1

Site Response and Ground Motions

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2

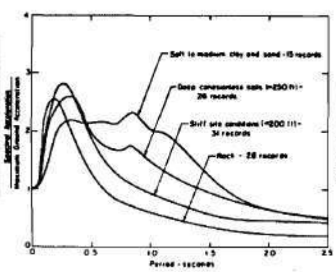
Site Effects – Historical Perspective

"... a movement ... must be modified while passing through media of different constitutions. Therefore, the earthquake effects will arrive to the surface with higher or lesser violence according to the state of aggregation of the terrain which conducted the movement. This seems to be, in fact, what we have observed in the Colchagua Province (of Chile) as well as in many other cases."

- Del Barrio (1855) cited in Toro and Silva (2001)

3

Site Effects – Historical Perspective



Seed et al. (1976)

4

Outline

- Ground motion parameters
- Seismic hazard analyses
- Dynamic soil properties
- Site response analyses
- Design ground motions
  - NEHRP/IBC2000 general procedure
  - Site-specific procedures

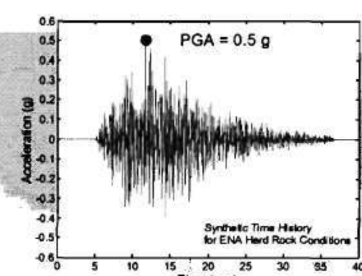
5

Ground Motion Parameters

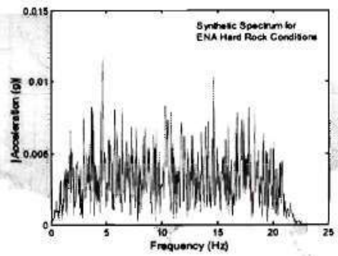
- Peak ground acceleration
- Fourier spectra
- Response spectra
- Uniform hazard response spectra

6

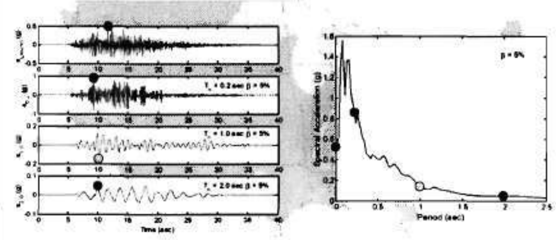
Peak Ground Acceleration



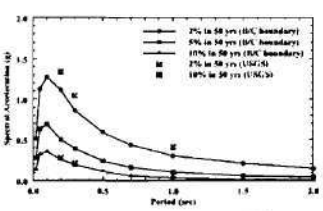
Fourier Spectra



Response Spectra



Uniform Hazard Response Spectra



UHS for B/C boundary soil conditions in Memphis, TN (Wen and Wu, 2001)

Uniform hazard spectra have equal probability of exceedance for spectral acceleration at each period

Seismic Hazard Analyses

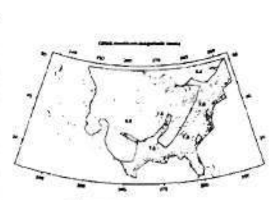
- Definitions
- Components of hazard analyses
- Deterministic analyses
- Probabilistic analyses
  - Return period
  - Epistemic and aleatory uncertainty

Hazard Definitions

- "The purpose of a seismic *hazard* evaluation is to arrive at earthquake ground motion parameters for use in evaluating the site and facility under construction during seismic loading conditions. Coupled with the vulnerability of the site and the facility under various levels of these ground motion parameters, the *risk* to which the site and facility may be subject can be assessed." (Idriss, 1985)
- Hazard – the expected *occurrence* of future seismic events
- Risk – the expected *consequences* of future seismic events

Components of Seismic Hazard Analyses

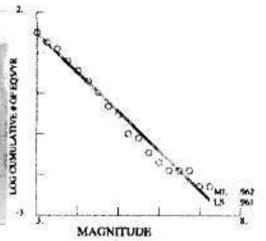
- Identification and characterization of source zones that may produce significant ground motions at the site of interest



Source zones for the CEUS (from Frankel et al., 1996)

Components of Seismic Hazard Analyses

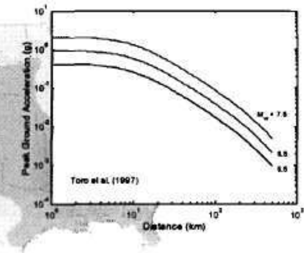
- Definition of the recurrence relationship that is used to characterize the seismicity or temporal distribution of earthquakes within each source zone



b-value plot for CEUS events (from Frankel et al., 1996)

Components of Seismic Hazard Analyses

- Selection of a regional attenuation relationship appropriate that shows the variation of ground motion parameters with:
  - Magnitude
  - Distance
  - Site conditions
  - Type of fault mechanism
- Attenuation relationships may be determined from:
  - Empirical data
  - Stochastic simulations



