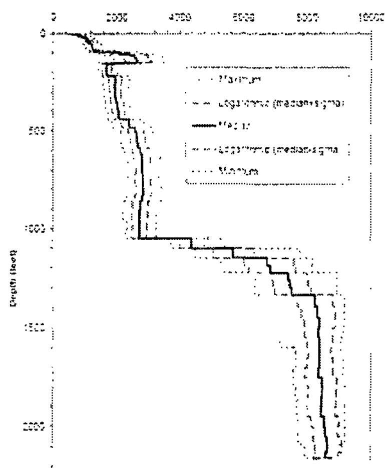
Comparisons: Strain Compatible Properties



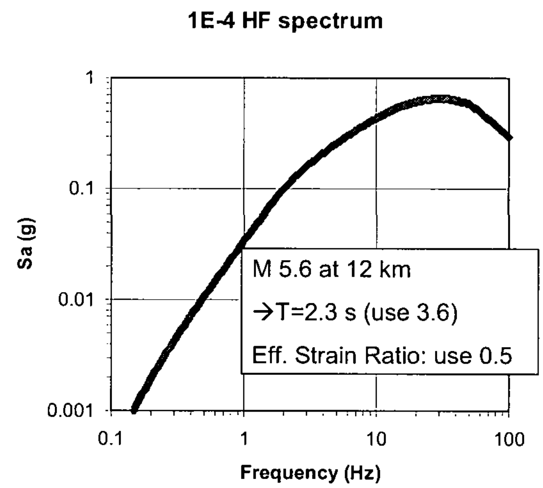


Example: Deep Site in S.E. US (120 artificial profiles)

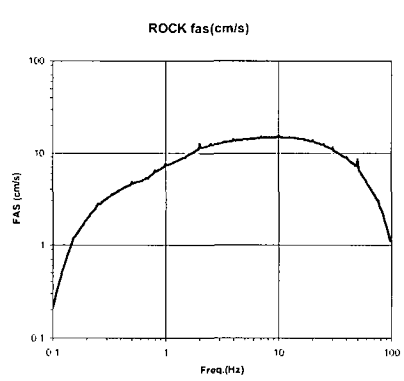


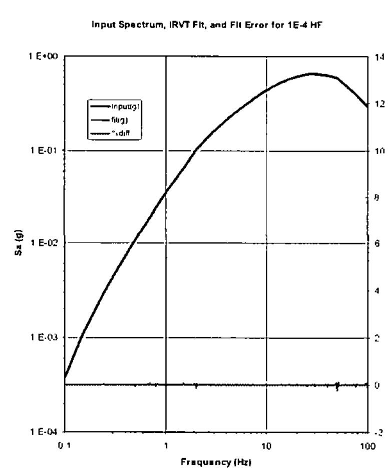


1E-4 HF Rock Motions

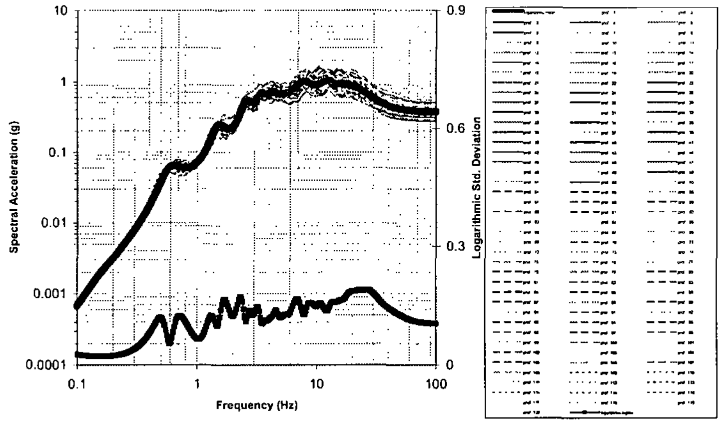


1E-4 HF Example: IRVT Step





Results: Soil Spectrum



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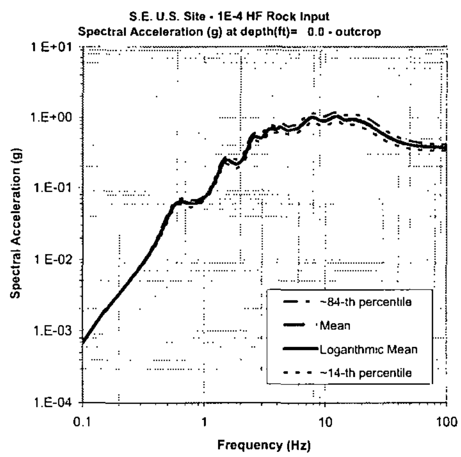
Results: Soil Spectrum (2)



