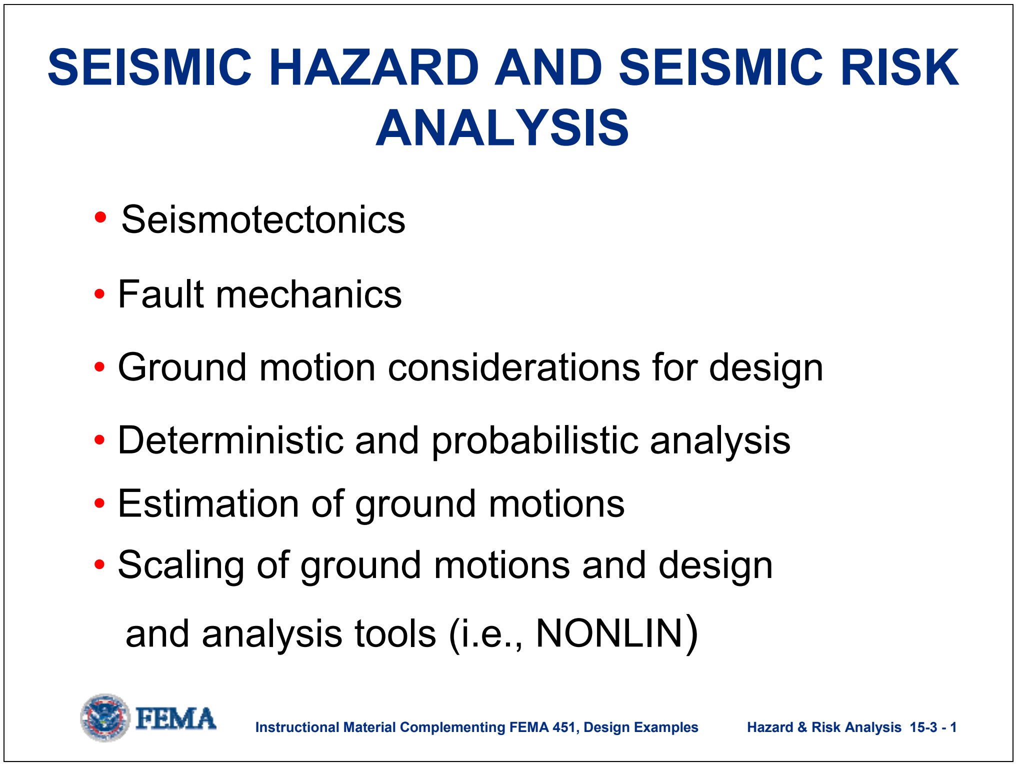
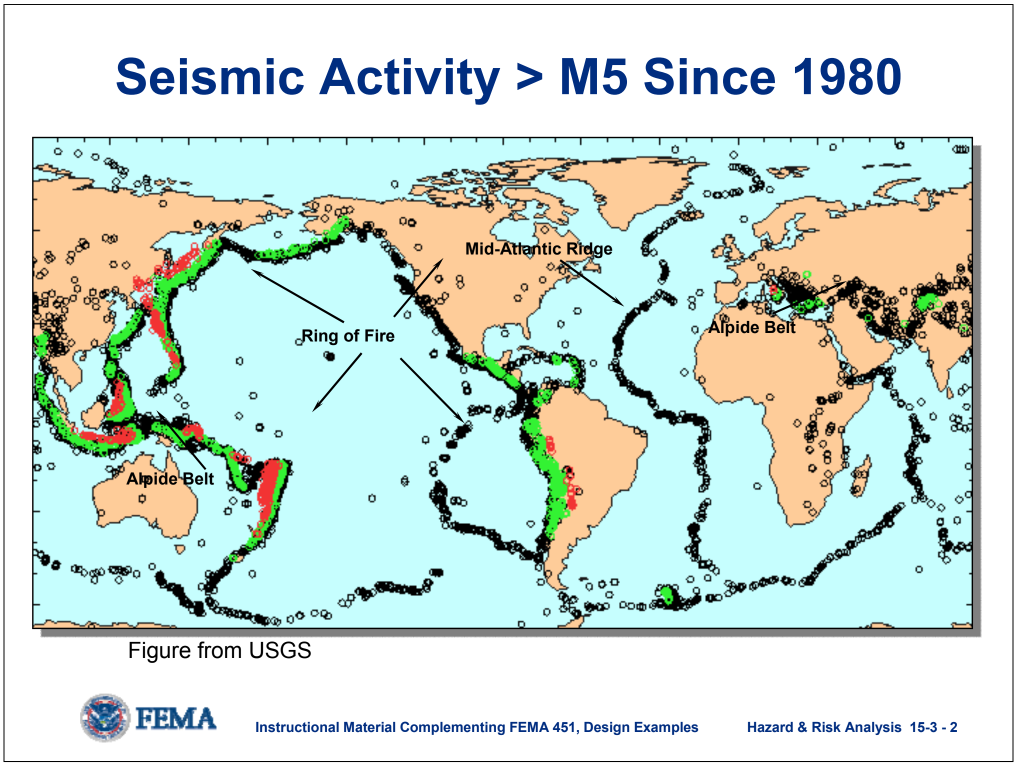


SEISMIC HAZARD AND SEISMIC RISK ANALYSIS

- 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)

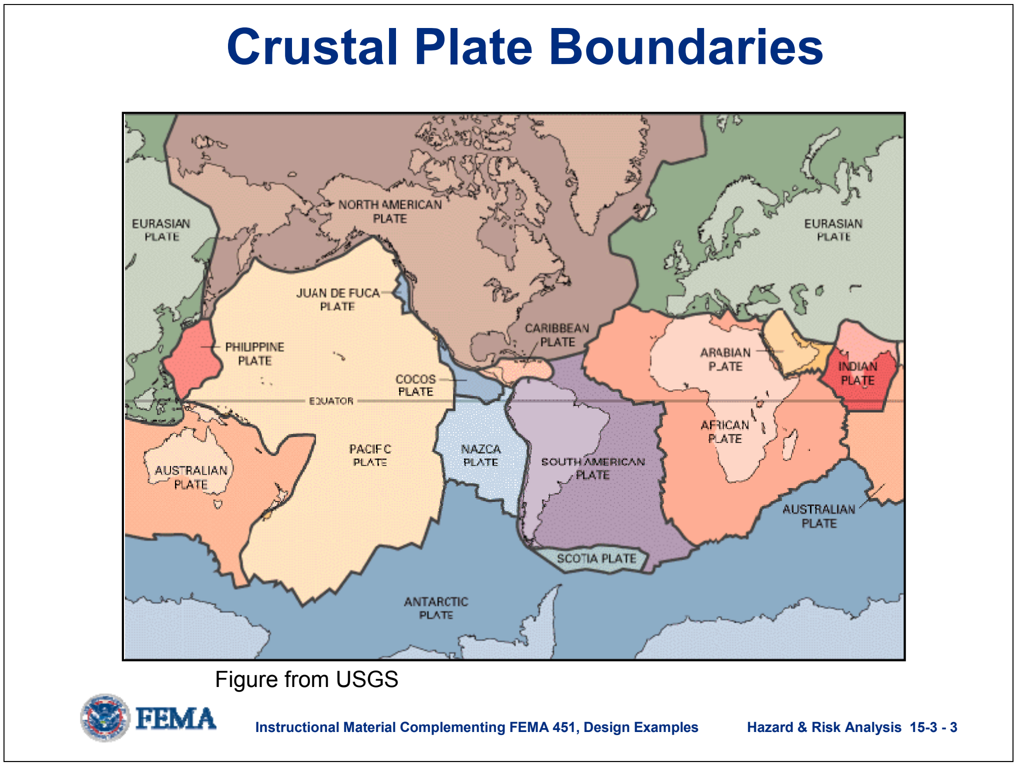
Note that many of the graphics used for this material were obtained from the U.S. Geological Survey (USGS) and other U.S. government sources. These graphics are in the public domain and not subject to copyright; however, appropriate credit is and should be given for such reproduced graphics.



Seismic Activity > M5 Since 1980

Figure from USGS

Figure above illustrates the location of the world’s three major seismic “belts” where 90% of the world’s earthquakes occur along these zones.



Crustal Plate Boundaries

Figure from USGS

Major plates and plate boundaries are shown. The existence of plates were first proposed around 1920 by A. Wegner, but it was not until the 1960s, with greatly improved seismic monitoring equipment and a marked increase in ocean floor research, that data revealed irrefutably the existence of a series of large plates. The locations of the earthquakes shown on the previous slide roughly delineate the boundaries of the major plates.

Convection Drives the Plates

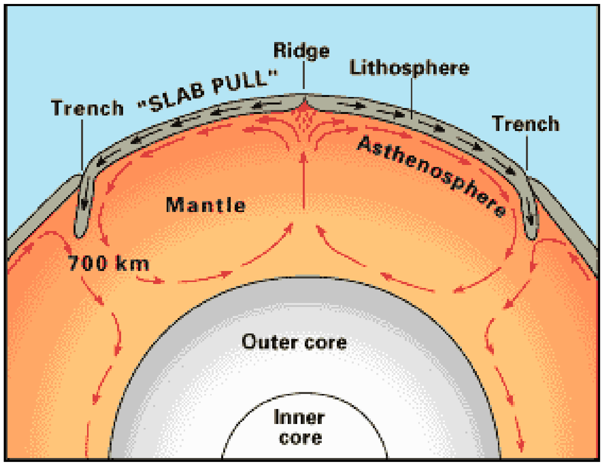
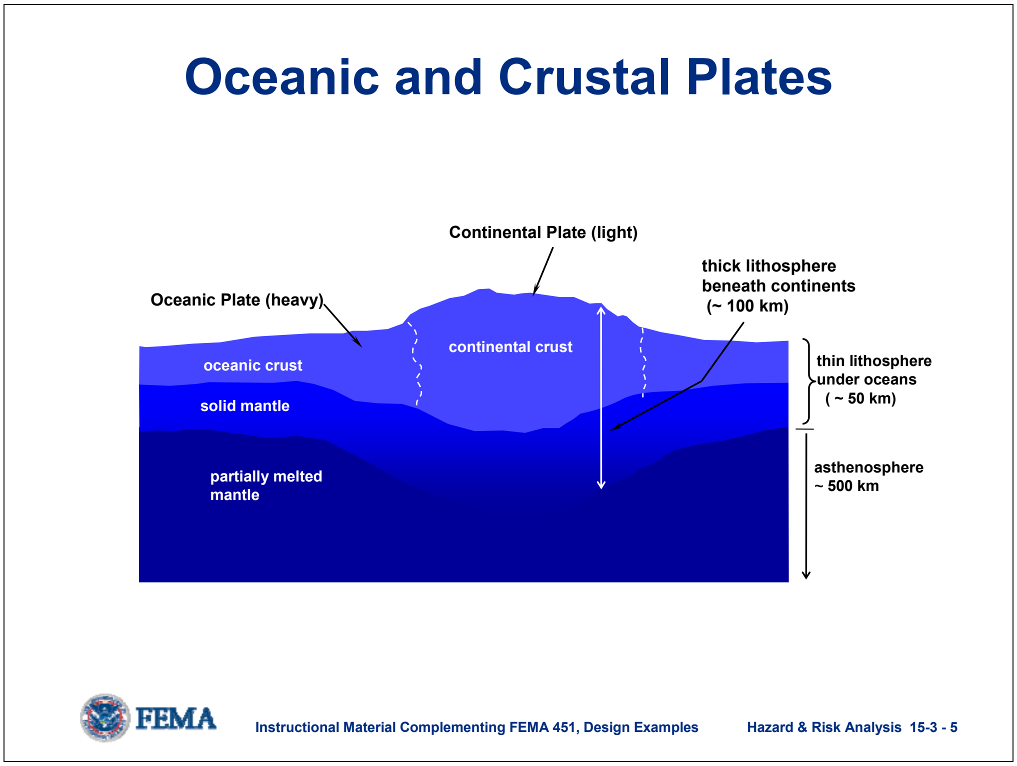


Figure credit: USGS.

Illustration of convection process that is the driving mechanism behind plate movements. The lithosphere is the outer part of the earth, consisting of the crust and upper mantle, approximately 100 km (62 mi.) thick on average. The asthenosphere is the upper zone of the earth's mantle that lies beneath the lithosphere and consists of several hundred kilometers of deformable rock.



Oceanic and Crustal Plates

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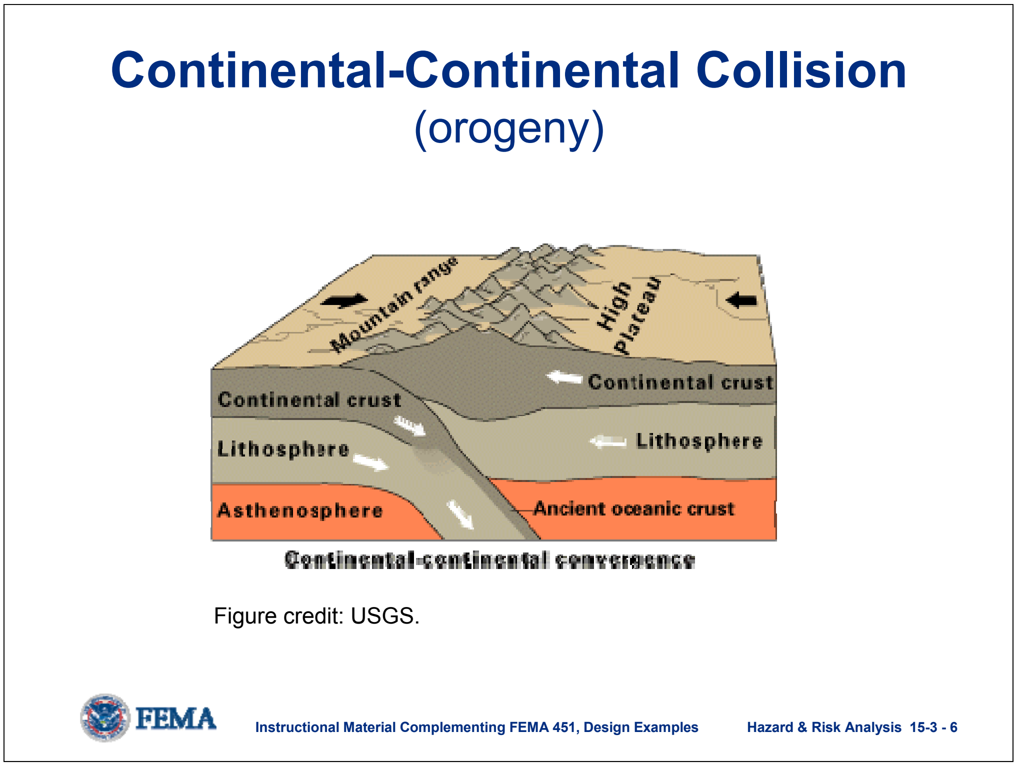
Depiction of typical relationship between the lithosphere and asthenosphere as well as difference between heavy oceanic crust and lighter continental crust. Lighter continental crust tends to “float” and heavy oceanic crust sinks or subducts below lighter continental crust when they collide. Continental crust is typically composed of silicic or granitic rocks with lighter minerals such as quartz and feldspar whereas oceanic crust is colder and denser and typically consists of mafic or basaltic rock rich in heavy mineral such as pyroxene or olivine.

