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"2nd Workshop on Earthquake Engineering for Nuclear Facilities: Uncertainties in Seismic Hazard"

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Uncertainties in the Attenuation Laws

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"Uncertainties in the Attenuation Laws"

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Unit 29 - K. Campbell, USA

Contents of the Presentation

- Introduction
- Model parameters
- Analysis methods
- Modelling of uncertainty
- Lessons learned and conclusions
- Summary of the presentation
- References and glossary

Introduction

“By Any Other Name”

- Attenuation laws (Europe)
- Attenuation relations (U.S. Engineers)
- Attenuation relationships (U.S. Engineers)
- Attenuation equations
- Ground motion relations (U.S. Seismologists)
- Ground motion prediction relations
- Ground motion prediction equations
- Ground motion estimation equations

Definition

"An attenuation law is a mathematical equation or engineering model that relates a strong-motion parameter to one or more parameters of the earthquake source, wave propagation path, and local site conditions"

Methods of Development

- Empirical methods
  - Derived from strong-motion recordings
- Hybrid empirical methods
  - Derived by modifying empirical attenuation laws in one region to use in another region based on seismological transfer functions usually derived using stochastic methods (see below)
- Stochastic methods
  - Derived from stochastic ground-motion simulations and simple seismological models
- Theoretical methods
  - Derived from kinematic and dynamic ground-motion simulations and rigorous seismological models

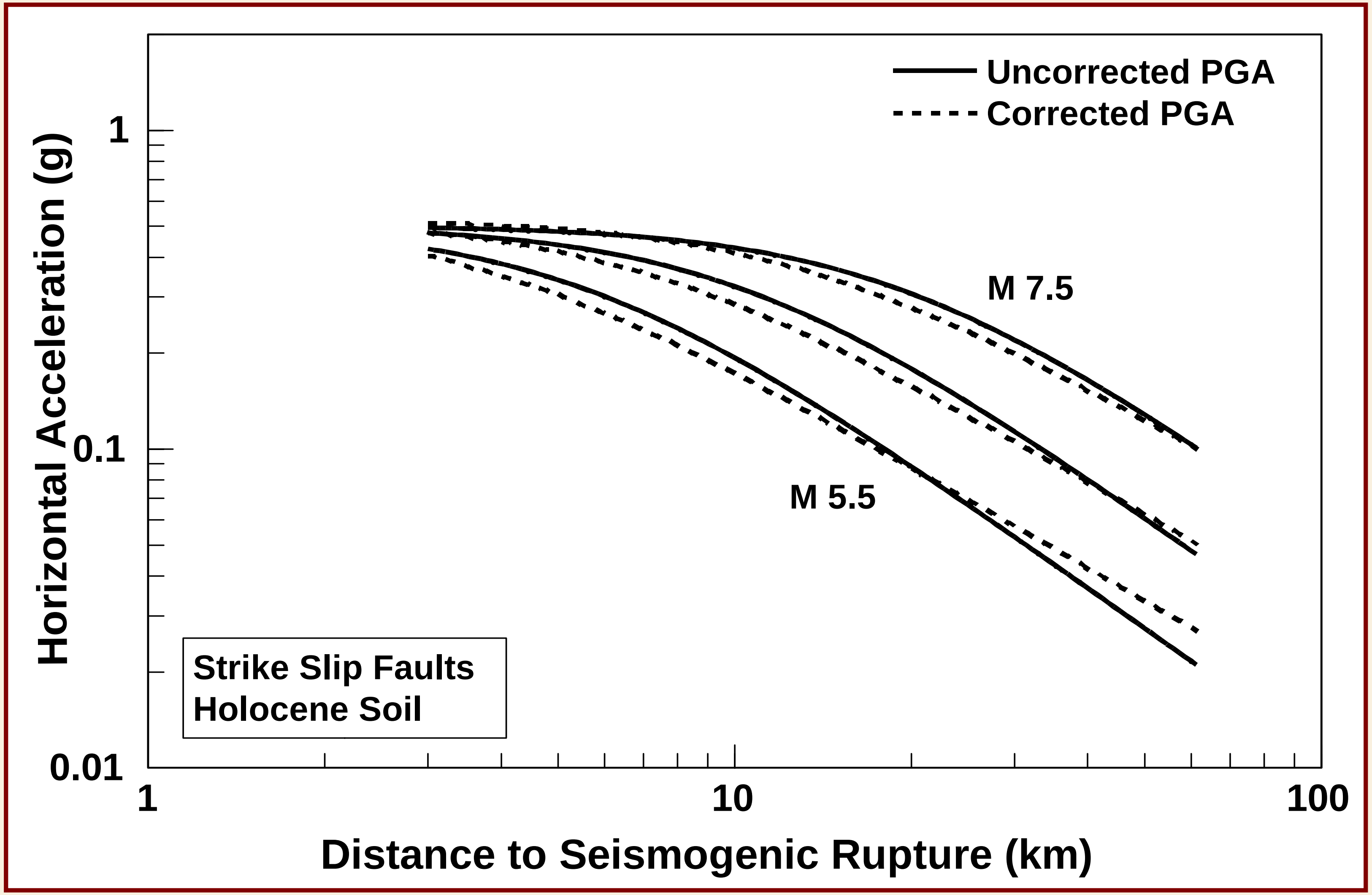
Basic Functional Form

$$\log Y = c_1 + c_2M - c_3 \log R - c_4R + \varepsilon_a + \varepsilon_e$$

where,

- $\log Y$ = log of strong-motion parameter
- M = earthquake magnitude or $f(M)$
- R = source-to-site distance or $f(R,M)$
- ε_a = aleatory uncertainty
- ε_e = epistemic uncertainty
- c_i = model coefficients

Example Attenuation Law



Classification of Uncertainties

- Aleatory Uncertainties (ε_a)
  - They are random in nature
  - For all practical purposes they cannot be known in detail or cannot be reduced
  - They are susceptible to analysis concerning their origin, their magnitude, and their role in PSHA
  - The are typically modeled using the standard error of the attenuation law, $\sigma^a_{\log Y}$, which is often a function of *M* or *Y*

Classification of Uncertainties

- Epistemic Uncertainties (ε_e)
  - They quantify the lack-of-knowledge arising because our scientific understanding is imperfect *for the present*
  - They are of a character that in principle are reducible through further research and gathering of more and better earthquake data
  - They are typically modeled using multiple attenuation laws and/or an epistemic standard deviation, $\sigma^{e}_{\log Y}$, which can be a function of *M*

Model Parameters

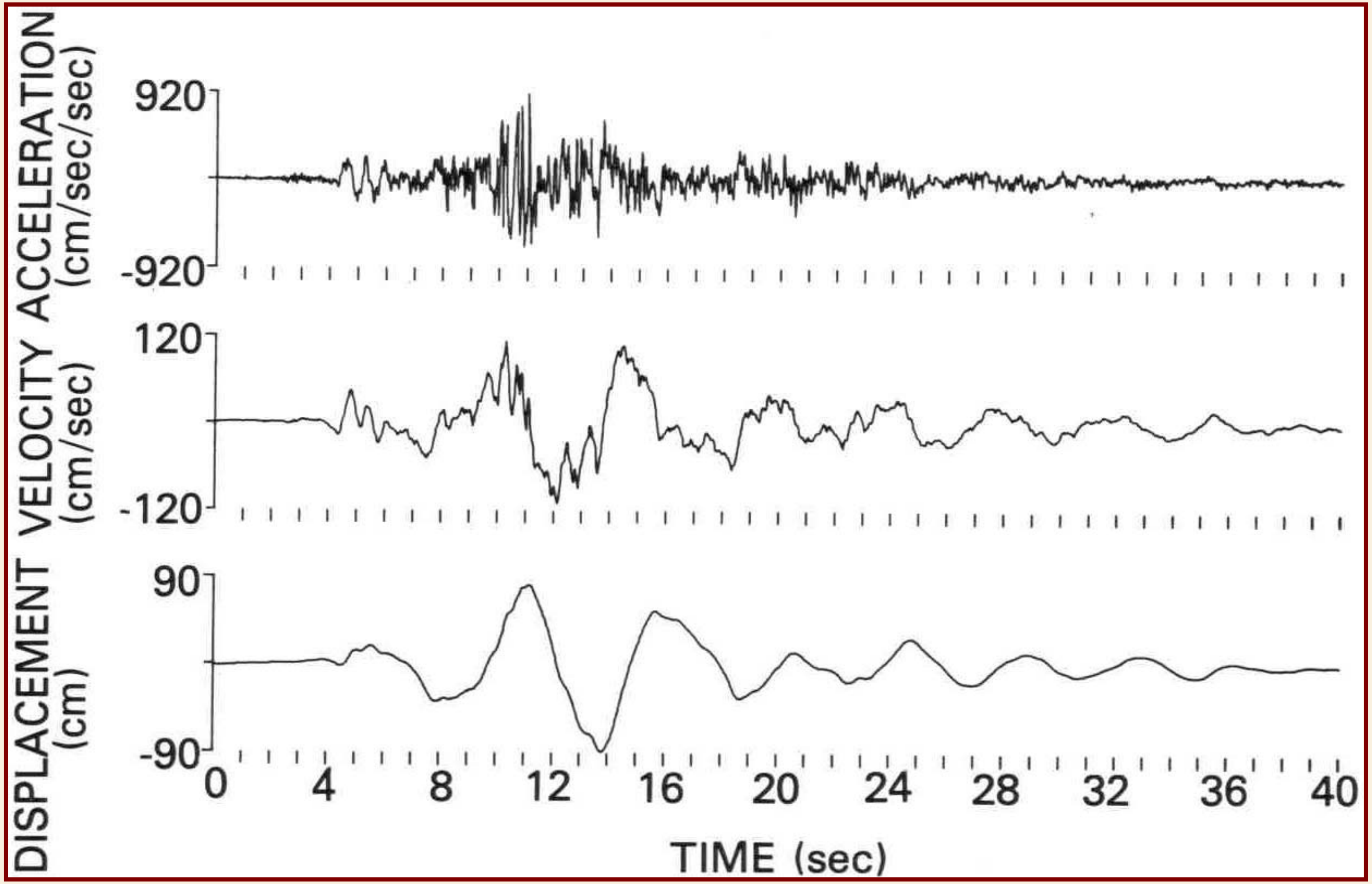
Common Parameters

- Ground-motion measure
- Earthquake magnitude
- Source-to-site distance
- Finite faulting effects
- Local site conditions
- Stress drop
- Hanging-wall effects
- Tectonic environment