Deterministic Hazard Analyses

- Identify and characterize source zones that may produce significant ground motions at the site of interest
- Determine the appropriate distance from each source zone to the site of interest
- Select the controlling earthquake (i.e., magnitude and distance)
- Calculate the ground motion parameters using a regional attenuation relationship

Probabilistic Hazard Analyses

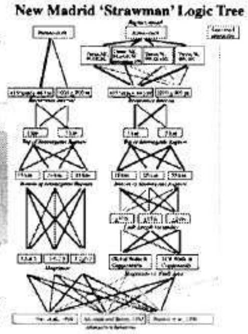
- Identify and characterize source zones that may produce significant ground motions at the site of interest including the spatial distribution and probability of earthquakes in each zone
- Characterize the temporal distribution and probability of earthquakes in each source zone via a recurrence relationship and probability model (usually Poisson)
- Select a regional attenuation relationship and associated uncertainty to calculate the variation of ground motion parameters with magnitude and distance
- Calculate the hazard by integrating over magnitude and distance for each source zone

$$P[Y > y^*] = \iint P[Y > y^* | m,r]\, f_M(m)\, f_R(r)\, dm\, dr$$

Probabilistic Hazard Analyses

- Incorporate model uncertainty via relative weighting of alternative models

New Madrid 'Strawman' Logic Tree



Source: USGS Memphis/Shelby County Hazard Mapping Project

Return Period

$$\text{Return period} = \frac{-t}{\ln(1-PE)}$$

Time Period (yrs)	Probability of Exceedance	Return Period (yrs)
50	10%	475
50	5%	975
50	2%	2475

19

Uncertainty

- Epistemic uncertainty – "Uncertainty that is due to incomplete knowledge and data about the physics of the earthquake process. In principle, epistemic uncertainty can be reduced by the collection of additional information."
- Aleatory uncertainty – "Uncertainty that is inherent to the unpredictable nature of future events. It represents unique details of source, path, and site response that cannot be quantified before the earthquake occurs. Aleatory uncertainty cannot be reduced by collection of additional information. One may be able, however, to obtain better estimates of the aleatory uncertainty by using additional data."

from Toro et. al. (1997)

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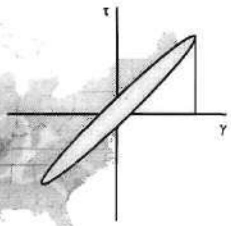
20

Dynamic Soil Properties

- Shear wave velocity profile
  $G_{max} = \rho V_s^2$
- Nonlinear soil behavior
  - Modulus reduction curve
    $G_{sec}/G_{max} = f(\gamma_{cyclic})$
  - Material damping ratio curve
    $D = \frac{1}{4\pi}\frac{\Delta W}{W} = f(\gamma_{cyclic})$



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21

In Situ Methods

- Invasive methods
  - Crosshole
  - Downhole/SCPT
  - P-S suspension logger
- Invasive methods for nonlinear soil properties
- Vertical arrays
- Non-invasive methods
  - Refraction
  - High-resolution seismic reflection
  - Surface wave methods
- Empirical correlations with SPT and CPT

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Laboratory Methods

- Resonant column
- Torsional shear
- Cyclic simple shear
- Cyclic triaxial
- Pulse propagation (i.e. bender elements)

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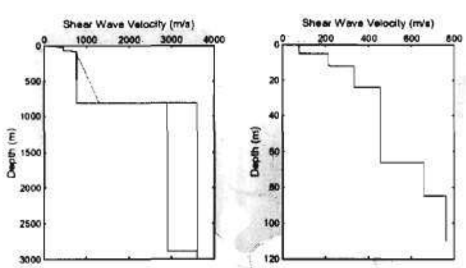
23

Charleston, SC V_s Profile



Wheeler and Cramer (2000)

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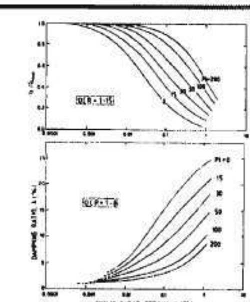
24

Modulus Reduction and Damping



Vucetic and Dobry (1991)

- Seed et al. (1986)
- Sun et al. (1988)
- Vucetic and Dobry (1991)
- EPRI (1993)
- Hwang (1997)
- Assimaki et al. (2000)
- Toro and Silva (2001)

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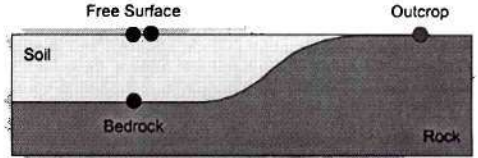
Site Response Analyses

- Amplification
  - Definitions
  - Fourier amplification spectra
  - Spectral amplification
- Site response mechanisms
- Linear analyses
- Quarter-wavelength approximation
- Equivalent linear analyses
- Nonlinear analyses

Amplification Definitions



$$\text{Amplification} = \frac{\text{Free Surface}}{\text{Bedrock}} \qquad \text{Amplification} = \frac{\text{Free Surface}}{\text{Outcrop}}$$