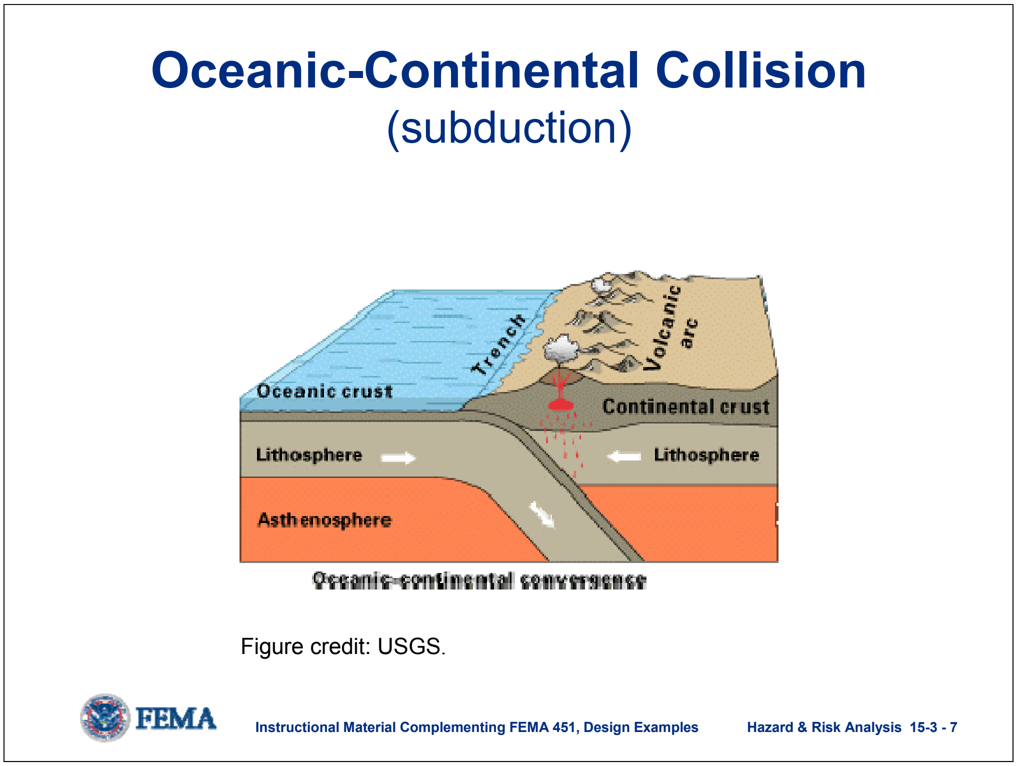


Continental-Continental Collision

(orogeny)

Figure credit: USGS.

Collisions of continental plates results in mountain building (orogeny).



Oceanic-Continental Collision

(subduction)

Figure credit: USGS.

When heavy oceanic crust collides with lighter continental crust, the heavy oceanic crust sinks below or subducts beneath the continental crust.

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 <u>interplate</u>** earthquakes.

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

Plate-boundary earthquake – 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. 90% of the world's earthquakes occur along plate boundaries. Frequent occurrence, relatively well understood behavior, as per plate tectonic theory.

Subduction zone earthquake - type of plate-boundary earthquake where one plate is subducting beneath the other. These earthquakes typically located very deep (up to 600 km depth recorded). Some of world's largest earthquakes are of this type. The 1985 Mexico City Earthquake was of this type.

Intraplate earthquake – earthquake that occurs along a fault within the stable region of a plate's interior (SICR). Examples of this type of earthquake are the New Madrid, MO Earthquakes of 1811-12 and the 1886 Charleston, SC earthquake. Several other active faults of this type are located in the central and eastern portions of North America. Intra-plate earthquakes can occur near plate margins -- the distinction between the two being whether the earthquake occurs on a fault forming the interface between two plates or otherwise. Infrequent occurrence, often poorly understood. There are many uncertainties about intraplate earthquakes. The causative faults for historical intraplate earthquakes in the central and eastern US are typically at depths of less than about 25 km, and involve shear failure of brittle rocks. The specific mechanisms for these earthquakes are poorly understood. Possible mechanisms are discussed below. Why do earthquakes occur in intraplate regions such as the eastern U.S.? Some possibilities: ancient "rifts" – very old fractures in crust related to previous episodes of continental spreading. Rifts are created as a continent breaks apart in tension due to dissimilar rates of spreading beneath the crust. Rifts can be found in the interior portions of continental plates. Earthquakes in Charleston and New Madrid are probably associated with faults from rift zones created due to spreading associated with what is now the Atlantic Ocean (i.e., Iapetan Ocean preceded Atlantic).

New Madrid and St. Lawerence Valley: Earthquakes here are associated with faults initially formed during the rifting of the proto-North American continent (Laurasia) during the formation of an ancient ocean called Iapetus, approximately 700 million years ago.

Charleston: probably associated with faults that formed in the mid Mesozoic Era (Late Triassic- early Jurassic Periods Mesozoic faulting 100-200 mill. yrs. ago) during rifting of Pangea accompanying the formation of the modern Atlantic Ocean. "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 during this process, stresses become more concentrated in the crust. 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?

Mississippi Embayment (weight of sediments caused fracture that generated New Madrid earthquakes?)

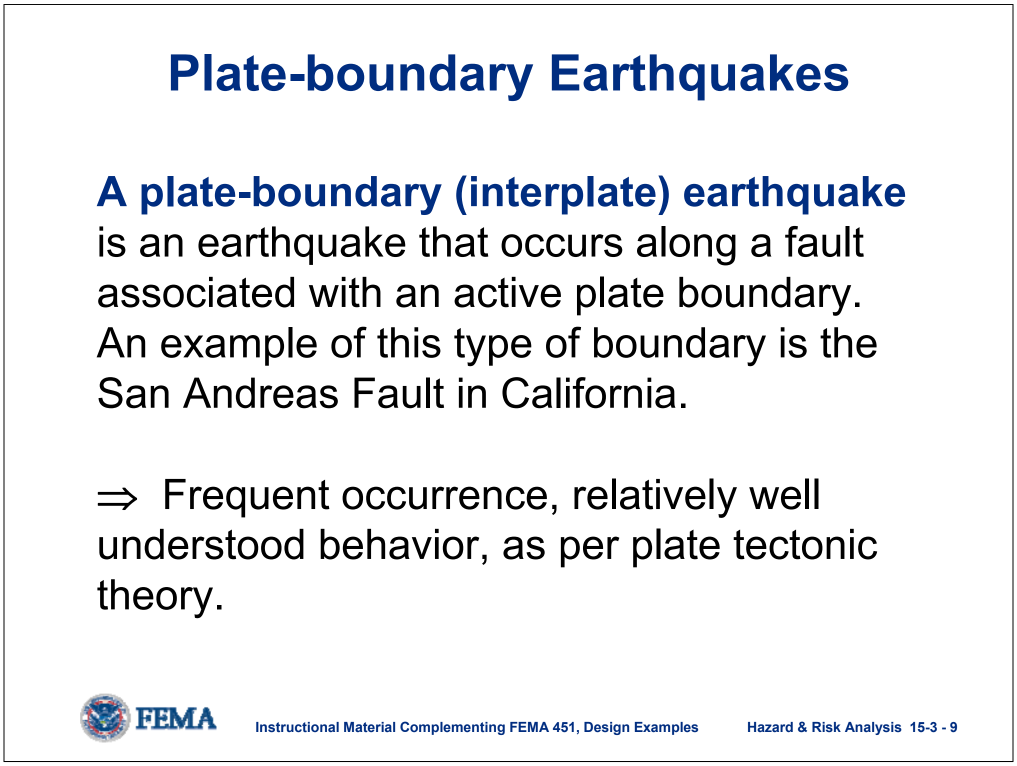
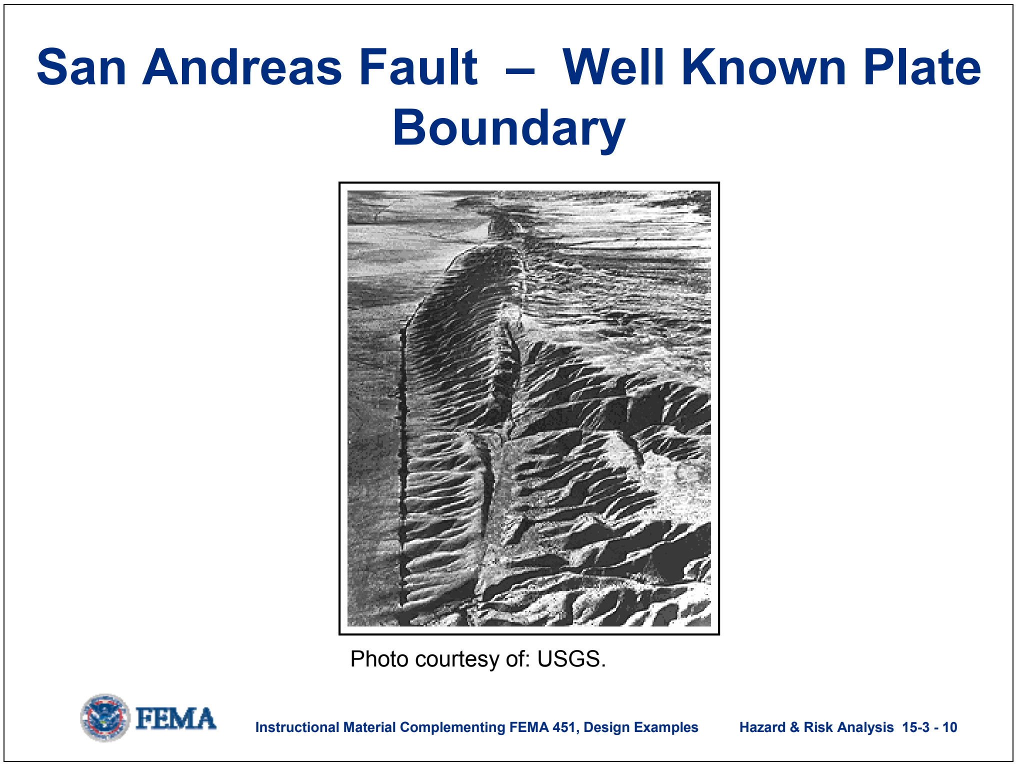


Plate-boundary Earthquakes

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.

Plate-boundary earthquake – 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. 90% of the world's earthquakes occur along plate boundaries.



San Andreas Fault – Well Known Plate Boundary

Photo courtesy of: USGS.

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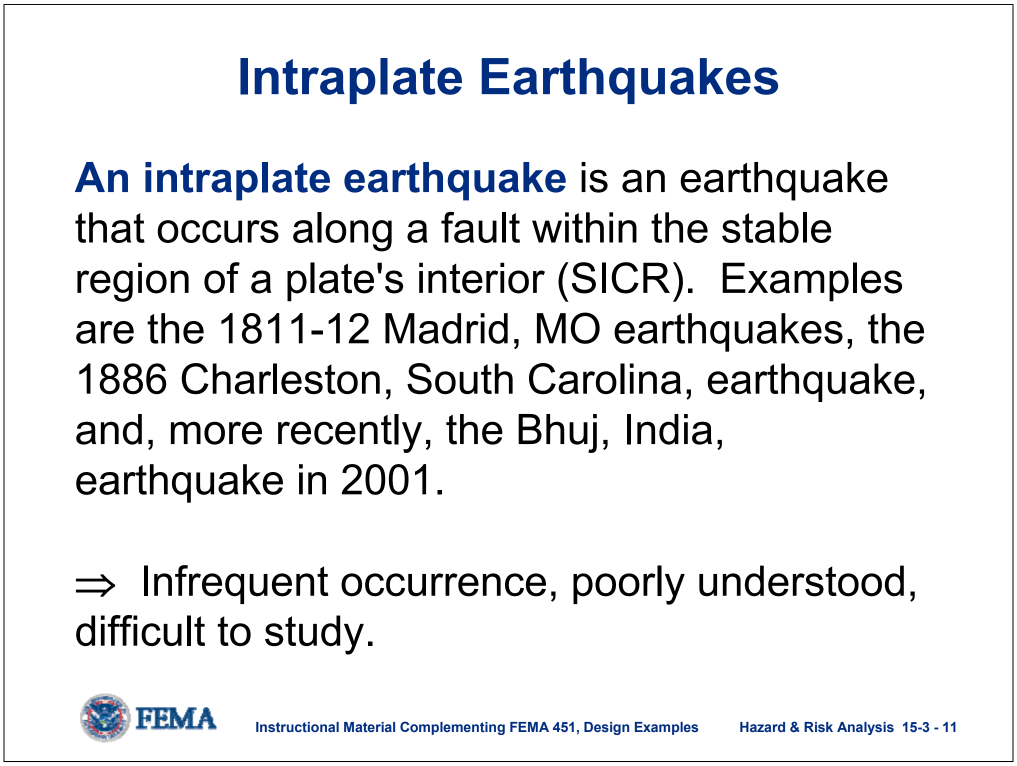
Slide shows the San Andreas Fault System. Note that there are at least two prominent fractures that can be seen. Thus, there are many smaller faults associated with he San Andreas Fault System as would be expected with two major plates meet. The San Andreas Fault involves mostly strike-slip type faulting movement.

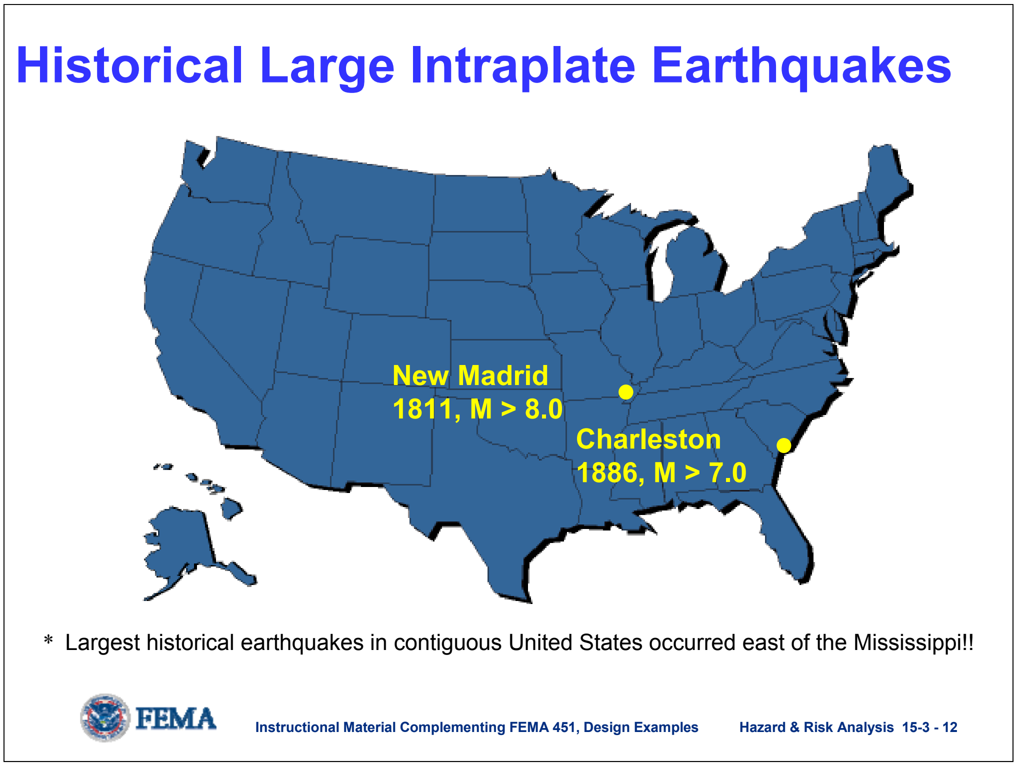


Intraplate Earthquakes

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.