Ground-Motion Measures

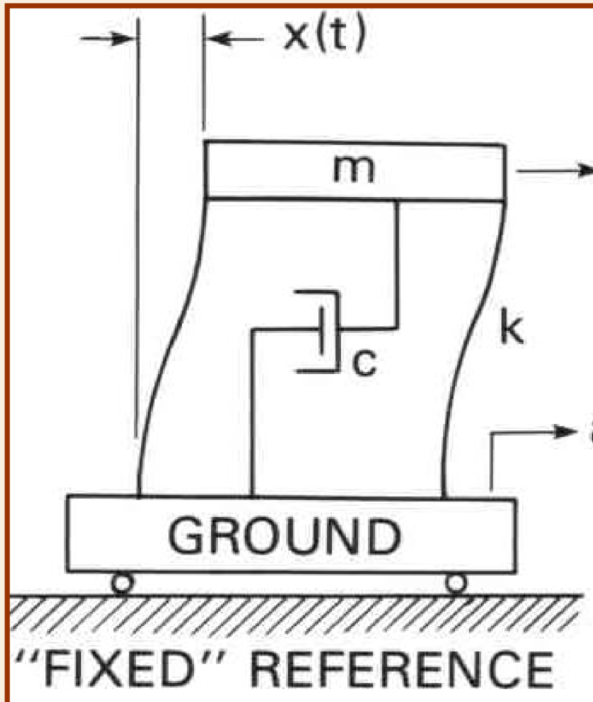
- Time domain
  - Peak ground acceleration (PGA)
  - Peak ground velocity (PGV)
  - Peak ground displacement (PGD)
- Frequency domain
  - Fourier amplitude spectrum (FAS)
  - Response of a single-degree-of-freedom system (SDOF)

Time Domain Measures



Response Spectral Measures

SDOF (single-degree-of-freedom system)



x(t) = RELATIVE MOTION OF m WITH RESPECT TO GROUND

y(t) = ABSOLUTE MOTION OF m WITH RESPECT TO "FIXED" REFERENCE

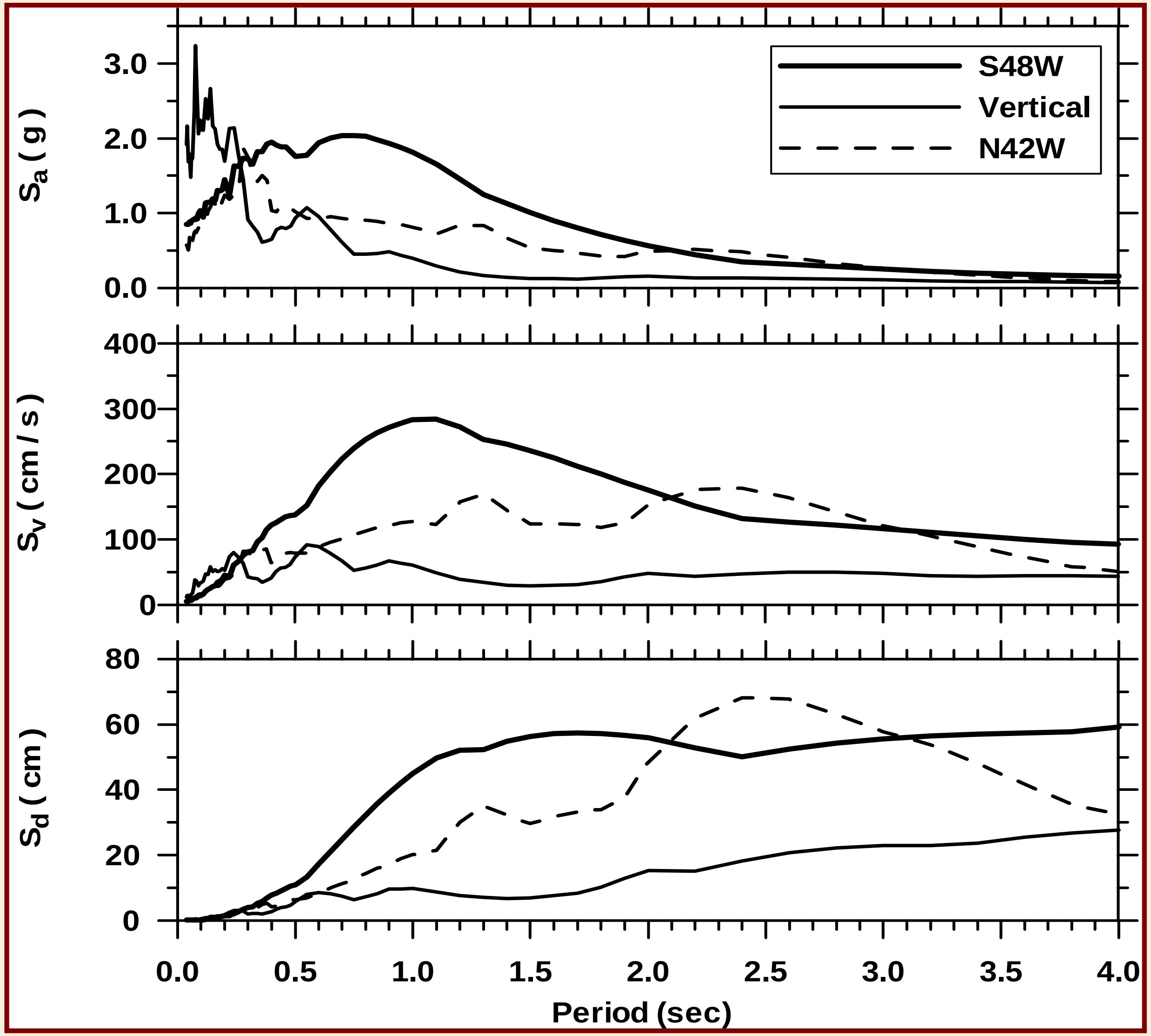
a(t) = ABSOLUTE ACCELERATION OF GROUND WITH RESPECT TO "FIXED" REFERENCE

Response Spectral Measures

- Typically used in U.S.
  - S_d = maximum relative* displacement
  - S_v = PSV = pseudo-velocity = $(2\pi f) \times S_d$
  - S_a = PSA = pseudo-acceleration = $(2\pi f)^2 \times S_d$
- Typically used in Europe or Japan
  - *SV* = maximum relative velocity
  - *SA* = maximum absolute acceleration

* *Relative to the ground; Note:* $S_a \approx SA$; $S_v \neq SV$

Example Response Spectra



Ground-Motion Components

- Horizontal Component
  - Largest absolute value of either horizontal trace
    - Component can vary for each spectral period (U.S.)
    - Component can be the same for each spectral period (Europe)
  - Geometric mean of largest absolute values of two horizontal traces, independent of when they occur
  - Largest values of both horizontal traces, independent of when they occur (same as geometric mean but with higher standard error)
  - Largest value of the vectoral combination (resultant) of two horizontal traces (Japan)
  - A consistent approach must be used throughout PSHA and design
- Vertical Component

