SEISMIC HAZARD AND SEISMIC RISK ANALYSIS

- Seismotectonics
- Fault mechanics
- Ground motion considerations for design
- Deterministic and probabilistic analysis
- Estimation of ground motions
- Scaling of ground motions and design and analysis tools (i.e., NONLIN)

Seismic Activity > M5 Since 1980

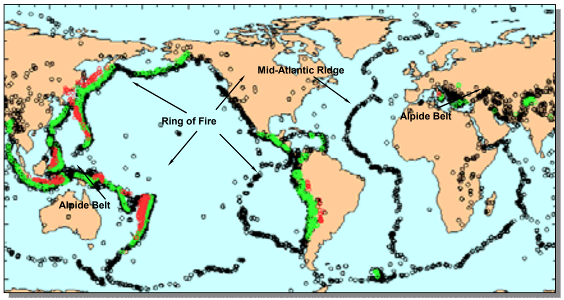


Figure from USGS

Crustal Plate Boundaries

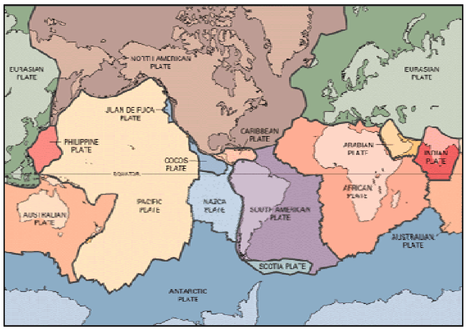


Figure from USGS

Convection Drives the Plates

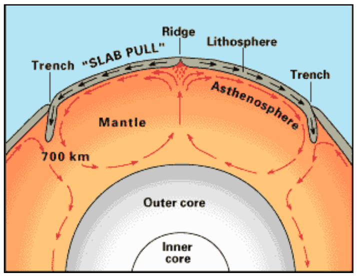
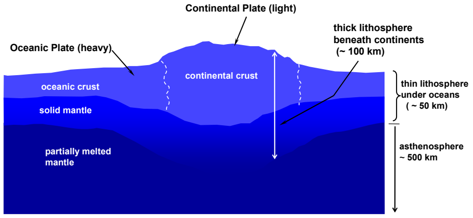


Figure credit: USGS.

Oceanic and Crustal Plates



Continental-Continental Collision

(orogeny)

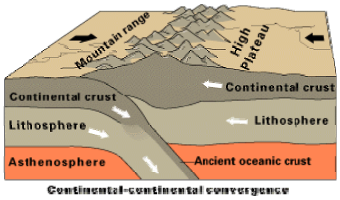


Figure credit: USGS.

Oceanic-Continental Collision

(subduction)

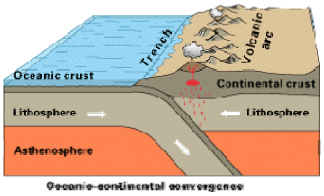


Figure credit: USGS.

Types of Earthquakes

About 90% of the earth's seismicity occurs at plate boundaries on faults directly forming the interface between two plates. These are called **plate-boundary or interplate** earthquakes.

The other 10% occur away from the plate boundary, in the interior of plates. These are called **intraplate** earthquakes.

Plate-boundary Earthquakes

A plate-boundary (interplate) earthquake is an earthquake that occurs along a fault associated with an active plate boundary. An example of this type of boundary is the San Andreas Fault in California.

⇒ Frequent occurrence, relatively well understood behavior, as per plate tectonic theory.

San Andreas Fault – Well Known Plate Boundary

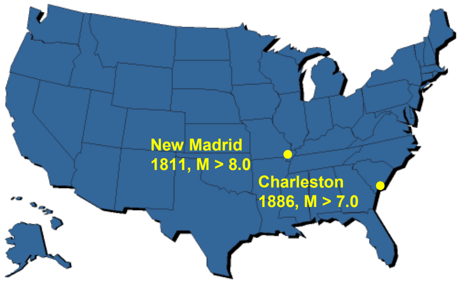
Photo courtesy of: USGS.

Intraplate Earthquakes

An intraplate earthquake is an earthquake that occurs along a fault within the stable region of a plate's interior (SICR). Examples are the 1811-12 Madrid, MO earthquakes, the 1886 Charleston, South Carolina, earthquake, and, more recently, the Bhuj, India, earthquake in 2001.

⇒ Infrequent occurrence, poorly understood, difficult to study.

Historical Large Intraplate Earthquakes

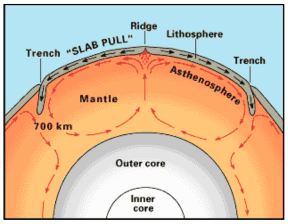


* Largest historical earthquakes in contiguous United States occurred east of the Mississippi!!

Why Intraplate Earthquakes?

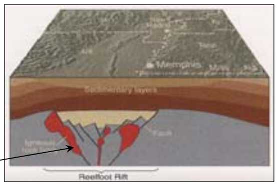
- Ancient "Rifts" – very old fractures in crust related to previous episodes of continental spreading.
- "Weak Spots" – heating up and thinning of lower crust such that the brittle-ductile transition (molten rock/crust boundary) migrates to a higher level. Because the overlying crust becomes thinner, stresses become more concentrated in the crust.

Why Intraplate Earthquakes?



Figures from USGS

Example of 700 million year old rift zone:



Rift allows stress concentrations

Why Intraplate Earthquakes?

- Thermal destabilization -- sinking of mafic rock mass (rock mass of heavy minerals) into underlying molten rock. As mafic block sinks, stresses are concentrated in overlying crust. Process thought to be due to rock density anomalies combined with thermal processes.
- Other localized mechanisms? (meteor impact craters, etc.)

Seismicity of North America

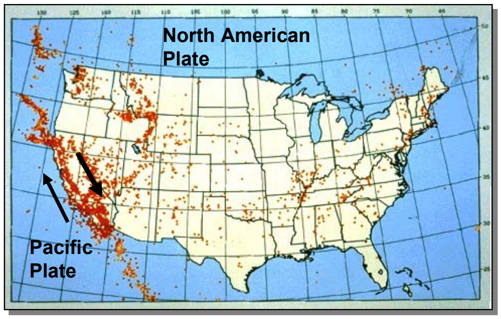


Figure credit: USGS.

California Seismicity

Seismicity relatively well understood

Figure credit: USGS.

Pacific Northwest – Cascadia Subduction Zone

Ultimate magnitude potential?

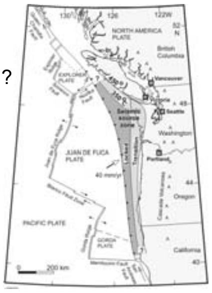


Figure Credit: USGS

Idaho, Utah, Wyoming

Recurring events along Wasatch Fault

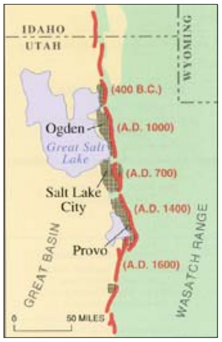
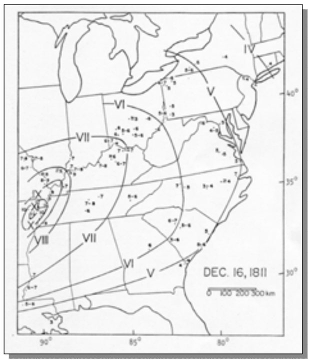


Figure credit: USGS.

Central US Seismic Zones

- Who really knows for sure?
- The Reelfoot Rift is associated with many events in this region.

Figure credit: USGS.



Isoseismal Map from New Madrid Earthquake, Dec. 16, 1811

Figure credit: USGS.

Reelfoot Rift Associated with Central US Earthquakes

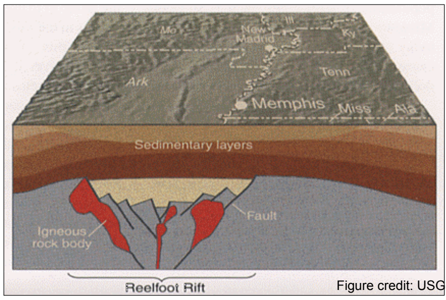


Figure credit: USGS.

1811-12 New Madrid Earthquakes (three M8+)

Isoseismal Map -- Dec. 16, 1811

Reelfoot Lake, Tennessee, was created due to subsidence and tectonic change

Figure and photo credit: USGS.

How Big is the CEUS Problem?

New Madrid Seismic Zone

- Highest hazard in the US outside the WUS
- M1-2 every other day (200 per year)
- M3 every year (felt)
- M4 every 1.5 years (local minor damage)
- M5 every 10 years (damaging event)
- M6 every 80 years (last one in 1895)
- M8+ every 400-600 years? (last one in 1812)

- M6-7.5 has 25-40% chance in 50 years
- M8+ has 4-10% chance in 50 years

How Big Is the CEUS Problem?

- A recurrence of the New Madrid earthquake, postulated with a 4-10% probability in the next 50 years, has been estimated to cause a total loss potential of $200 billion with 26 states affected.
- Approximately 2/3 of the projected losses will be due to **interruptions in business operations and the transport** of goods across mid-America.
- This **economic loss is of the same order as that caused by the terrorist attacks of September 11**, 2001 (NRC, 2003).

Southeastern Seismicity

- Tennessee relatively active
- 1886 South Carolina event not fully explained
- Magnetic signature from North Carolina to Georgia similar to Charleston area; same potential?

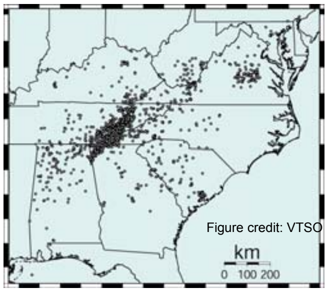


Figure credit: VTSO

Epicenters of earthquakes (M > 0.0) in the southeastern US from 1977 through 1999.

Isoseismal Map from the 1886 Charleston Earthquake

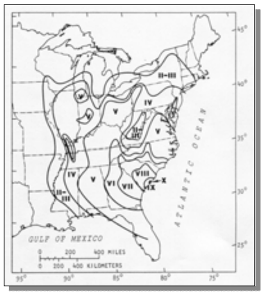


Figure credit: USGS.

Isoseismal Map for the Giles County, Virginia, Earthquake of May 31, 1897; M ≈ 6?

Figure credit: USGS.

Recent Paleoseismological Studies

- Studies in the central and southeastern United States indicate recurring large prehistoric earthquakes – this has increased hazard
- Studies in Pacific Northwest debatable

Isoseismal Map from the 1886 Charleston Earthquake

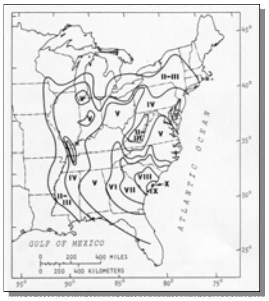
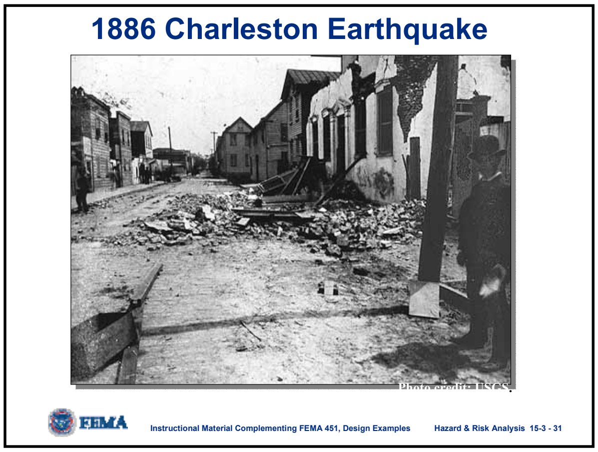


Figure credit: USGS.



1886 Charleston Earthquake

Photo credit: USGS

FEMA

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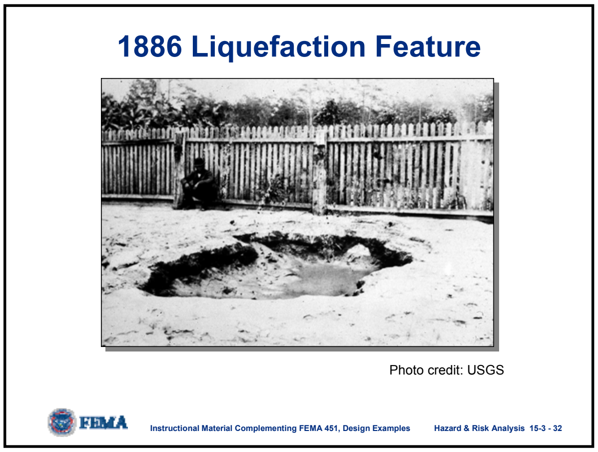

1886 Liquefaction Feature

Photo credit: USGS

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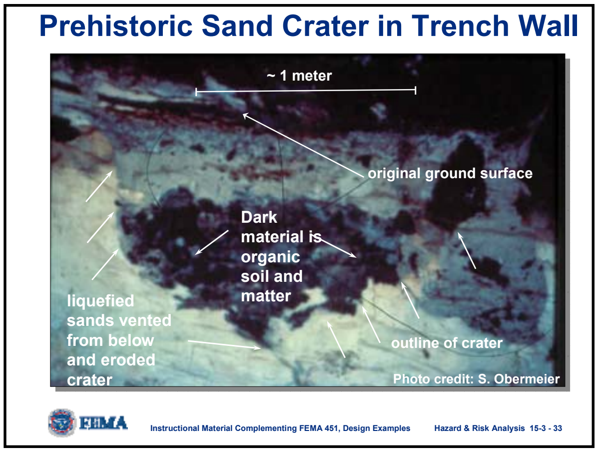

Prehistoric Sand Crater in Trench Wall

~ 1 meter

original ground surface

Dark material is organic soil and matter

liquefied sands vented from below and eroded crater

outline of crater

Photo credit: S. Obermeier

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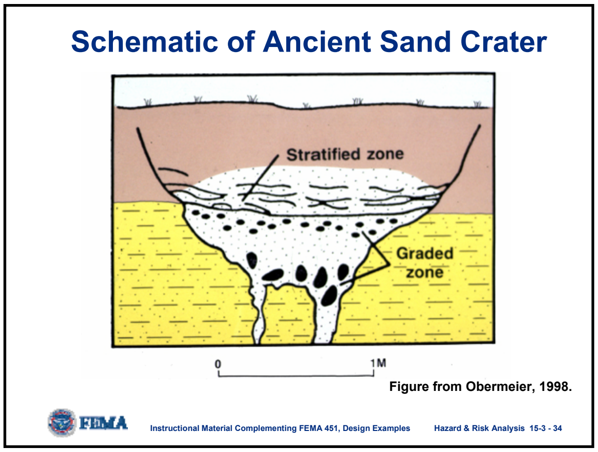

Schematic of Ancient Sand Crater

Stratified zone

Graded zone

0

1M

Figure from Obermeier, 1998.

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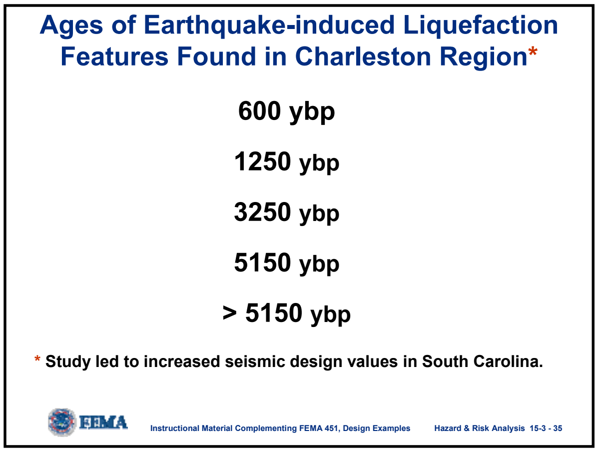

Ages of Earthquake-induced Liquefaction Features Found in Charleston Region*

600 ybp

1250 ybp

3250 ybp

5150 ybp

> 5150 ybp

* Study led to increased seismic design values in South Carolina.

FEMA

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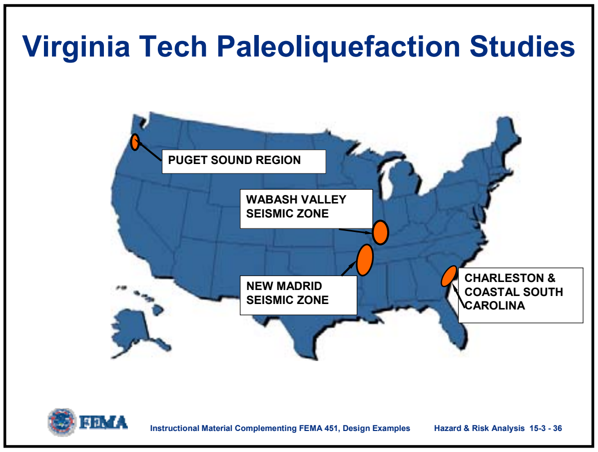

Virginia Tech Paleoliquefaction Studies

PUGET SOUND REGION

WABASH VALLEY SEISMIC ZONE

NEW MADRID SEISMIC ZONE

CHARLESTON & COASTAL SOUTH CAROLINA

FEMA

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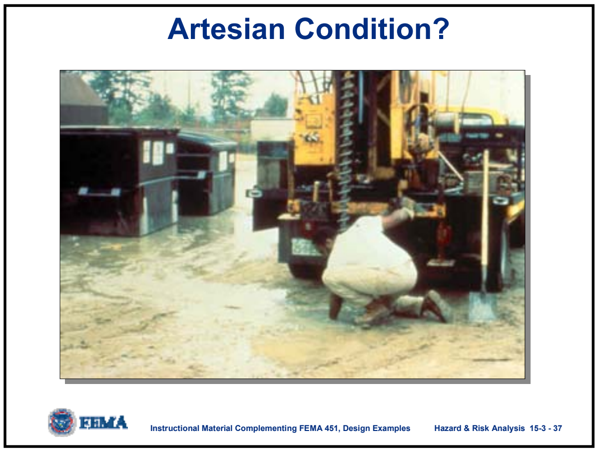
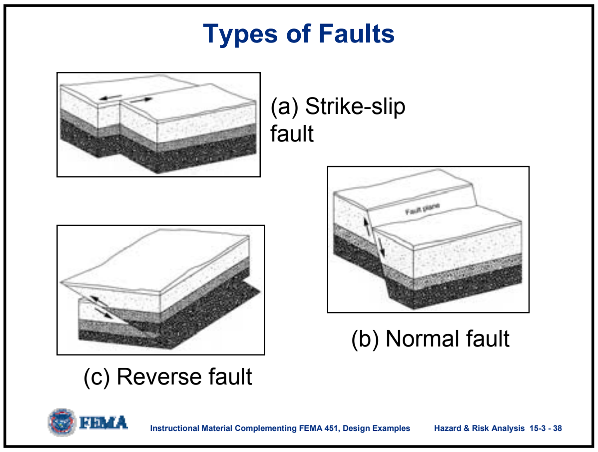


Artesian Condition?