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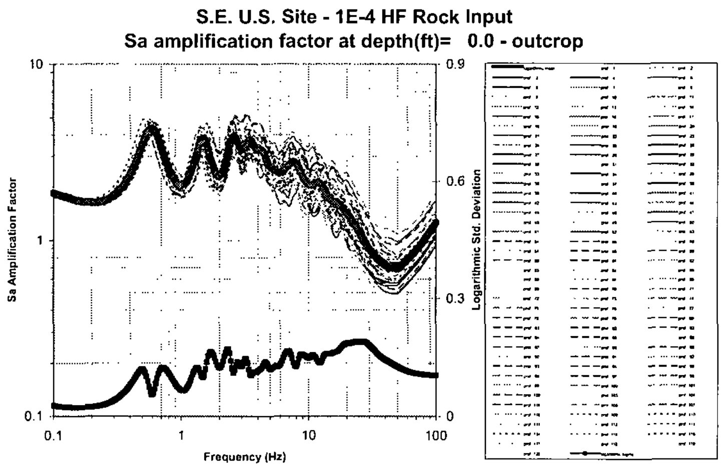
Results: AF



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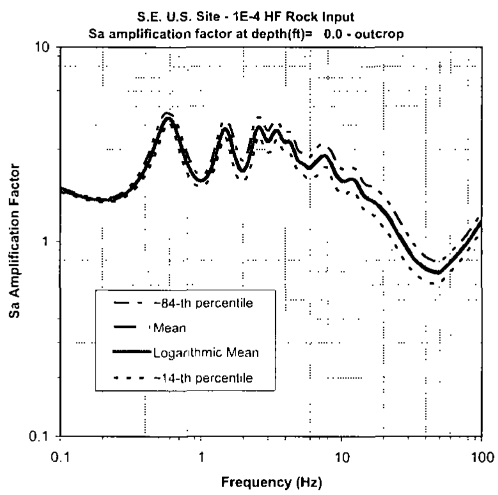
Results: AF(2)



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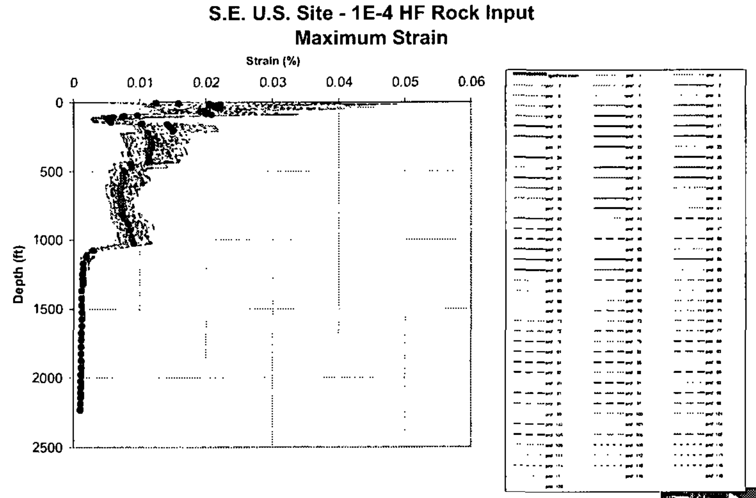
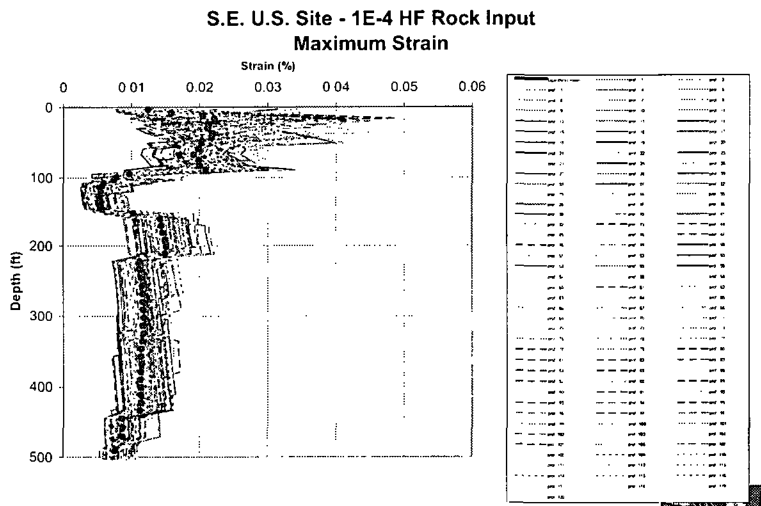
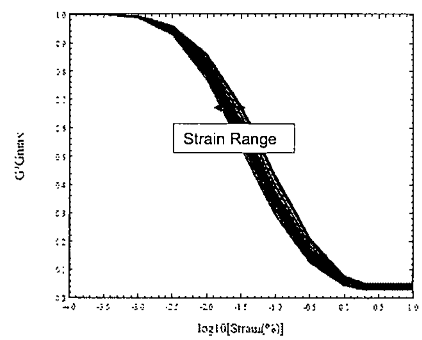
Results: Peak Strains