Amplification Definitions

- Fourier amplification spectra

$$\frac{a_{\text{free surface}}(f)}{a_{\text{outcrop}}(f)}$$

- Spectral amplification

$$\frac{S_{a,\text{free surface}}(T)}{S_{a,\text{outcrop}}(T)}$$

Site Response Mechanisms

- Constant flux rate

$$\rho V_S \dot{u}^2 = \text{constant}$$

- Resonances within soil column

H V_s $\quad f_n = \frac{V_s}{4H}$

- Low-strain damping and apparent attenuation in soil
- Nonlinear soil behavior

} Amplification (flux rate, resonances)

} Deamplification (damping, nonlinear behavior)

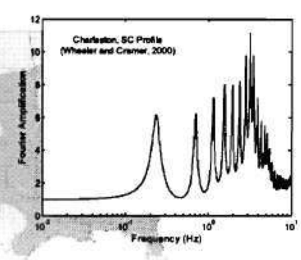
Site Response Calculations

1	h_1, V_{s1}, D_1, ρ_1	↑↓
2	h_2, V_{s2}, D_2, ρ_2	↑↓
⋮		
n	h_n, V_{sn}, D_n, ρ_n	↑↓
n+1	$V_{s(n+1)}, D_{n+1}, \rho_{n+1}$	↑

- Layered profile
- Vertically propagating, horizontally polarized shear waves
- Calculate amplitude of up-going and down-going waves in each layer by enforcing compatibility of displacements and stresses at each layer interface

Linear Analyses

- Constant V_s (i.e., G) and D (or Q)



Amplification from Pre-Cretaceous unconformity (outcrop) to ground surface

Quarter-Wavelength Approximation

- Convert velocity to travel time

$$tt(z) = \sum_i \left(\frac{h_i}{V_{s,i}} \right)$$

- Calculate average velocity to a given depth

$$\bar{V}_s(z) = \frac{z}{tt(z)}$$

- Calculate the Fourier amplification spectrum between motion at the free surface and motion at the surface of a half space with properties V_r and ρ_r

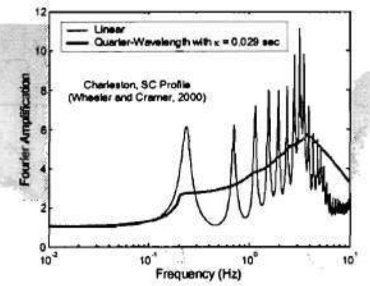
$$A(f(z)) = \sqrt{\frac{\rho_r V_r}{\bar{\rho}\, \bar{V}_s}} \exp(-\pi\kappa f)$$

where

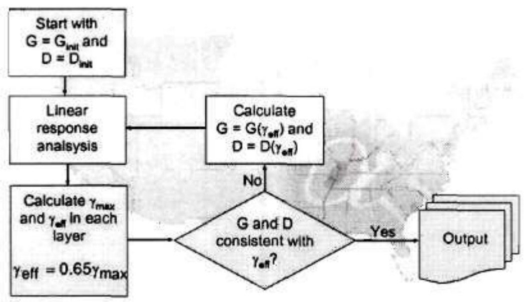
$$f(z) = \frac{1}{4\,tt(z)} \qquad \kappa = \sum_i \frac{2 h_i D_i}{V_{s,i}}$$

$$\text{Note}: \; z = \frac{1}{4}\frac{\bar{V}_s}{f} = \frac{1}{4}\lambda$$

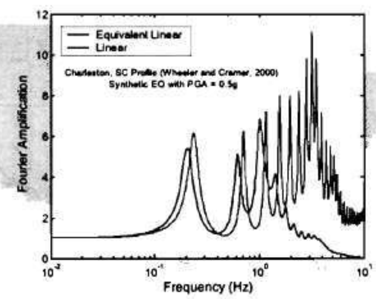
Quarter-Wavelength Approximation



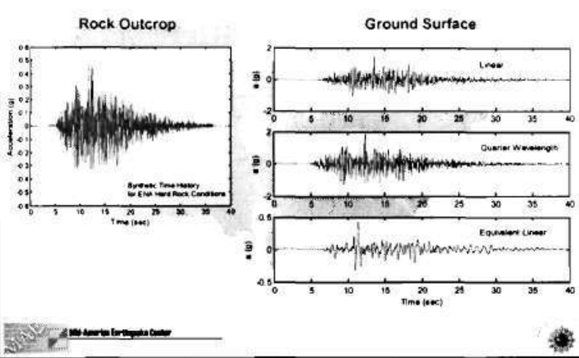
Equivalent Linear Analyses



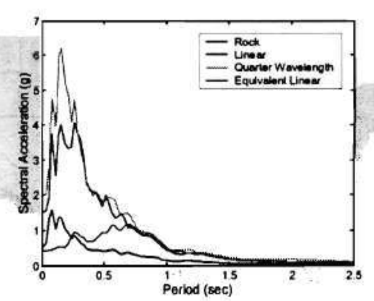
Equivalent Linear Analyses



Response Analysis Comparison



Response Analysis Comparison

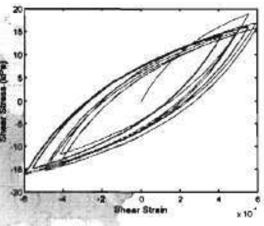


Nonlinear Analyses

- Integrate the equation of motion for vertically propagating shear waves in the time domain

$$\frac{\partial \tau}{\partial z} = \rho \frac{\partial \dot{u}}{\partial t}$$

- Choose a constitutive model capable of reproducing cyclic, nonlinear soil behavior