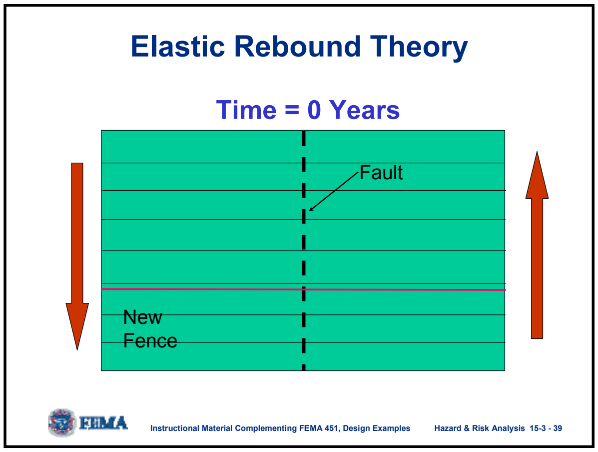


Types of Faults

(a) Strike-slip fault

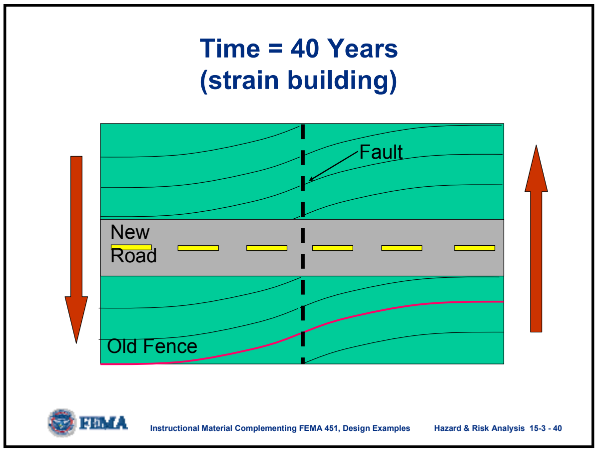
(b) Normal fault

(c) Reverse fault

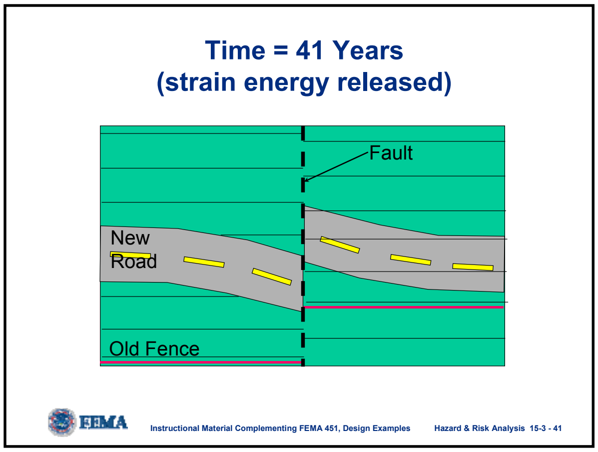


Elastic Rebound Theory

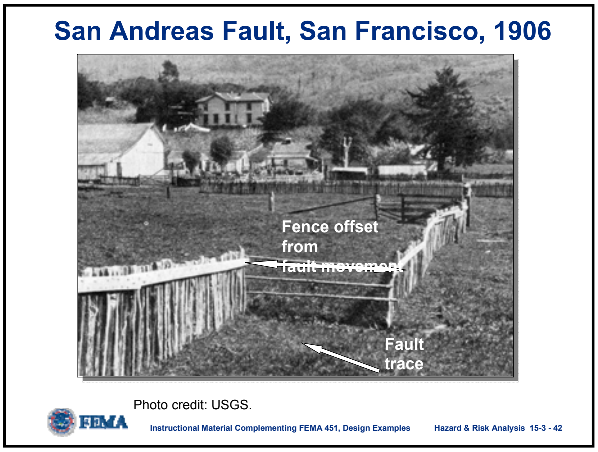
Time = 0 Years



Time = 40 Years (strain building)

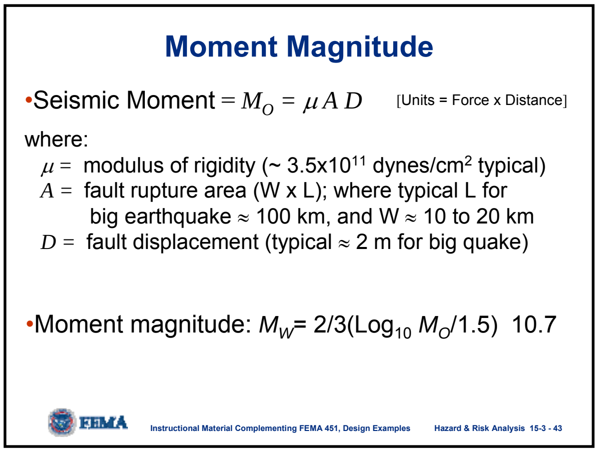


Time = 41 Years (strain energy released)



San Andreas Fault, San Francisco, 1906

Photo credit: USGS.



Moment Magnitude

- Seismic Moment = $M_O = \mu A D$ [Units = Force x Distance]

where:

μ = modulus of rigidity (~ 3.5x10^{11} dynes/cm^2 typical)
A = fault rupture area (W x L); where typical L for big earthquake ≈ 100 km, and W ≈ 10 to 20 km
D = fault displacement (typical ≈ 2 m for big quake)

- Moment magnitude: M_W= 2/3(Log$_{10}$ M_O/1.5) 10.7

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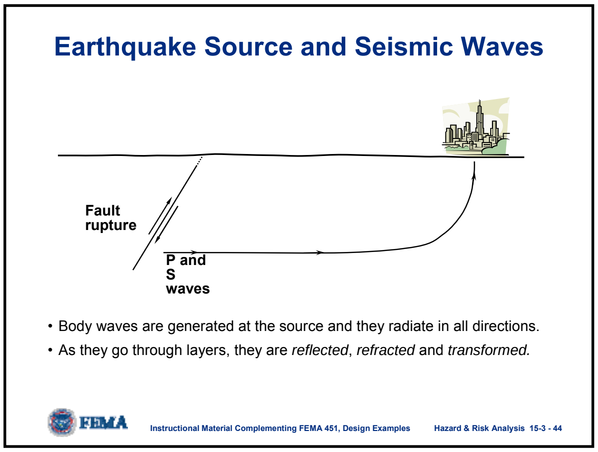

Earthquake Source and Seismic Waves

- Body waves are generated at the source and they radiate in all directions.
- As they go through layers, they are *reflected*, *refracted* and *transformed.*

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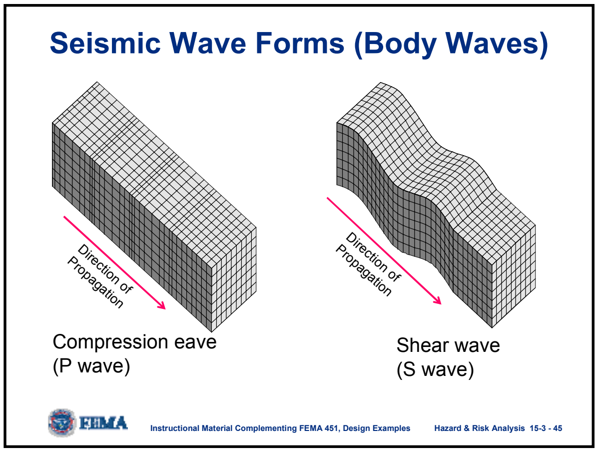

Seismic Wave Forms (Body Waves)

Compression eave
(P wave)

Shear wave
(S wave)

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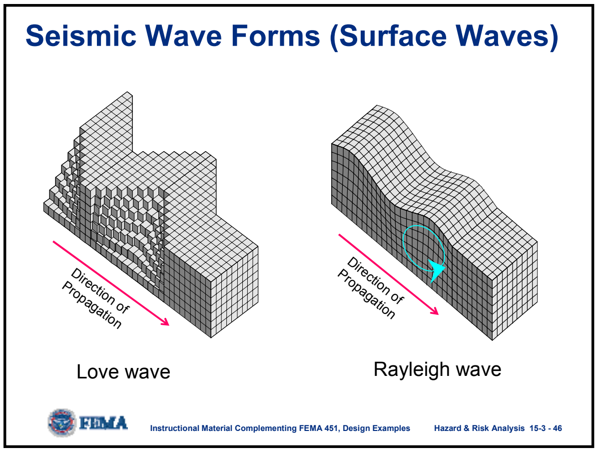

Seismic Wave Forms (Surface Waves)

Love wave

Rayleigh wave

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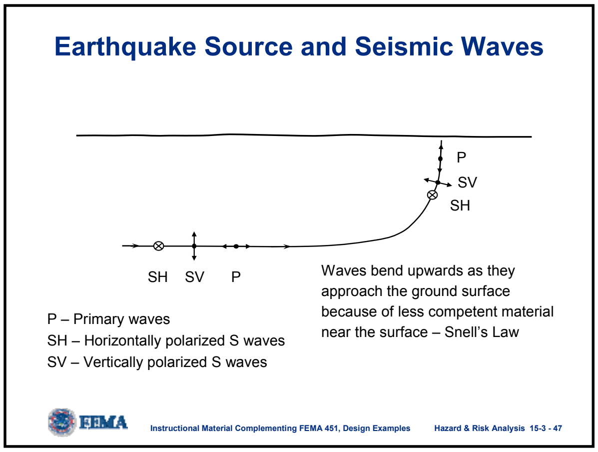

Earthquake Source and Seismic Waves

Waves bend upwards as they approach the ground surface because of less competent material near the surface – Snell's Law

P – Primary waves
SH – Horizontally polarized S waves
SV – Vertically polarized S waves

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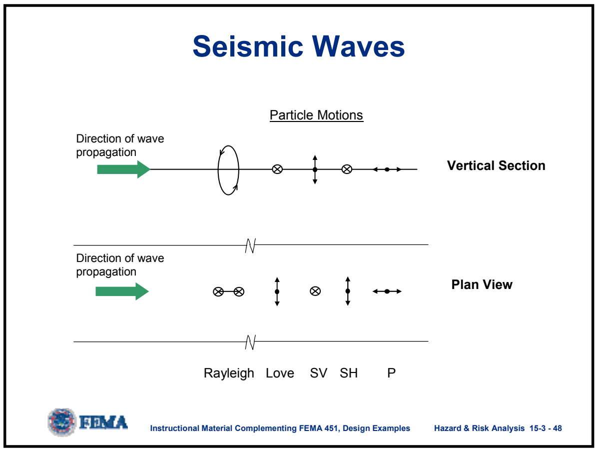

Seismic Waves

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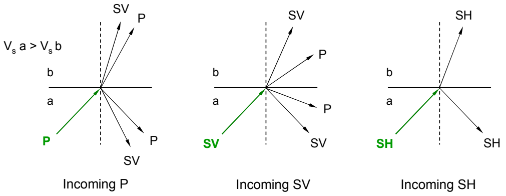
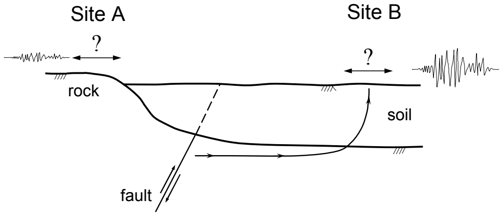
Reflection and Refraction at Boundary



- Amplitude and direction of reflected and refracted waves with respect to the incoming wave is given by Snell's Law
- Earth's crust is layered, with seismic velocities increasing with depth; therefore as waves approach ground surface wave path will get near-vertical

Ground Motion Estimation



What ground motions at Site A and B? Two steps:

1. Define earthquake scenario
2. Estimate site response and ground motions

⇒ Must be done in context of structure, type of analysis

Different Structures, Responses, Analyses, and Issues

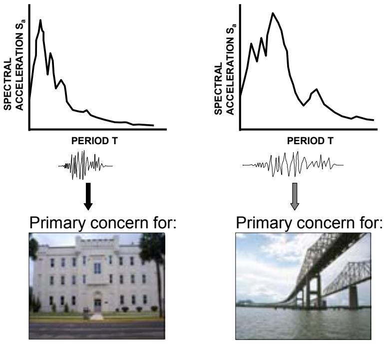
Ground Motion Estimation

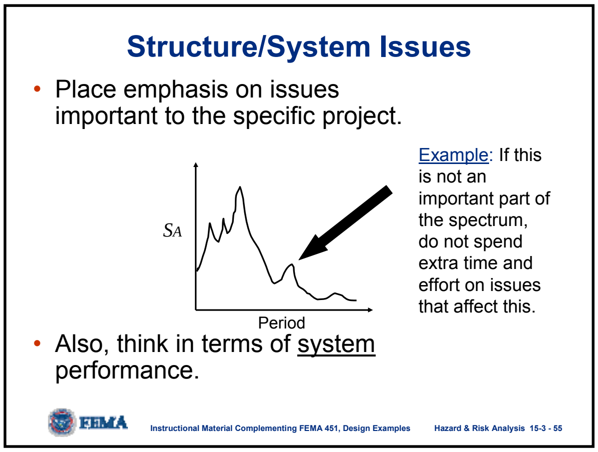
- No "universal" set of ground motions for any region.
- Uncertainties are inherent to the process and will cause differences in results.
- Judgment is required, even with probability.
- Inconsistency among governing agencies.

Ground Motion Estimation

- Two analyses using same models and basic parameters can give different answers (EPRI vs. NRC/LLNL studies in 1980s).
- Where time and effort are focused during the process is function of structure/system being analyzed.
- Not possible to predict actual motion that will occur at a site; mainly concerned with capturing characteristics important to performance of project.
- Seismologist and engineers must have continuous feedback!

Structure/System Considerations



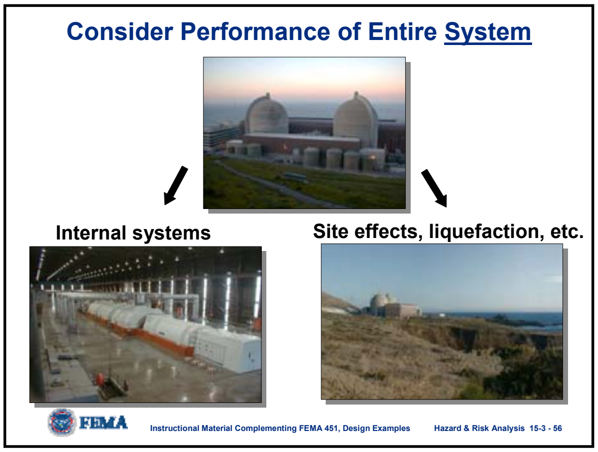


Structure/System Issues

- Place emphasis on issues important to the specific project.

Example: If this is not an important part of the spectrum, do not spend extra time and effort on issues that affect this.

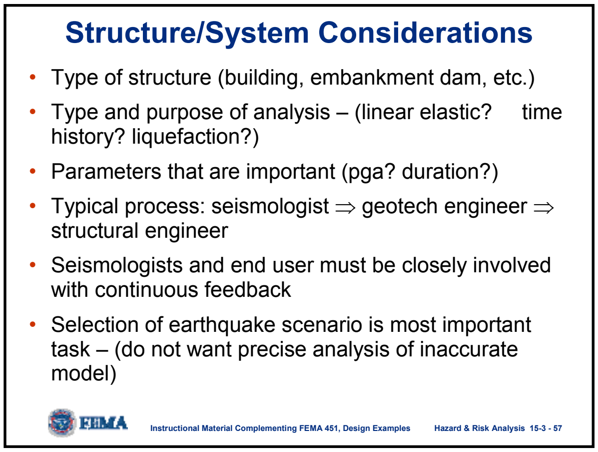
- Also, think in terms of system performance.



Consider Performance of Entire System

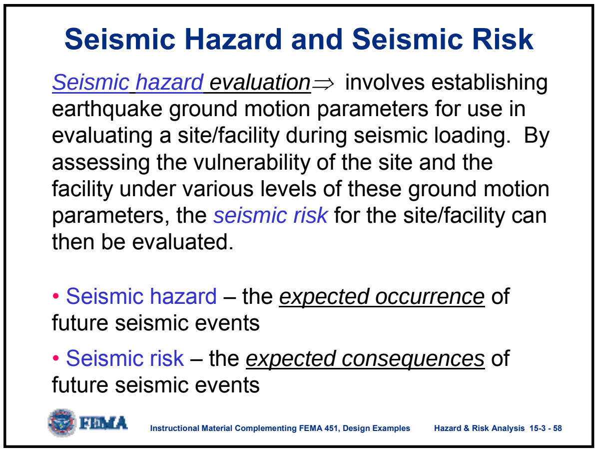
Internal systems

Site effects, liquefaction, etc.



Structure/System Considerations

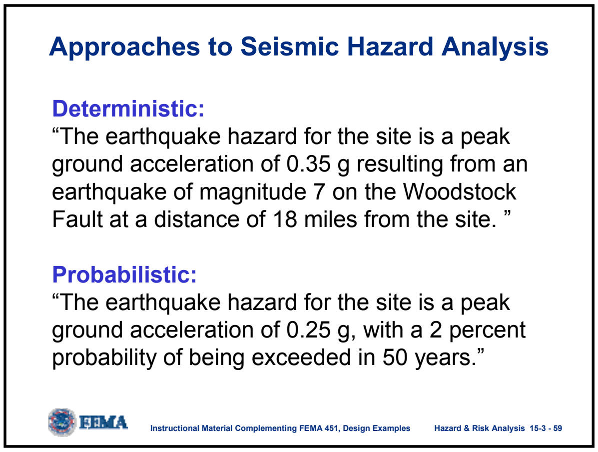
- Type of structure (building, embankment dam, etc.)
- Type and purpose of analysis – (linear elastic? time history? liquefaction?)
- Parameters that are important (pga? duration?)
- Typical process: seismologist ⇒ geotech engineer ⇒ structural engineer
- Seismologists and end user must be closely involved with continuous feedback
- Selection of earthquake scenario is most important task – (do not want precise analysis of inaccurate model)



Seismic Hazard and Seismic Risk

Seismic hazard evaluation ⇒ involves establishing earthquake ground motion parameters for use in evaluating a site/facility during seismic loading. By assessing the vulnerability of the site and the facility under various levels of these ground motion parameters, the *seismic risk* for the site/facility can then be evaluated.