Intraplate earthquake – earthquake that occurs along a fault within the stable region of a plate's interior (SICR). Examples of this type of earthquake are the New Madrid, Missouri, earthquakes of 1811-12 and the 1886 Charleston, South Carolina, earthquake. Several other active faults of this type are located in the central and eastern portions of North America.



Historical Large Intraplate Earthquakes

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

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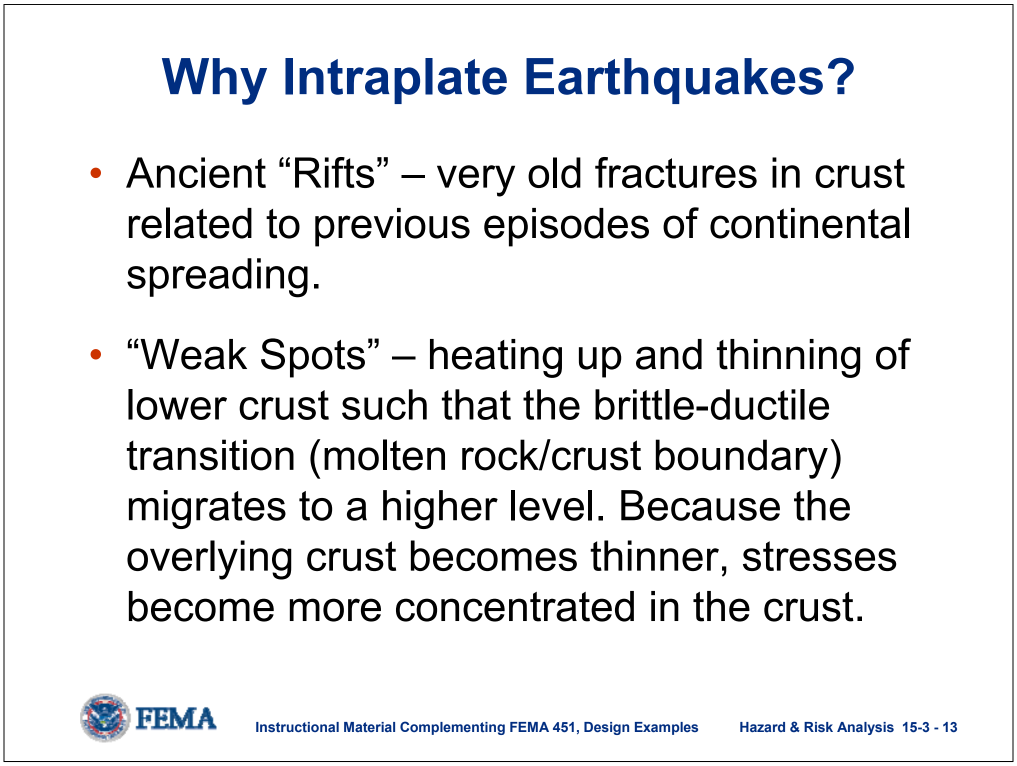
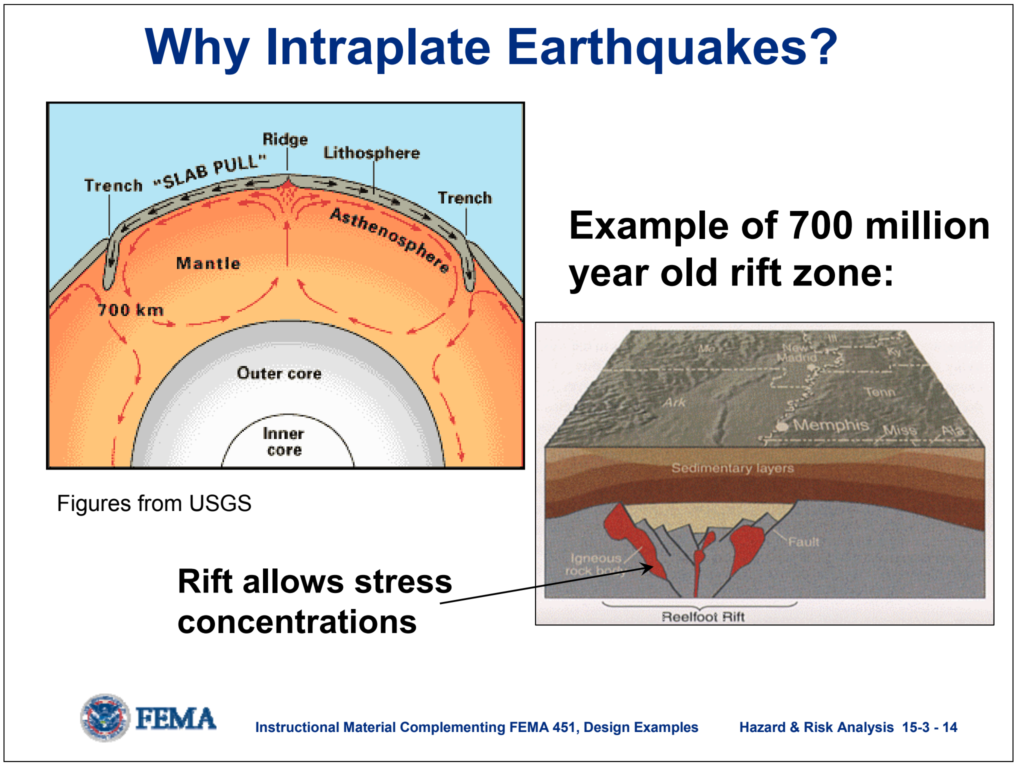
Note that two of the largest historical earthquakes in the contiguous United States occurred east of the Mississippi River. This should be a surprising fact to many.



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.

Rift zones from episodes of continental rifting (breaking of crust in tension basically) are associated with earthquakes in several intraplate regions, especially in the central and eastern United States (CEUS and EUS); however, other mechanisms such as weak spots are less definitive in terms of the occurrence of intraplate earthquakes.



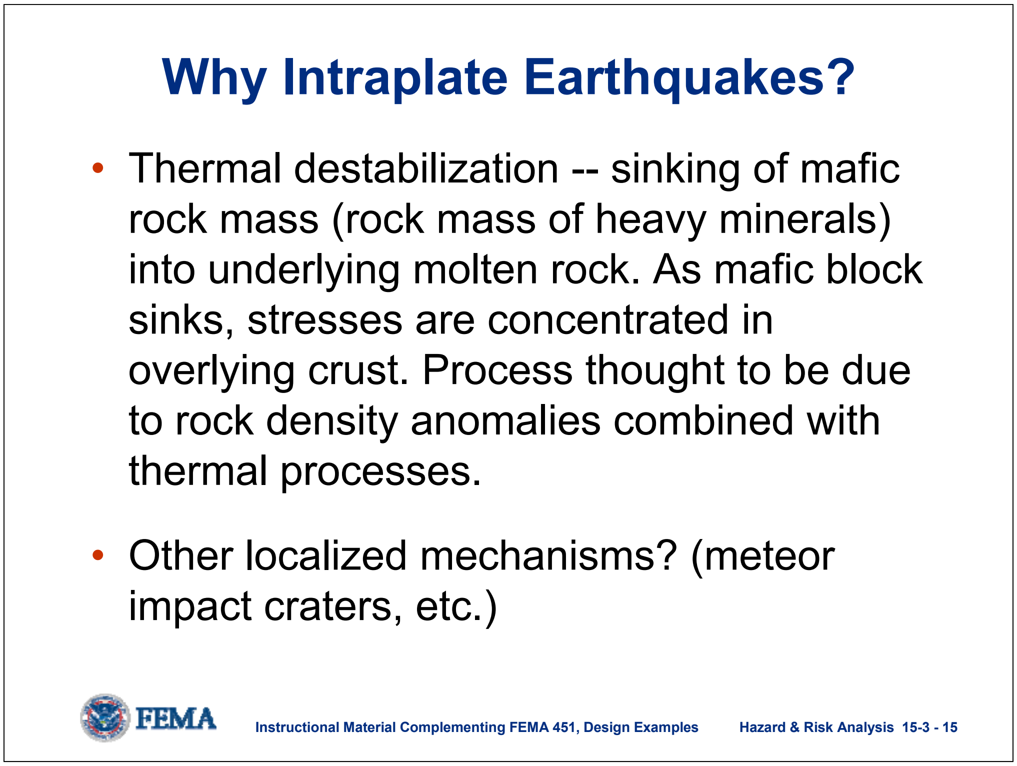
Why Intraplate Earthquakes?

Figures from USGS

Example of 700 million year old rift zone:

Rift allows stress concentrations

The Reelfoot Rift is associated with seismicity in the New Madrid region. The rift formed approximately 700 millions years ago. There is an estimated 86-97% chance of a magnitude 6.0 or larger earthquake occurring in the NMSZ by the year 2035; see various USGS and CERI studies (i.e., see http://www.ceri.memphis.edu).



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.)

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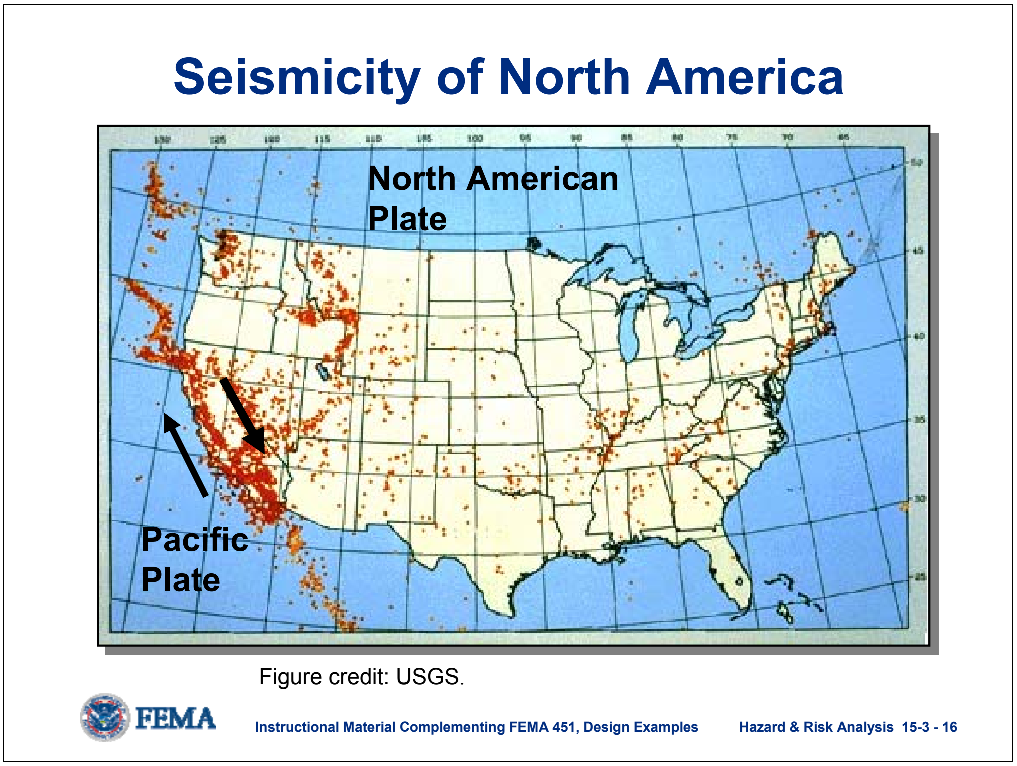
Rift zones from episodes of continental rifting (breaking of crust in tension basically) are associated with earthquakes in several intraplate regions, especially in the central and eastern US; however, other mechanisms such as weak spots are less definitive in terms of the occurrence of intraplate earthquakes.



Seismicity of North America

Figure credit: USGS.

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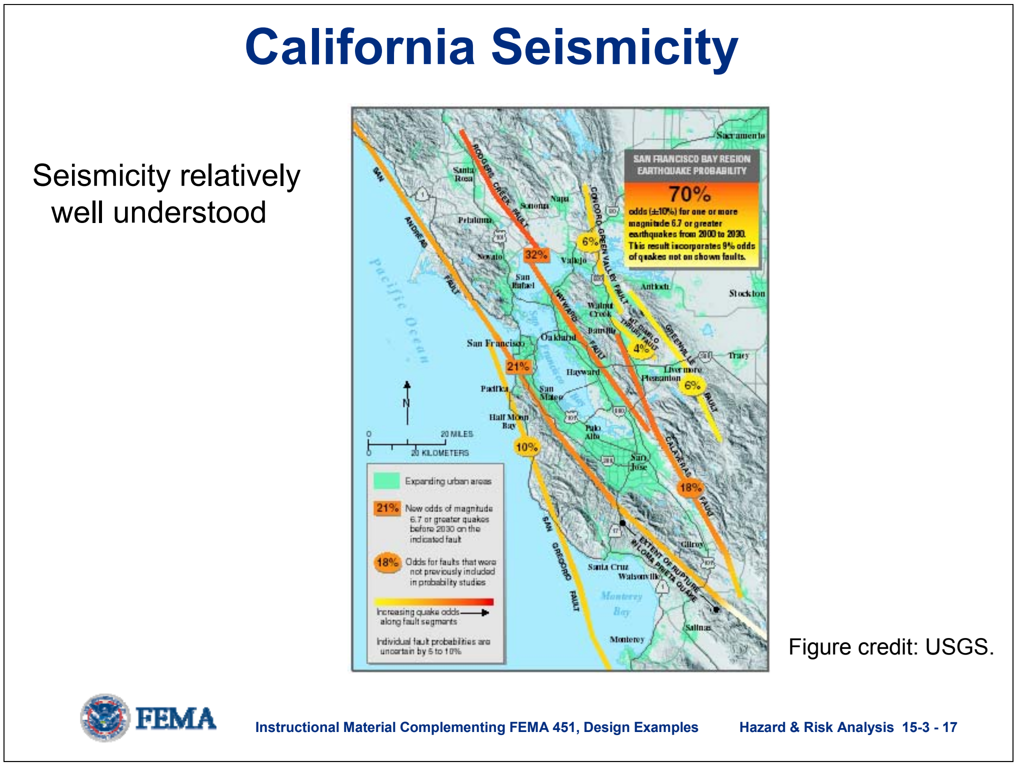
Red data points in figure indicate locations of recorded earthquakes in 48 states. Map above represents earthquake activity over about a 20-year period and earthquakes shown are large enough to have been felt (> magnitude 4 or so). The map indicates that most US seismicity is located in the western states, but earthquake occur in many regions of the US, including the interior portions of the plate. In general, east of the Rockies, individual known faults and fault lines are unreliable guides to the likelihood of earthquakes. In California, a large earthquake can generally be associated with a particular fault because we have watched the fault break and offset the ground surface during the earthquake. In contrast, east of the Rockies things are less straightforward, because it is rare for earthquakes to break the ground surface. In particular, east of the Rockies, most known faults and fault lines do not appear to have anything to do with modern earthquakes. We don't know why. We do know that most earthquake locations cannot be measured very accurately east of the Rockies. Earthquakes typically occur several miles deep within the Earth. Their locations, including their depths, are usually uncertain by a mile or more. Although the larger faults extend from their fault lines downward deep into the Earth, their locations at earthquake depths are usually wholly unknown. The uncertain underground locations of earthquakes and faults make it terrifically hard to determine whether a particular earthquake occurred on a particular known fault. We also know that there are many faults hidden underground that are large enough to generate damaging earthquakes, but which are also too small to extend from earthquake depths all the way up to ground level where we have the best chance of seeing the faults. These hidden faults are likely to be at least as numerous as the faults we know about. Accordingly, an earthquake is as likely to occur on an unknown fault as on a known fault, if not more likely. The result of all this is that fault lines east of the Rockies are unreliable guides to where earthquakes are likely to occur.