Equivalent Linear vs. Nonlinear

From Kramer (1996):

- The inherent linearity of equivalent linear analyses can lead to spurious resonances.
- The use of effective shear strain can lead to an over-softened and over-damped system when the peak shear strain is not representative of the remainder of the shear-strain time history and vice versa.
- Nonlinear methods can be formulated in terms of effective stress to model generation of excess pore pressures.
- Nonlinear methods require a robust constitutive model that may require extensive field and lab testing to determine the model parameters.
- Differences between equivalent linear and nonlinear analyses depend on the degree of nonlinearity in the soil response. For low to moderate strain levels (i.e., weak input motions and/or stiff soils), equivalent linear methods provide satisfactory results.

"The equivalent linear model is deeply rooted in engineering practice and will remain so until an easily parameterized and well-tested alternative is available." (Field et al., 1998)

Design Ground Motions

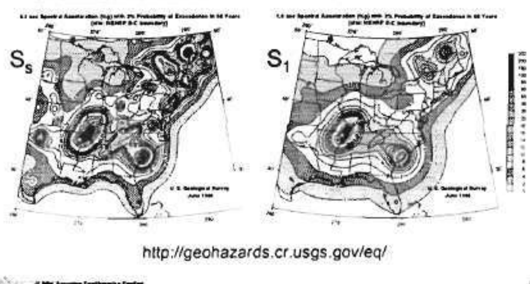
- NEHRP/IBC2000 general procedure
- Site-specific procedures

NEHRP/IBC2000 General Procedure

- NEHRP/IBC2000 Maximum Considered Earthquake (MCE) maps based on the 1996 USGS maps
- Probabilistic hazard analysis for a 2% probability of exceedance in 50 years modified by deterministic bounds near major faults (i.e., California, western Nevada, coastal Oregon and Washington, and parts of Alaska and Hawaii)
- Maps provide spectral accelerations for T = 0.2 sec (S_s) and T = 1.0 sec (S_1)
- Maps provide motions for a site corresponding to the NEHRP B/C boundary
- Local site effects included via generic site coefficients (F_a and F_v) for NEHRP site classes
- Design response spectra constructed from S_s, S_1, F_a and F_v

NEHRP/IBC2000 General Procedure

- Determine S_s and S_1 from the maps



http://geohazards.cr.usgs.gov/eq/

NEHRP/IBC2000 General Procedure

A Hard rock with measured shear wave velocity, v_s > 5,000 ft/sec (1500 m/s)

B Rock with 2,500 ft/sec < v_s ≤ 5,000 ft/sec (760 m/s < v_s ≤ 1500 m/s)

C Very dense soil and soft rock with 1,200 ft/sec < v_s ≤ 2,500 ft/sec (360 m/s < v_s ≤ 760 m/s) or with either N > 50 or s_u ≥ 2,000 psf (100 kPa)

D Stiff soil with 600 ft/sec ≤ v_s ≤ 1,200 ft/sec (180 m/s ≤ v_s ≤ 360 m/s) or with either 15 ≤ N ≤ 50 or 1,000 psf ≤ s_u ≤ 2,000 psf (50 kPa ≤ s_u ≤ 100 kPa)

E A soil profile with v_s < 600 ft/sec (180 m/s) or with either

N < 15, s_u < 1,000 psf or any profile with more than 10 ft (3 m) of soft clay defined as soil with PI > 20, w ≥ 40 percent, and s_u < 500 psf (25 kPa)

F Soils requiring site-specific evaluations:

1. Soils vulnerable to potential failure or collapse under seismic loading such as liquefiable soils, quick and highly sensitive clays, collapsible weakly cemented soils.
2. Peats and/or highly organic clays (H > 10 ft [3 m] of peat and/or highly organic clay where H = thickness of soil)
3. Very high plasticity clays (H > 25 ft [8 m] with PI > 75)
4. Very thick soft/medium stiff clays (H > 120 ft [36 m])

Exception: When the soil properties are not known in sufficient detail to determine the Site Class, Site Class D shall be used. Site Classes E or F need not be assumed unless the authority having jurisdiction determines that Site Classes E or F could be present at the site or in the event that Site Classes E or F are established by geotechnical data.