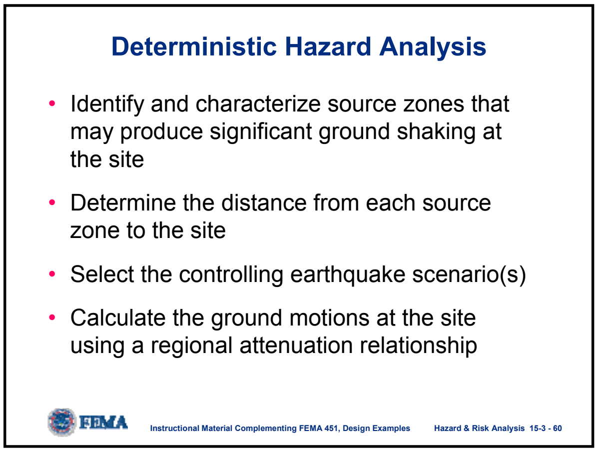
- Seismic hazard – the *expected occurrence* of future seismic events
- Seismic risk – the *expected consequences* of future seismic events



Approaches to Seismic Hazard Analysis

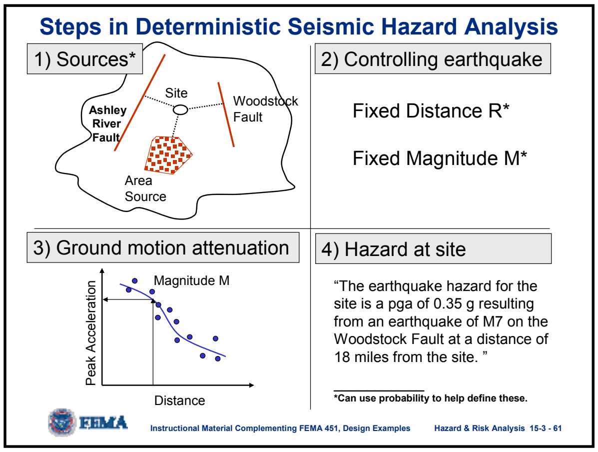
Deterministic:
"The earthquake hazard for the site is a peak ground acceleration of 0.35 g resulting from an earthquake of magnitude 7 on the Woodstock Fault at a distance of 18 miles from the site. "

Probabilistic:
"The earthquake hazard for the site is a peak ground acceleration of 0.25 g, with a 2 percent probability of being exceeded in 50 years."



Deterministic Hazard Analysis

- Identify and characterize source zones that may produce significant ground shaking at the site
- Determine the distance from each source zone to the site
- Select the controlling earthquake scenario(s)
- Calculate the ground motions at the site using a regional attenuation relationship



Steps in Deterministic Seismic Hazard Analysis

1) Sources*

2) Controlling earthquake

Fixed Distance R*

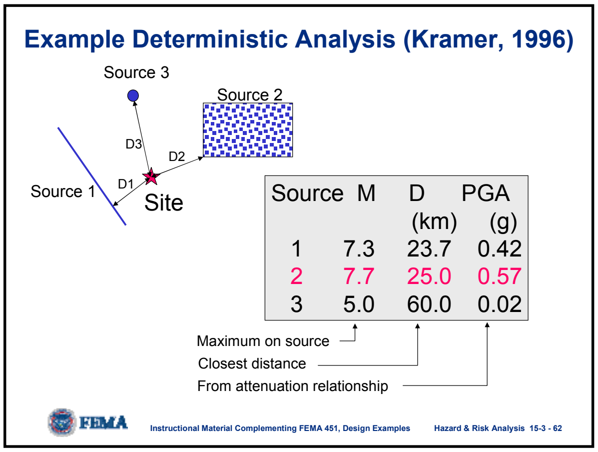
Fixed Magnitude M*

3) Ground motion attenuation

4) Hazard at site

"The earthquake hazard for the site is a pga of 0.35 g resulting from an earthquake of M7 on the Woodstock Fault at a distance of 18 miles from the site. "

*Can use probability to help define these.



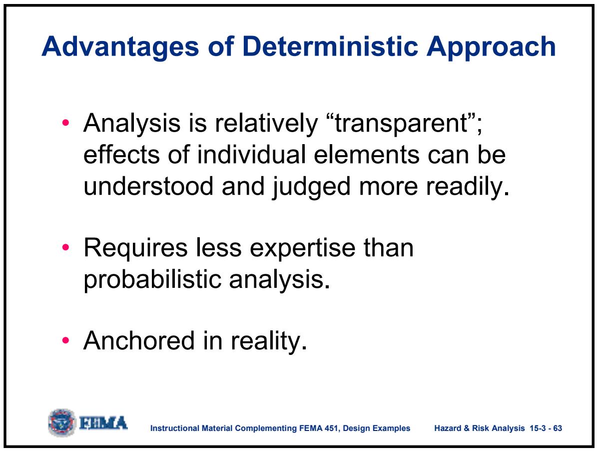
Example Deterministic Analysis (Kramer, 1996)

Source	M	D (km)	PGA (g)
1	7.3	23.7	0.42
2	7.7	25.0	0.57
3	5.0	60.0	0.02

Maximum on source

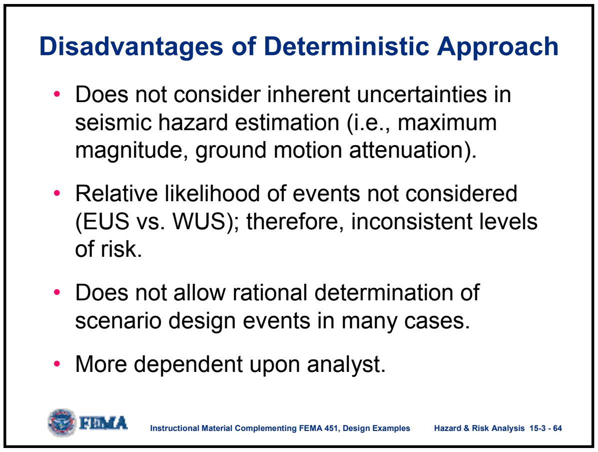
Closest distance

From attenuation relationship



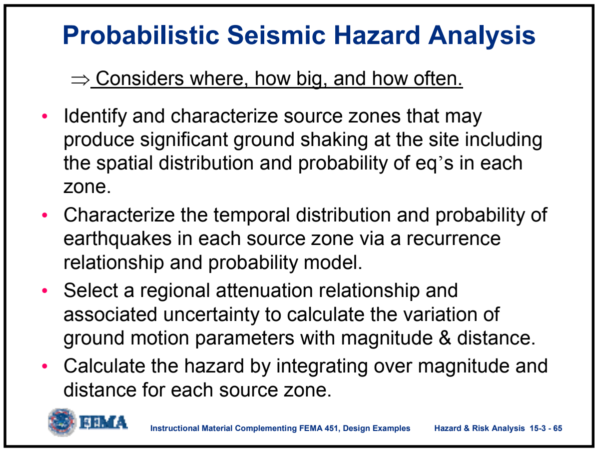
Advantages of Deterministic Approach

- Analysis is relatively "transparent"; effects of individual elements can be understood and judged more readily.
- Requires less expertise than probabilistic analysis.
- Anchored in reality.



Disadvantages of Deterministic Approach

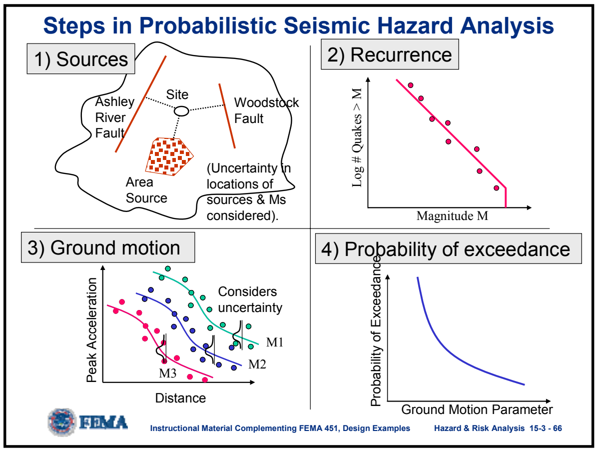
- Does not consider inherent uncertainties in seismic hazard estimation (i.e., maximum magnitude, ground motion attenuation).
- Relative likelihood of events not considered (EUS vs. WUS); therefore, inconsistent levels of risk.
- Does not allow rational determination of scenario design events in many cases.
- More dependent upon analyst.



Probabilistic Seismic Hazard Analysis

⇒ Considers where, how big, and how often.

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



Steps in Probabilistic Seismic Hazard Analysis

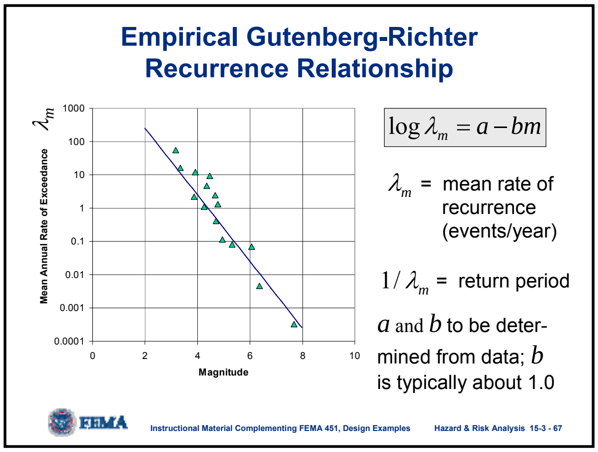
1) Sources

2) Recurrence

3) Ground motion

4) Probability of exceedance

Empirical Gutenberg-Richter Recurrence Relationship



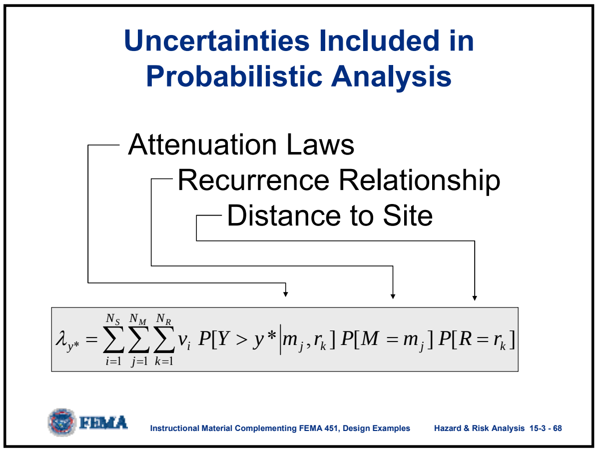
$$\log \lambda_m = a - bm$$

λ_m = mean rate of recurrence (events/year)

$1/\lambda_m$ = return period

a and b to be determined from data; b is typically about 1.0

Uncertainties Included in Probabilistic Analysis


Attenuation Laws
Recurrence Relationship
Distance to Site

$$\lambda_{y^*} = \sum_{i=1}^{N_S}\sum_{j=1}^{N_M}\sum_{k=1}^{N_R} v_i \; P[Y > y^* \,|\, m_j, r_k] \; P[M = m_j] \; P[R = r_k]$$

We Commonly Use Two Approaches to Predict the Likelihood of Earthquakes

- Time-independent (Poisson Model)
- Time-dependent Models

Poisson Model

- The simplest, most used model for earthquake probability.
- It is a time-independent model -- the probability that an earthquake will occur in an interval of time starting from now does not depend on when "now" is, because a Poisson process has no "memory."

Poisson Distribution (general form)

$$\mathbf{P\ (X = k) = \frac{(\lambda t)k\ e^{-(\lambda t)}}{k!}}$$

where λ = rate (events/year)
t = exposure interval
k = no. of events

Poisson Distribution (for one event)

$$P = 1 - e^{-\lambda t}$$

where λ = rate (events/year) ⇐ key!!
t = exposure interval
1/λ = return period

Poisson Model

- Note that the probabilistic earthquake risk level can be put in the form of an earthquake return interval:

Earthquake Return Period = t/-ln(1-PE)

PE	t	Return Period
10%	50 yrs.	475
5%	50 yrs.	975
2%	50 yrs.	2475

Note that when the exponent of the equation, λt, is small, then $P \approx \lambda t$.

Example- Poisson Model

Is a 2%/50-year event the same as a 10%/250-year event?

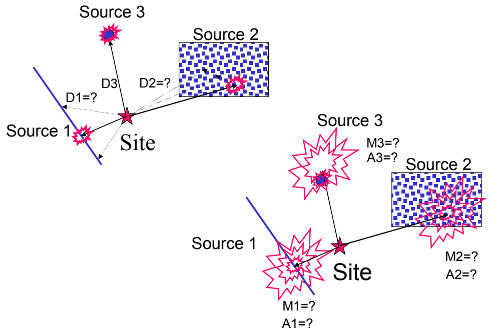
- For 2%/50 years, we have 50/(-ln(1-0.02))= 2,475 year return period
- For 10%/250 years, we have 250/(-ln(1-0.10))= 2,372 year return period

⇒ These events (probabilities) are not exactly equal, but are “equal” from design standpoint.

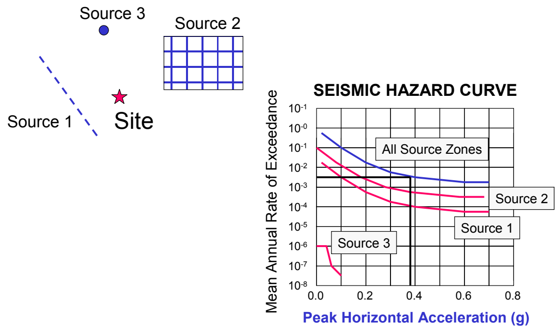
Time-Dependent Models

- Used less than simpler Poisson model
- Time-dependent means that the probability of a large earthquake is small immediately after the last, and then grows with time.
- Such models use various probability density functions to describe the time between earthquakes including Gaussian, log-normal, and Weibull distributions.

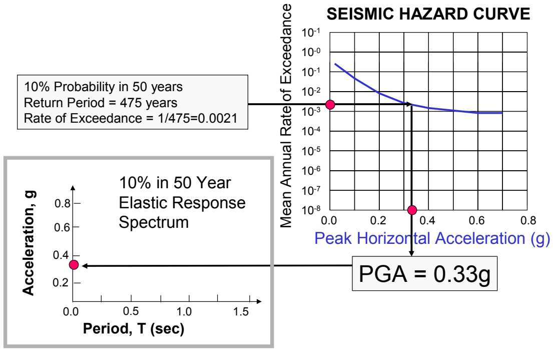
Example Probabilistic Analysis (Kramer)



Result of Probabilistic Hazard Analysis

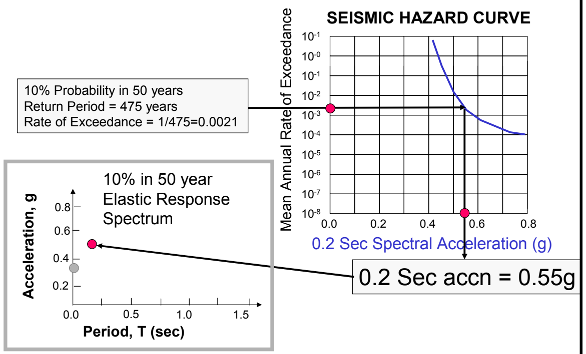


Use of PGA Seismic Hazard Curve

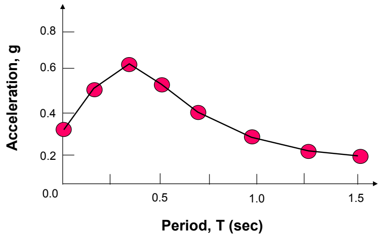


10% Probability in 50 years
Return Period = 475 years
Rate of Exceedance = 1/475=0.0021

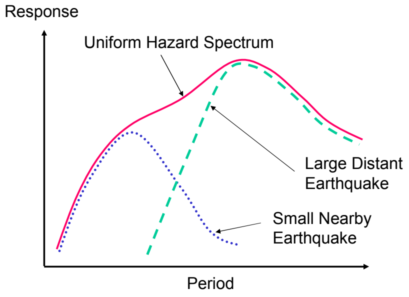
Use of 0.2 Sec. Seismic Hazard Curve



10% in 50 year Elastic Response Spectrum (UHS)



Uniform Hazard Spectrum (UHS)



Uniform Hazard Spectrum

- Developed from *probabilistic* analysis.
- Represents contributions from small local and large distant earthquakes.
- May be overly conservative for modal response spectrum analysis.
- May not be appropriate for artificial ground motion generation, especially in CEUS.

Advantages of Probabilistic Approach

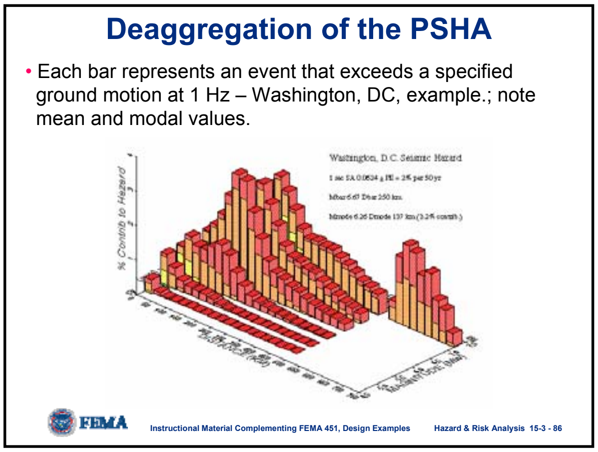
- Reflects true state of knowledge and lack thereof.
- Consider inherent uncertainties in seismic hazard estimation (i.e., maximum magnitude, ground motion attenuation).
- Considers likelihood of events considered; basis for consistent levels of risk established.
- Allows more rationale comparison among many scenarios and to other hazards.
- Less dependent upon analyst.

Disadvantages of Probabilistic Approach

- Analyses are not transparent; the effects of individual parameters cannot be easily recognized and understood.
- “Quantitatively seductive” -- encourages use of precision that is out of proportion with the accuracy with which the input is known.
- Requires special expertise.
- May provide unrealistic scenarios (i.e., probabilistic design event could correspond to location where actual fault does not exist).
- Analyst still has big influence (methods, etc.).

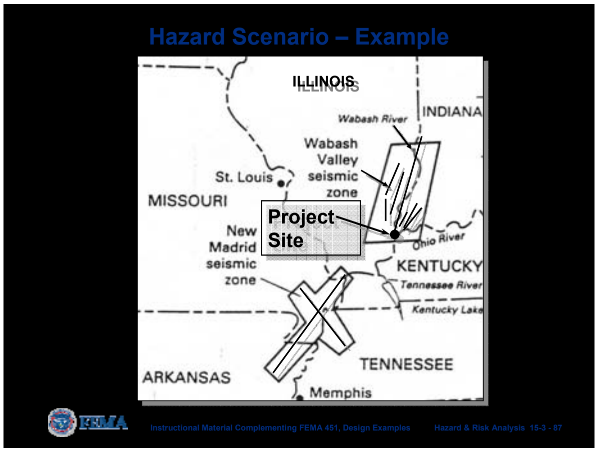
Probabilistic vs. Deterministic

- Results of probabilistic and deterministic analyses are often similar in the WUS; not true for CEUS.
- Deterministic scenarios typically very difficult to define in CEUS.
- Best to use integrated or hybrid method that combines both approaches.