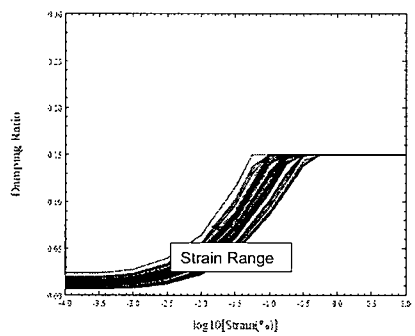


Results: Peak Strains (top 500 ft)

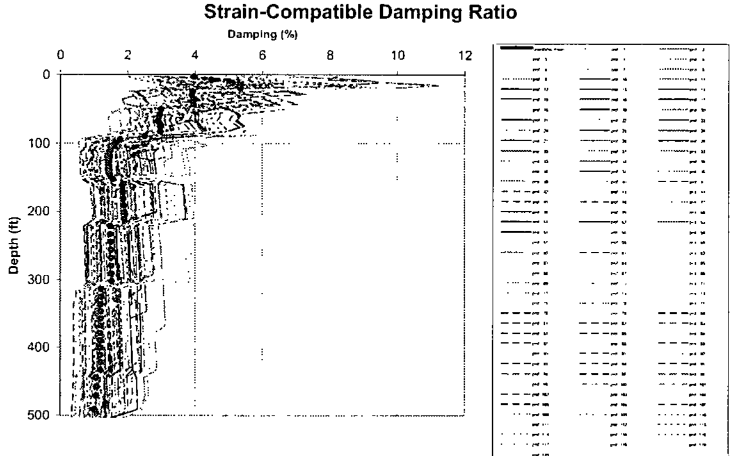


Peak Strains (20-50 ft depth; soil 2)