NEHRP 1997

- Determine the site class from the soil properties in the upper 30 m

NEHRP/IBC2000 General Procedure

- Determine the site coefficients F_a and F_v from the values of S_s, S_1 and site class

TABLE 4.1.2.4a Values of F_a as a Function of Site Class and Mapped Short-Period Maximum Considered Earthquake Spectral Acceleration

Site Class	Mapped Maximum Considered Earthquake Spectral Response Acceleration at Short Periods				
	$S_s \le 0.25$	$S_s = 0.50$	$S_s = 0.75$	$S_s = 1.00$	$S_s \ge 1.25$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0
D	1.6	1.4	1.2	1.1	1.0
E	2.5	1.7	1.2	0.9	a
F	a	a	a	a	a

NOTE: Use straight line interpolation for intermediate values of S_s.
a Site-specific geotechnical investigation and dynamic site response analyses shall be performed.

TABLE 4.1.2.4b Values of F_v as a Function of Site Class and Mapped 1 Second Period Maximum Considered Earthquake Spectral Acceleration

Site Class	Mapped Maximum Considered Earthquake Spectral Response Acceleration at 1 Second Periods				
	$S_1 \le 0.1$	$S_1 = 0.2$	$S_1 = 0.3$	$S_1 = 0.4$	$S_1 \ge 0.5$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.7	1.6	1.5	1.4	1.3
D	2.4	2.0	1.8	1.6	1.5
E	3.5	3.2	2.8	2.4	a
F	a	a	a	a	a

NOTE: Use straight line interpolation for intermediate values of S_1.
a Site-specific geotechnical investigation and dynamic site response analyses shall be performed.

NEHRP 1997

NEHRP/IBC2000 General Procedure

- Adjust the values of maximum considered values of S_s and S_1 for site effects

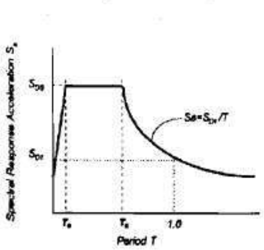
$$S_{MS} = F_a S_s \qquad S_{M1} = F_v S_1$$

- Calculate the design values of S_s and S_1

$$S_{DS} = \frac{2}{3} S_{MS} \qquad S_{D1} = \frac{2}{3} S_{M1}$$

NEHRP/IBC2000 General Procedure

- Develop the design response spectrum



$T \le T_0$: $\quad S_a = 0.6 \frac{S_{DS}}{T_0} T + 0.4 S_{DS}$

$T_0 \le T \le T_S$: $\quad S_a = S_{DS}$

$T_S \le T$: $\quad S_a = \frac{S_{D1}}{T}$

where

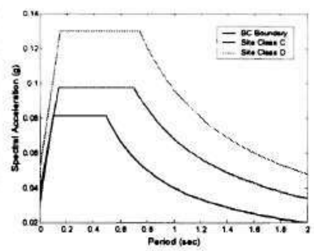
$T_0 = 0.2 \frac{S_{D1}}{S_{DS}}$

$T_S = \frac{S_{D1}}{S_{DS}}$

NEHRP/IBC2000 General Procedure

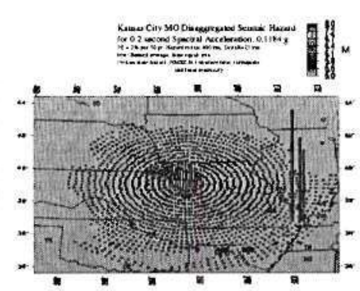
Kansas City
(39.12N – 94.64W)