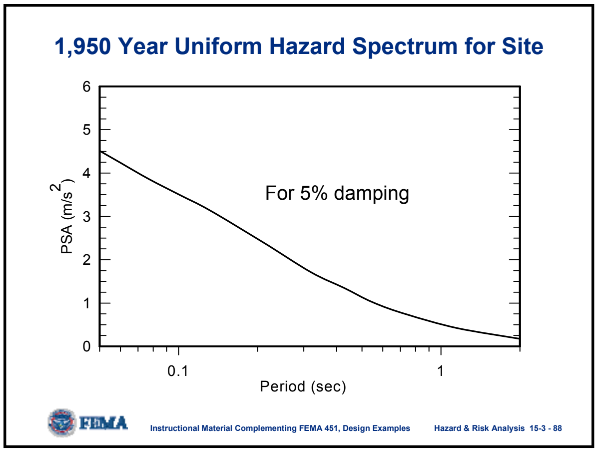


Deaggregation of the PSHA

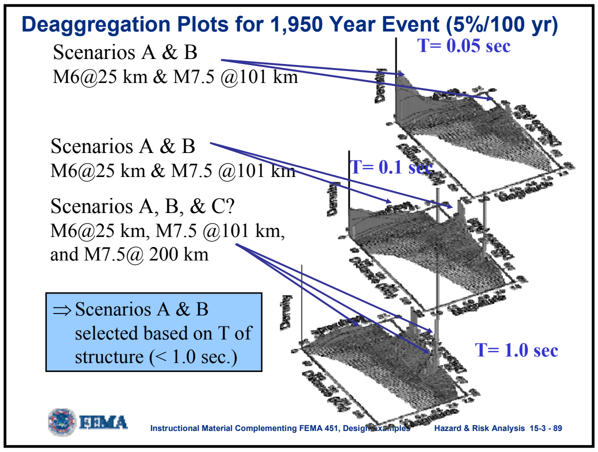
- Each bar represents an event that exceeds a specified ground motion at 1 Hz – Washington, DC, example.; note mean and modal values.



Hazard Scenario – Example



1,950 Year Uniform Hazard Spectrum for Site



Deaggregation Plots for 1,950 Year Event (5%/100 yr)

Scenarios A & B
M6@25 km & M7.5 @101 km

T= 0.05 sec

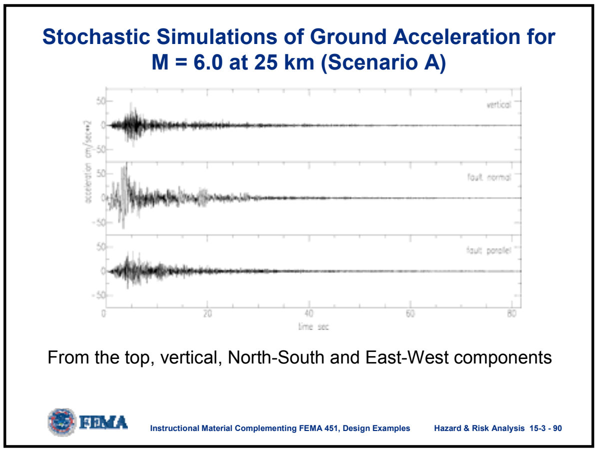
Scenarios A & B
M6@25 km & M7.5 @101 km

T= 0.1 sec

Scenarios A, B, & C?
M6@25 km, M7.5 @101 km,
and M7.5@ 200 km

⇒Scenarios A & B selected based on T of structure (< 1.0 sec.)

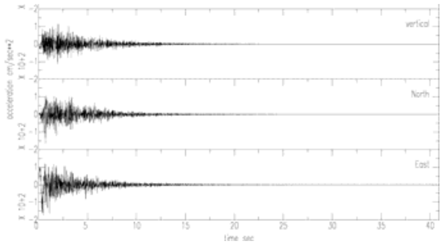
T= 1.0 sec



Stochastic Simulations of Ground Acceleration for M = 6.0 at 25 km (Scenario A)

From the top, vertical, North-South and East-West components

Stochastic Simulations of Ground Acceleration for M = 7.5 at 101 km (Scenario B)



Vertical, fault normal and fault parallel refer to finite fault calculations, and show 3-orthogonal components of motion, oriented with respect to source

Discussion of Selected Scenarios A & B

- What kind of analysis to be performed?
- Is duration important, or just pga?
- Basic question: "*Does it matter which event caused motions to be exceeded*?"
- Seismologist and end user should be closely linked from the beginning!!

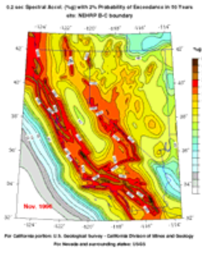
National Seismic Hazard Maps

- Developed by U.S. Geological Survey.
- Adopted (almost exactly) by building codes and reference standards (i.e., IBC2003) and, therefore, very important!!!
- Based on probability ⇒ maps show contours of maximum expected ground motion for a given level of certainty (90%, 98%, etc.) in 50 years; or, said differently, contours of ground motions that have a common given probability of exceedance, PE, in 50 years (10%, 2%, etc.).

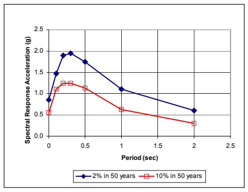
Earthquake Probability Levels

- Note that the term "2500 year earthquake" does not indicate an event that occurs once every 2,500 years!
- Rather, this term reflects a **probability**, that is, the earthquake event that has a probability of 1 in 2500 of occurring in one year.
- For instance, the "100-year flood" can actually occur several years in a row or even several times in one year (as occurred in the 1990s in Virginia).

USGS PROBABILISTIC HAZARD MAPS (2002/2003 versions most recent)*



HAZARD MAP



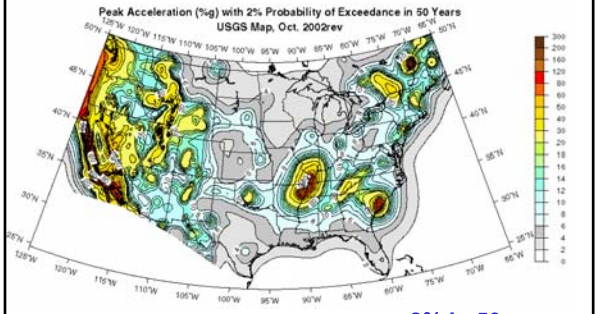
Uniform Hazard Spectra

*2002 versions revised April 2003

USGS PROBABILISTIC HAZARD MAPS (and *NEHRP Provisions* Maps)

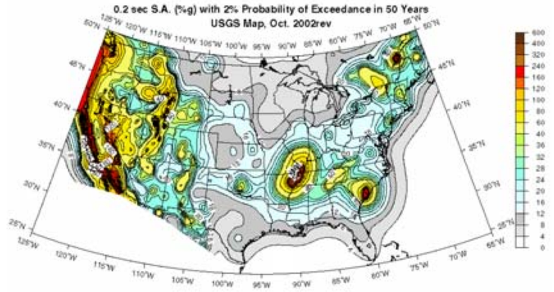
Earthquake Spectra
Theme Issue : Seismic Design Provisions and Guidelines
Volume 16, Number 1
February, 2000

USGS SEISMIC HAZARD MAP (PGA)



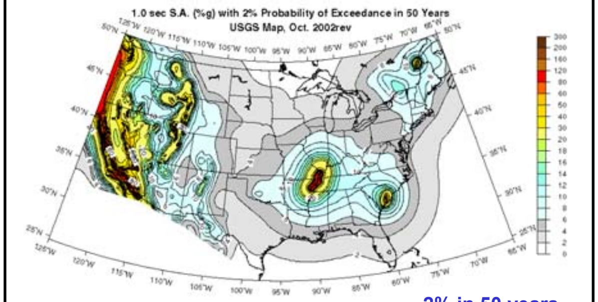
2% in 50 years

USGS SEISMIC HAZARD MAP OF US (0.2 sec)



2% in 50 years

USGS SEISMIC HAZARD MAP OF US (1.0 sec)



2% in 50 years

USGS Website: ZIP CODE Values

http://eqint.cr.usgs.gov/eq/html/zipcode.html

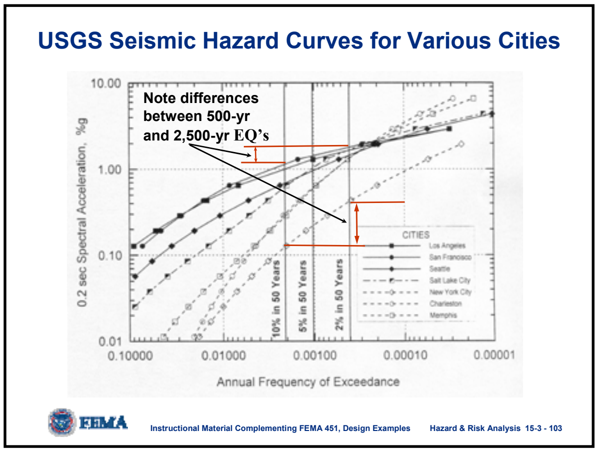
```
   The input zip-code is 80203. (DENVER)
   ZIP CODE                         80203
   LOCATION                         39.7310 Lat. -104.9815 Long.
   DISTANCE TO NEAREST GRID POINT  3.7898 kms
   NEAREST GRID POINT               39.7 Lat. -105.0 Long.
   Probabilistic ground motion values, in %g, at the Nearest Grid
point are:

               10%PE in 50 yr   5%PE in 50 yr   2%PE in 50 yr
      PGA        3.299764         5.207589        9.642159
   0.2 sec SA    7.728900        11.917400       19.921591
   0.3 sec SA    6.178438         9.507714       16.133711
   1.0 sec SA    2.334019         3.601994        5.879917
```

USGS Seismic Hazard Maps

- Hazard in some areas increased relative to previous maps due to recent studies.
- Maps developed for motions on B-C soil boundary (soft rock).
- Maps do not account for regional geological effects such as deep profiles of unconsolidated sediments– this is big effect in CEUS (i.e., in Charleston ~1 km thick).
- New 2002 versions of maps revised in April 2003.

National Seismic Hazard Maps Uses:

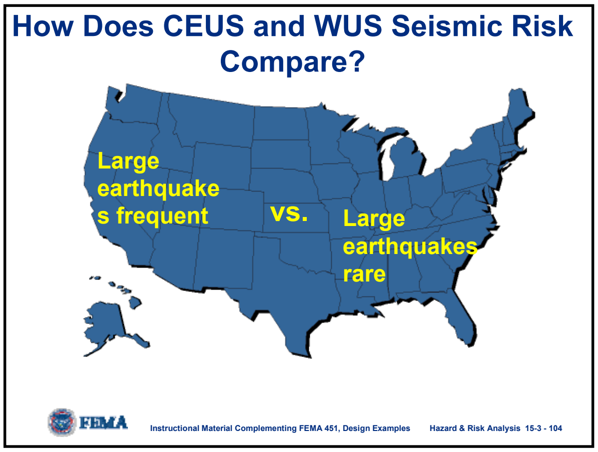
- can illustrate relative probability of a given level of earthquake ground motion of one part of the country relative to another.
- illustrate the relative demand on structures in one region relative to another, at a given probability level.
- as per building codes, use maps as benchmark to determine the resistance required by buildings to resist damaging levels of ground motion.
- with judgment and sometimes special procedures, use maps to determine the input ground motions for geotechnical earthquake analyses (liquefaction,etc.)



USGS Seismic Hazard Curves for Various Cities

Instructional Material Complementing FEMA 451, Design Examples

Hazard & Risk Analysis 15-3 - 103



How Does CEUS and WUS Seismic Risk Compare?

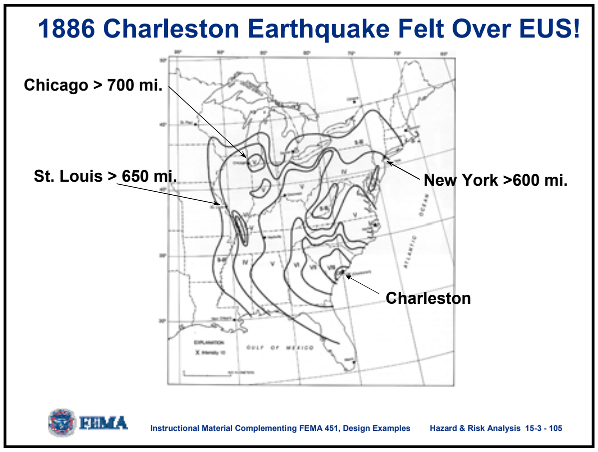
Large earthquakes frequent

vs.

Large earthquakes rare

Instructional Material Complementing FEMA 451, Design Examples

Hazard & Risk Analysis 15-3 - 104



1886 Charleston Earthquake Felt Over EUS!

Chicago > 700 mi.

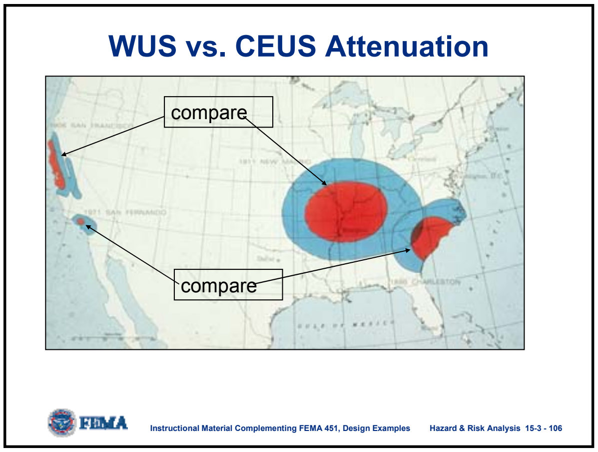
St. Louis > 650 mi.

New York >600 mi.

Charleston

Instructional Material Complementing FEMA 451, Design Examples

Hazard & Risk Analysis 15-3 - 105



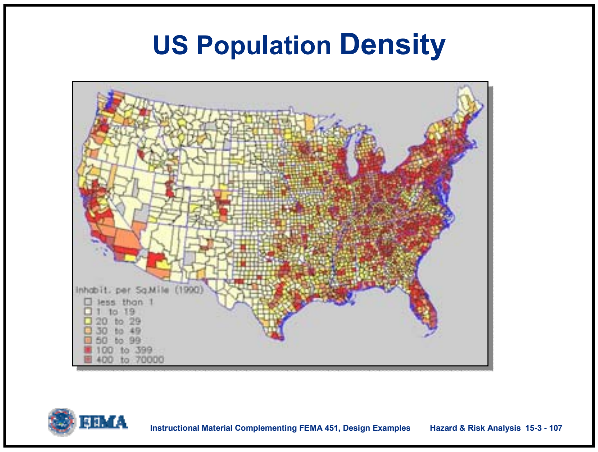
WUS vs. CEUS Attenuation

compare

compare

Instructional Material Complementing FEMA 451, Design Examples

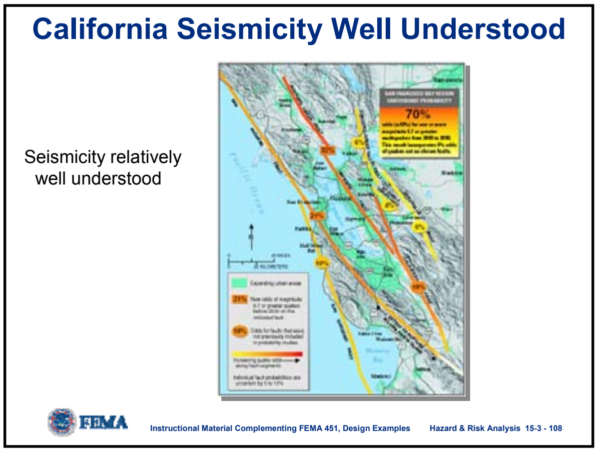
Hazard & Risk Analysis 15-3 - 106



US Population Density

Instructional Material Complementing FEMA 451, Design Examples

Hazard & Risk Analysis 15-3 - 107



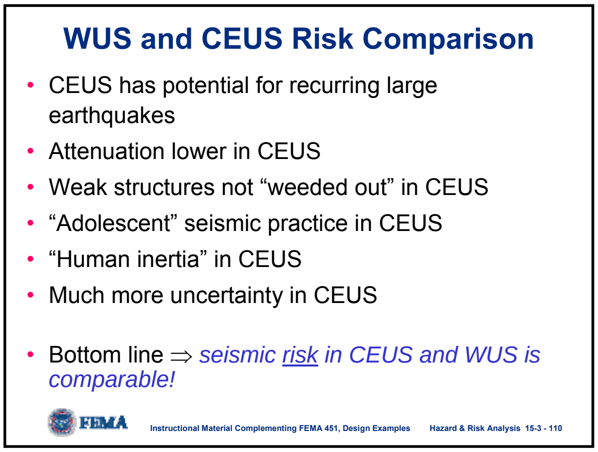
California Seismicity Well Understood

Seismicity relatively
well understood

Instructional Material Complementing FEMA 451, Design Examples

Hazard & Risk Analysis 15-3 - 108

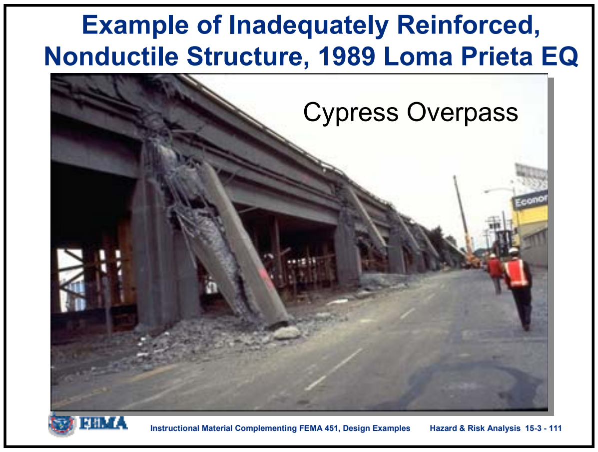
Seismically Weak Infrastructure in CEUS



WUS and CEUS Risk Comparison

- CEUS has potential for recurring large earthquakes
- Attenuation lower in CEUS
- Weak structures not “weeded out” in CEUS
- “Adolescent” seismic practice in CEUS
- “Human inertia” in CEUS
- Much more uncertainty in CEUS

- Bottom line ⇒ *seismic risk in CEUS and WUS is comparable!*



Example of Inadequately Reinforced, Nonductile Structure, 1989 Loma Prieta EQ

Cypress Overpass

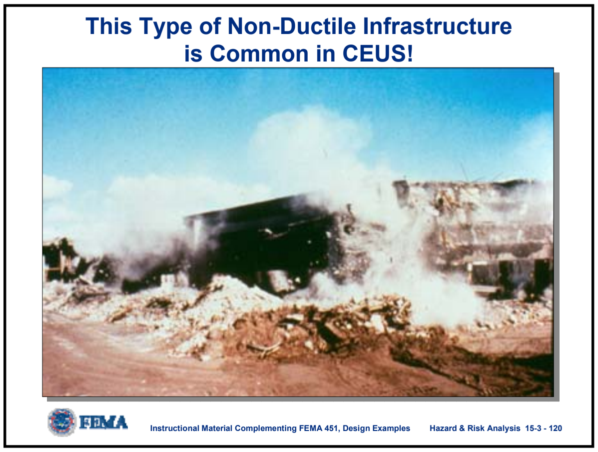
FEMA Instructional Material Complementing FEMA 451, Design Examples Hazard & Risk Analysis 15-3 - 115

FEMA Instructional Material Complementing FEMA 451, Design Examples Hazard & Risk Analysis 15-3 - 116

FEMA Instructional Material Complementing FEMA 451, Design Examples Hazard & Risk Analysis 15-3 - 117

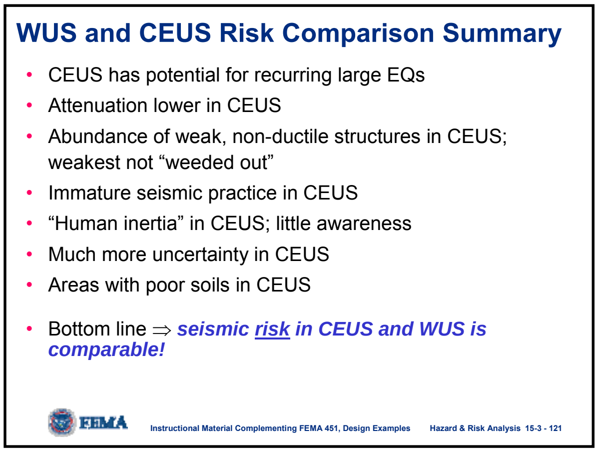
FEMA Instructional Material Complementing FEMA 451, Design Examples Hazard & Risk Analysis 15-3 - 118

FEMA Instructional Material Complementing FEMA 451, Design Examples Hazard & Risk Analysis 15-3 - 119



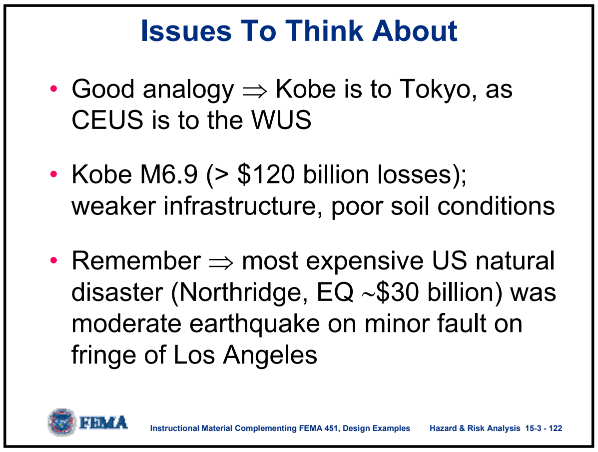
This Type of Non-Ductile Infrastructure is Common in CEUS!