Accordingly, the best guide to earthquake hazard east of the Rockies is probably the earthquakes themselves. This doesn't mean that future earthquakes will occur exactly where past ones did, although that can happen. It means that future earthquakes are most likely to occur in the same general regions that had past earthquakes. Some future earthquakes are likely to occur far from past ones, in areas that have had few or no past earthquakes. However, these surprises are not too common. Most earthquakes tend to occur in the same general regions that are already known to have earthquakes.



California Seismicity

Seismicity relatively well understood

Figure credit: USGS.

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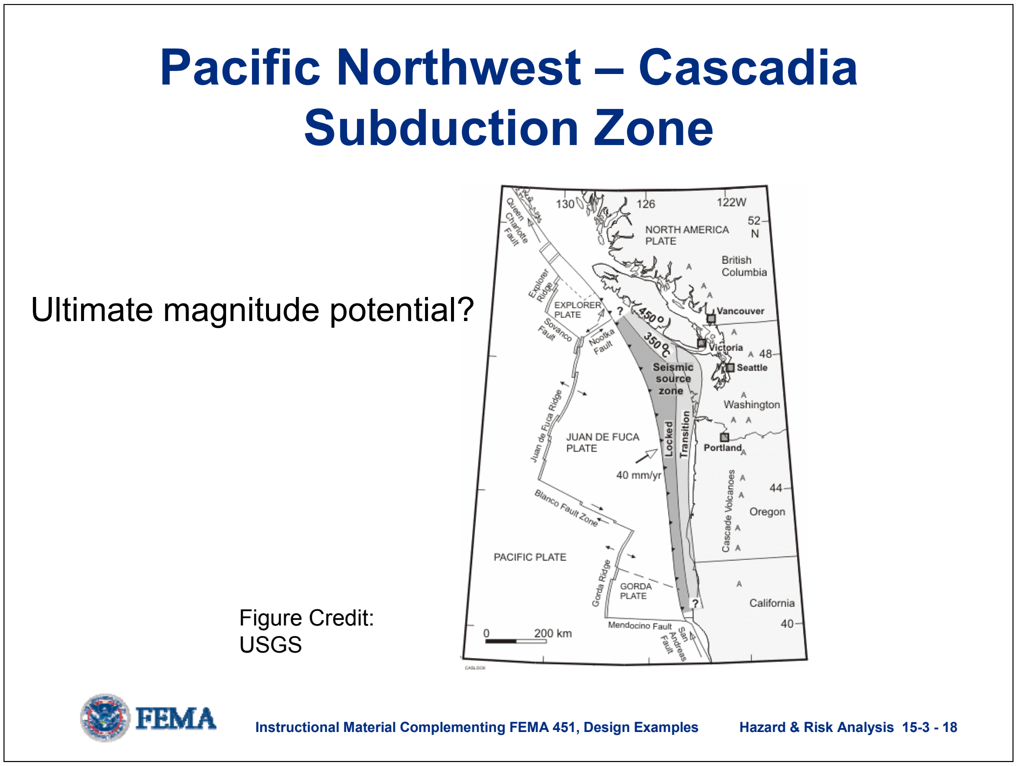
Map indicates seismicity of northern California region, along with estimated probabilities of earthquake occurring in that region. Seismicity in this region, as well as in southern California, is relatively well understood. Northern California is used here as an example of the type of seismic hazard studies that have been performed for much of California.



Pacific Northwest – Cascadia Subduction Zone

Ultimate magnitude potential?

Figure Credit:
USGS

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Although the seismic mechanism is relatively well understood for earthquakes in the Pacific Northwest – most are associated with the Cascadia Subduction Zone, there is still much debate as to how large earthquakes along this zone can be. More specifically, there is debate as to how strong ground shaking would be inland in the populated regions. Some have suggested the possibility of great earthquakes, exceeding magnitude 8. However recent studies have refuted these claims and do not suggest earthquake shaking from events this large during the last several thousand years.

Idaho, Utah, Wyoming

Recurring events along Wasatch Fault

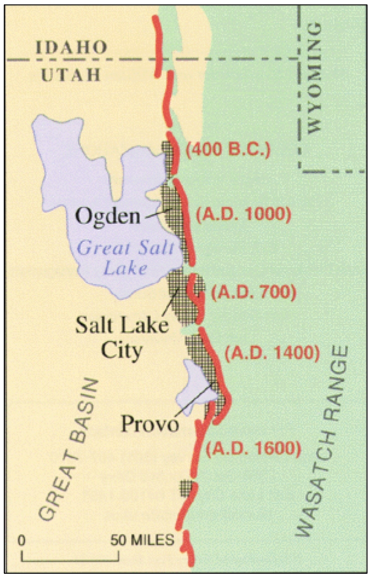
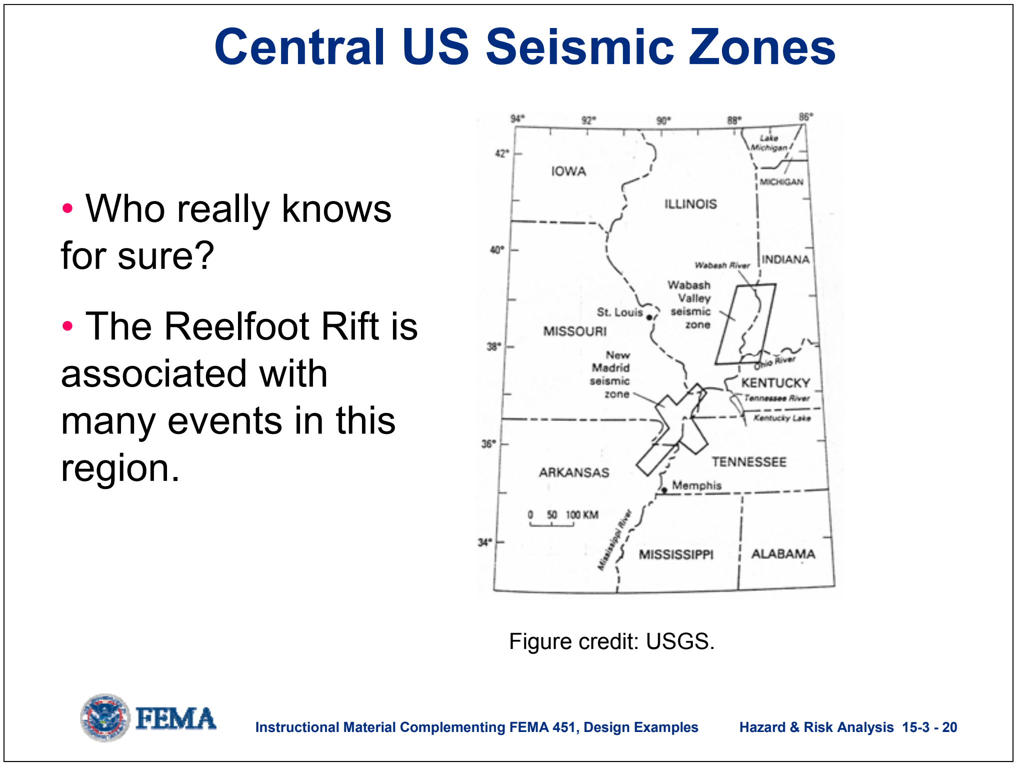


Figure credit: USGS.

Figure illustrates paleo-evidence of recurring earthquakes along the Wasatch Fault. The dates of the earthquakes were determined from paleoseismic investigations.



Central US Seismic Zones

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

Figure credit: USGS.

FEMA

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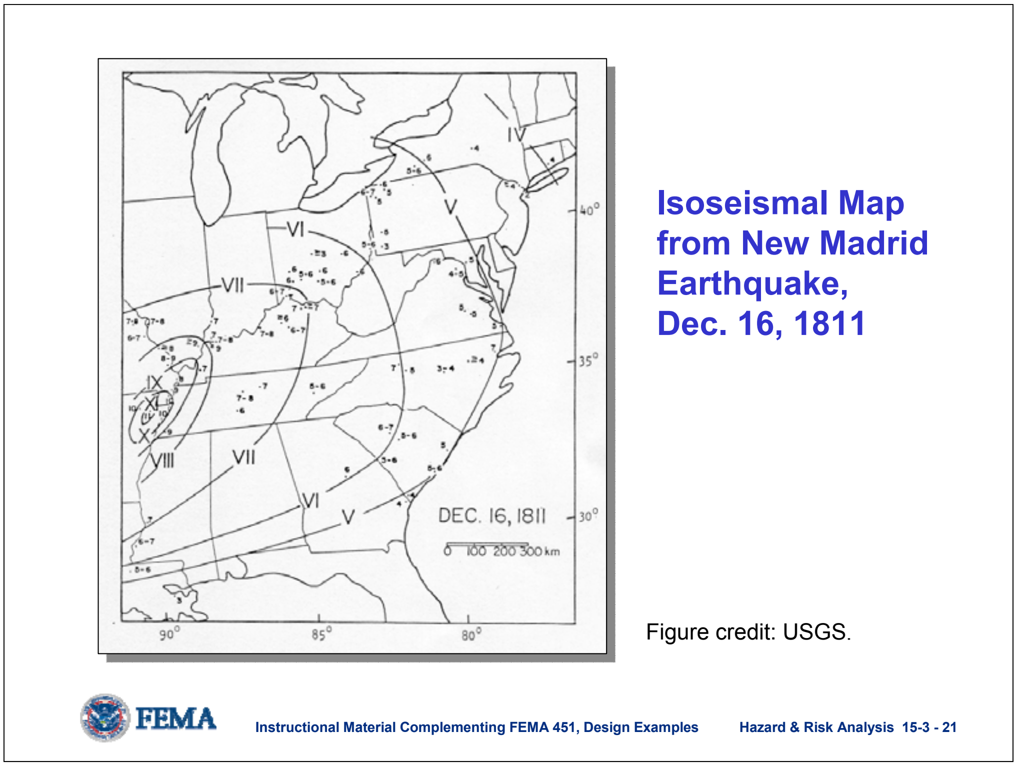
Specific seismic mechanisms in the CEUS are not as well understood, but the Reelfoot Rift is known to be associated with many earthquakes in this region. (Rift zones from episodes of continental rifting (breaking of crust in tension basically) are associated with earthquakes in several intraplate regions, especially in the central and eastern US; however, other mechanisms such as weak spots are less definitive in terms of the occurrence of intraplate earthquakes).



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

Figure credit: USGS.

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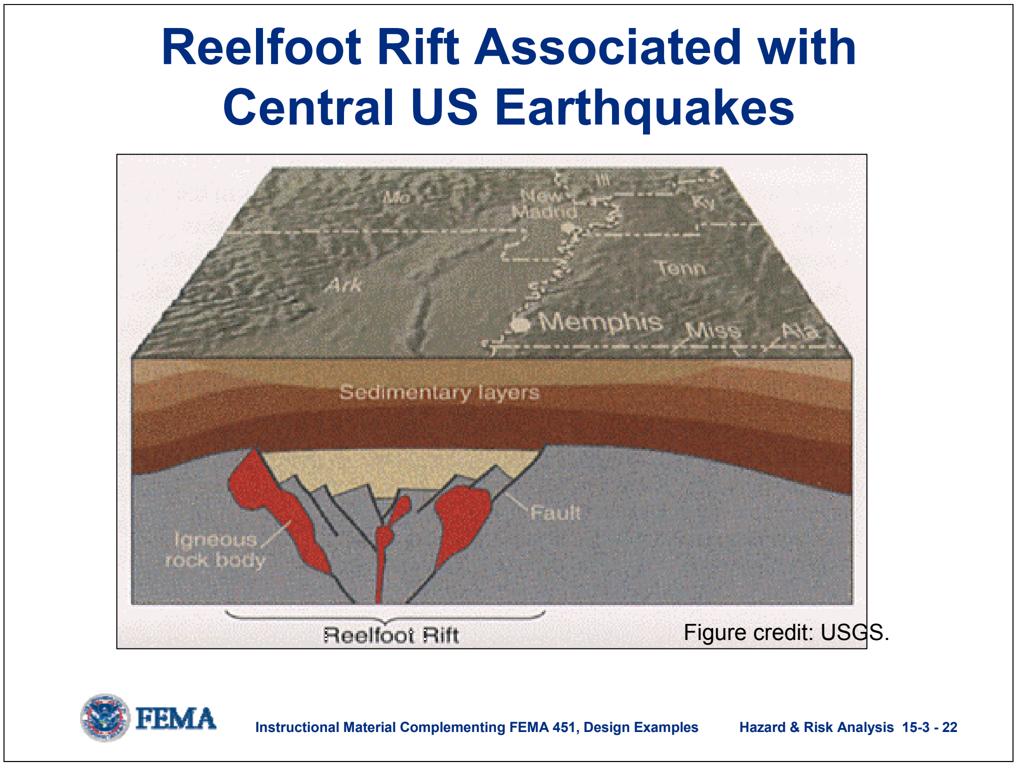
Isoseismal patterns from M 8+ event in 1811 indicate this event was felt over a very large area. The attenuation (dying out of earthquake energy) in this region is much lower than in the active plate margin regions of the western US.



Reelfoot Rift Associated with Central US Earthquakes

Figure credit: USGS.