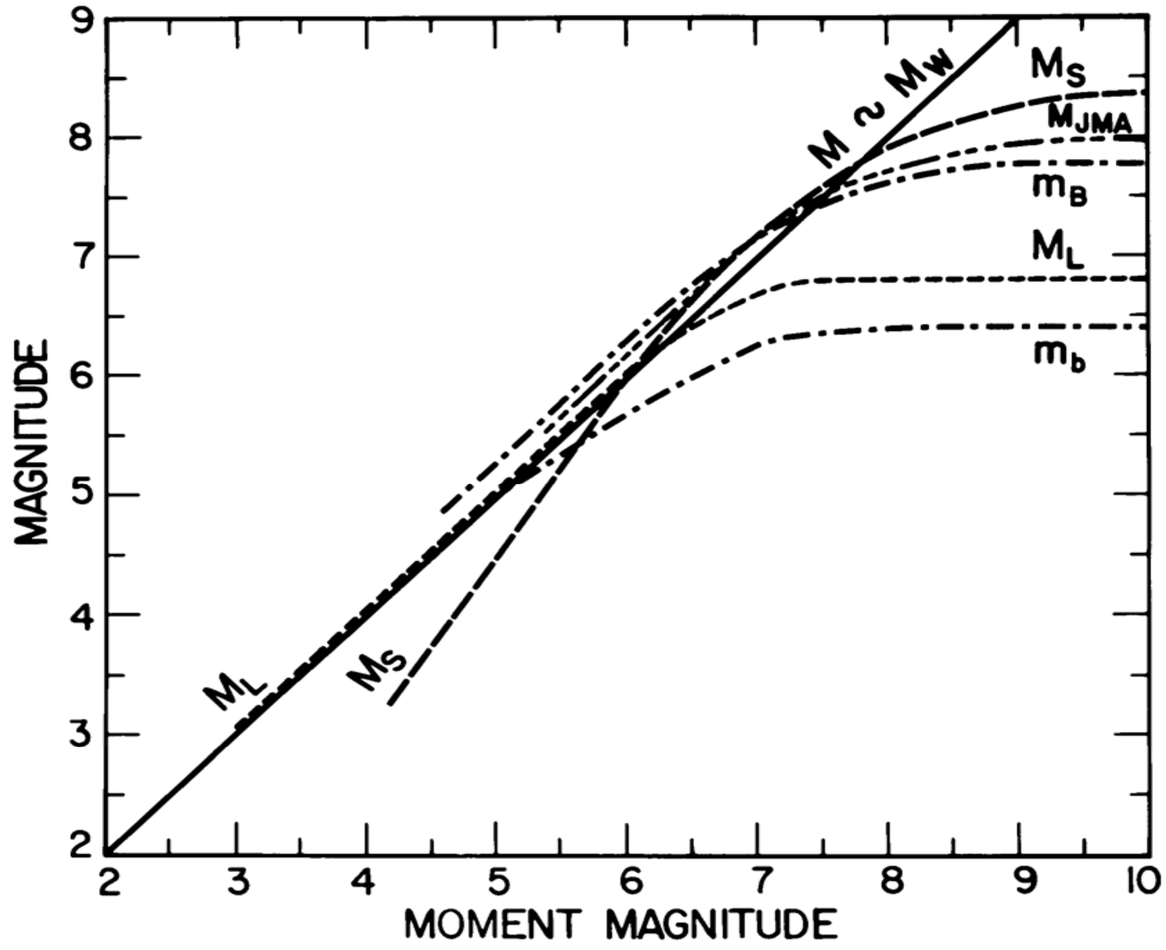
Earthquake Magnitude

“Earthquake magnitude is a single quantifiable geological or seismological measure of the size of an earthquake”

Magnitude Scales

- Common magnitude scales include:
  - Moment magnitude (M_w or **M**)
  - Surface-wave magnitude (M_S)
  - Short-period body-wave magnitude (m_b)
  - Japan Meteorological Agency magnitude (M_{JMA})
  - Regional magnitude scales (m_d, m_{Lg}, M_L, etc.)
- The same magnitude scale should be used to define both the attenuation and earthquake recurrence laws, or a magnitude scale-to-scale conversion will be necessary, with a corresponding increase in *aleatory* and *epistemic* uncertainty

Comparison of Magnitude Scales



Moment Magnitude

- Moment magnitude is the preferred magnitude scale for PSHA because it is based on a physically quantifiable measure of earthquake energy and it can be calculated from both geological and seismological data

  $M_w = \frac{2}{3} \log M_0 - 10.7$

  where,

  - M_0 = seismic moment in dyne-cm
  - $M_0 = \mu AD$ (geological definition)
  - $M_0 = 2\mu E_S / \Delta\sigma$ (seismological definition)

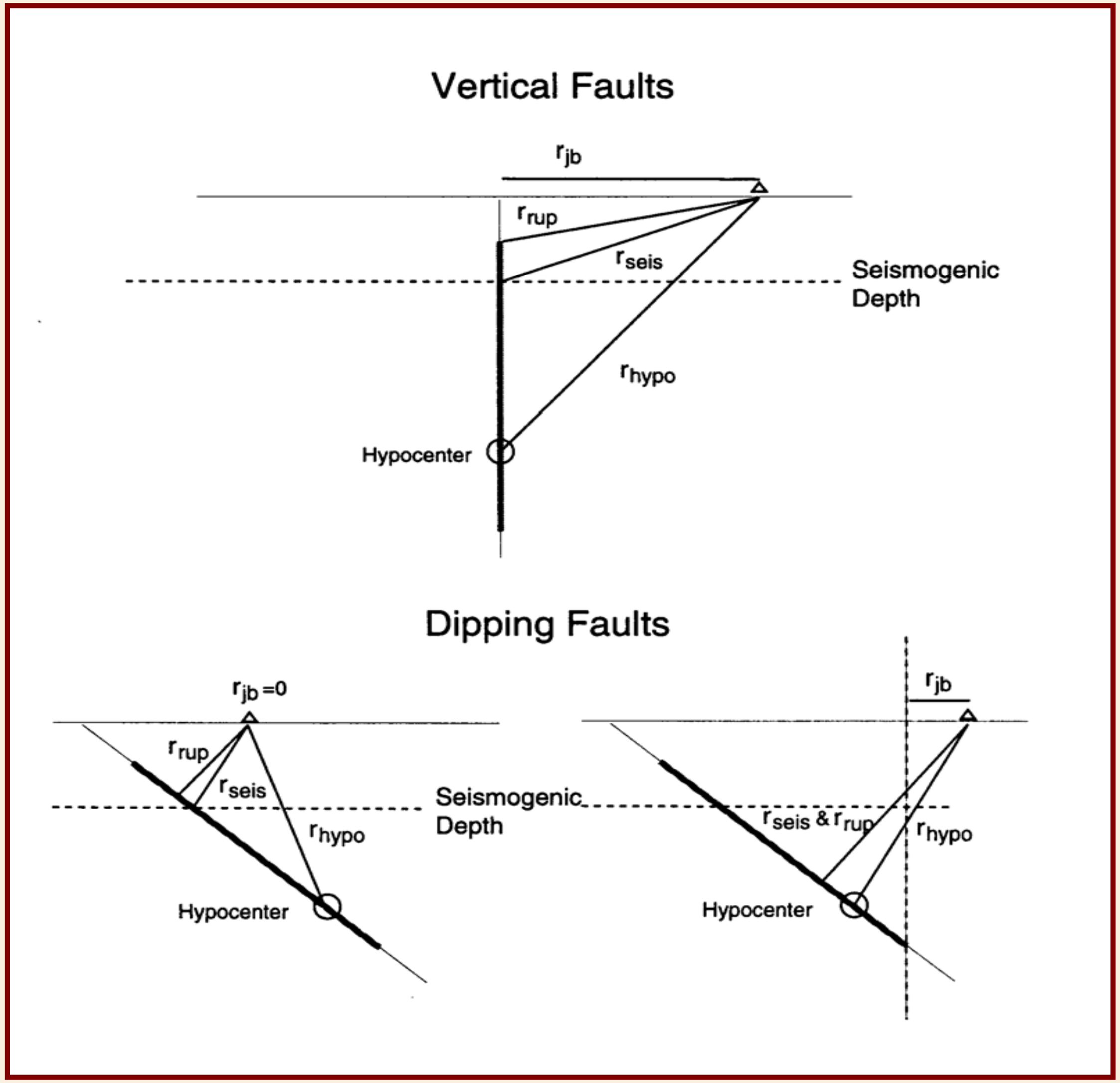
Source-to-Site Distance

"Source-to-site distance characterizes the decrease of ground motion as the wave front propagates away from the source of the earthquake, and represents both geometrical (spatial) and anelastic (damping and scattering) attenuation effects"

Distance Measures

- Point source
  - Epicentral distance (r_{epi})
  - Hypocentral distance (r_{hypo})
- Finite source
  - Closest distance to rupture (r_{rup})
  - Closest distance to surface projection of rupture (r_{jb})
  - Closest distance to seismogenic part of rupture (r_{seis})
- Must use appropriate measure for attenuation law in the PSHA, or a distance measure-to-measure conversion will be necessary, with a corresponding increase in *aleatory* uncertainty