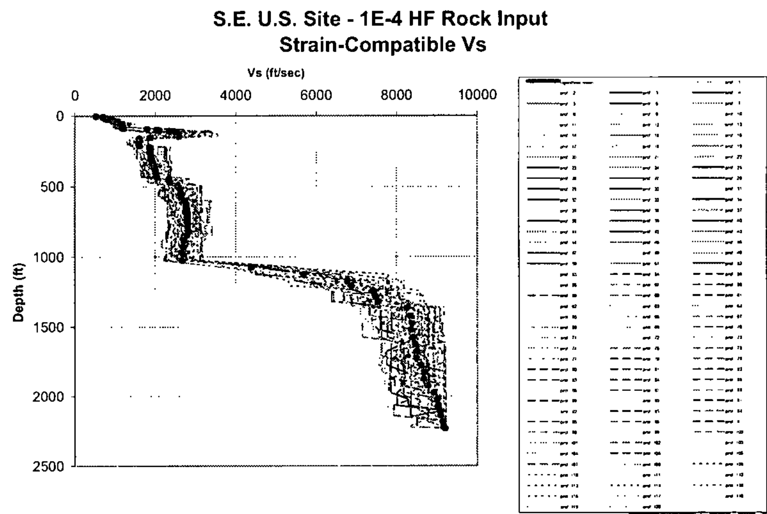




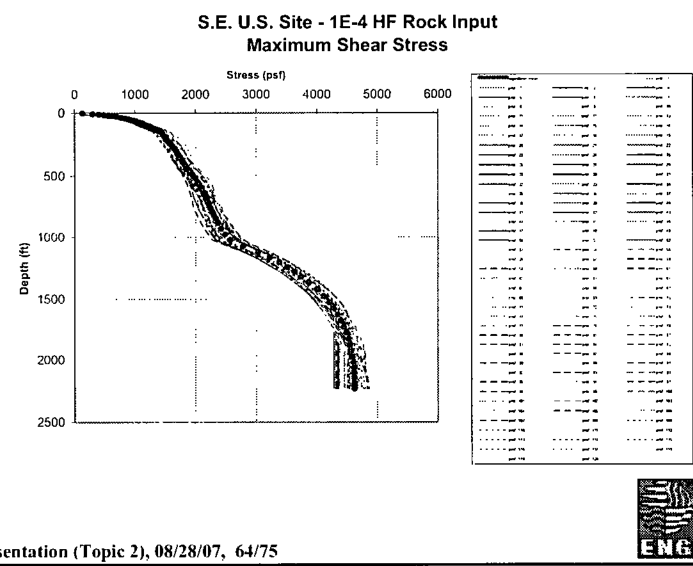
Results: Damping Ratios



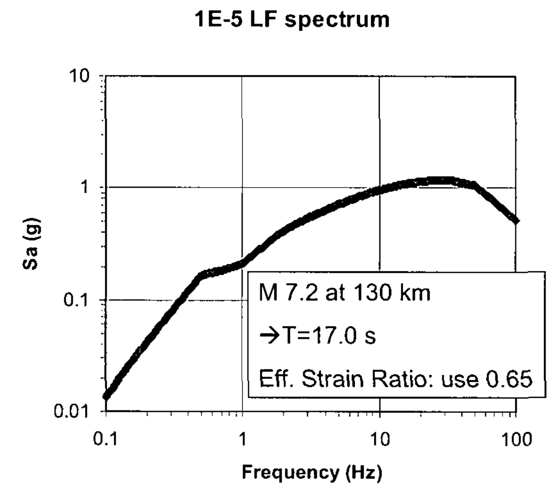
Results: Strain-Compatible Vs



Results: Max. Shear Stress

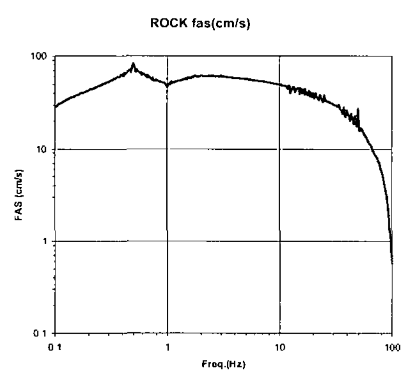


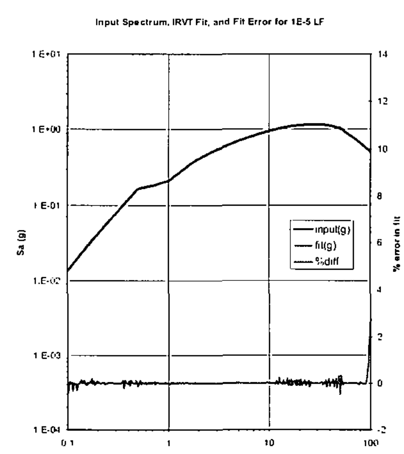
1E-5 LF Rock Motions



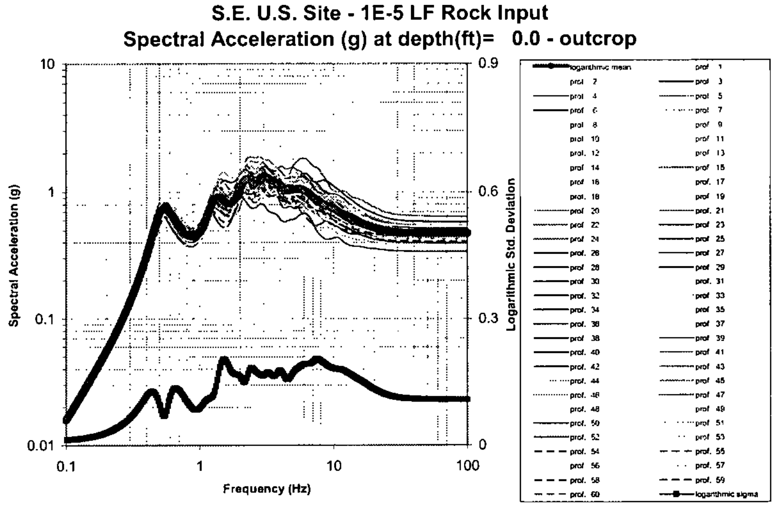
Used 60 profiles only

1E-5 LF Example: IRVT Step