FEMA Instructional Material Complementing FEMA 451, Design Examples Hazard & Risk Analysis 15-3 - 120



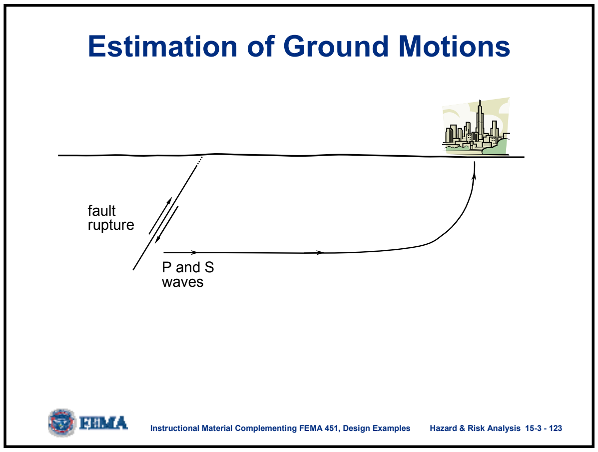
WUS and CEUS Risk Comparison Summary

- CEUS has potential for recurring large EQs
- Attenuation lower in CEUS
- Abundance of weak, non-ductile structures in CEUS; weakest not “weeded out”
- Immature seismic practice in CEUS
- “Human inertia” in CEUS; little awareness
- Much more uncertainty in CEUS
- Areas with poor soils in CEUS
- Bottom line ⇒ ***seismic <u>risk</u> in CEUS and WUS is comparable!***

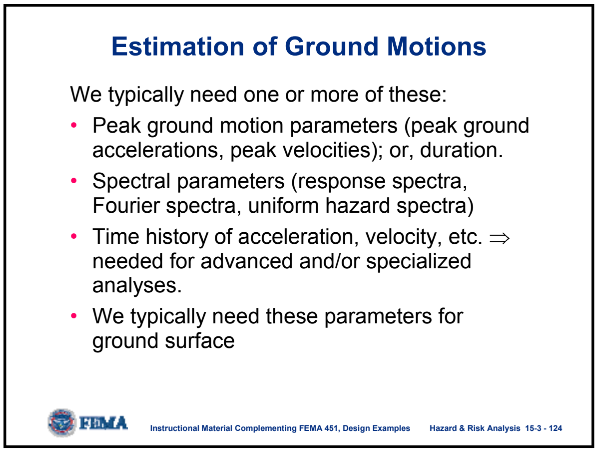


Issues To Think About

- Good analogy ⇒ Kobe is to Tokyo, as CEUS is to the WUS
- Kobe M6.9 (> $120 billion losses); weaker infrastructure, poor soil conditions
- Remember ⇒ most expensive US natural disaster (Northridge, EQ ~$30 billion) was moderate earthquake on minor fault on fringe of Los Angeles



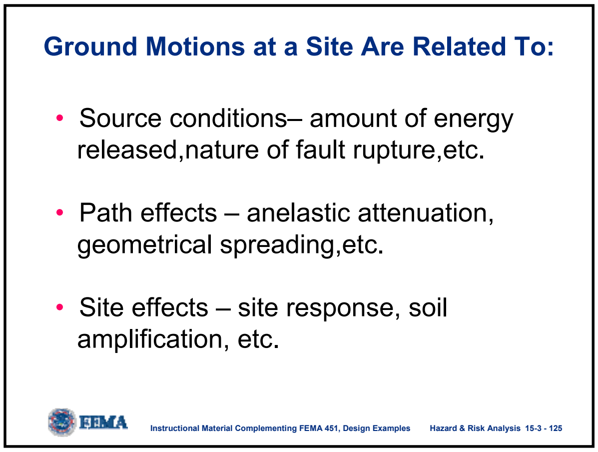
Estimation of Ground Motions



Estimation of Ground Motions

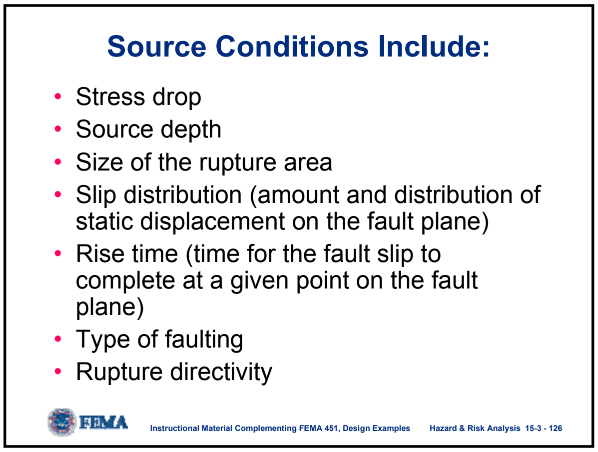
We typically need one or more of these:

- Peak ground motion parameters (peak ground accelerations, peak velocities); or, duration.
- Spectral parameters (response spectra, Fourier spectra, uniform hazard spectra)
- Time history of acceleration, velocity, etc. ⇒ needed for advanced and/or specialized analyses.
- We typically need these parameters for ground surface



Ground Motions at a Site Are Related To:

- Source conditions– amount of energy released,nature of fault rupture,etc.
- Path effects – anelastic attenuation, geometrical spreading,etc.
- Site effects – site response, soil amplification, etc.



Source Conditions Include:

- Stress drop
- Source depth
- Size of the rupture area
- Slip distribution (amount and distribution of static displacement on the fault plane)
- Rise time (time for the fault slip to complete at a given point on the fault plane)
- Type of faulting
- Rupture directivity

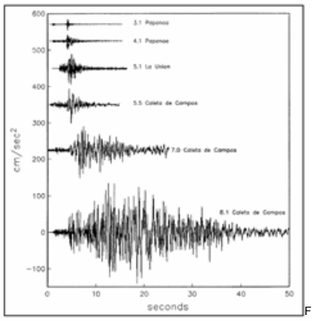
Transmission Path Includes:

- Crustal structure
- Shear-wave velocity (or Q) and damping characteristics of the crustal rock

Site Conditions Include:

- Rock properties beneath the site to depths of up to about 2 km (hard crystalline rock)
- Local soil conditions at the site to depths of up to several hundred feet (typically)
- Topography of the site

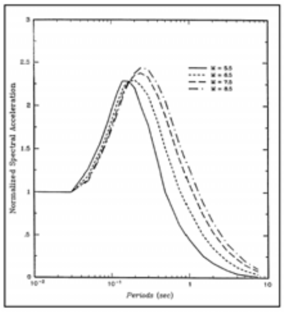
Effects of Magnitude



From USACE, 2000

Figure 3-1. An example of accelerograms recorded in 1985 and 1986 on the Guerrero accelerograph array (Anderson and Quaas (1988), courtesy of Earthquake Engineering Research Institute, Oakland, CA)

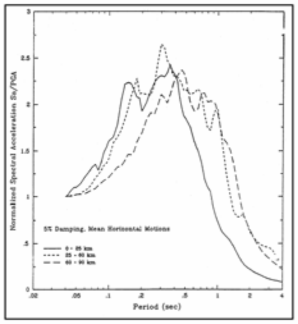
Effects of Magnitude



From USACE, 2000

Figure 3-3. Effect of magnitude M on response spectral shape of rock motions based on attenuation relationships of Sadigh et al. (1993), 30-km distance from source to site, 5 percent damping

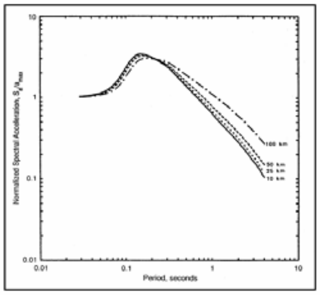
Effects of Distance



From USACE, 2000

Figure 3-4. Variation of spectral shape with distance for rock recordings of the October 17, 1989, Loma Prieta earthquake

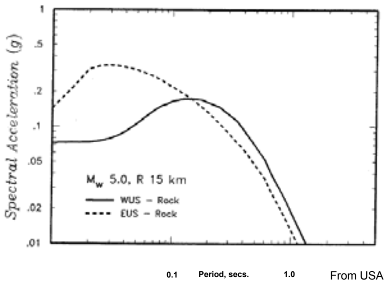
Effects of Distance



From USACE, 2000

Figure 3-5. Effect of distance on response spectral shapes for a moment magnitude M_w 6.5 earthquake using western North American parameters (Silva and Green 1989, courtesy of Earthquake Engineering Research Institute, Oakland, CA)

Regional Effects



From USACE, 2000

Effect of Local Site Conditions

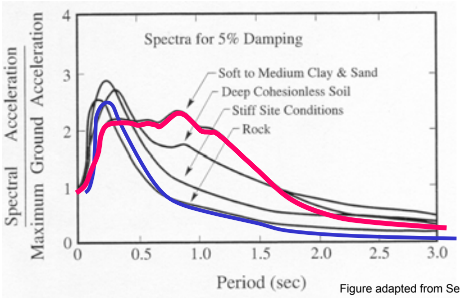


Figure adapted from Seed and Idriss (1984); EERI.

Special Near-source Effects

“Near-source” can be interpreted differently. For many engineering applications, a zone within about 20 km of the fault rupture is considered near-source. Other cases near-source is considered within a distance roughly equal to the ruptured length of the fault; 20 to 60 km typical

Near-source effects:

- Directiviity
- Fling
- Radiation pattern

Important Near-Fault Effects

Two Causes of large velocity pulses:

- Directivity
- Fling

Causes of Velocity Pulses

Directivity:

- Related to the direction of the rupture front
  - Forward directivity: rupture toward the site (site away from the epicenter)
  - Backward directivity: rupture away from the site (site near the epicenter)

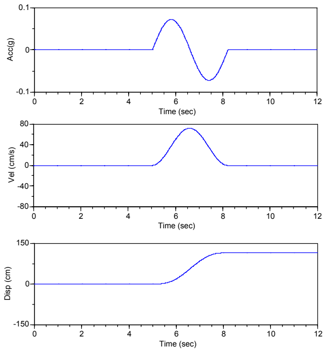
Fling:

- Related to the permanent tectonic deformation at the site

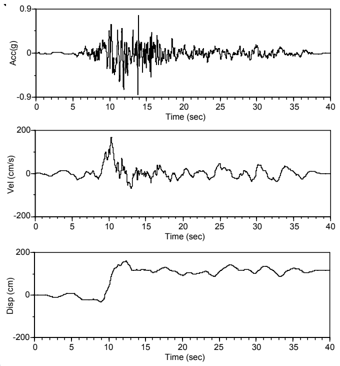
Velocity Pulses

- Directivity
  - Two-sided velocity pulse due to constructive interference of SH waves from generated from parts of the rupture located between the site and epicenter; affects fault-normal component
  - Occurs at sites located close to the fault but away from the epicenter
- Fling
  - One-sided velocity pulse due to tectonic deformation; affects fault-parallel component
  - Occurs at sites located near the fault rupture independent of the epicenter location

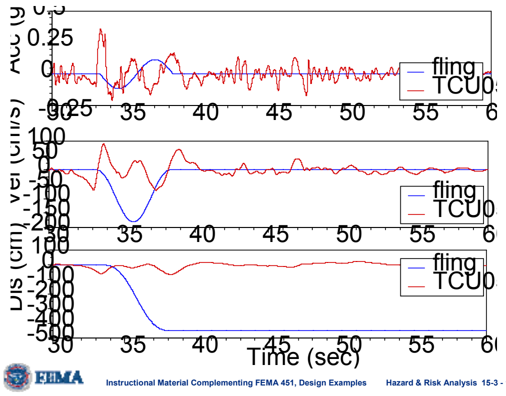
Preliminary Model for Fling



Vibratory Ground Motion + Fling

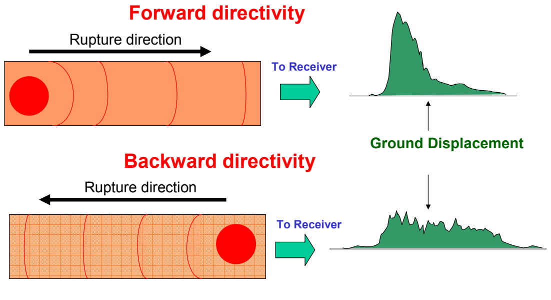


TCU052 (1999 Chi-Chi)



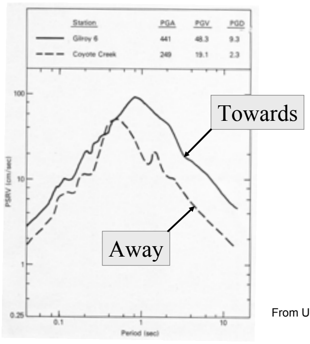
Effects of Fling

- Not currently known which types of structures are sensitive to fling ground motions.
- Preliminary results indicate some long-span structure may be sensitive to fling.
- Need to evaluate various types of structures to ground motions with and without fling to determine the effect.



The areas under the far-field displacement pulses are equal, but the amplitudes and durations differ. This has major effects on the ground velocity and acceleration.

Effect of Directivity on Response Spectra



From USACE, 2000

Effect of Directivity

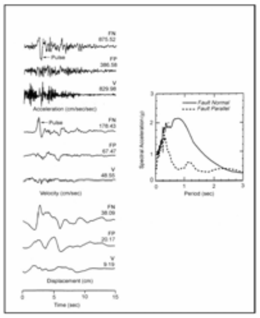


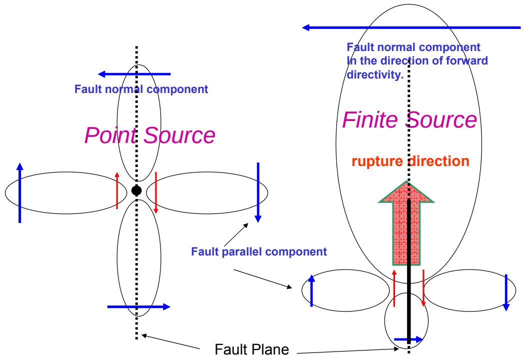
Figure 3-6. Time-histories and horizontal response spectra (5 percent damping) for the fault strike-normal (FN) and fault strike-parallel (FP) components of ground motion (V = vertical) for the Rinaldi recording obtained 7.5 km from the fault rupture during the 1994 Northridge, California, earthquake (Somerville (1997), courtesy of Multidisciplinary Center for Earthquake Engineering Research, State University of New York at Buffalo)

From USACE, 2000

Effects of Fling and Directivity

- Directivity can cause amplification of motions for sites close to the fault rupture.
- Unclear as to engineering significance of fling.
- Current attenuation relations do not include these effects.

SH Radiation Pattern for Vertical Strike-slip



Fault normal component in the direction of forward directivity.

Fault normal component

Point Source

Finite Source

rupture direction

Fault parallel component

Fault Plane

Other Important Effects

- Also, vertical motions tend to be higher than 2/3 maximum horizontal motions when near-source.
- Subduction zone EQs vs. shallow EQs
- Topographical effects (especially basins).
- Surface waves may be important for certain long-span structures (relative motion among supports).
- Others…

Three Classes of Methods for Ground Motion Estimates

- Generalized, simplified (i.e., IBC2003)⇐
- Site-specific, simplified (i.e., attenuation curves, site amplification factors)
- Site-specific, rigorous (time history analysis)

Generalized, Simplified (i.e., IBC 2003)

- Simple to use.
- Based on probabilistic maps.
- Does not account for regional geological effects (maps assume standard depth for B-C boundary and profile layering) ⇒ in WUS, B-C boundary is shallow bedrock, but in some CEUS areas the B-C boundary is deep as 1 km.
- Accounts for local site effects in general manner– cannot handle special site conditions.
- Not well-suited to many geotechnical analyses (no magnitude, UHS approach, etc.).

IBC 2003 - Overview

- Developed from a combination of three legacy model codes (UBC, BOCA, & SBC).
- Based largely on FEMA 368 and 369, *NEHRP Recommended Provisions* and *Commentary.*
- Adopted in 45 states (as of July 2004) and by the DoD.
- Incorporates most recent (2002/2003) USGS seismic hazard maps; USGS map values capped in some areas by IBC 2003.