$S_S = 0.122$ g
$S_1 = 0.060$ g



Deaggregations

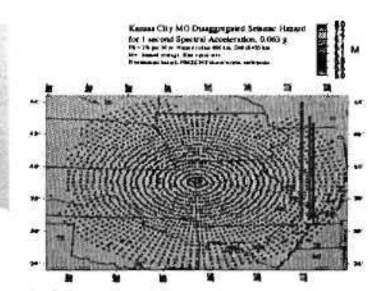
T = 0.2 sec



Source: USGS National Seismic Hazards Mapping Project

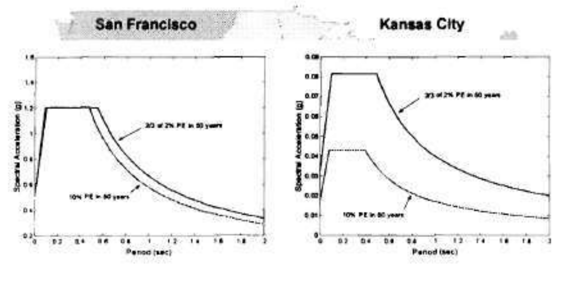
Deaggregations

T = 1.0 sec

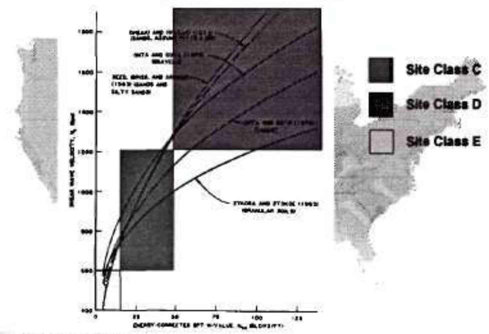


Source: USGS National Seismic Hazards Mapping Project

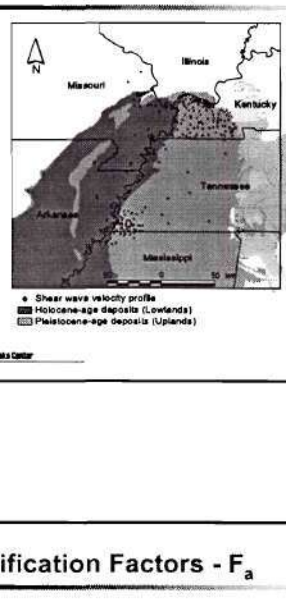
Observations



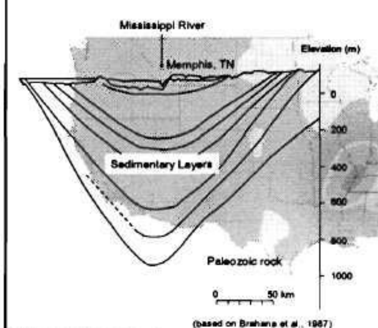
Observations



Upper Mississippi Embayment

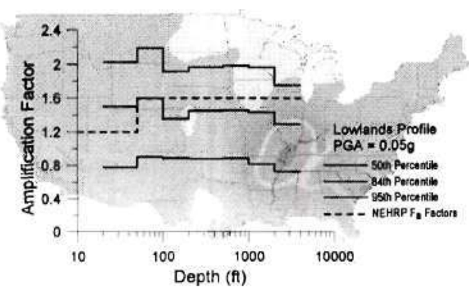


Upper Mississippi Embayment

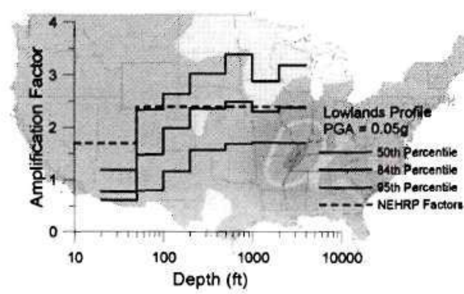


- Embayment composed of low-velocity geologic deposits overlying Knox Dolomite of Paleozoic age
- Depth of 1000 meters near Memphis, Tennessee

Site Amplification Factors - F_a

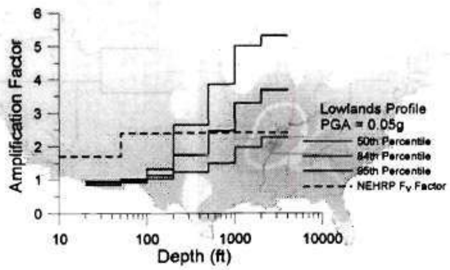


Site Amplification Factors - F_v



55

Site Amplification Factors - F_d



56

2002 Update of the National Maps

- Same basic methodology
- More explicit treatment of uncertainty
- Incorporate changes in source characteristics of New Madrid and Charleston, SC zones
- Utilize addition attenuation relations
- Hard-rock site conditions to complement BC site conditions

57

Site-Specific Procedures

- Hazard estimates can be:
  - tailored to local conditions
  - based on project-specific return periods
  - used to obtain hazard-consistent ground surface motions
- Site-specific analyses require more effort and expertise to conduct
- NEHRP/IBC2000 places limits on results obtained by site-specific procedures

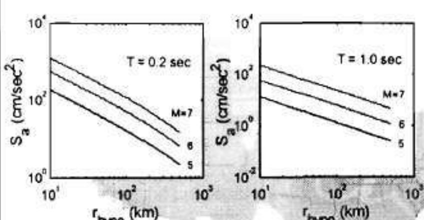
58

Site-Specific Procedures

- Two-step procedures:
  - Probabilistic "base level" ground motions combined with regional or geology-based site amplification factors
  - Probabilistic "base level" ground motions combined with a site-specific response analysis
- One-step procedure:
  - Site effects included directly in attenuation relationships (allows one to obtain hazard-consistent ground surface motions)

59

ENA Attenuation Relationships

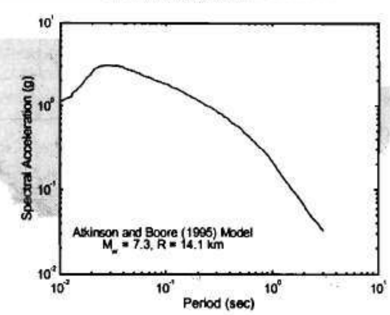


Atkinson and Boore (1997) attenuation for hard rock site conditions typical of ENA

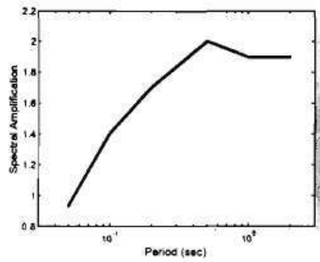
- Stochastic Model
  - Frankel et al. (1996)
  - Atkinson and Boore (1997)
  - Toro et al. (1997)
- Empirical Data (modified WNA relationships)
  - Atkinson (2001)