Comparison of Distance Measures

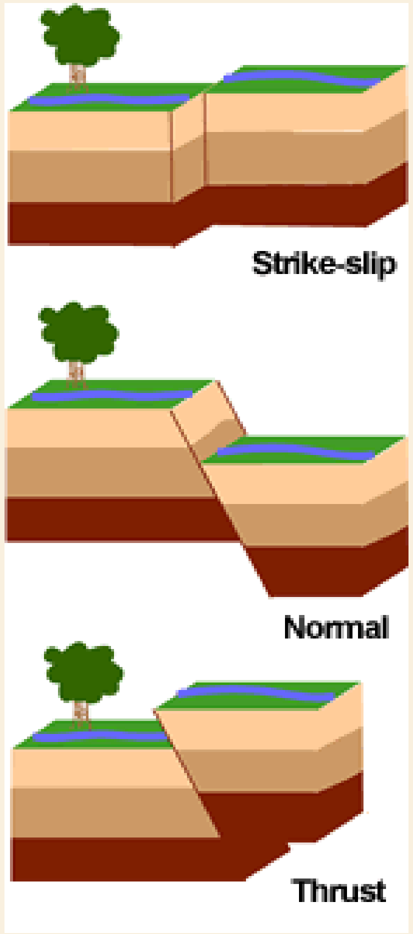


Finite Faulting Effects

"Finite faulting effects characterize the faulting mechanism, or style of faulting, of an earthquake, as represented by the direction of slip on the fault plane (rake), and the closely related effects of radiation pattern (symmetrical spatial effects) and source directivity (asymmetrical spatial effects)"

Style of Faulting

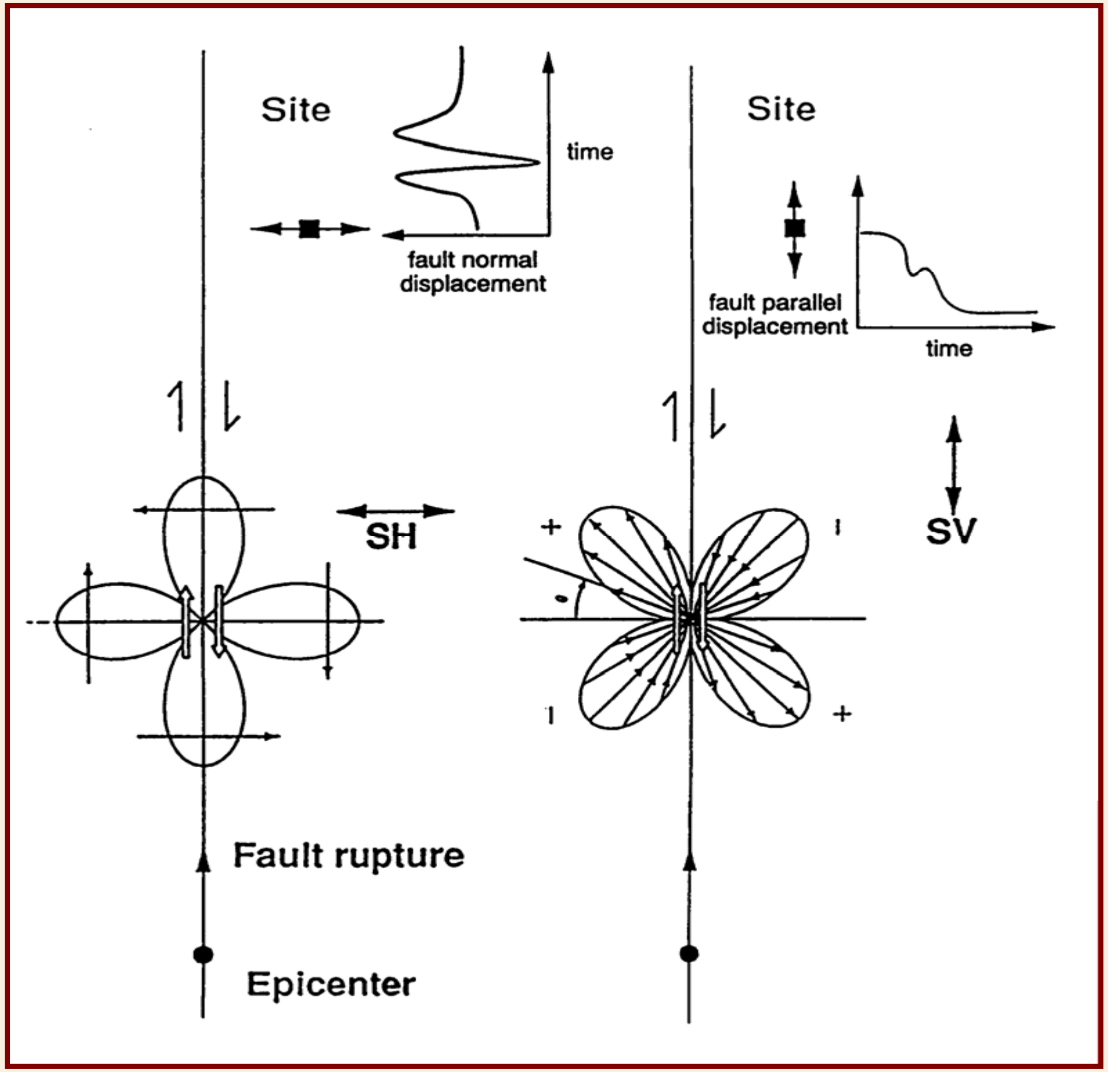
- Strike slip
  - Left-lateral
  - Right-lateral
- Reverse and reverse-oblique
  - Steeply dipping thrust faults
- Thrust and thrust-oblique
  - Shallow dipping thrust faults
  - Often blind (buried)
- Normal and normal-oblique



Radiation Pattern

- Affects fault-normal and fault-parallel components differently at close distances
- Effects are generally averaged out when the geometric mean of the horizontal traces is used to define the ground-motion measure
- Not explicitly used in any attenuation law
- Average radiation pattern is explicitly used in stochastic methods
- Explicit definition of radiation pattern is used in theoretical methods (at least at long periods; short periods are usually modeled stochastically)