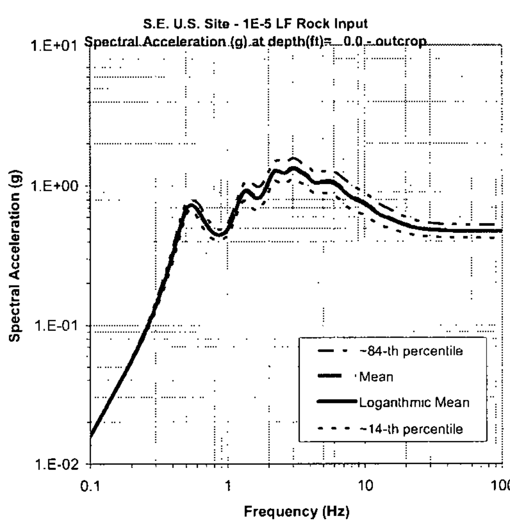




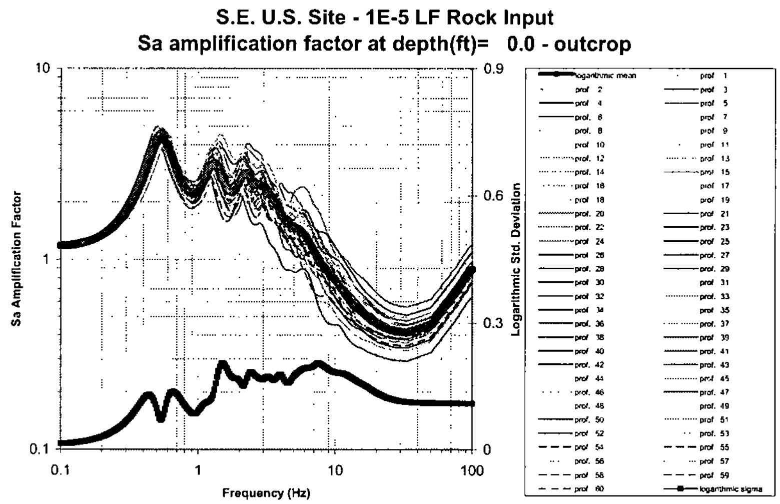
Results: Soil Spectrum



Results: Soil Spectrum(2)



Results: Amplif. Factor



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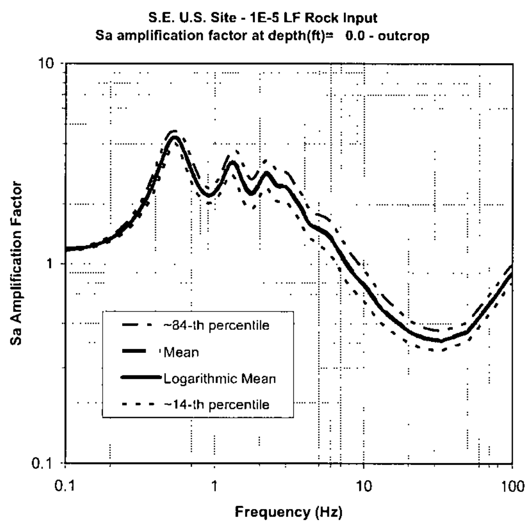
Results: Amplif. Factor (2)



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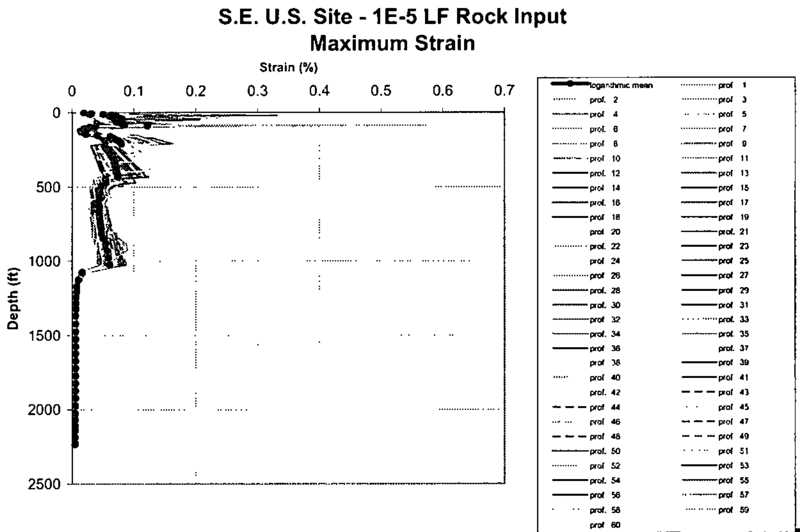
Results: Peak Strains