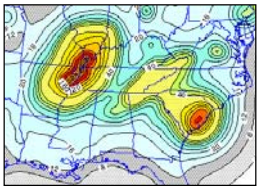
IBC 2003 – General Procedure

- Maximum Considered Earthquake (MCE) based on 2002/2003 USGS probabilistic hazard maps (deterministic limits used in high seismicity areas – here hazard can be driven by tails of distributions).
- Maps provide and spectral accelerations for T = 0.2 sec (S_s), and T = 1.0 sec (S_1) for B-C boundary.
- Local soil conditions considered using site coefficients (F_a and F_v)
- Develop design spectrum using S and F values

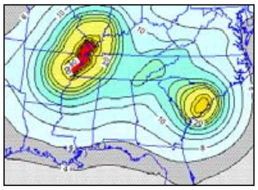
IBC 2003 – General Procedure

- Determine S_s and S_1 from the maps

S_s (0.2 sec) map



S_1 (1.0 sec) map



IBC 2003 – General Procedure

- Determine site class based on top 30 m:

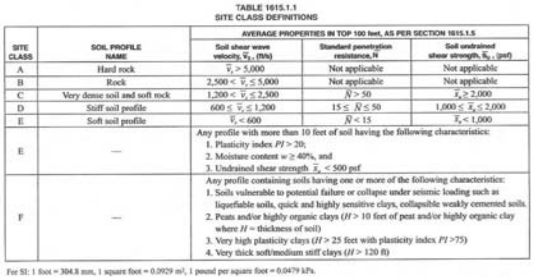


TABLE 1615.1.1
SITE CLASS DEFINITIONS

SITE CLASS	SOIL PROFILE NAME	AVERAGE PROPERTIES IN TOP 100 feet, AS PER SECTION 1615.1.5		
		Soil shear wave velocity, $\bar{v}_s$, (ft/s)	Standard penetration resistance, $\bar{N}$	Soil undrained shear strength, $\bar{s}_u$, (psf)
A	Hard rock	$\bar{v}_s > 5{,}000$	Not applicable	Not applicable
B	Rock	$2{,}500 < \bar{v}_s \le 5{,}000$	Not applicable	Not applicable
C	Very dense soil and soft rock	$1{,}200 < \bar{v}_s \le 2{,}500$	$\bar{N} > 50$	$\bar{s}_u \ge 2{,}000$
D	Stiff soil profile	$600 \le \bar{v}_s \le 1{,}200$	$15 \le \bar{N} \le 50$	$1{,}000 \le \bar{s}_u \le 2{,}000$
E	Soft soil profile	$\bar{v}_s < 600$	$\bar{N} < 15$	$\bar{s}_u < 1{,}000$
E	—	Any profile with more than 10 feet of soil having the following characteristics: 1. Plasticity index $PI > 20$, 2. Moisture content $w \ge 40\%$, and 3. Undrained shear strength $\bar{s}_u < 500$ psf		
F	—	Any profile containing soils having one or more of the following characteristics: 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 ($H > 10$ feet of peat and/or highly organic clay where H = thickness of soil) 3. Very high plasticity clays ($H > 25$ feet with plasticity index $PI > 75$) 4. Very thick soft/medium stiff clays ($H > 120$ ft)		

For SI: 1 foot = 304.8 mm, 1 square foot = 0.0929 m², 1 pound per square foot = 0.0479 kPa.

IBC 2003 – General Procedure

- Determine F_a & F_v values from S_s, S_1 and site class:

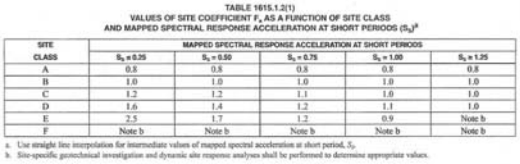


TABLE 1615.1.2(1)
VALUES OF SITE COEFFICIENT F_a AS A FUNCTION OF SITE CLASS
AND MAPPED SPECTRAL RESPONSE ACCELERATION AT SHORT PERIODS (S_S)[a]

SITE CLASS	MAPPED 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	Note b
F	Note b	Note b	Note b	Note b	Note b

a. Use straight line interpolation for intermediate values of mapped spectral acceleration at short period, S_S.
b. Site-specific geotechnical investigation and dynamic site response analyses shall be performed to determine appropriate values.

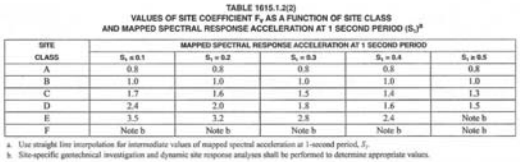
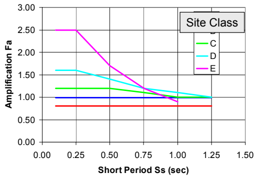


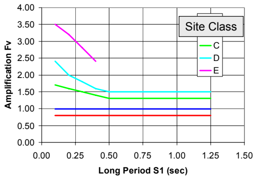
TABLE 1615.1.2(2)
VALUES OF SITE COEFFICIENT F_V AS A FUNCTION OF SITE CLASS
AND MAPPED SPECTRAL RESPONSE ACCELERATION AT 1 SECOND PERIOD (S_1)[a]

SITE CLASS	MAPPED SPECTRAL RESPONSE ACCELERATION AT 1 SECOND PERIOD				
	$S_1 \le 0.1$	$S_1 = 0.2$	$S_1 = 0.3$	$S_1 = 0.4$	$S_1 \ge 0.5$
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	Note b
F	Note b	Note b	Note b	Note b	Note b

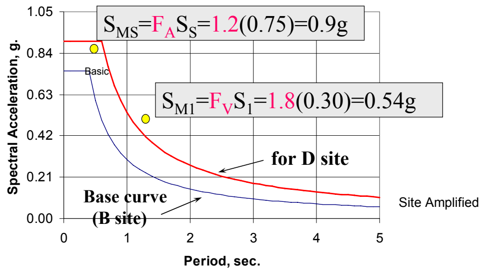
a. Use straight line interpolation for intermediate values of mapped spectral acceleration at 1-second period, S_1.
b. Site-specific geotechnical investigation and dynamic site response analyses shall be performed to determine appropriate values.

NEHRP Provisions Site Amplification for Site Classes A through E





Example: 2% in 50 Year Spectrum Modified for Site Class D (5% Damping)



IBC 2003 - General Procedure

- Adjust MCE values of S_s and S_1 for local site effects:

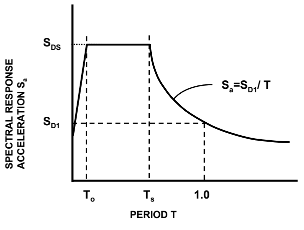
  $S_{MS} = F_a•S_s$ $S_{M1} = F_v•S_1$

- Calculate the spectral design values S_{DS} and S_{D1}:

  $S_{DS} = 2/3•S_{MS}$ $S_{D1} = 2/3•S_{M1}$

IBC2003 – General Procedure

- From S_{DS} and S_{MS}, develop the design response spectrum



DESIGN RESPONSE SPECTRUM

Scaling of Spectra by 2/3 for "Margin of Performance"

- Design with current 2%/50-yr. maps but scale by 2/3.
- Buildings designed according to current procedures assumed to have margin of collapse of 1.5.
- Judgment of "lower bound" margin of collapse given by current design procedures.
- Results in 2/3 x 1.5 = 1.0 deterministic earthquake (where applicable).
- 2/3 (2500-yr. EQ) = 500-year motions in WUS, but 2/3 (2500-yr. EQ) ≈ 1600-year motions in EUS
- 2/3 factor not related to geotechnical performance!

Three Classes of Methods for Ground Motion Estimates

- Generalized, simplified (i.e., IBC 2003)
- Site-specific, simplified (i.e., attenuation curves, site amplification factors) ⇐
- Site-specific, rigorous (time history analysis)

Site-Specific, Simplified

- Relatively simple (chart-based procedures).
- Based on probabilistic motions or deterministic scenarios.
- Can account for regional geological effects (within 2 km of surface; USGS maps assume standard depth for B-C boundary and hard rock).
- Accounts for local site (within few hundred feet of surface) effects in simplified, but more specific manner.
- Better-suited to many geotechnical analyses.

Site-Specific, Simplified: Comments

- Note IBC 2003 limits site-specific “benefit” (in terms of reduced design) motions to 20% for A-E sites.
- Site-specific analysis in some CEUS area less than probabilistic maps values; opposite may be true in WUS.

Site-Specific Simplified Procedures

Typical deterministic scenario:

1. Knowing fault location and earthquake magnitude, estimate ground motion parameter (i.e, pga or spectral values) for hard rock from attenuation relationships.
2. If appropriate, correct for regional geological conditions such as deep unconsolidated sediments (Vs >700m/s and typically within 2 km of surface)
3. Modify motions for near-surface soils (V_s < 700 m/s and within few hundred of surface)*

*covered in detail in a following lecture.

1. Estimating Motions on Hard Rock

- Typically use region-specific attenuation curve (but can use probabilistic maps also).
- Curves developed from empirical data from recorded motions in most regions.
- Curves in CEUS developed from few small EQs, plus stochastic simulations using methods developed in WUS but with CEUS geological parameters (Q, stress drop, etc.).
- Most curves provide PGA, PGV, and spectral values.

Ground Motion Attenuation Basic Empirical Relationships

$$\ln \hat{Y} = \ln b_1 + f_1(M) + \ln f_2(R) + \ln f_3(M,R) + \ln f_4(P_i) + \ln \varepsilon$$

$\hat{Y}$	Ground Motion Parameter (e.g. PGA)
b_1	Scaling factor
$f_1(M)$	Function of Magnitude
$f_2(R)$	Function of Distance
$f_3(M,R)$	Function of Magnitude and Distance
$f_4(P_i)$	Other Variables
ε	Error Term

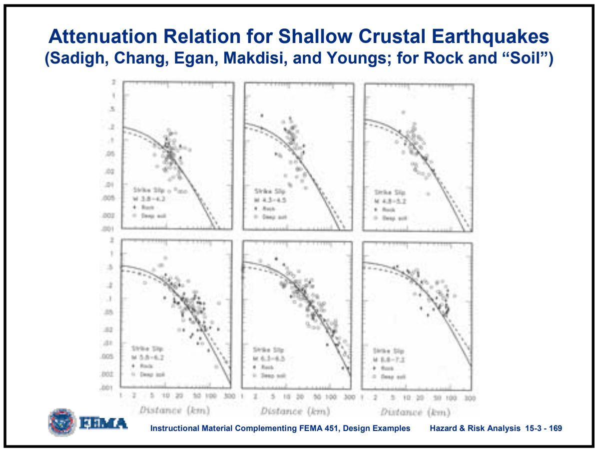
Ground Motion Attenuation Relationships for Different Conditions

- Central and Eastern US
- Subduction Zone Earthquakes
- Shallow Crustal Earthquakes
- Near-Source Attenuation
- Extensional Tectonic Regions
- Many Others
- Most are for hard rock, some for “soil”

May be developed for any desired quantity (PGA, PGV, Spectral Response)

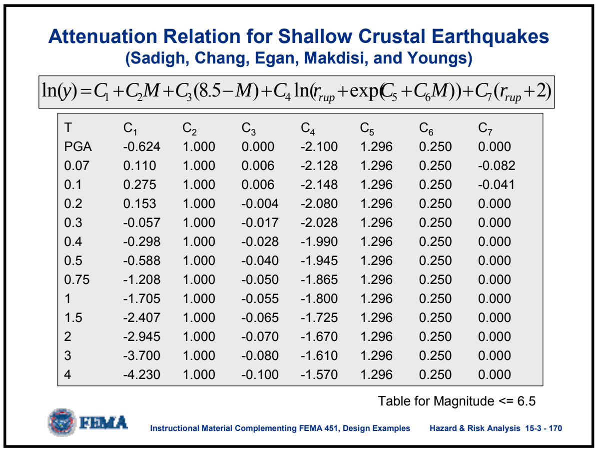
Ground Motion Attenuation Relationships

Seismological Research Letters
Volume 68, Number 1
January/February, 1997



Attenuation Relation for Shallow Crustal Earthquakes

(Sadigh, Chang, Egan, Makdisi, and Youngs; for Rock and "Soil")



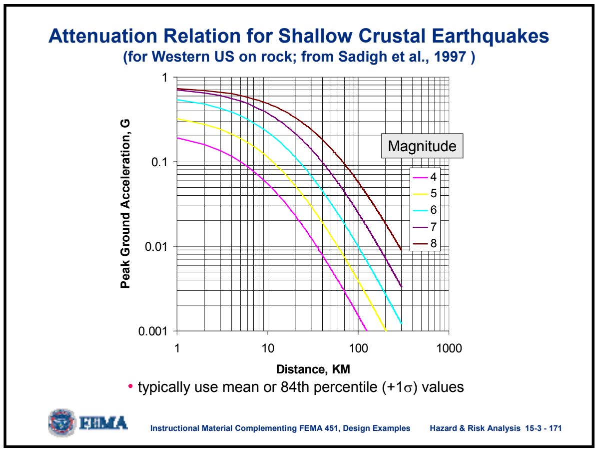
Attenuation Relation for Shallow Crustal Earthquakes

(Sadigh, Chang, Egan, Makdisi, and Youngs)

$$\ln(y)=C_1+C_2M+C_3(8.5-M)+C_4\ln(r_{rup}+\exp(C_5+C_6M))+C_7(r_{rup}+2)$$

T	C_1	C_2	C_3	C_4	C_5	C_6	C_7
PGA	-0.624	1.000	0.000	-2.100	1.296	0.250	0.000
0.07	0.110	1.000	0.006	-2.128	1.296	0.250	-0.082
0.1	0.275	1.000	0.006	-2.148	1.296	0.250	-0.041
0.2	0.153	1.000	-0.004	-2.080	1.296	0.250	0.000
0.3	-0.057	1.000	-0.017	-2.028	1.296	0.250	0.000
0.4	-0.298	1.000	-0.028	-1.990	1.296	0.250	0.000
0.5	-0.588	1.000	-0.040	-1.945	1.296	0.250	0.000
0.75	-1.208	1.000	-0.050	-1.865	1.296	0.250	0.000
1	-1.705	1.000	-0.055	-1.800	1.296	0.250	0.000
1.5	-2.407	1.000	-0.065	-1.725	1.296	0.250	0.000
2	-2.945	1.000	-0.070	-1.670	1.296	0.250	0.000
3	-3.700	1.000	-0.080	-1.610	1.296	0.250	0.000
4	-4.230	1.000	-0.100	-1.570	1.296	0.250	0.000

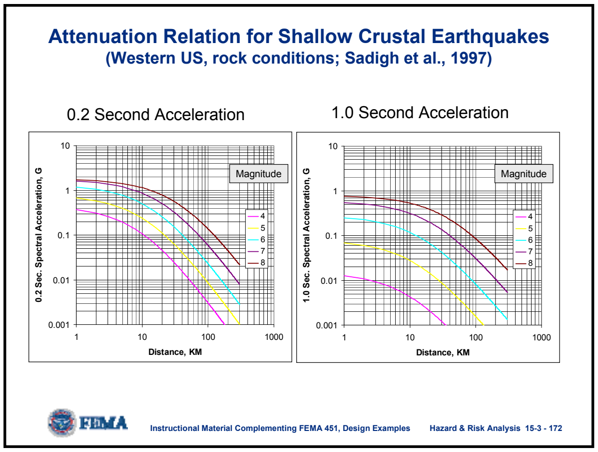
Table for Magnitude <= 6.5



Attenuation Relation for Shallow Crustal Earthquakes

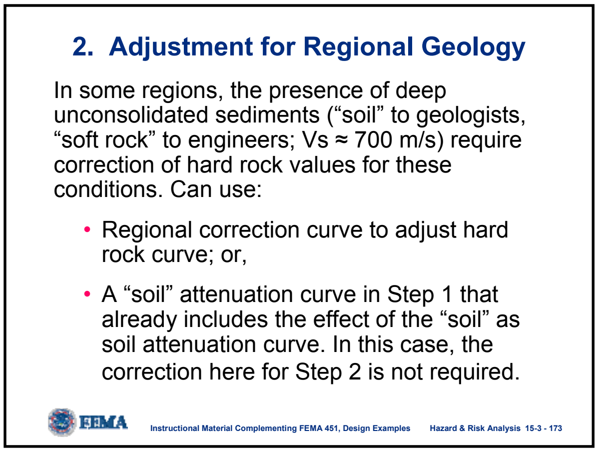
(for Western US on rock; from Sadigh et al., 1997)

- typically use mean or 84th percentile (+1σ) values



Attenuation Relation for Shallow Crustal Earthquakes

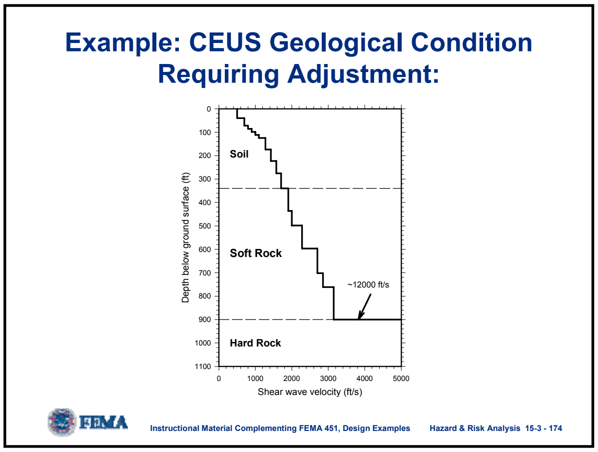
(Western US, rock conditions; Sadigh et al., 1997)



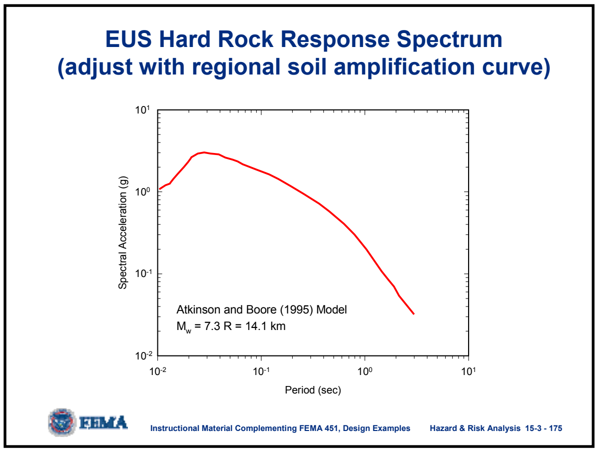
2. Adjustment for Regional Geology

In some regions, the presence of deep unconsolidated sediments ("soil" to geologists, "soft rock" to engineers; Vs ≈ 700 m/s) require correction of hard rock values for these conditions. Can use:

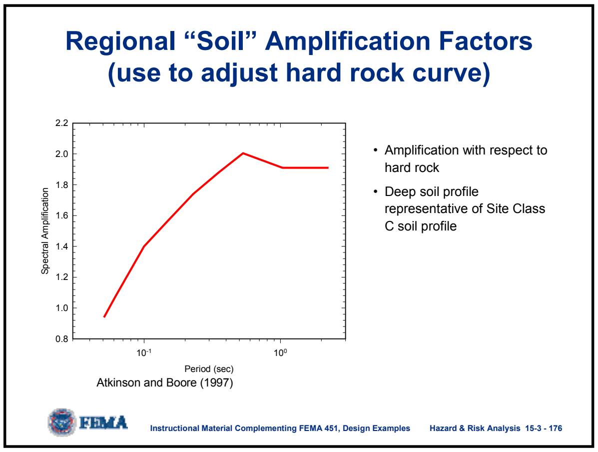
- Regional correction curve to adjust hard rock curve; or,
- A "soil" attenuation curve in Step 1 that already includes the effect of the "soil" as soil attenuation curve. In this case, the correction here for Step 2 is not required.