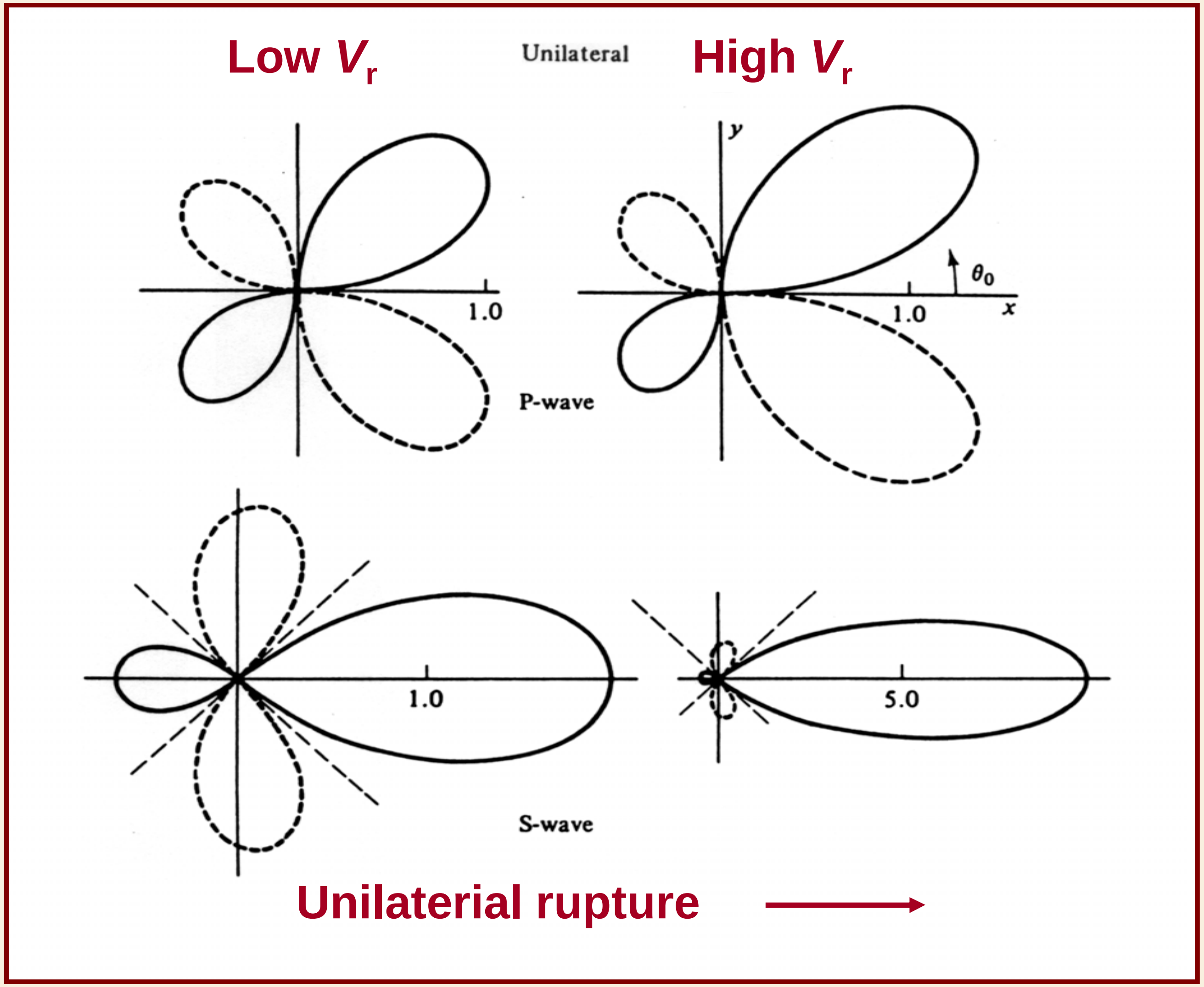
Radiation Pattern Effects



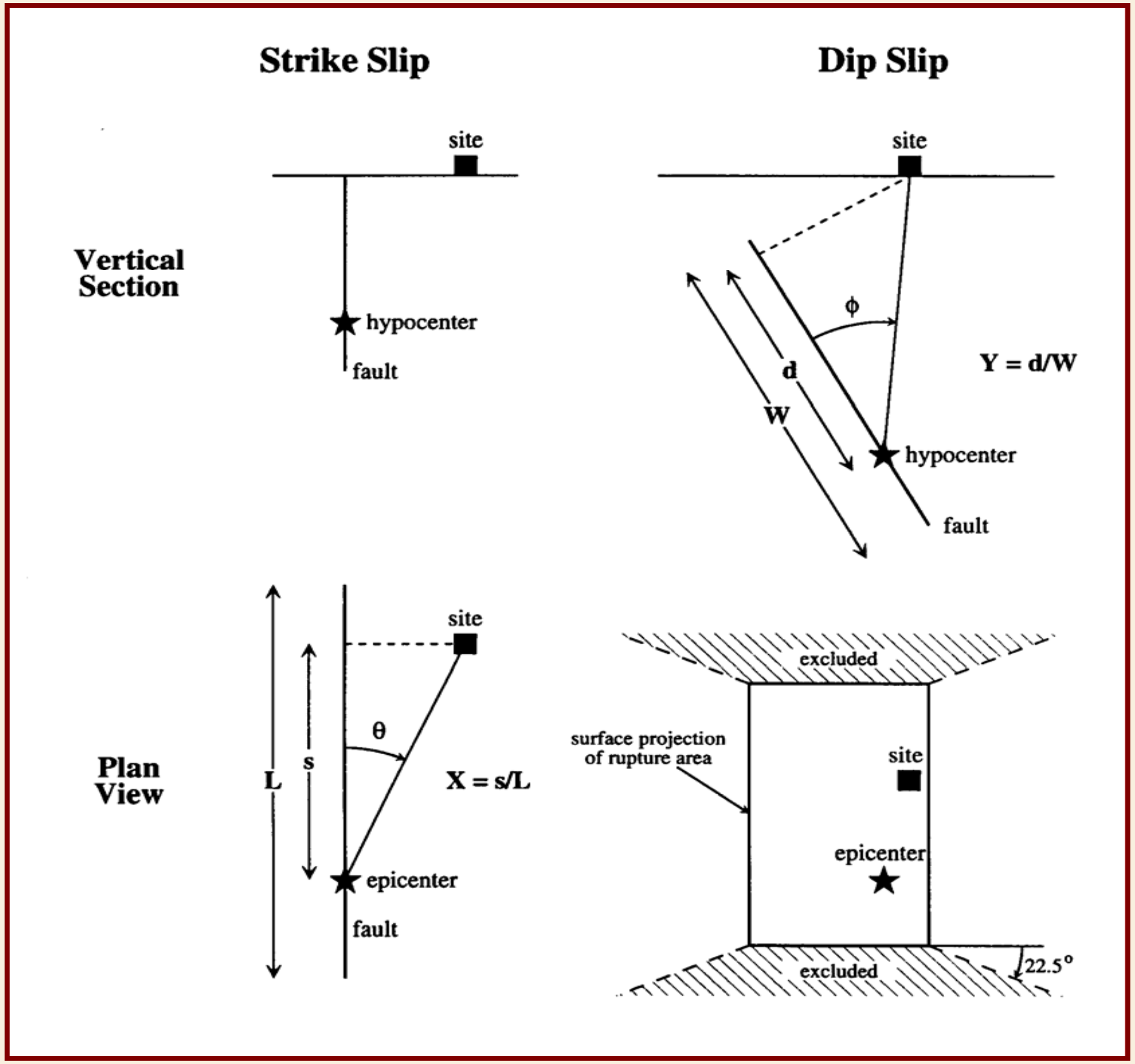
Source Directivity

- Not averaged out when the geometric mean of the two horizontal traces is used as the ground-motion measure
- Generally effects sites at close distances from large earthquakes, but can be far-reaching at long periods
- Effects fault-normal and fault-parallel components differently
- A simple empirical model is available
- Included in finite-fault stochastic and theoretical methods

Source Directivity Effects



Empirical Model of Directivity Effects



Local Site Conditions

“Local site conditions characterize the type and stiffness of the geological deposits that lie beneath a site and the relative differences in ground-motion amplification caused by these deposits”

Site Classification Schemes

- Geological site categories
- NEHRP site categories
- Shear-wave velocity
  - Averaged over top 30 m (V_{s30})
  - Averaged over ¼-wavelength
    (used in stochastic and theoretical methods)
- Sediment or basin depth

Geological Site Categories

- Generic descriptions
  - Soil
  - Rock
- More specific descriptions
  - Soft soil
  - Firm soil
  - Soft rock
  - Firm rock
  - Hard rock

NEHRP Site Categories

Class	Soil Profile Name	V_{s30} (m/s)
A	Hard rock	≥ 1500
B	Rock	760 – 1500
C	Very dense soil & soft rock	360 – 760
D	Stiff soil	180 – 360
E	Soft soil	< 180

NEHRP Site Amplification Factors

Class	S_a at Short Periods (0.2 s) on Site Class B				
	0.25*g*	0.50*g*	0.75*g*	1.00*g*	1.25*g*
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	0.9

NEHRP Site Amplification Factors

Class	S_a at 1-sec Period on Site Class B				
	0.10g	0.20g	0.30g	0.40g	0.50g
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	2.4

Stress Drop

“Stress drop is the amount of stress on a fault that is relieved as a result of the slip on the earthquake rupture plane; also called the stress parameter in simple seismological source models (e.g., Brune)”

Stress-Drop Parameters

- Static stress drop
  - The difference in static stress before and after an earthquake; closely related to seismic moment
- Dynamic (“Brune”) stress drop or stress parameter
  - The difference in dynamic stress at the rupture front, which effects the high-frequency amplitude of ground motion; closely related to slip velocity
- Not explicitly used in any attenuation law
- Explicit representation of stress drop, stress parameter and/or slip velocity is used in stochastic and theoretical methods

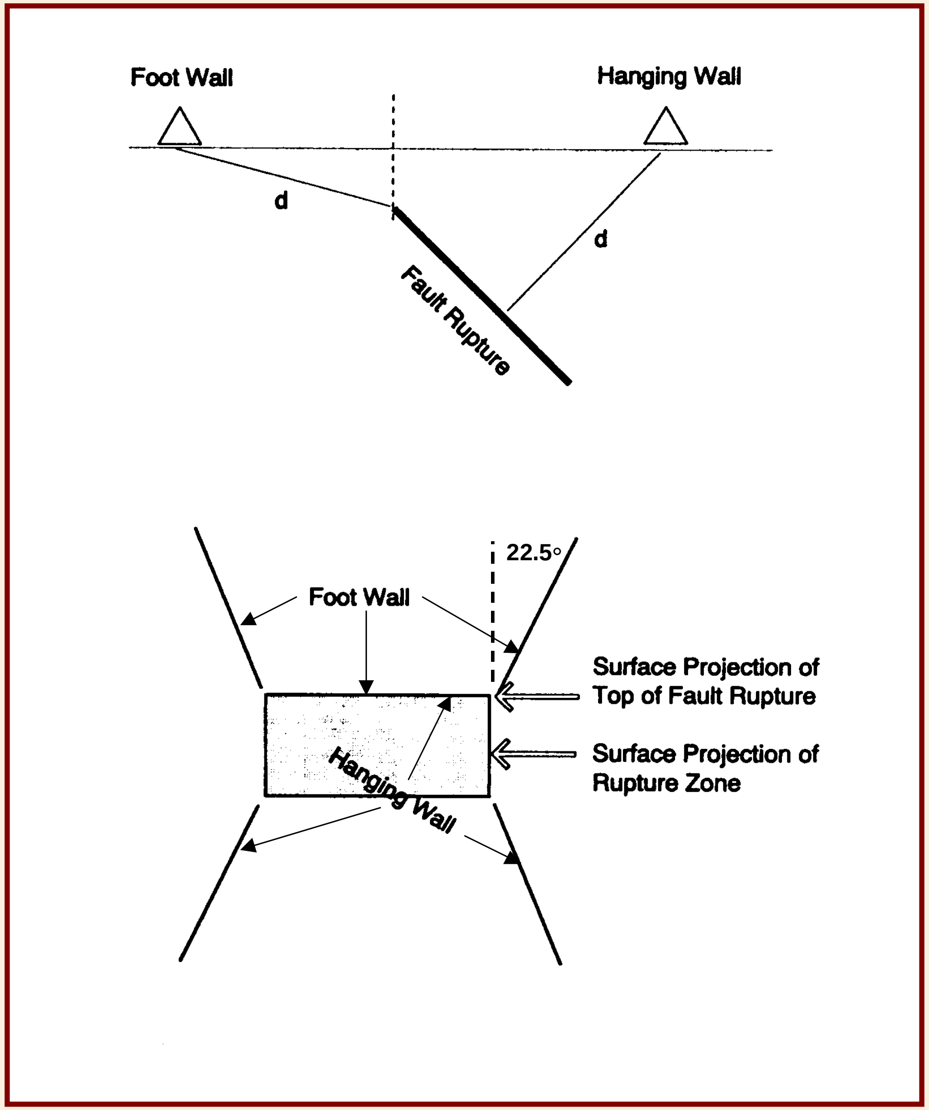
Hanging-Wall Effects

"Hanging-wall effects refer to the increase in the amplitude of ground motion at sites located over the hanging-wall of the earthquake rupture plane"