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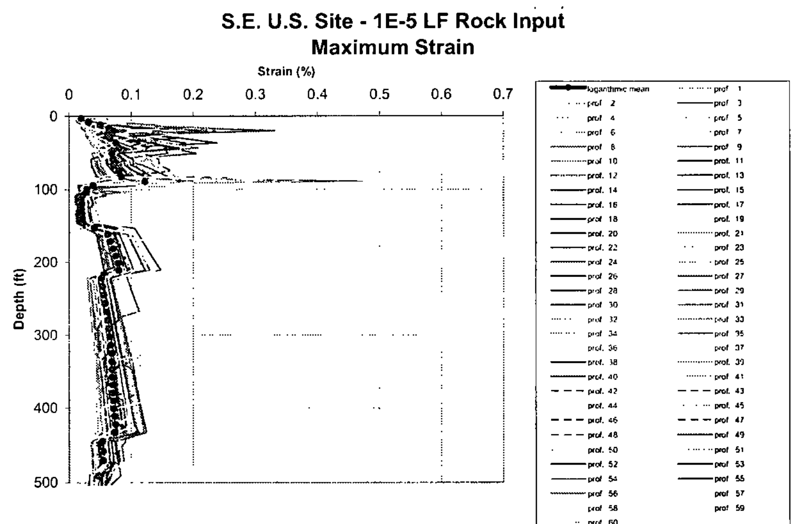
Results: Peak Strains (top 500 ft)



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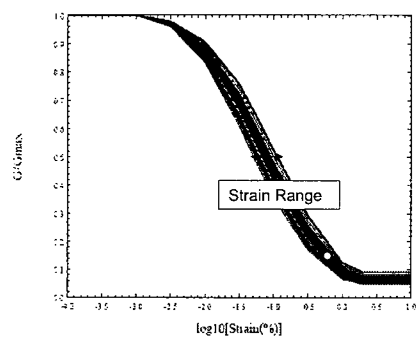
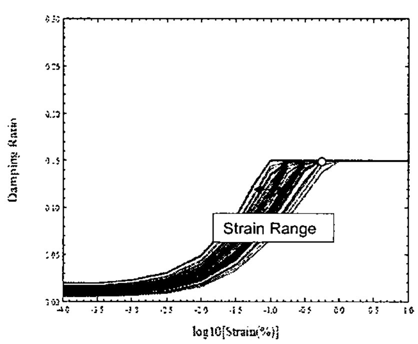
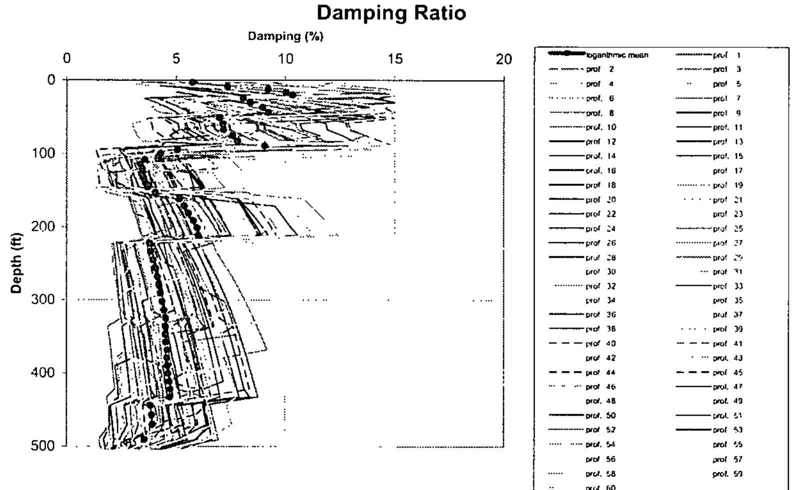
Peak Strains (20-50 ft depth; soil 2)





Range shown: logarithmic mean+- sigma

Results: Strain-Compatible Damping



Summary

- Profile Randomization Procedure
  - → accounts for within-category, within-footprint, and depth-wise uncertainty in Vs, G/Gmax & Damping
  - → Smooths out AF(f), except for significant features
- RVT Site-Response Calculation
  - → Equivalent to multi-timehistory SHAKE
  - → Allows for the efficient quantification of site response
  - → Performed separately for each "Representative Earthquake" (e.g., 1E-4 HF, 1E-4 LF)
- Combined Profile Randomization + RVT Site Response produce mean and logarithmic sigma of AF (as required by Approaches 2-4)

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