Example: CEUS Geological Condition Requiring Adjustment:



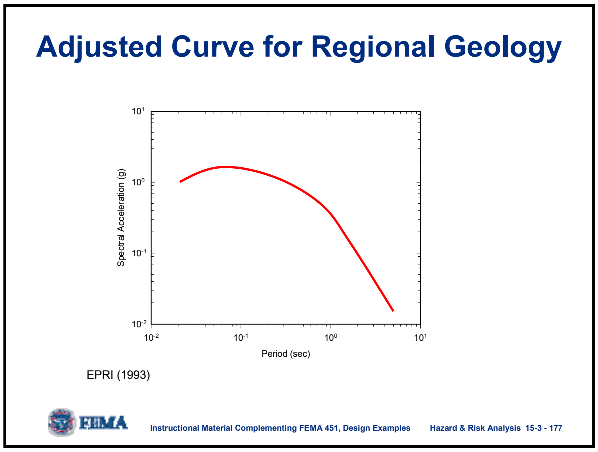
EUS Hard Rock Response Spectrum (adjust with regional soil amplification curve)



Regional "Soil" Amplification Factors (use to adjust hard rock curve)

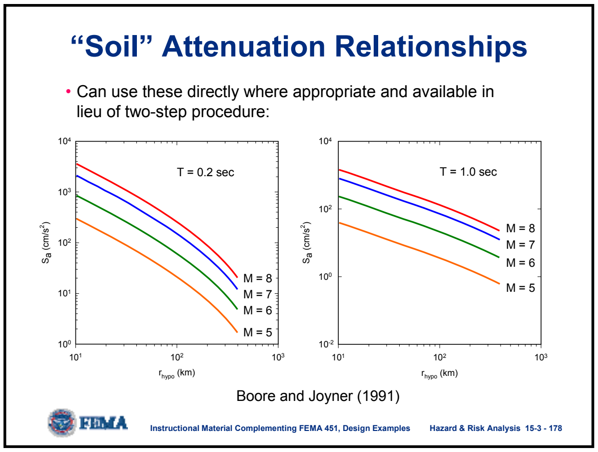
- Amplification with respect to hard rock
- Deep soil profile representative of Site Class C soil profile

Atkinson and Boore (1997)



Adjusted Curve for Regional Geology

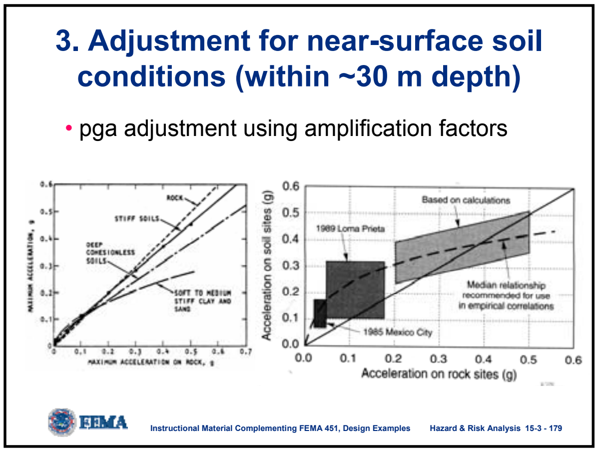
EPRI (1993)



"Soil" Attenuation Relationships

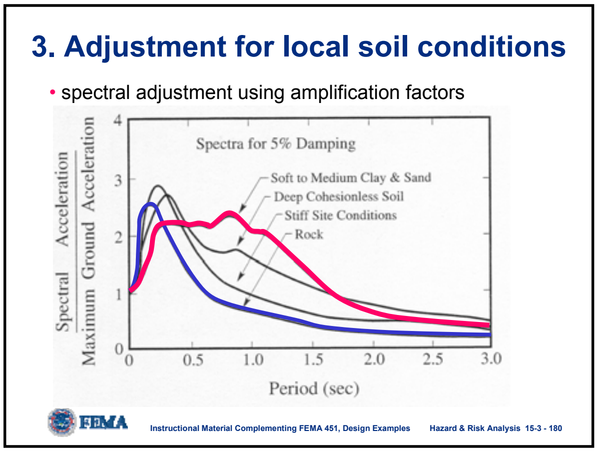
- Can use these directly where appropriate and available in lieu of two-step procedure:

Boore and Joyner (1991)



3. Adjustment for near-surface soil conditions (within ~30 m depth)

- pga adjustment using amplification factors



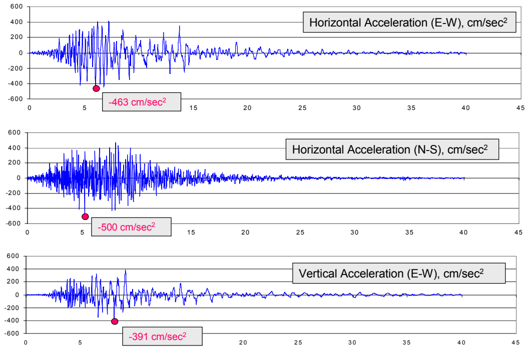
3. Adjustment for local soil conditions

- spectral adjustment using amplification factors

Three Classes of Methods for Ground Motion Estimates

- Generalized, simplified (i.e., IBC 2003)
- Site-specific, simplified (i.e., attenuation curves, site amplification factors)
- Site-specific, rigorous (time history analysis) ⇐

Typical Earthquake Acceleration Time History Set



Loma Prieta Earthquake

Time History analyses

- Allows best possible analysis (usually)
- Increasing in usage
- Time histories can be obtained from:
  - Databases of recorded motions such as
    - National and state data catalogs (NSMDS)
    - USGS web page
    - other sources (i.e., NONLIN)
  - By developing the motions using
    - modified recorded motions
    - synthetic motions

Obtaining Time Histories

Conditions for which there are few records available:

- Moderate to large earthquakes in CEUS
- Large-magnitude (8+) shallow crustal events
- Near-source, large-magnitude (7.5+) events

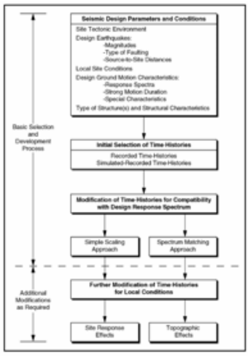
Time History Analysis

- Objective: develop a set or sets of time-histories, usually acceleration time histories, that are representative of site ground motions for the design earthquake(s)* and that are appropriate for the type of analyses planned.
- Will not be able to predict actual motions, rather interested in *representing characteristics most important for design.*

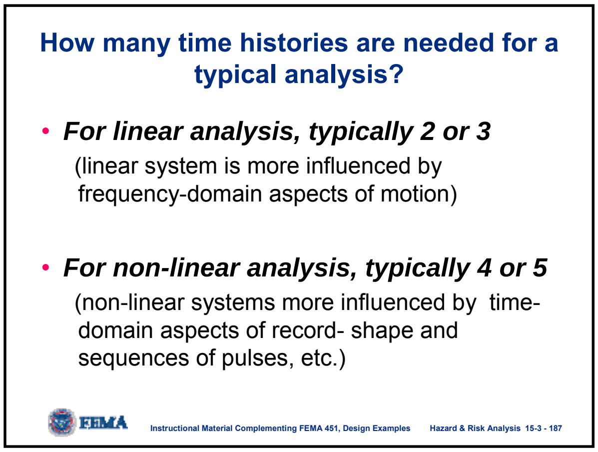
---

* Discussed earlier. The design earthquake can be from deterministic or probabilistic analysis; but, if probabilistic, the uniform hazard spectrum should probably not be used as the target spectrum. Rather, deterministic scenarios should be developed from deaggregation of the PSHA.

Process for selecting/modifying time histories:



From: (USACE, 2000)



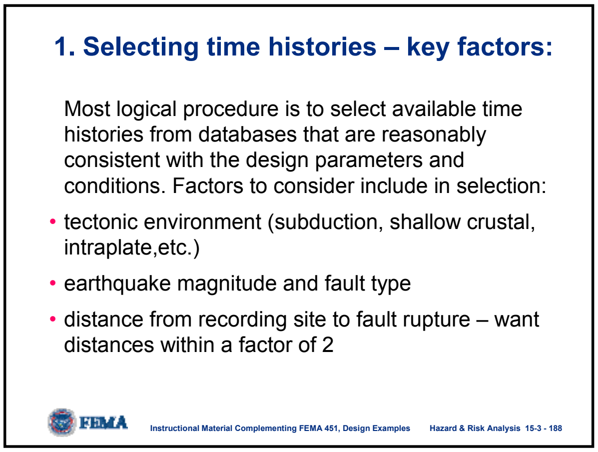
How many time histories are needed for a typical analysis?

- ***For linear analysis, typically 2 or 3***

  (linear system is more influenced by frequency-domain aspects of motion)

- ***For non-linear analysis, typically 4 or 5***

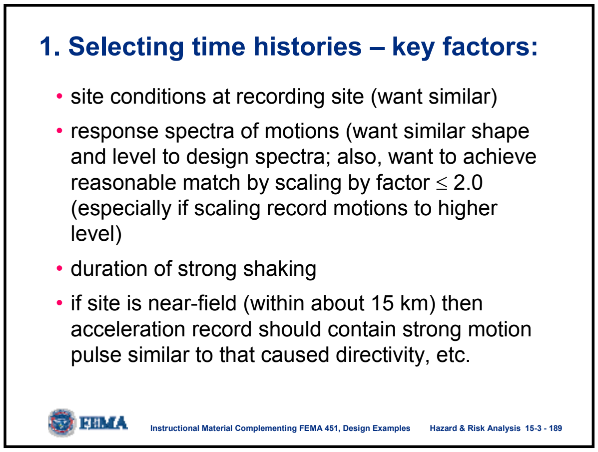
  (non-linear systems more influenced by time-domain aspects of record- shape and sequences of pulses, etc.)



1. Selecting time histories – key factors:

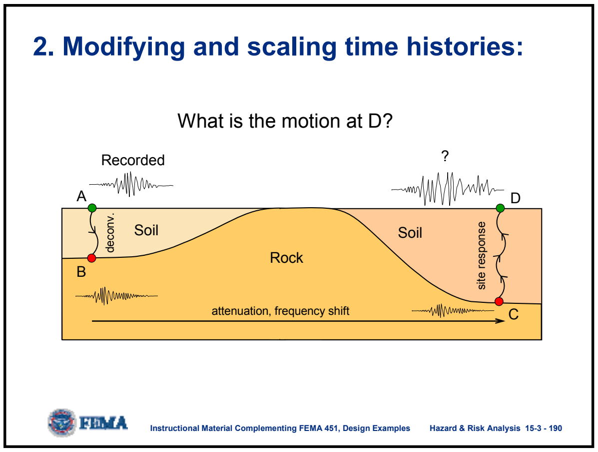
Most logical procedure is to select available time histories from databases that are reasonably consistent with the design parameters and conditions. Factors to consider include in selection:

- tectonic environment (subduction, shallow crustal, intraplate,etc.)
- earthquake magnitude and fault type
- distance from recording site to fault rupture – want distances within a factor of 2



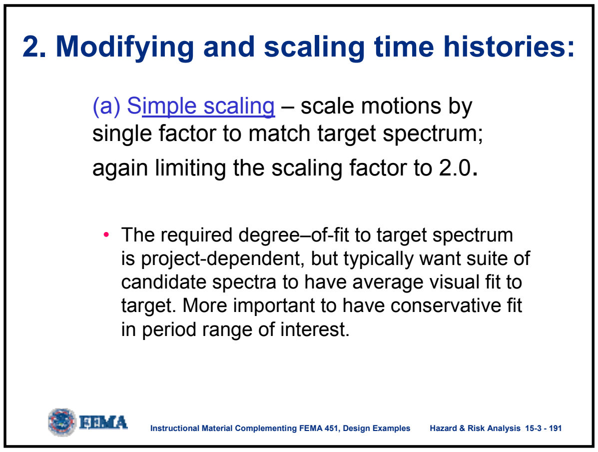
1. Selecting time histories – key factors:

- site conditions at recording site (want similar)
- response spectra of motions (want similar shape and level to design spectra; also, want to achieve reasonable match by scaling by factor ≤ 2.0 (especially if scaling record motions to higher level)
- duration of strong shaking
- if site is near-field (within about 15 km) then acceleration record should contain strong motion pulse similar to that caused directivity, etc.



2. Modifying and scaling time histories:

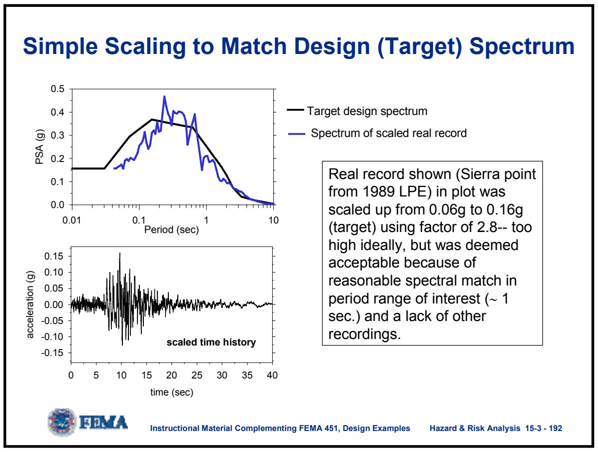
What is the motion at D?



2. Modifying and scaling time histories:

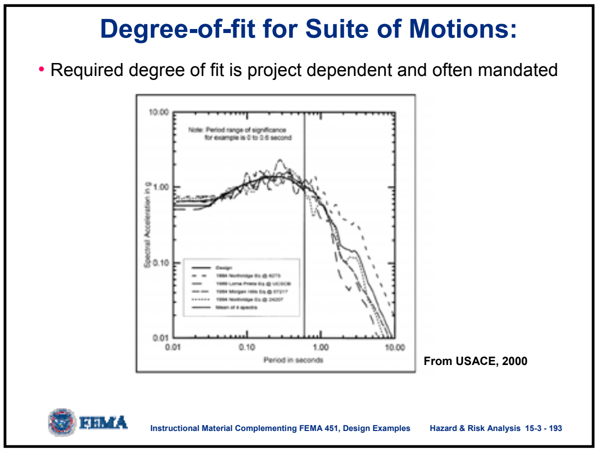
(a) Simple scaling – scale motions by single factor to match target spectrum; again limiting the scaling factor to 2.0.

- The required degree–of-fit to target spectrum is project-dependent, but typically want suite of candidate spectra to have average visual fit to target. More important to have conservative fit in period range of interest.



Simple Scaling to Match Design (Target) Spectrum

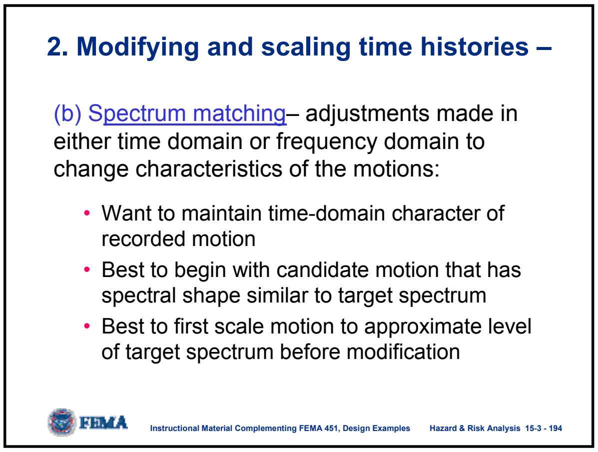
Real record shown (Sierra point from 1989 LPE) in plot was scaled up from 0.06g to 0.16g (target) using factor of 2.8-- too high ideally, but was deemed acceptable because of reasonable spectral match in period range of interest (~ 1 sec.) and a lack of other recordings.



Degree-of-fit for Suite of Motions:

- Required degree of fit is project dependent and often mandated

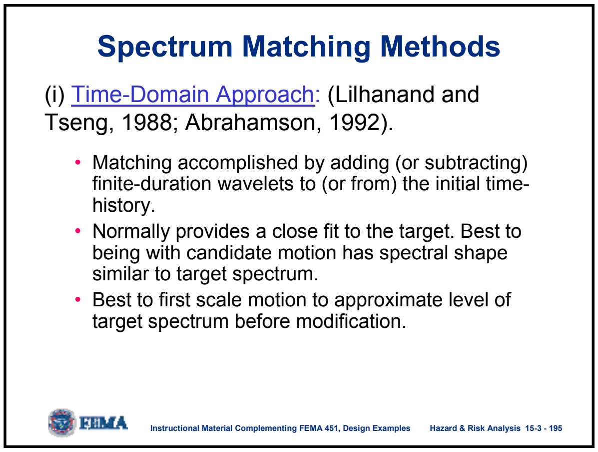
From USACE, 2000



2. Modifying and scaling time histories –

(b) Spectrum matching– adjustments made in either time domain or frequency domain to change characteristics of the motions:

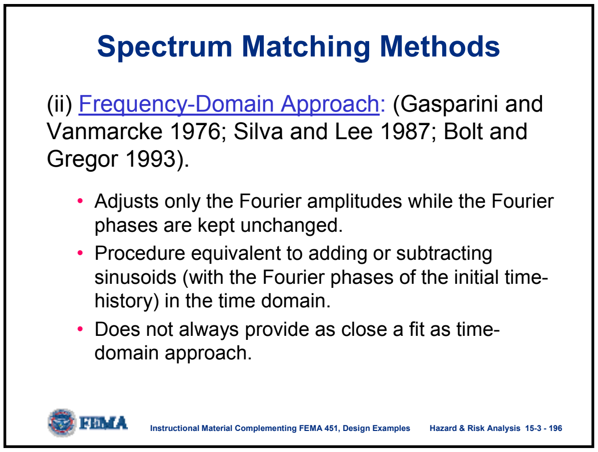
- Want to maintain time-domain character of recorded motion
- Best to begin with candidate motion that has spectral shape similar to target spectrum
- Best to first scale motion to approximate level of target spectrum before modification



Spectrum Matching Methods

(i) Time-Domain Approach: (Lilhanand and Tseng, 1988; Abrahamson, 1992).