Hanging-Wall Effects

- Possibly caused by a combination of:
  - Radiation pattern effects
  - Source directivity effects
  - Entrapment of waves above the rupture surface
- Simple empirical models are available

Empirical Hanging-Wall Model



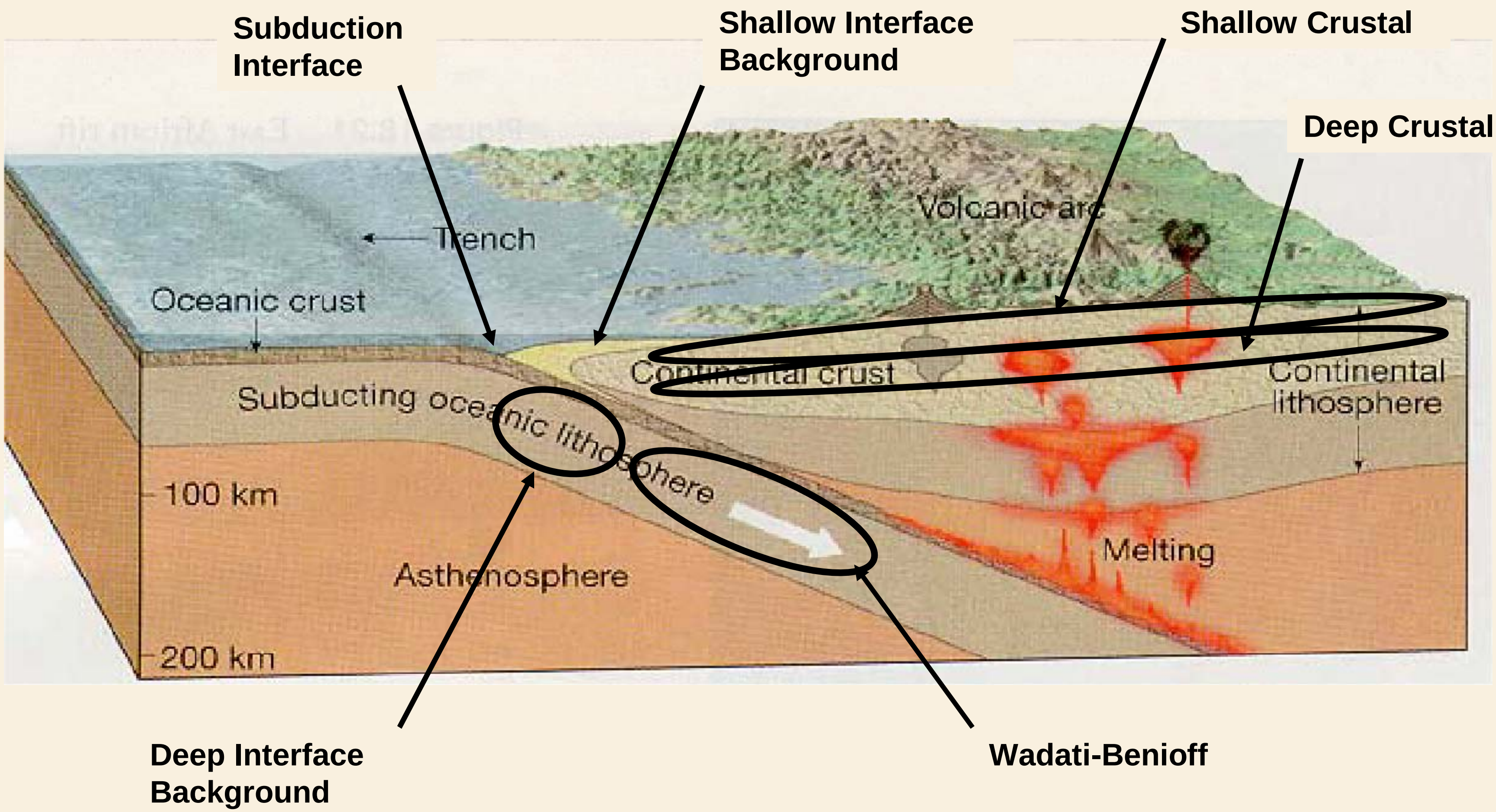
Tectonic Environment

"Tectonic environment refers to the general state of stress, mode of stress release, and attenuation characteristics of the crust in the source region and between the source and the site"

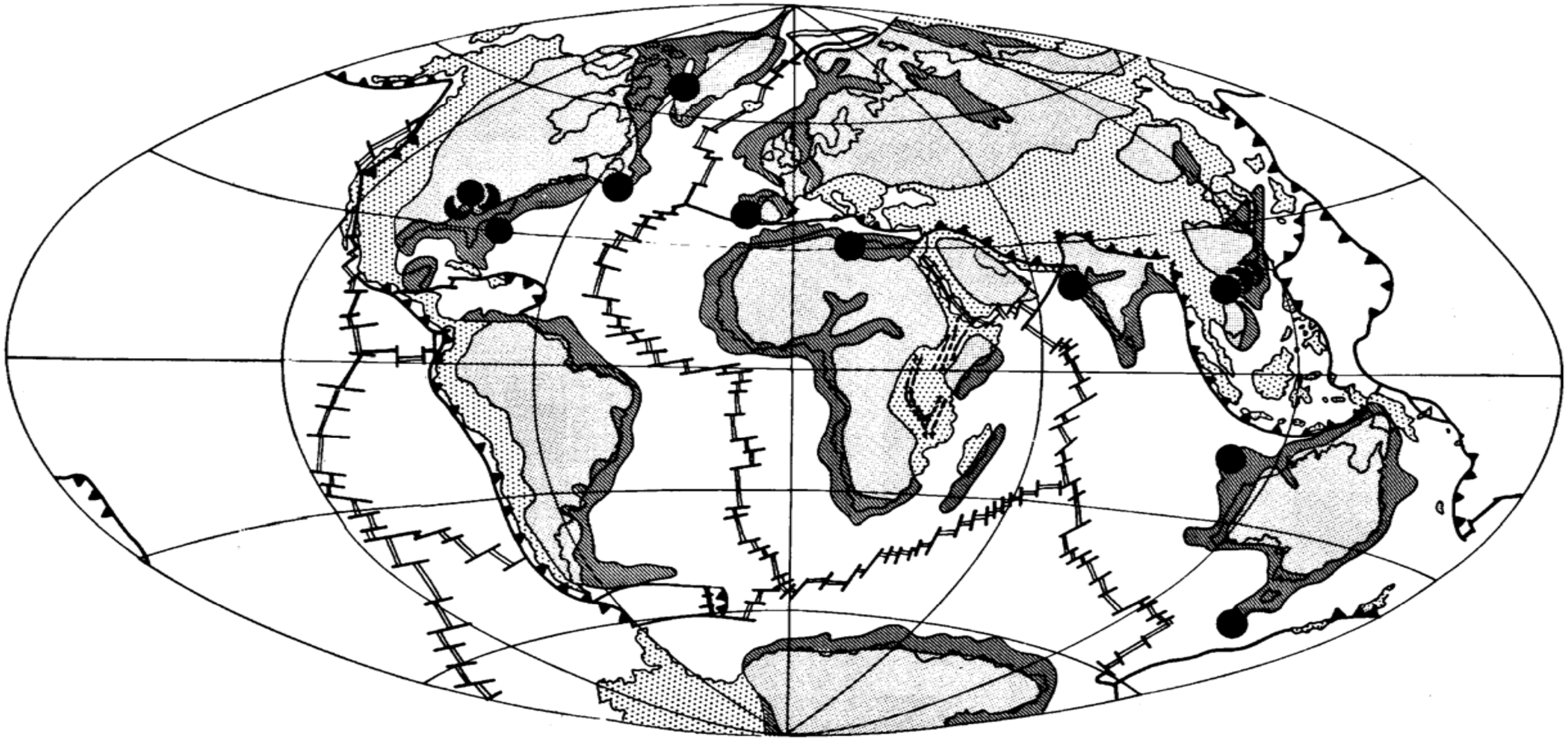
Types of Tectonic Environment

- Shallow crust in active tectonic regions
  - WNA, Japan, most of Europe, etc.
- Shallow crust in stable tectonic regions
  - ENA, No. Europe, Australia, etc.
- Intermediate-depth (Wadati-Benioff or intraslab) zones
  - Inland of subduction zones and their remnants
  - Often applied to deep crustal earthquakes
- Megathrust Interface of subduction zones