60

ENA Hard Rock Response Spectrum



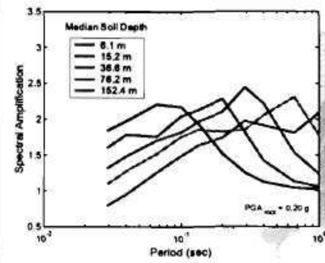
Regional Soil Amplification Factors



Atkinson and Boore (1997)

- Amplification with respect to hard rock
- Deep soil profile representative of Soil Profile Type S2 or Site Class C
- Quarter-wavelength method used for soil amplification

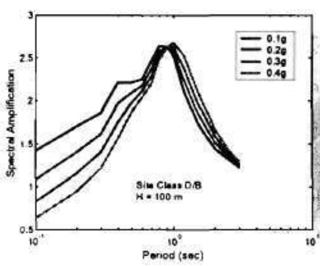
Regional Soil Amplification Factors



EPRI (1993)

- Stochastic simulation using ENA source and path parameters
- Amplification factors for soil profiles representative of ENA conditions with respect to hard rock
- Equivalent linear method of soil amplification with parametric variation of V_s, G/G_{max}, and D

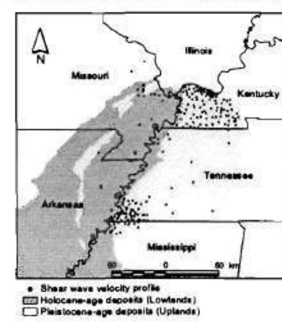
Regional Soil Amplification Factors



Hwang et al. (1997)

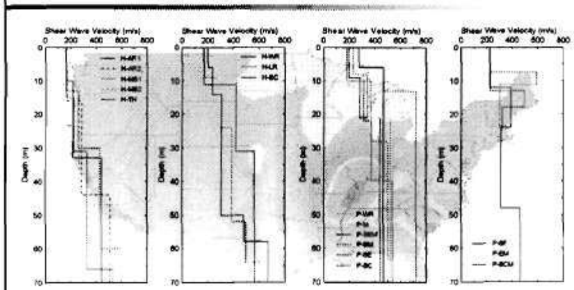
- Stochastic simulation using ENA source and path parameters
- Amplification factors for NEHRP Site Class C, D and E sites with H = 100 m with respect to Site Class B
- Equivalent linear method of soil amplification with parametric variation of V_s, G/G_{max}, and D
- F_a and F_v site coefficients provided

Geology-Based Amplification Factors



Romero and Rix (2001) and Romero (2001)

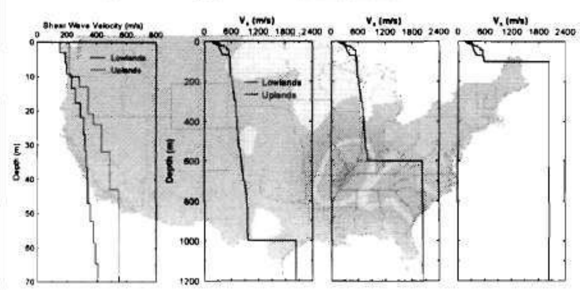
Geology-Based Amplification Factors



Holocene-age profiles

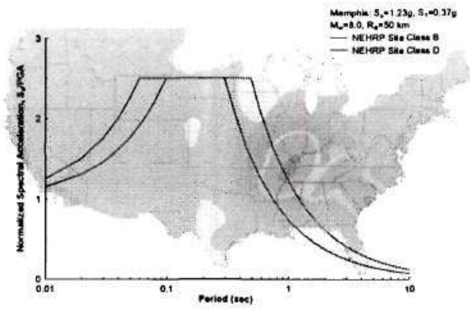
Pleistocene-age profiles

Geology-Based Amplification Factors



67

Geology-Based Amplification Factors



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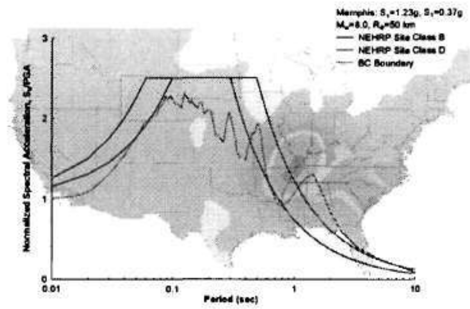
68