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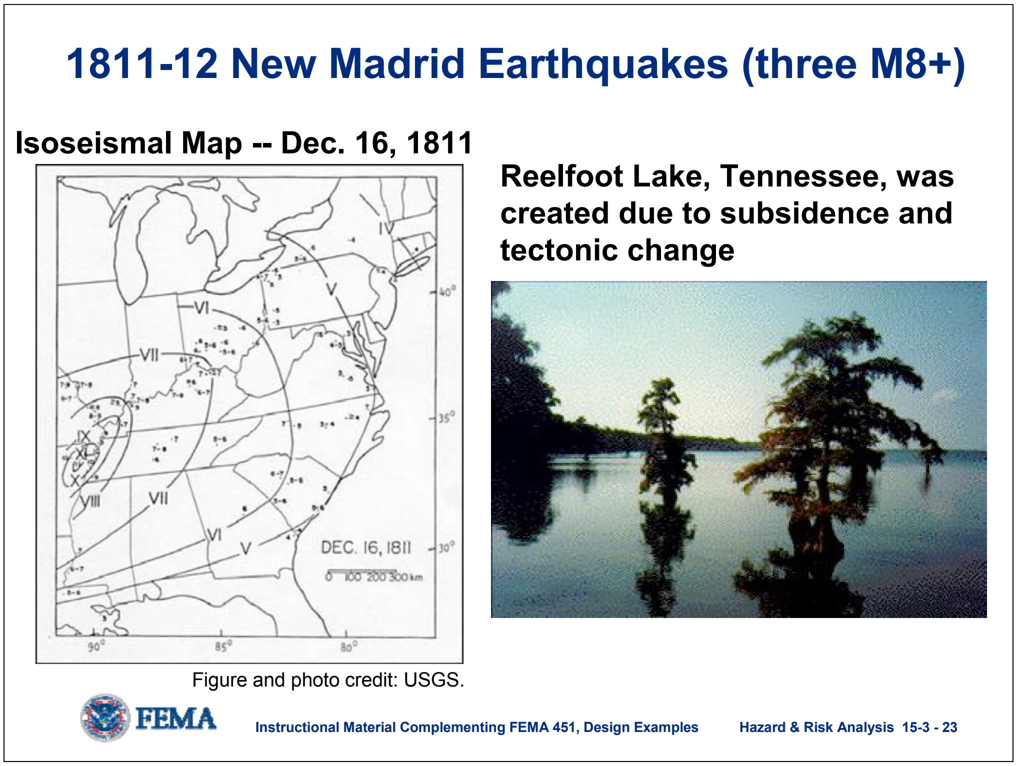
The Reelfoot Rift is associated with seismicity in the New Madrid region. The Rift is thought to be associated with Iapetan Faults approximately 700 million years old.



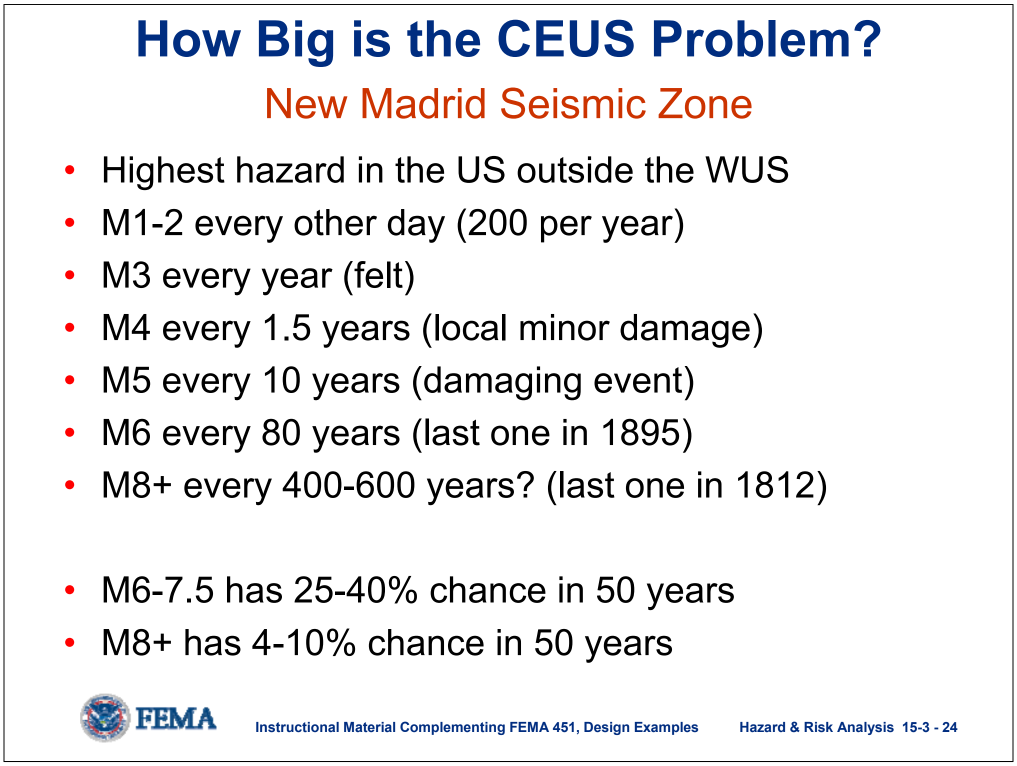
1811-12 New Madrid Earthquakes (three M8+)

Isoseismal Map -- Dec. 16, 1811

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

Figure and photo credit: USGS.

The 1811-12 New Madrid Earthquakes were felt over a significant portion of the eastern US. The tectonic land-level changes in the region caused the Mississippi River to temporarily flow backwards forming Reelfoot Lake.



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

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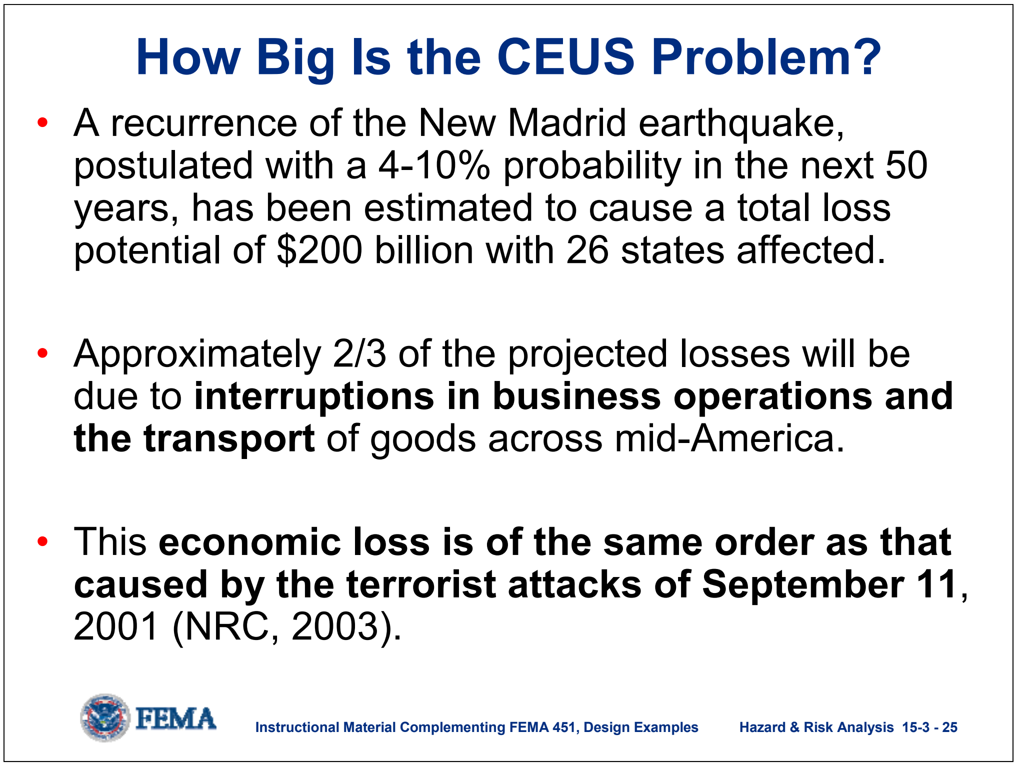
The New Madrid Zone has the highest seismic hazard outside the WUS. Of particular concern is the repeat of the M6 event (last one in 1895) from this source zone, as this event is relatively likely to occur and would result in significant damages over a widespread area. Data above is taken from:



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).

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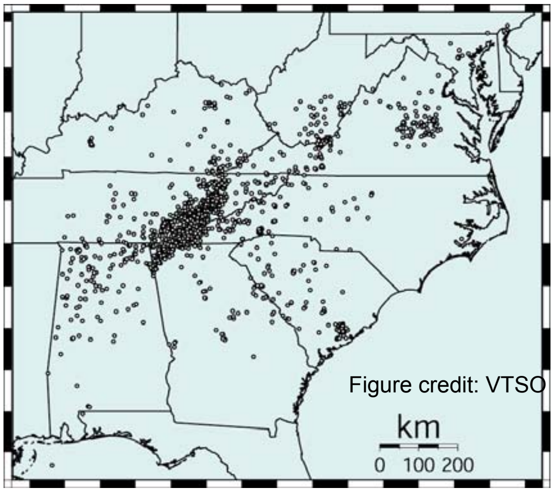
The large projected losses associated with to interruptions in business operations and the transport of goods across Mid-America can be better understood when it is considered that many transportation structures, such as key bridges, are very vulnerable to earthquake shaking and typically require long periods before they can be repaired or re-built. Consider the transportation situation in mid-America if key bridges along major highways are down and/or blocking river traffic as well.

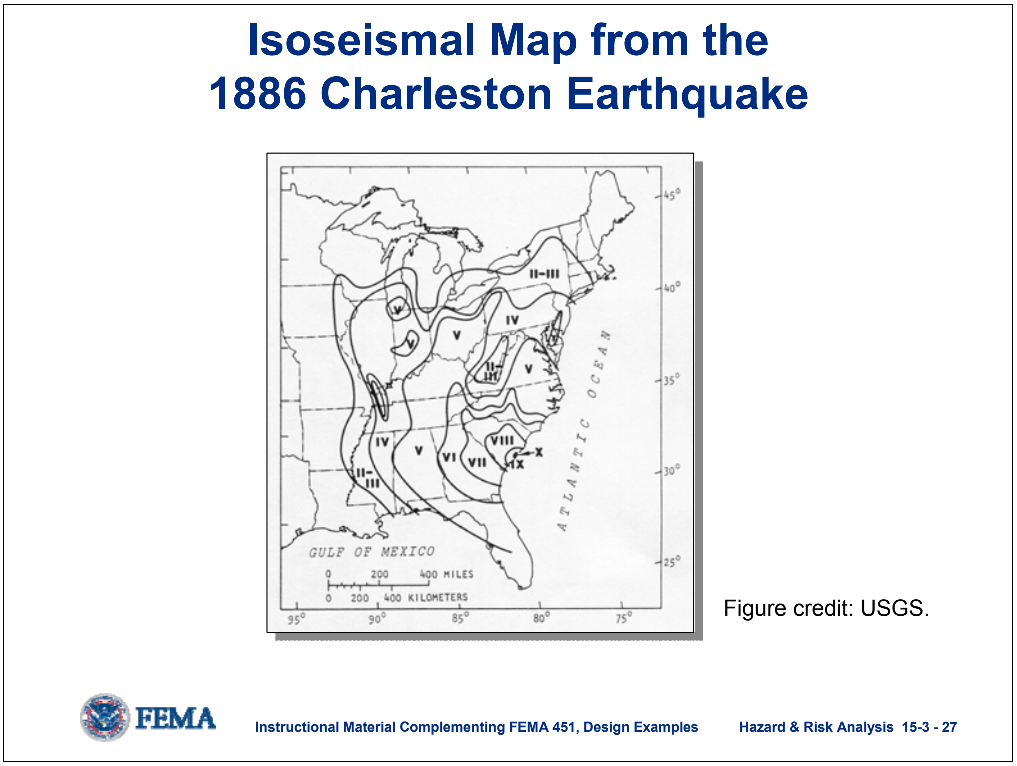
Southeastern Seismicity

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



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

Eastern Tennessee is one of the most active seismic regions in the eastern US. The more small earthquakes occur, the more likely large earthquakes will occur. Thus, the active seismicity in the region is of concern.



Isoseismal Map from the 1886 Charleston Earthquake

Figure credit: USGS.

Motions for the 1886 Charleston, SC were felt over much of the US reflecting the low rate of attenuation.

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

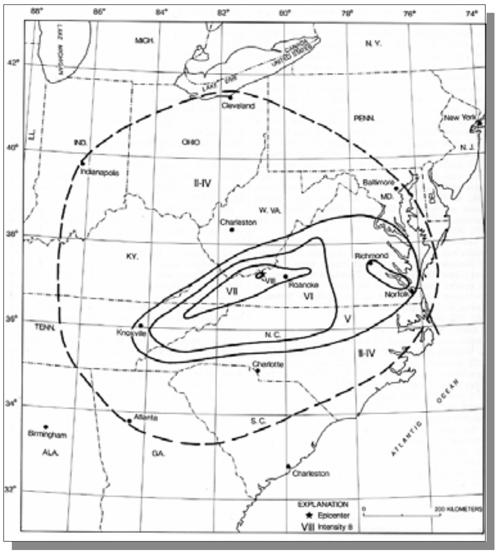


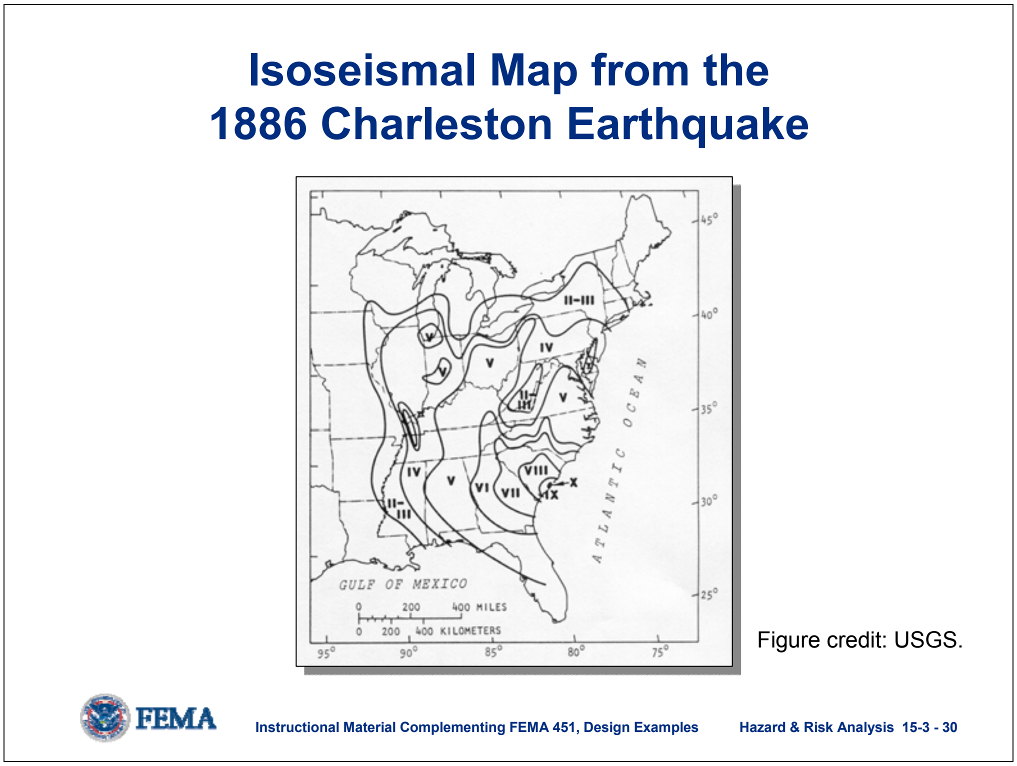
Figure credit: USGS.

Isoseismal Map for the Giles County, Virginia, earthquake of 1897. This event was felt over a large area for its relatively small size (M5.5+ range).

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

None.



Isoseismal Map from the 1886 Charleston Earthquake

Figure credit: USGS.