Types of Tectonic Environments



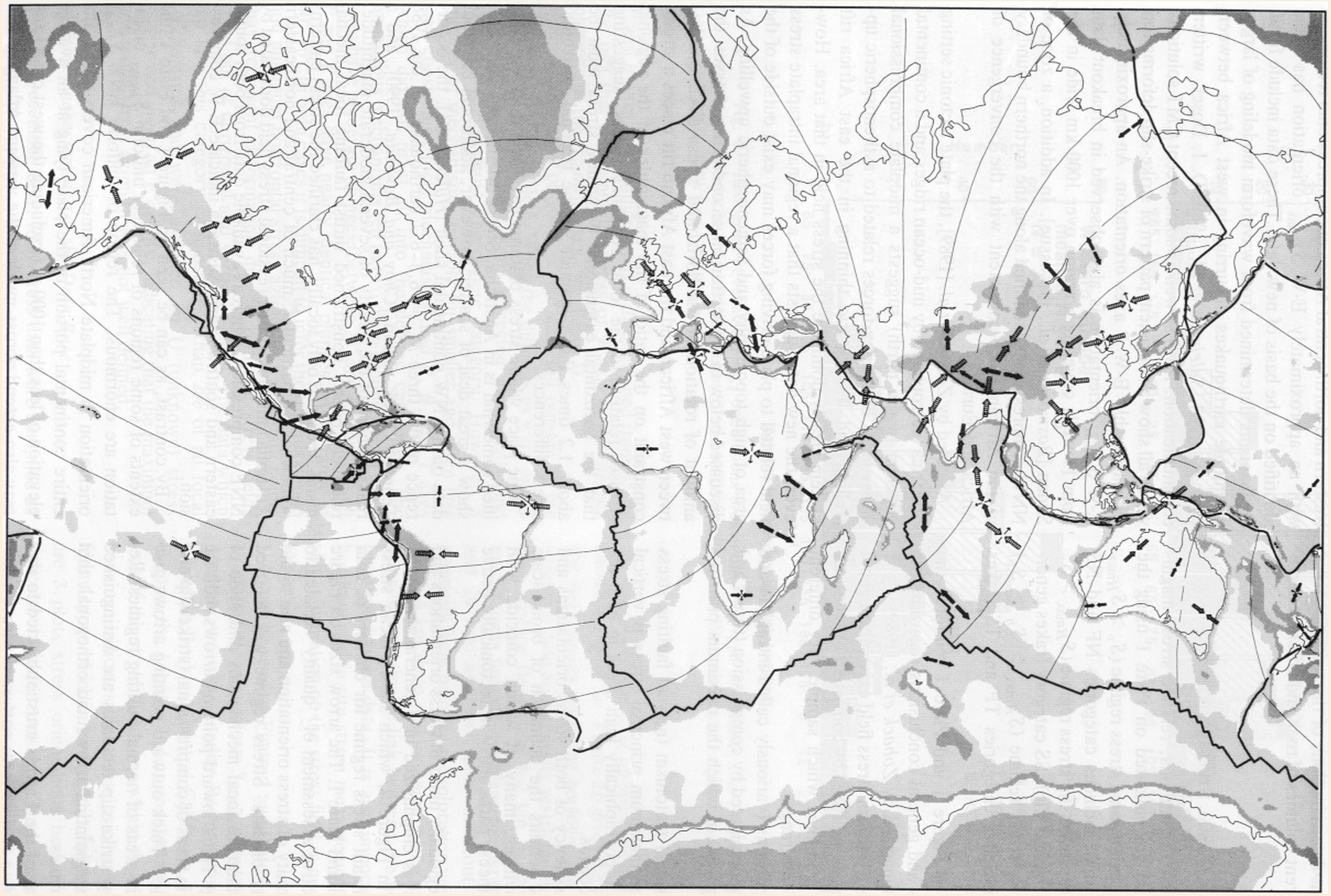
Map of Stable Continental Crust



Shallow Active Tectonic Regions

- Non-extensional
  - Stress is compressive or neutral
  - Strike-slip, reverse, and thrust faulting
- Extensional
  - Stress is tensional
  - Strike-slip and normal faulting
  - Might result in lower ground motion than non-extensional strike-slip faulting (controversial)

Map of Stress Conditions

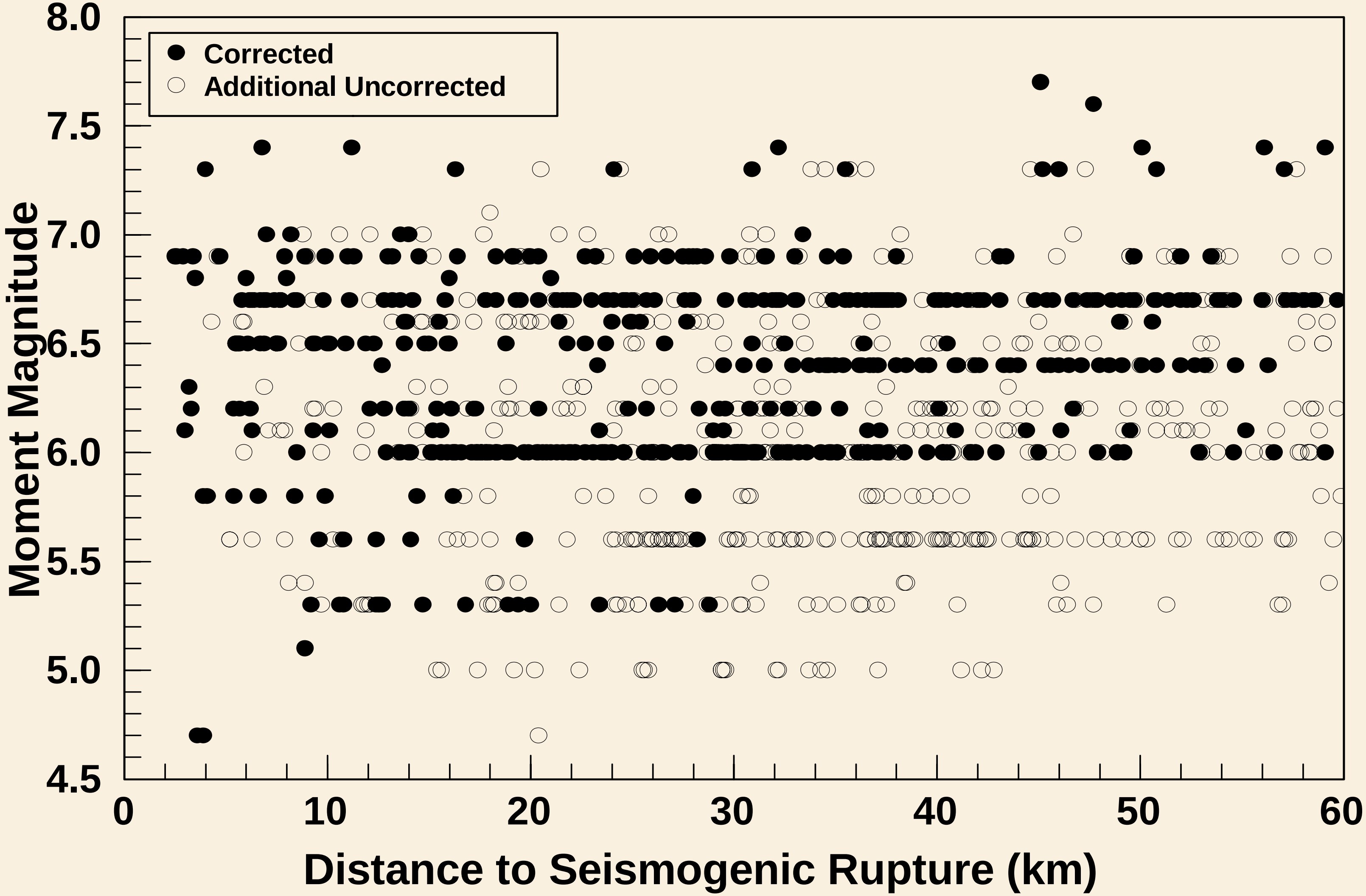


Analysis Methods

Database Selection Criteria

- Definition of “free field”
  - Should represent free-field conditions
  - Might include recordings in building basements
  - Might include recordings on dam abutments
- Tectonic environment
  - Should represent a single tectonic environment
  - Should represent similar attenuation characteristics
- Applicability
  - Should represent appropriate uniform range of *M* and *R*
  - Should represent uniform local site conditions (reference site condition)

Example Database in WNA



Regression Analysis

- One-step nonlinear least squares
  - With weights based on distance bins
  - Without weights if uniform in *M* and *R*
- Two-step nonlinear least squares
  - Attenuation and site conditions modeled in first step
  - Magnitude and faulting effects modeled in second step
  - Naturally separates inter- and intra-EQ errors
- Random or mixed effects (maximum likelihood)
  - Partitions variance between inter- and intra-EQ errors

Predicted Value (DSHA)

- Aleatory Fractile of Y

  $Y(x)_a$ = value of y where $P[Y \leq y]_a = x$

  $\log(Y(x)_a) = \log(Y) + z_x \sigma^a_{\log Y}$ (lognormal distribution of Y)

- Epistemic Fractile of Y

  $Y(x)_e$ = value of y where $P[Y \leq y]_e = x$

  $\log(Y(x)_e) = \log(Y) + z_x \sigma^e_{\log Y}$ (lognormal distribution of Y)