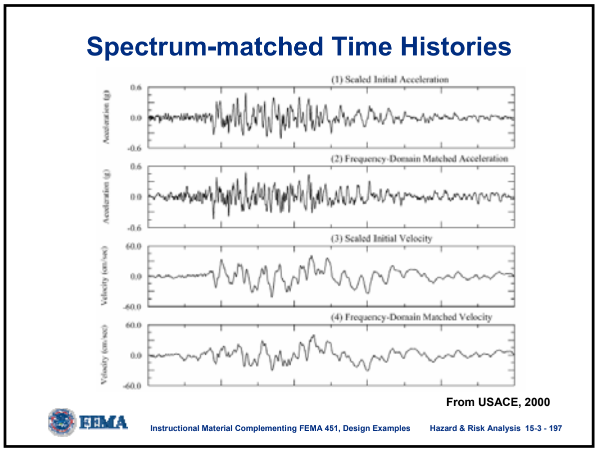
- Matching accomplished by adding (or subtracting) finite-duration wavelets to (or from) the initial time-history.
- Normally provides a close fit to the target. Best to being with candidate motion has spectral shape similar to target spectrum.
- Best to first scale motion to approximate level of target spectrum before modification.



Spectrum Matching Methods

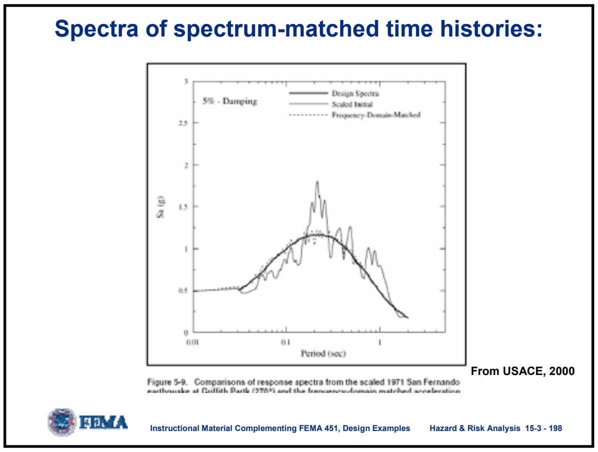
(ii) Frequency-Domain Approach: (Gasparini and Vanmarcke 1976; Silva and Lee 1987; Bolt and Gregor 1993).

- Adjusts only the Fourier amplitudes while the Fourier phases are kept unchanged.
- Procedure equivalent to adding or subtracting sinusoids (with the Fourier phases of the initial time-history) in the time domain.
- Does not always provide as close a fit as time-domain approach.



Spectrum-matched Time Histories

From USACE, 2000



Spectra of spectrum-matched time histories:

Figure 5-9. Comparisons of response spectra from the scaled 1971 San Fernando earthquake at Griffith Park (270°) and the frequency-domain matched acceleration

From USACE, 2000

Other corrections…

- Ensure records are instrument and base-line corrected, etc.

3. Modification for local site conditions

- Dynamic site response analysis is best approach (discussed in following lecture).

Real vs. Synthetic Time Histories

- What is considered a “real”record? (i.e., how much modification is allowed?)
- Un-scaled record motion vs. scaled recorded motion vs. synthetic.
- Synthetic motions developed using Fourier phase spectra from real earthquake probably “real” in most important ways.

Synthetic Time Histories – Pros and Cons

- One main concern: Is true character of real motion present?
- One main advantage: Can develop motions to match regional and site conditions (i.e., motion recorded on outcrops actually have surface wave energy included but we commonly input this to base).
  - there are many data gaps in database of motions (no strong motions for CEUS)
  - certainly better to have reasonable region-specific synthetic motion than inappropriate real motion

Developing Synthetic Motions

- Process should be performed by expert, typically seismologist.
- Seismologists typically develop a suite of time histories for hard rock or B-C (soft rock) boundary.
- Geotechnical engineers typically generate top-of-profile motions using site response analysis.

Synthetic Ground Motion Development

The computational model for generating synthetic seismograms consists of:

- The seismic source process;
- The process of seismic wave propagation from the source region to the design site; and
- Shallow site response (site response is discussed later).

Synthetic Ground Motion Development

Source Parameters Required

- Rupture velocity, rupture initiation point, and slip-time functions over the ruptured area are the primary source parameters needed.

Propagation (Path) Parameters Required

- Average propagation usually developed with Green's functions -- requires knowledge of the crustal parameters such as the P and S-wave velocities, density, and damping factor (or seismic *Q* factor, where *Q* = 0.5/damping ratio).

Synthetic Ground Motion Generation

- To model complexity of seismogram, randomness (stochastic model) is often introduced, either in the source process or in the wave propagation.
  - very erratic, irregular high-frequency waves from rupture process usually characterized as a "stochastic" process that must be modeled with randomness
  - deterministic process often used for low-frequency portion of motion
- Hybrid models combine deterministic with random process.

Synthetic Ground Motion Generation

- With fault slip model and Green's functions, ground motions are computed using the representation theorem (deconvolution process); see Aki and Richards 1980; Hartzell, Frazier, and Brune 1978.
- Simulation procedure simply sums a suite of Green's functions lagged in time (delay caused by the rupture propagation plus the time needed for the seismic waves to travel from the corresponding point source to the site).

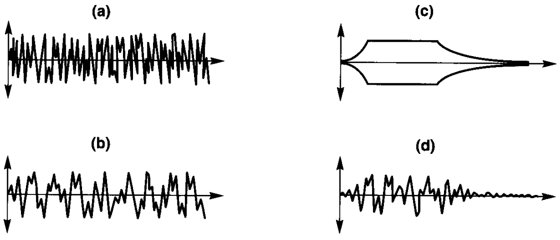
⇒ Green's Function is heart of the process.

Synthetic Ground Motion Methods

(1) Boore (1983): developed Band-Limited-White-Noise model for stochastic simulation of high-frequency ground motions.

- This simulation procedure does not use stochastic slip model.
- Procedure generates random white noise, multiplies it by a window function appropriate for the expected source duration, and then filters the windowed white noise to obtain a time-history having a band-limited Fourier amplitude spectrum specified by the ω^2-source Brune (1970) model.
- Incorporates wave propagation effects of a homogeneous crust with 1/*R* geometrical attenuation.

Boore (1983) – Illustration of Concept*:



Boore (1983): Example of time-domain generation of synthetic time history: (a) time history of white noise is filtered in the time domain to produce (b) time history of filtered white noise. Filtered white noise is multiplied by envelope function in (c) to produce the artificial ground motion shown in (d).

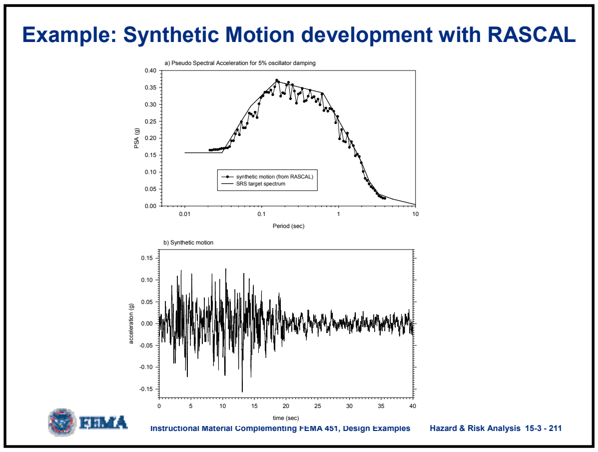
***Figure adapted from Kramer (1996)**

Synthetic Ground Motion Methods

(2) Silva and Lee (1987): method uses formulation for the Fourier amplitude spectrum similar to Boore, but the phase spectrum from a natural time-history to generate the synthetic time-history.

(3) Publicly available computer codes: Some public domain simulation codes are: RASCAL (Silva and Lee 1987) and SMSIM (Boore 1996).

⇒ The above methods (1 through 3) are well-established.



Example: Synthetic Motion development with RASCAL

Source Modeling for Synthetic Motions

1) Point source models (i.e., Brune source spectrum):
- Simple model where the source is represented by a point.
- Assumes "stationary" signal; provides average component.
- Need Magnitude, stress drop $\Delta\sigma$, density, crust modulus.

2) Finite fault models – modeling the actual rupture:
- Fault is divided into segments and each segment ruptures after another simulating energy release.
- Energy radiation from each segment is modeled using Green's Function.
- Motion from all segments added up to generate motion at a point from the fault.
- It models directivity, radiation, and non-stationarity.

1) Point Source Modeling – Brune Model

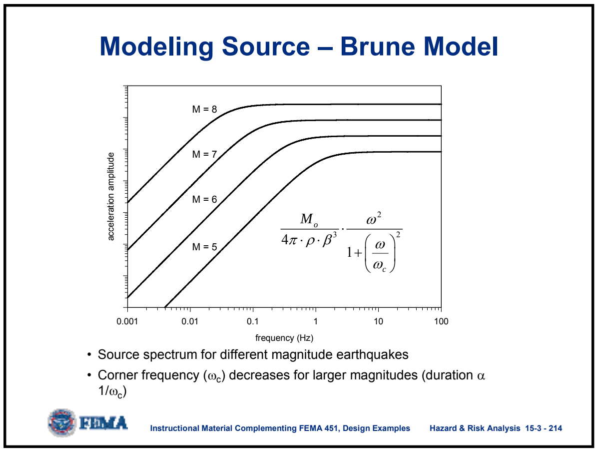
$$\text{Source }(\omega) = \frac{M_o}{4\pi \cdot \rho \cdot \beta^3} \cdot \frac{\omega^2}{1 + \left(\frac{\omega}{\omega_c}\right)^2}$$

M_o : seismic moment

ρ : mass density of earth's crust

β : shear wave velocity of earth's crust

ω_c : corner frequency ($2\pi f_c$) $f_c = 4.91 \times 10^6 \beta \left(\frac{\Delta\sigma}{M_o}\right)^{1/3}$



Modeling Source – Brune Model

$$\frac{M_o}{4\pi \cdot \rho \cdot \beta^3} \cdot \frac{\omega^2}{1 + \left(\frac{\omega}{\omega_c}\right)^2}$$

- Source spectrum for different magnitude earthquakes
- Corner frequency (ω_c) decreases for larger magnitudes (duration α $1/\omega_c$)

Modeling Path Effects

$$\text{Path }(\omega) = \frac{1}{r} \cdot e^{-\frac{\pi \cdot f \cdot r}{\beta \cdot Q(f)}}$$

r : distance to the source

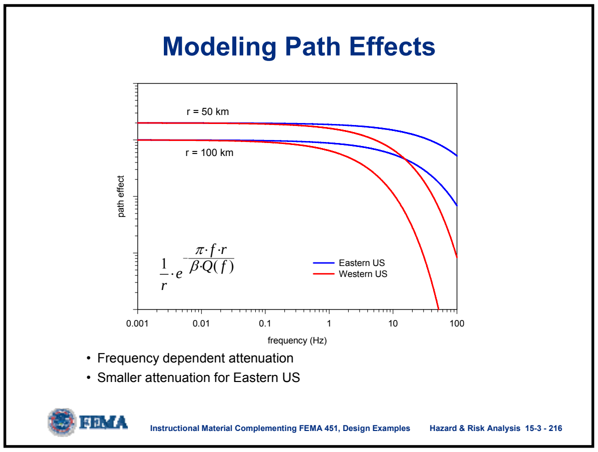
f : frequency

β : shear wave velocity of earth's crust

Q : quality factor (1/2D, D = damping ratio)

Q = 200 $f^{0.2}$ – Western US

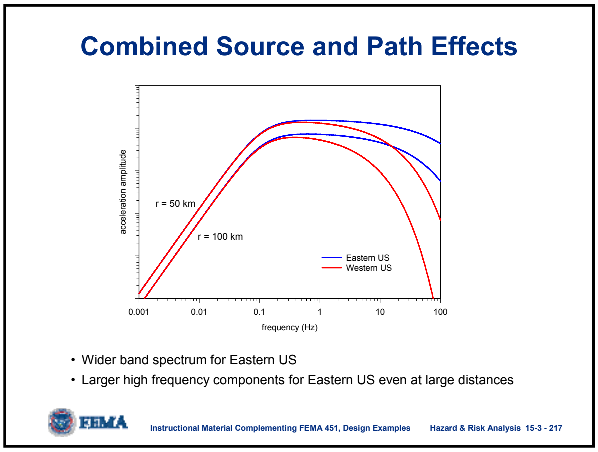
Q = 680 $f^{0.34}$ – Eastern US



Modeling Path Effects

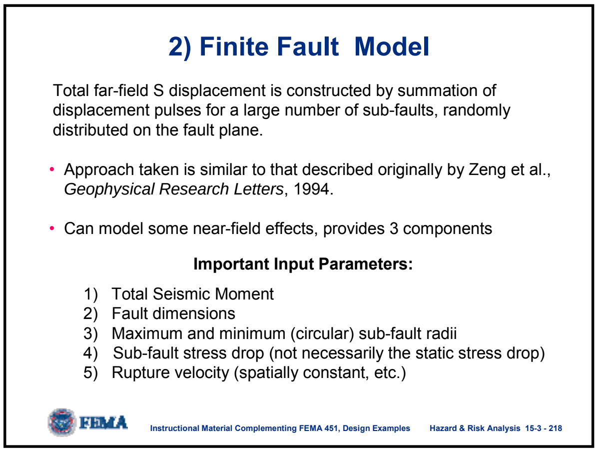
$$\frac{1}{r} \cdot e^{-\frac{\pi \cdot f \cdot r}{\beta \cdot Q(f)}}$$

- Frequency dependent attenuation
- Smaller attenuation for Eastern US



Combined Source and Path Effects

- Wider band spectrum for Eastern US
- Larger high frequency components for Eastern US even at large distances



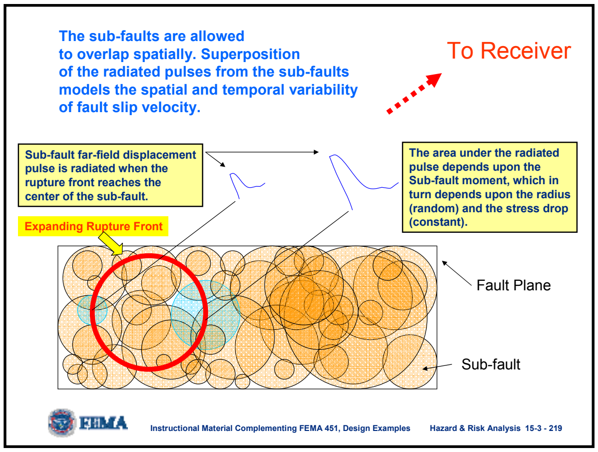
2) Finite Fault Model

Total far-field S displacement is constructed by summation of displacement pulses for a large number of sub-faults, randomly distributed on the fault plane.

- Approach taken is similar to that described originally by Zeng et al., *Geophysical Research Letters*, 1994.
- Can model some near-field effects, provides 3 components

Important Input Parameters:

1) Total Seismic Moment
2) Fault dimensions
3) Maximum and minimum (circular) sub-fault radii
4) Sub-fault stress drop (not necessarily the static stress drop)
5) Rupture velocity (spatially constant, etc.)



The sub-faults are allowed to overlap spatially. Superposition of the radiated pulses from the sub-faults models the spatial and temporal variability of fault slip velocity.

To Receiver

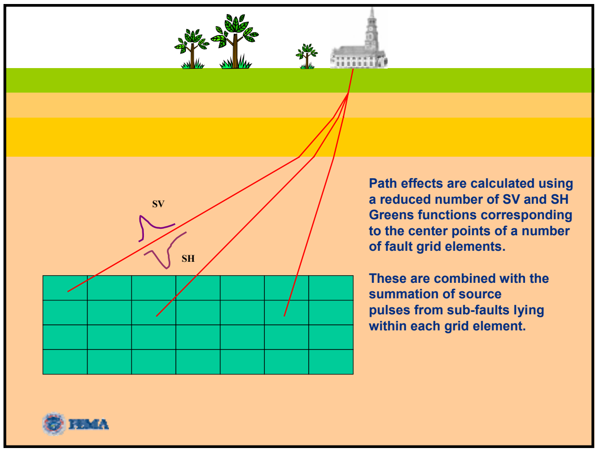
Sub-fault far-field displacement pulse is radiated when the rupture front reaches the center of the sub-fault.

The area under the radiated pulse depends upon the Sub-fault moment, which in turn depends upon the radius (random) and the stress drop (constant).

Expanding Rupture Front

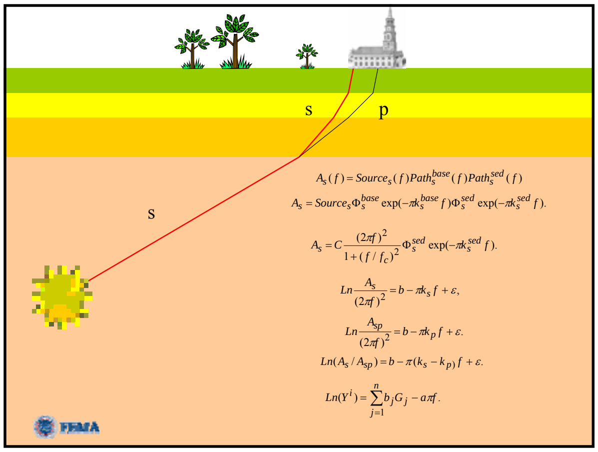
Fault Plane

Sub-fault



Path effects are calculated using a reduced number of SV and SH Greens functions corresponding to the center points of a number of fault grid elements.

These are combined with the summation of source pulses from sub-faults lying within each grid element.



$$A_s(f) = Source_s(f)Path_s^{base}(f)Path_s^{sed}(f)$$

$$A_s = Source_s\Phi_s^{base}\exp(-\pi k_s^{base} f)\Phi_s^{sed}\exp(-\pi k_s^{sed} f).$$

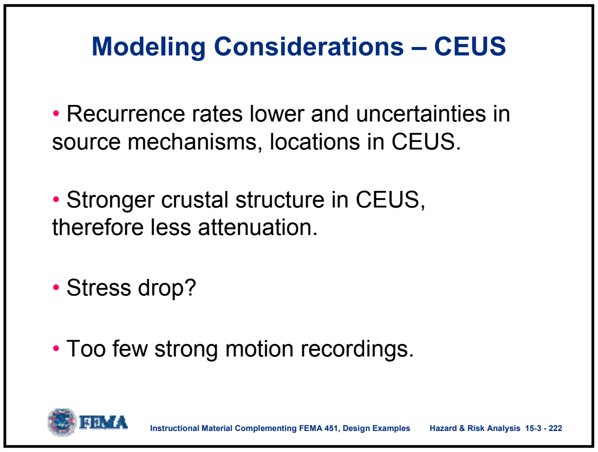
$$A_s = C\frac{(2\pi f)^2}{1+(f/f_c)^2}\Phi_s^{sed}\exp(-\pi k_s^{sed} f).$$

$$Ln\frac{A_s}{(2\pi f)^2} = b - \pi k_s f + \varepsilon,$$

$$Ln\frac{A_{sp}}{(2\pi f)^2} = b - \pi k_p f + \varepsilon.$$

$$Ln(A_s/A_{sp}) = b - \pi(k_s - k_{p)} f + \varepsilon.$$

$$Ln(Y^i) = \sum_{j=1}^{n} b_j G_j - a\pi f.$$



Modeling Considerations – CEUS

- Recurrence rates lower and uncertainties in source mechanisms, locations in CEUS.
- Stronger crustal structure in CEUS, therefore less attenuation.
- Stress drop?
- Too few strong motion recordings.