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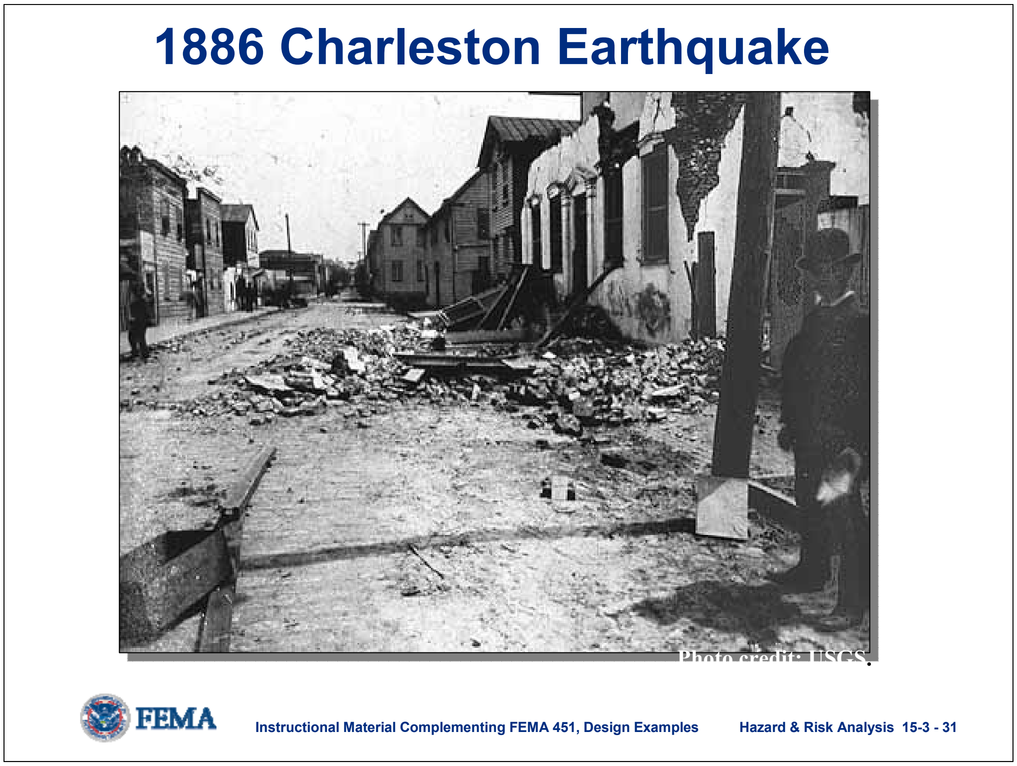
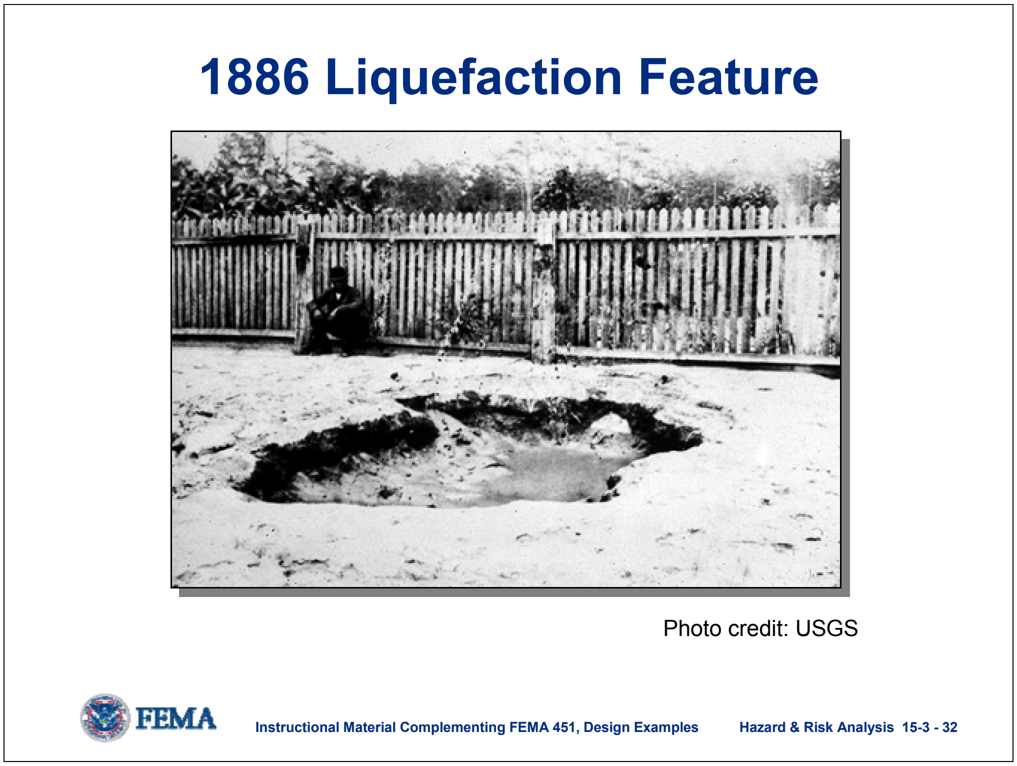
Motions for the 1886 earthquake in Charleston, South Carolina, were felt over much of the eastern US.



1886 Charleston Earthquake

Photo credit: USGS.

Photograph of downtown Charleston following the 1886 earthquake. Damage resulted from strong ground shaking as well as soil liquefaction.



1886 Liquefaction Feature

Photo credit: USGS

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Liquefaction crater formed during the 1886 Charleston earthquake near Ten Mile Hill. This location is near the current Charleston Airport/AFB. Craters such as these filled in during the days and weeks following the earthquake. These features can still be readily identified within the geologic profile when unearthed by trenching as shown on the following slides.

Prehistoric Sand Crater in Trench Wall

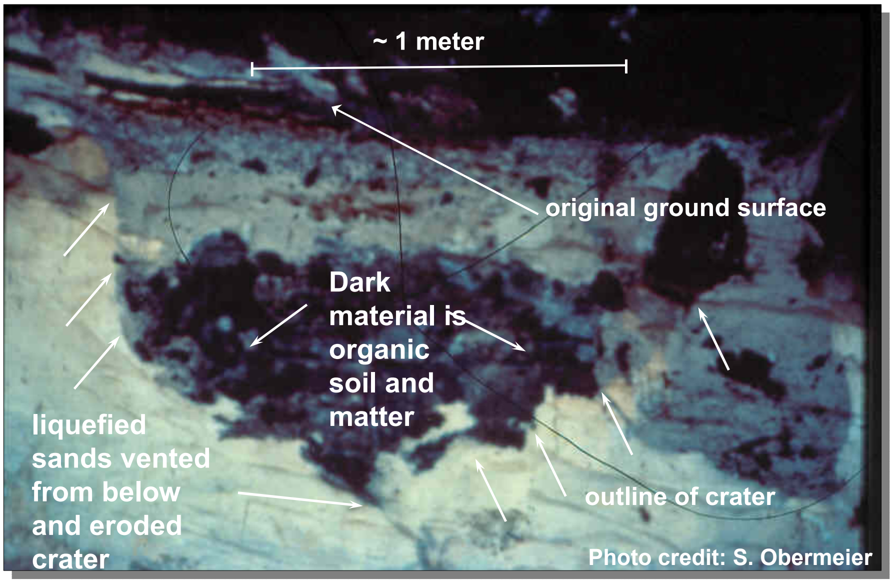
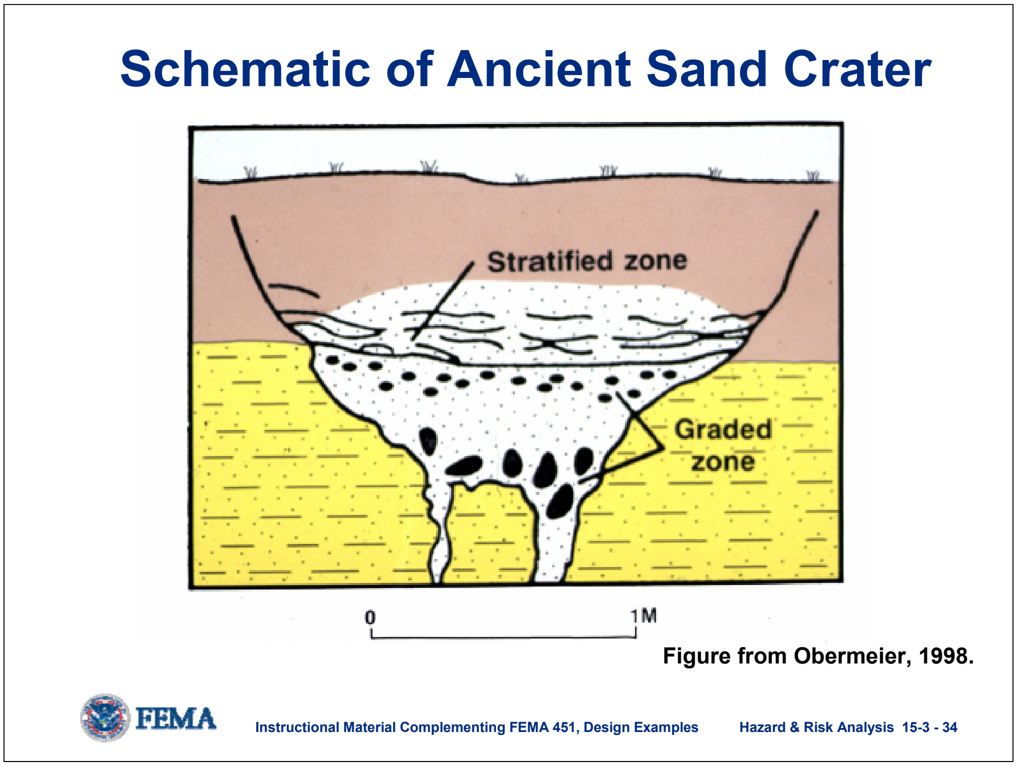


Photo credit: S. Obermeier

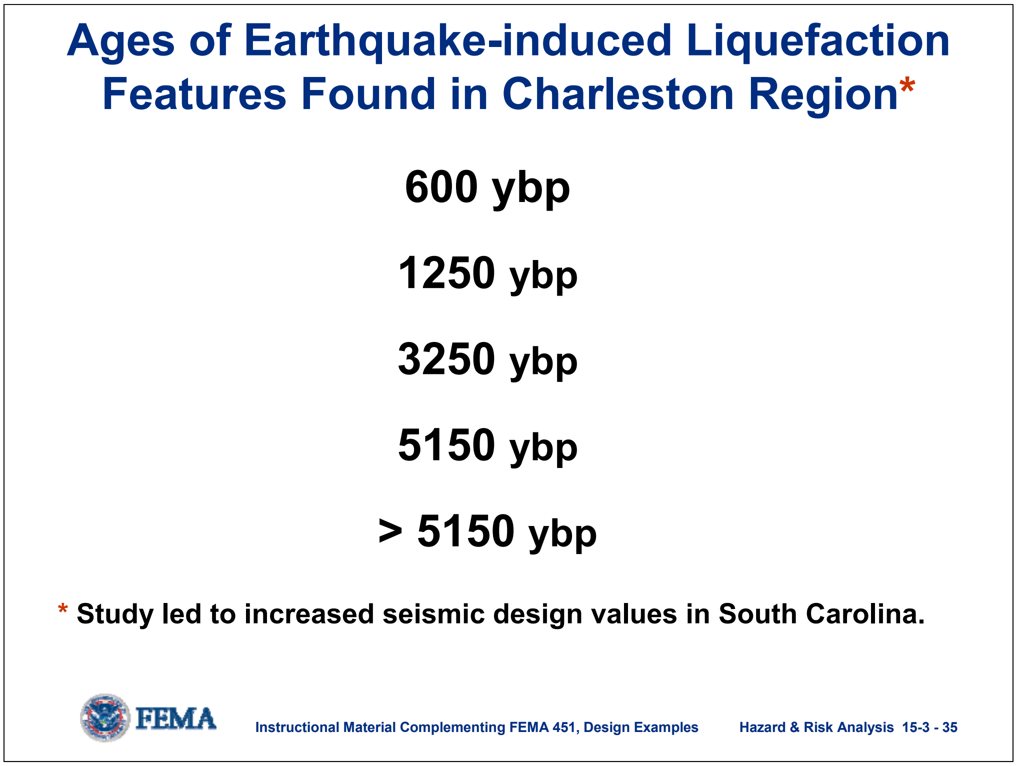
Ancient liquefaction crater found in wall of freshly excavated ditch in the Charleston area. Dark matter is humate-rich soil from the original B-horizon. This material often contains organic material that can be dated using Carbon-14 or other technique. Arrows above delineate the outline of the crater. Note that the liquefaction occurred in sand beds below the crater and were vented to the ground surface.



Schematic of Ancient Sand Crater

Figure from Obermeier, 1998.

Depiction of ancient sand boil. Figure from: Obermeier, Steve F., Seismic Liquefaction Features: Examples From Paleoseismic Investigations In The Continental United States, Open-File Report 98-488, U.S. Geological Survey, Reston, Virginia.



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.**

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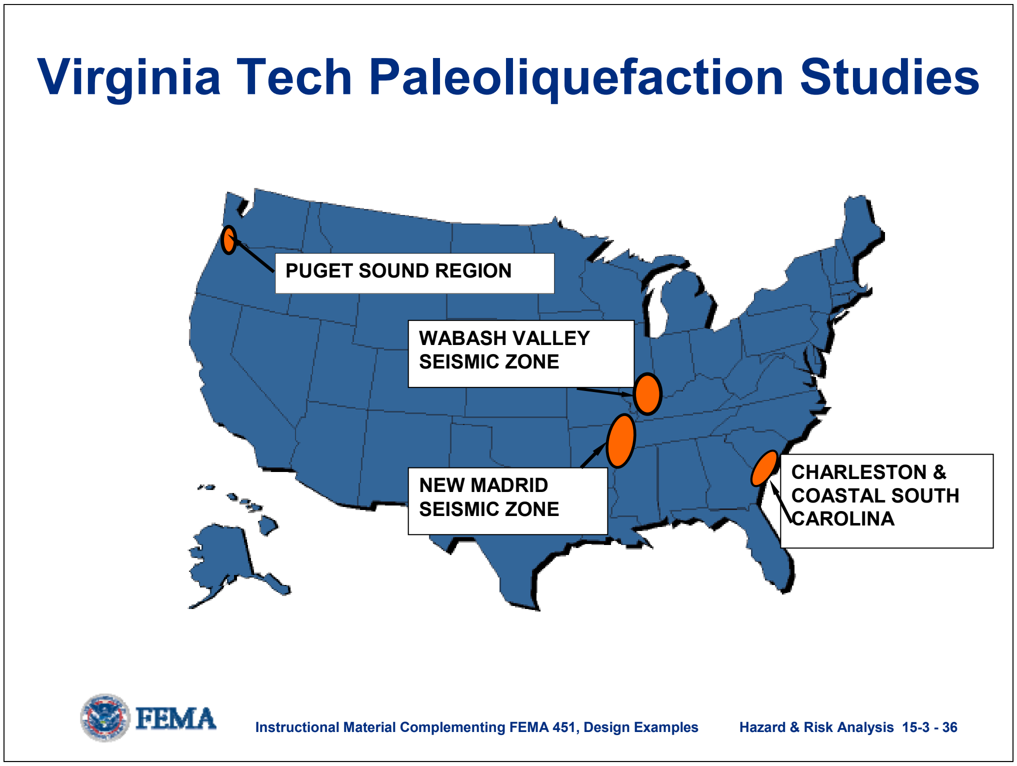
There is still no definitive explanation of the specific causes for these recurrent large (inferred to be) earthquakes in South Carolina.