- Total Fractile of Y

  $Y(x)$ = value of y where $P[Y \leq y]_a \times P[Y \leq y]_e = x$

  $\log(Y(x)) = \log(Y) + z_x ({\sigma^a_{\log Y}}^2 + {\sigma^e_{\log Y}}^2)^{1/2}$ (lognormal distribution of Y)

Note: x = xth-percentile; z = standard normal variate

Modeling of Uncertainties

Aleatory Uncertainties

- Define ε_a as Gaussian (i.e., *Y* as lognormal) with zero mean and standard deviation equal to σ^a_{logY}
- Truncate the distribution at ±2.5–3.0 σ^a_{logY} to avoid unrealistic predicted values at long return periods (controversial; renormalize CDF to 1.0)
- Use the value of σ^a_{logY} that corresponds to the selected attenuation law
- If there is no corresponding σ^a_{logY} for the attenuation law, use an appropriate value from similar attenuation laws or from expert opinion
- When applying the attenuation law in a different region, there might be a need to augment the aleatory uncertainty by including additional uncertainty to address the increased or decreased randomness in some of the explicit or implicit parameters (e.g., magnitude or stress drop)
- When part of the aleatory uncertainty is explicitly modeled as epistemic uncertainty, it should be reduced accordingly (i.e., do not double count)

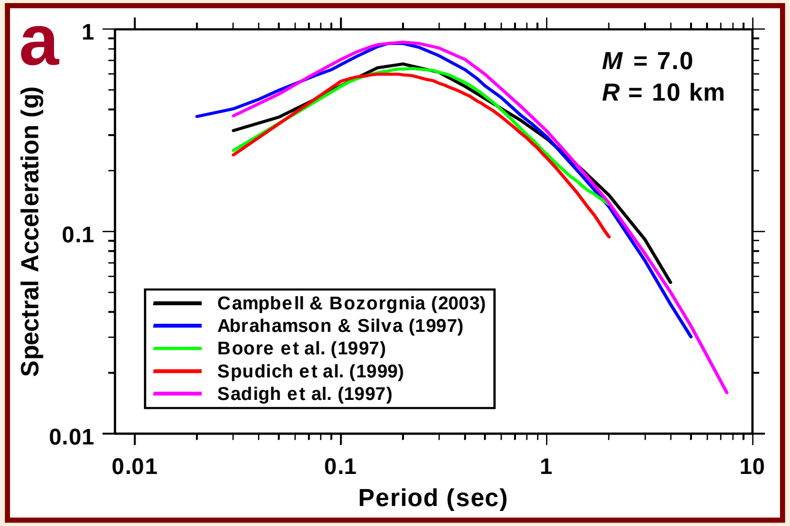
Epistemic Uncertainties

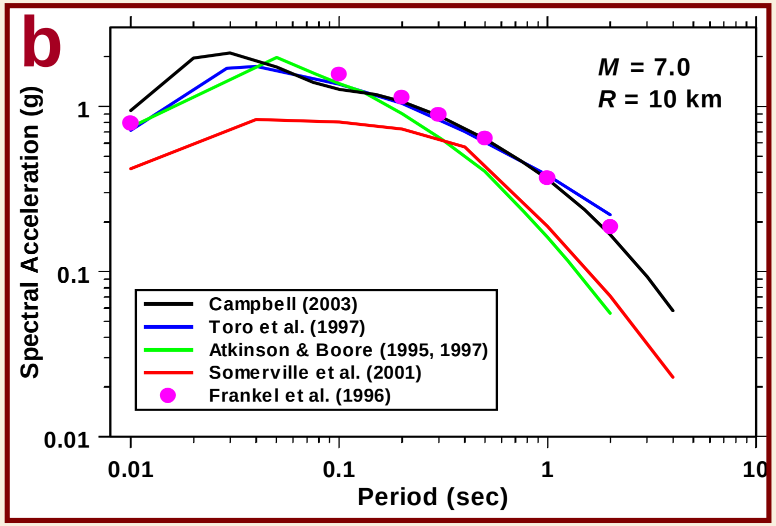
- First alternative method
  - If available, use multiple (preferably 3 or more) attenuation laws for each tectonic environment of interest and assign them weights
  - Select the attenuation laws from those available worldwide, not just from those available locally or regionally
  - Selected set of attenuation laws should represent the range of *informed* scientific opinion to adequately sample uncertainty
  - Weights should be equal, unless justification is given (note: in PSHA, weights are applied to exceedance frequency, not to Y)
  - In addition, there might be a need to augment the inferred epistemic uncertainty by including additional uncertainty to address the applicability of the selected attenuation laws to the site or region of interest or artificially low uncertainty at some M and R

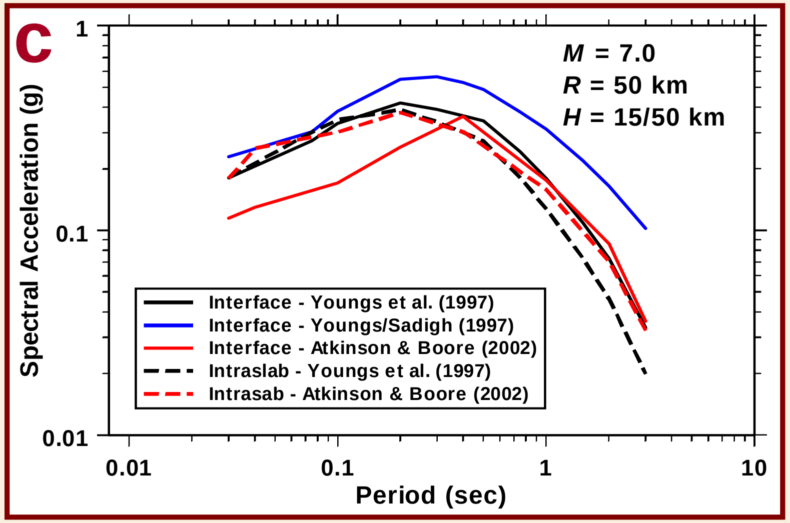
Epistemic Uncertainties

- Second alternative method
  - As an alternative, or when multiple attenuation laws are not available or are limited in number, define ε_e as Gaussian (i.e., *Y* as lognormal) with zero mean and standard deviation equal to σ^e_{logY}
  - The distribution can be discrete (e.g., when used with full enumeration of a logic tree) or continuous (e.g., when used with Monte Carlo sampling of a logic tree)
  - If continuous, truncate the distribution at ±2.5–3.0 σ^a_{logY} to avoid unrealistic predictions at long return periods (controversial; renormalize CDF to 1.0)
  - The value of σ^e_{logY} should be selected by expert opinion and/or from careful consideration of the applicability of the attenuation law(s) to the site or region of interest

Example Epistemic Uncertainties







(a) Shallow active region (WNA)

(b) Shallow stable region (ENA)

(c) Subduction zone
Interface (megathrust)
Intraslab (Wadati-Benioff)

Contributors to Aleatory Uncertainty

- Randomness in implicitly included parameters
  - Finite faulting effects
  - Stress drop
- Randomness within general categories
  - Uniform local soil condition (reference site condition)
  - Tectonic environment
- Randomness due to incomplete modeling
  - Source-related terms (e.g., *M*)
  - Path-related terms (e.g., *R*)
- Parameter conversion (random part)
  - Distance measure conversion
  - Magnitude scale conversion
  - Ground-motion parameter conversion

Contributors to Epistemic Uncertainty

- Type of tectonic environment
- Applicability of attenuation law to region of interest
- Attenuation law (epistemic part)
  - Functional form
  - Database selection criteria
  - Characterization of site conditions
  - Method of analysis
- Parameter conversion (epistemic part)
  - Magnitude scale conversion relations
  - Ground-motion parameter conversion relations
  - Reference site condition conversion relations

Uncertainty Modeling Trade-offs

- Avoid *double-counting* uncertainties by inadvertently including them as both aleatory and epistemic (easier said than done)
- Aleatory uncertainty might need to be reduced if one of its components is explicitly treated as epistemic (i.e., included in the logic tree)
- Aleatory uncertainty might need to be increased if model parameters that are explicitly included in an attenuation law (e.g., style of faulting) are not evaluated *and* are not treated as epistemic
- Unnecessary uncertainties can be reduced by avoiding parameter conversions whenever possible, which can easily increase both aleatory and epistemic uncertainties

Lessons Learned and Conclusions

- Uncertainties in ground-motion predictions are a major contributor to uncertainties in PSHA
- All relevant *aleatory* (randomness) and *epistemic* (knowledge) uncertainties should be considered in the selection and evaluation of the attenuation laws and their standard errors without double-counting these uncertainties
- There needs to be a proper balance between aleatory and epistemic uncertainties; avoid applying conservatism
- Attenuation laws should be selected to represent, as closely as possible, the:
  - Tectonic environment(s)
  - Anelastic attenuation characteristics
  - Local site conditions (reference site condition)

Summary of the Presentation

- Attenuation laws are a major component of PSHA and should be chosen carefully
- They should be selected based on informed scientific opinion
- They should be selected from amongst those available worldwide
- They should include two types of uncertainty
  - Aleatory (randomness)
  - Epistemic (knowledge)

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