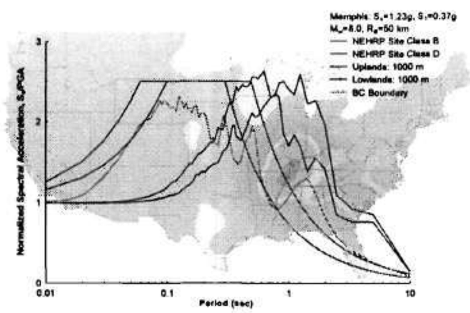
Geology-Based Amplification Factors



Mid-America Earthquake Center

69

Geology-Based Amplification Factors



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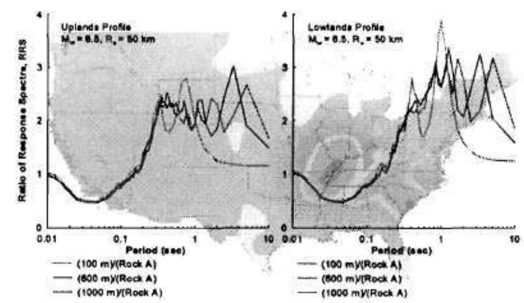
70

Geology-Based Amplification Factors



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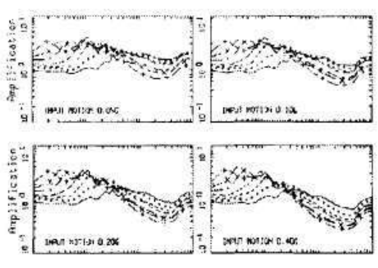
71

Geology-Based Amplification Factors



Toro and Silva (2001)

Enveloped, median spectral amplification for Central U.S. "Lowlands" profile for H = 10 to 1000 m

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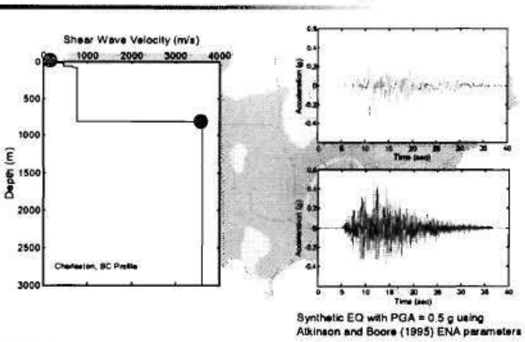
72

Site-Specific Response Analysis



Synthetic EQ with PGA = 0.5 g using Atkinson and Boore (1995) ENA parameters

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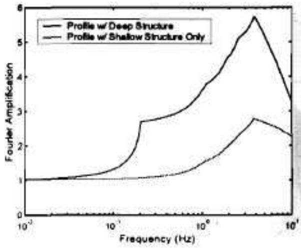
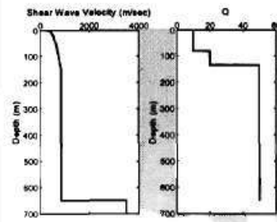
Site-Specific Response Analysis



- It is important to include deep stratigraphy (i.e., velocity contrasts) in the profile to obtain accurate low-frequency response

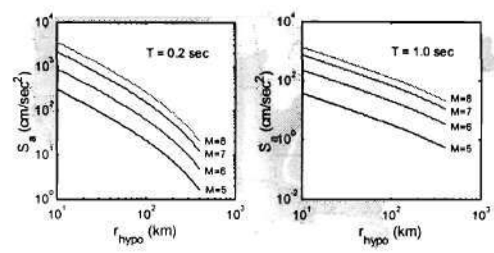
Soil Attenuation Relationships



Boore and Joyner (1991)

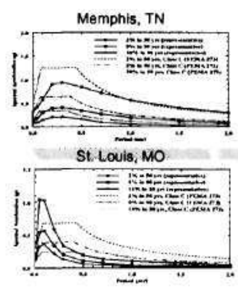
- Stochastic simulation of ground motions using source, path and site parameters typical of ENA
- Deep soil profile representative of Soil Profile Type S2 or Site Class C
- Quarter-wavelength method used for soil amplification
- Epistemic and aleatory uncertainty not modeled

Soil Attenuation Relationships



Boore and Joyner (1991)

Specific Locations

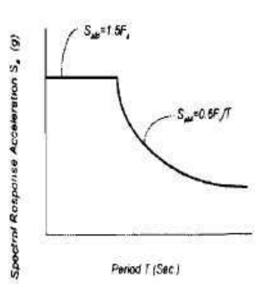


from Wen and Wu (2001)

- Stochastic simulation of ground motions for Memphis, TN; St. Louis, MO; and Carbondale, IL
- Quarter-wavelength method used for soil amplification
- Uncertainty included via $\sigma_{lny} = 0.75$

NEHRP/IBC2000 Limits

- Site-specific *maximum considered* ground motions are taken as the lesser of the ground motions from a probabilistic analysis for 2% PE in 50 yrs. and 150% of the median ground motions from a deterministic analysis of a characteristic earthquake on known faults, but may not be less than the deterministic limit shown at the right.
- Site-specific *design* ground motions are equal to 2/3 of the maximum considered ground motions, but may not be less than 80% of the values obtained via the general procedure.



Additional Topics

- Topography and basin effects
- 2D and 3D site response
- Near-fault effects
- Spatial variability of ground motions

Acknowledgements

- Mid-America Earthquake Center
- Dr. Salome Romero-Hudock
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- Dr. David M. Boore

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