Note: YBP refers to “years before present.” However, the finding of evidence for the repeated occurrence of large earthquakes in that region greatly increased the seismic hazard for that region.



Virginia Tech Paleoliquefaction Studies

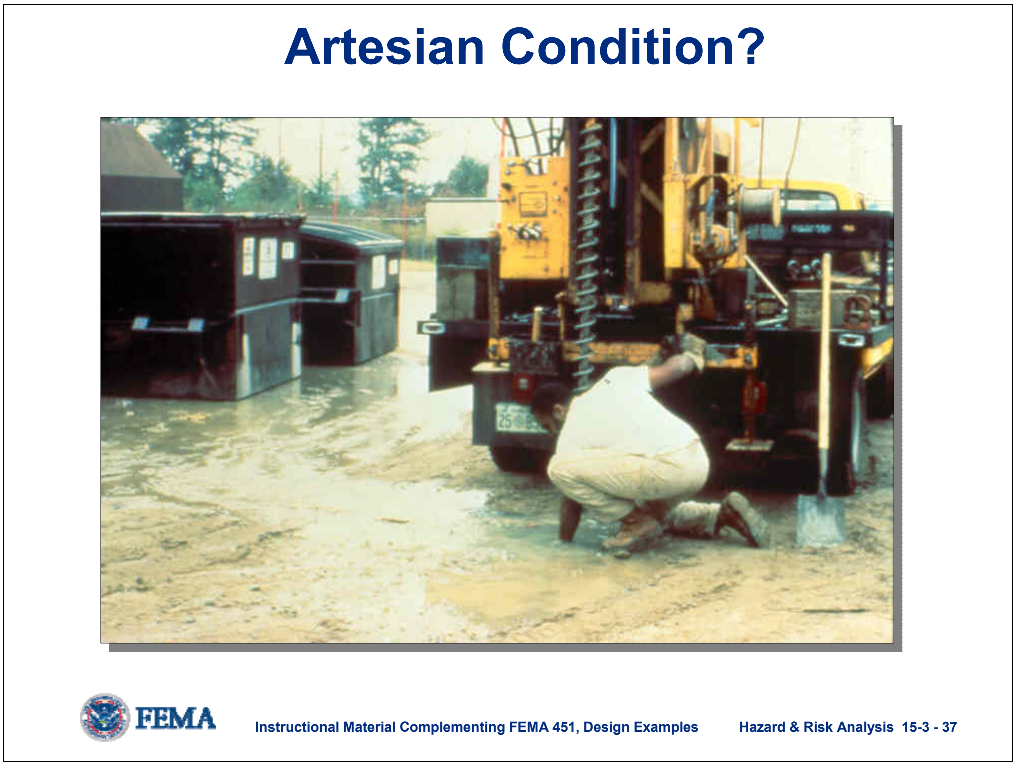
PUGET SOUND REGION

WABASH VALLEY SEISMIC ZONE

NEW MADRID SEISMIC ZONE

CHARLESTON & COASTAL SOUTH CAROLINA

Locations where paleoliquefaction studies have been conducted by researchers from Virginia Tech, USGS, and other agencies and universities.



Artesian Condition?

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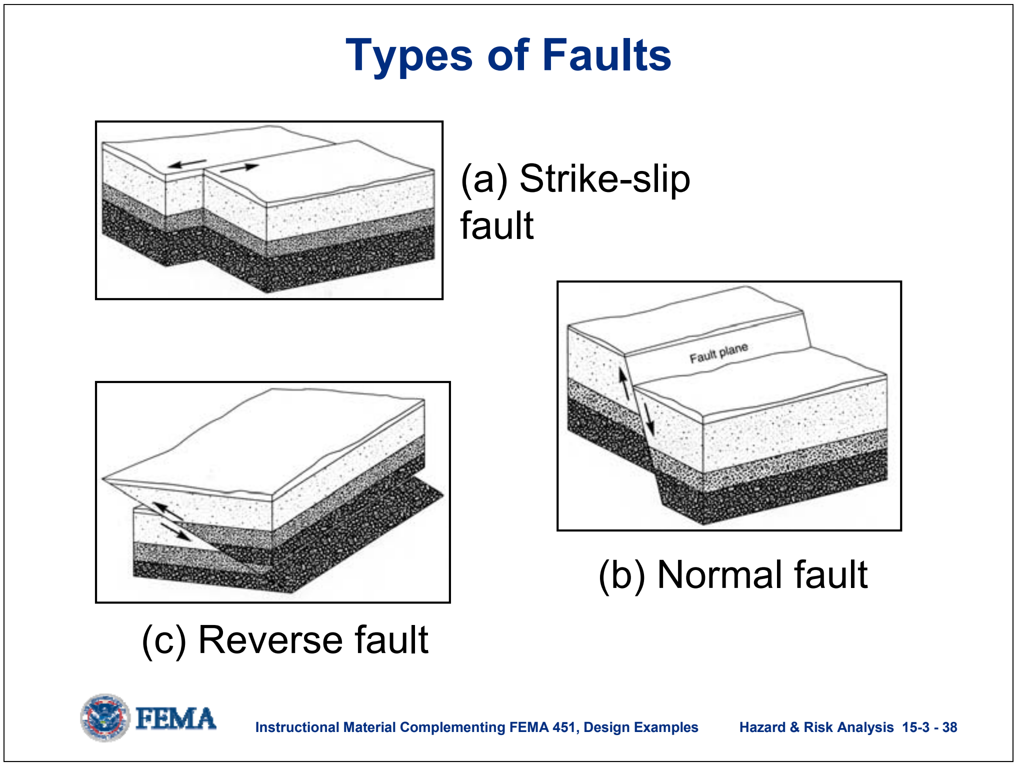
The author remembers an interesting start to earthquake engineering.



Types of Faults

(a) Strike-slip fault

(b) Normal fault

(c) Reverse fault

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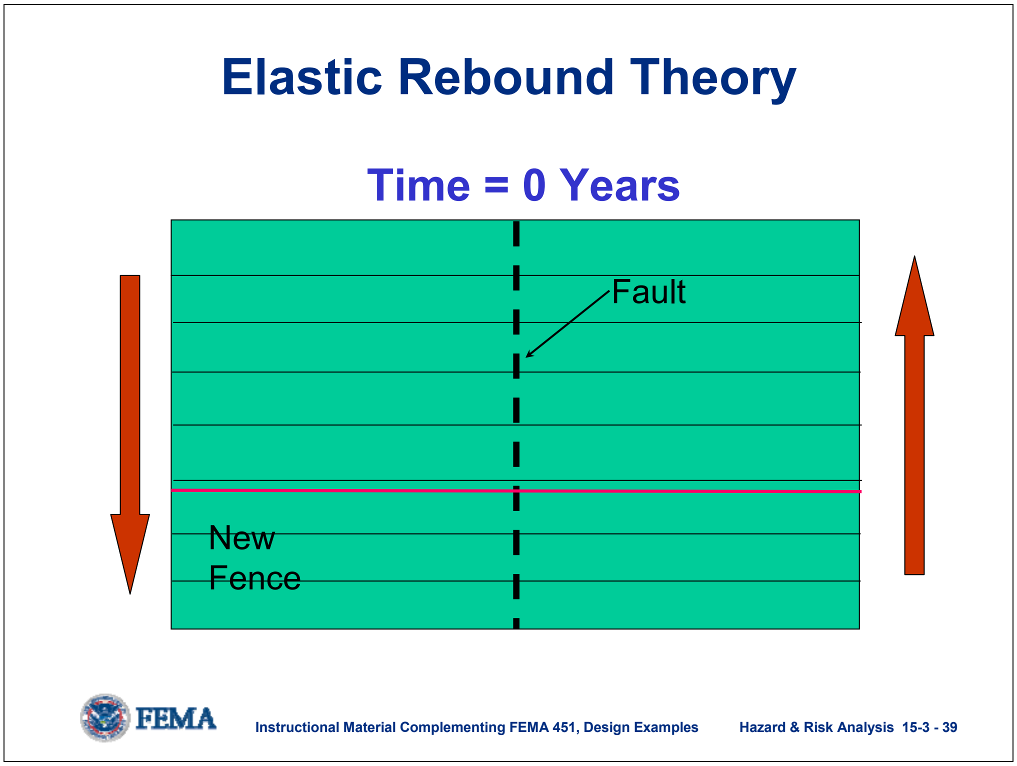
Figure above depicts common fault types. Many faults actually have a combination of more than one type of movement. That is, a fault may be mostly strike-slip but also have some normal-type fault movement when it slips.



Elastic Rebound Theory

Time = 0 Years

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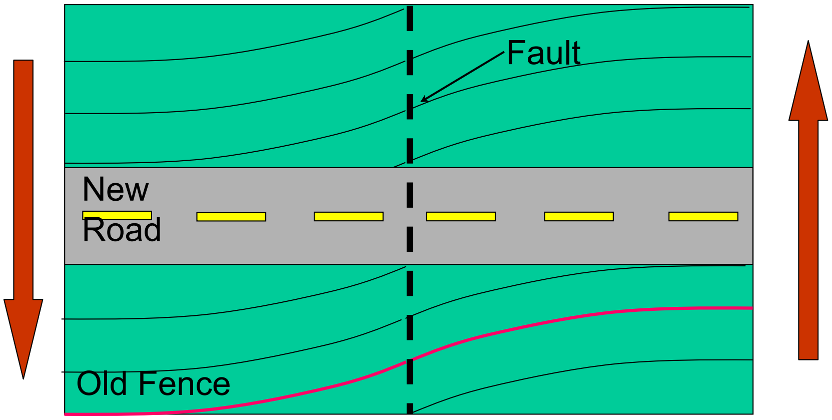
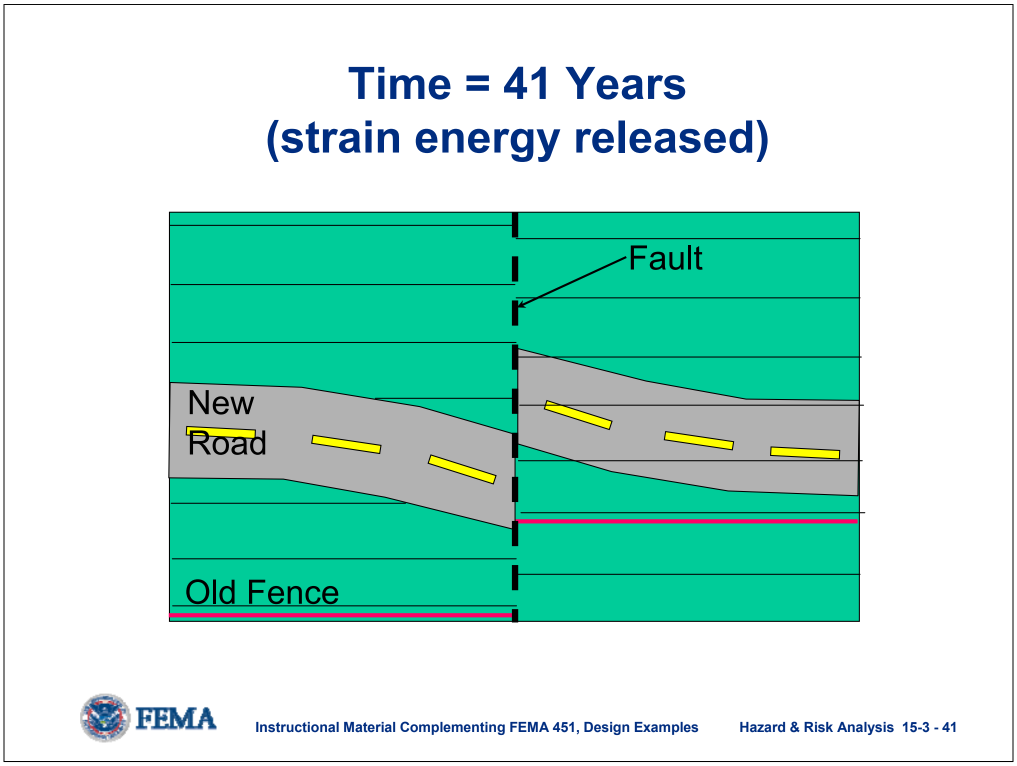
What produces seismic waves? The rocks that generate earthquakes have elastic properties that cause them to deform when subjected to tectonic forces (red arrows) and to “snap back” and vibrate when energy is suddenly released. During the rupture, the rough sides of the fault rub against each other. Energy is used up by crushing of rock and by sliding friction. Earthquake waves are generated by both the rubbing and crushing of rock as well as the elastic rebounding of the rocks along adjacent sides of the ruptured fault.

Time = 40 Years
(strain building)



The rocks that generate earthquakes have elastic properties and will deform elastically, building up strain energy, in response to the steady tectonic forces (red arrows). The rocks will continue to build up strain energy to a point…



Time = 41 Years (strain energy released)

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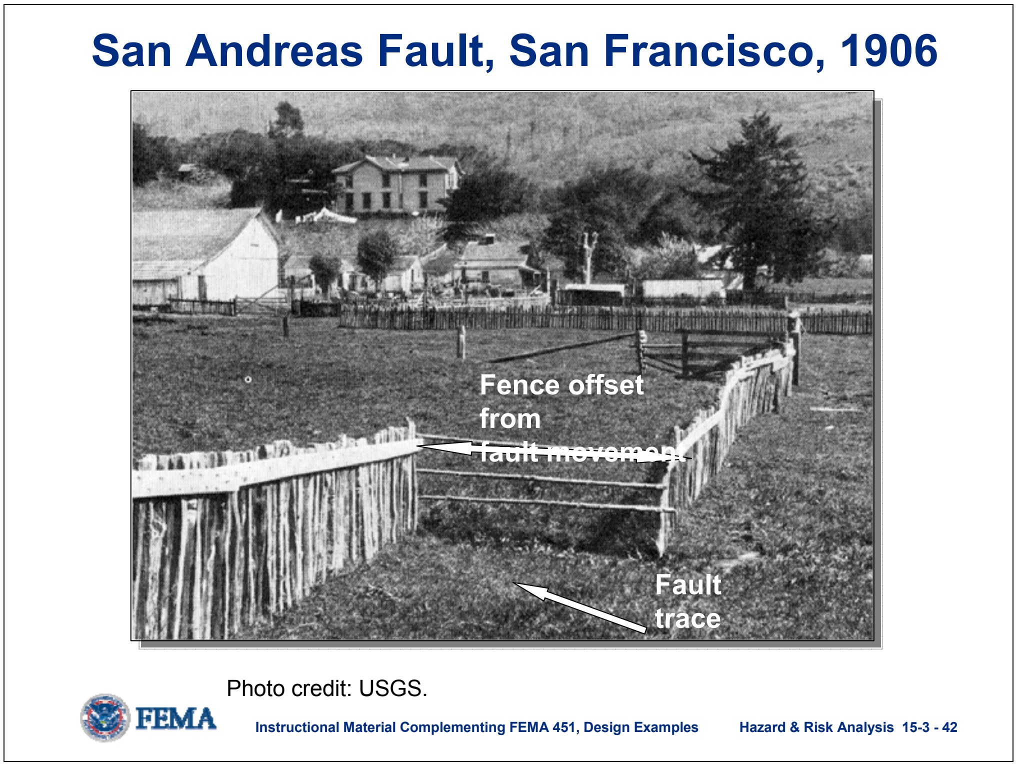
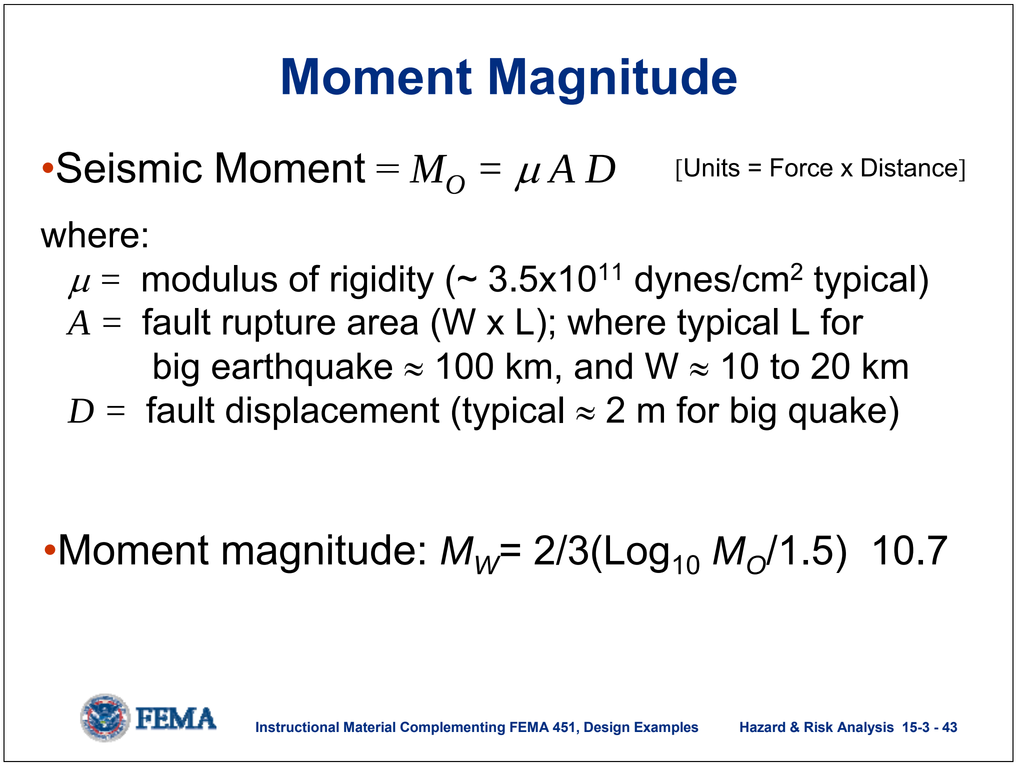
when the interface resistance along the fault is exceeded, sudden slippage occurs and the rocks “snap back” and vibrate when energy is suddenly released -- we feel the effects of this motion as an earthquake. Earthquake waves are generated by both the rubbing and crushing of rock as well as the elastic rebounding of the rocks along adjacent sides of the ruptured fault. The relative movement along the ruptured portion of the fault results in permanent ground displacement (see offset fence line).



San Andreas Fault, San Francisco, 1906

Photo credit: USGS.

Fence shown above was offset during fault movement associated with the 1906 San Francisco Earthquake with about 3 m of movement.



Moment Magnitude

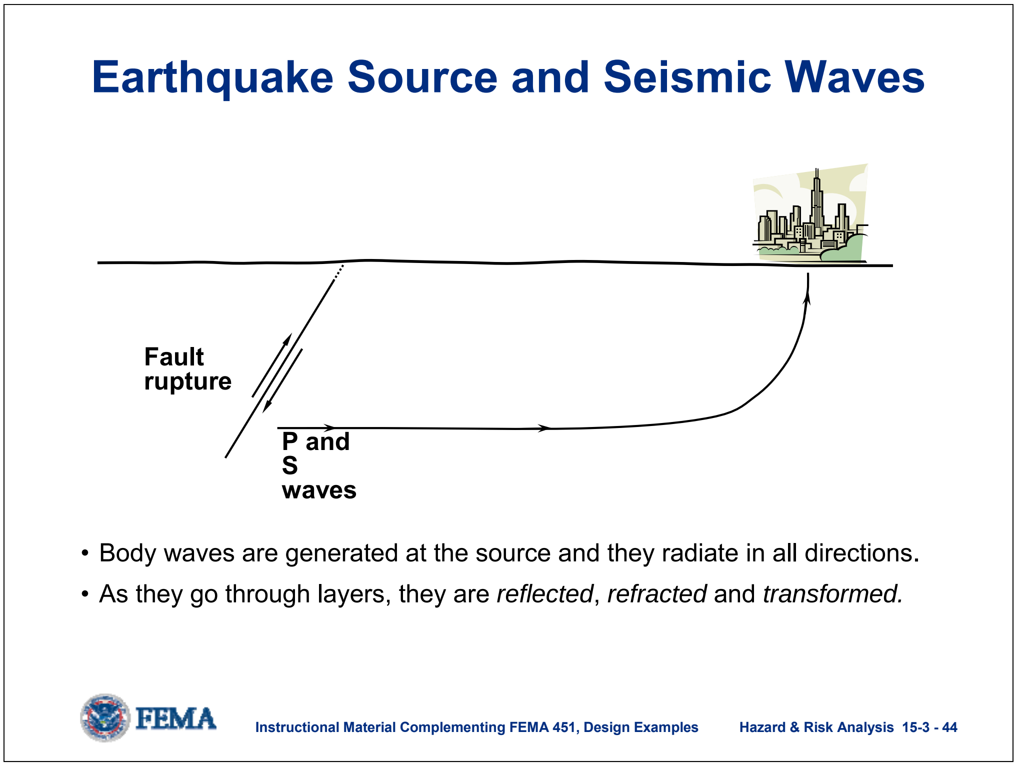
- Seismic Moment $= M_O = \mu A D$ [Units = Force x Distance]

where:

$\mu =$ modulus of rigidity (~ $3.5\text{x}10^{11}$ 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: $M_W = 2/3(\text{Log}_{10}\, M_O/1.5)\ \ 10.7$

Moment magnitude is now the preferred standard for characterizing earthquake energy. The concept is based on the principles of mechanics. As can be shown above, the larger the average fault displacement, the larger the amount of energy released (and the larger the magnitude). Typical Mo value = $1 \text{ x } 10^{27}$ dyne-cm for big earthquake. Note larger fault size and displacement produces larger magnitude, but accelerations may not necessarily be larger, as the duration of ground shaking is the primary parameter to always increase with magnitude.



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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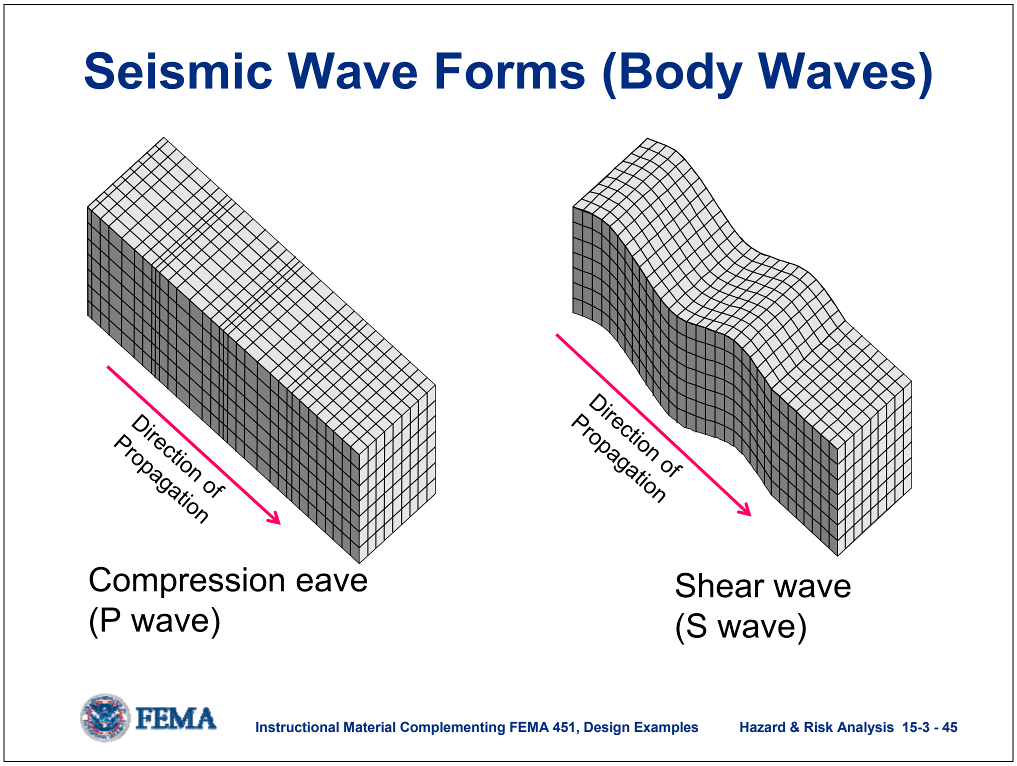
Body waves are generated at the source and they radiate in all directions as they go through layers, they are *reflected*, *refracted* and *transformed.* As per Snell's Law, the wave path is nearly vertical by the time they reach the ground surface.



Seismic Wave Forms (Body Waves)

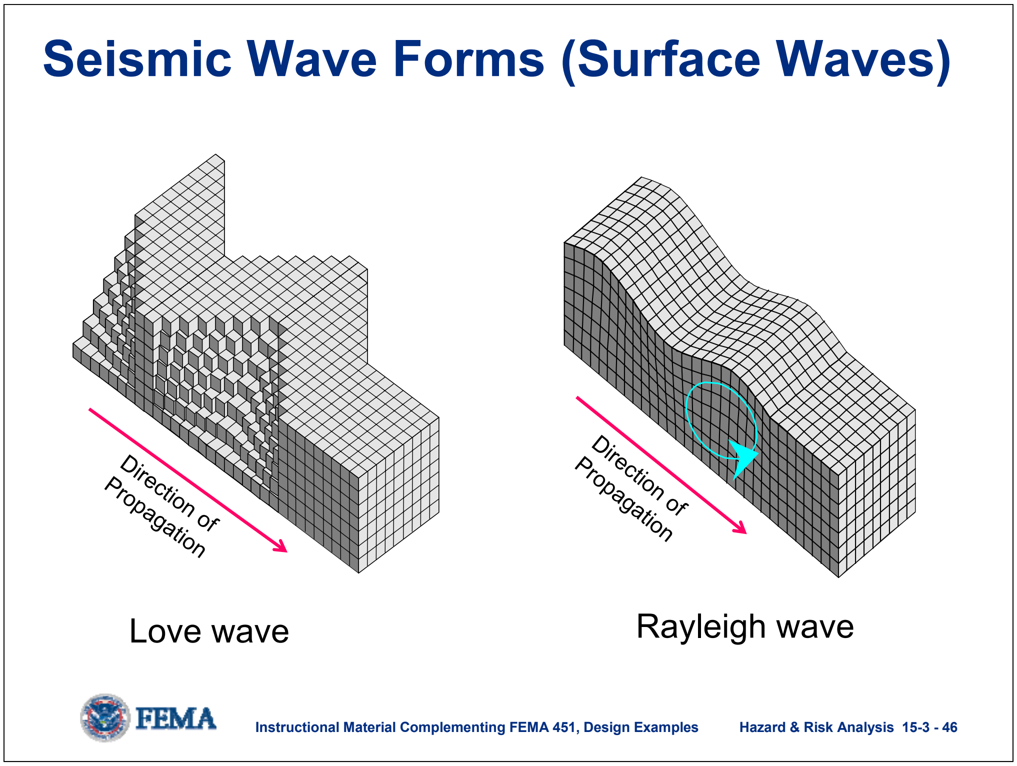
Direction of Propagation

Compression eave
(P wave)

Direction of Propagation

Shear wave
(S wave)

Shear wave are the main culprit that produces the majority of the damage during



Seismic Wave Forms (Surface Waves)

Direction of Propagation

Love wave

Direction of Propagation

Rayleigh wave

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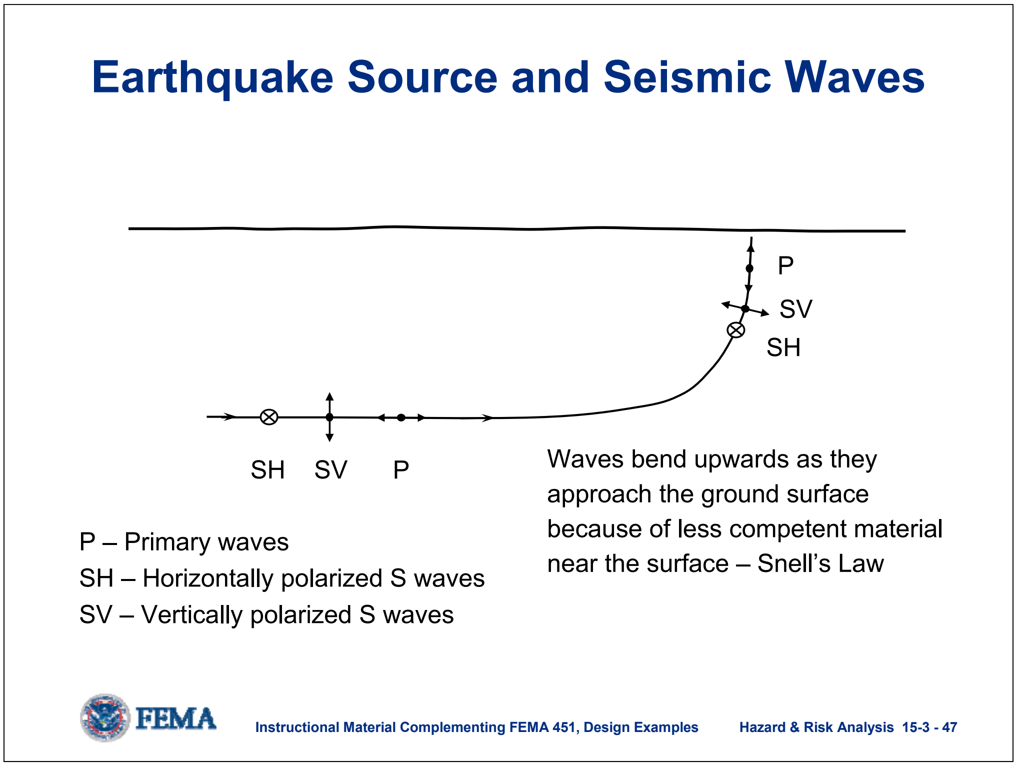
Surface waves typically cause less than 15% of total seismic damage from strong ground shaking, but can be damaging to long-span structures.

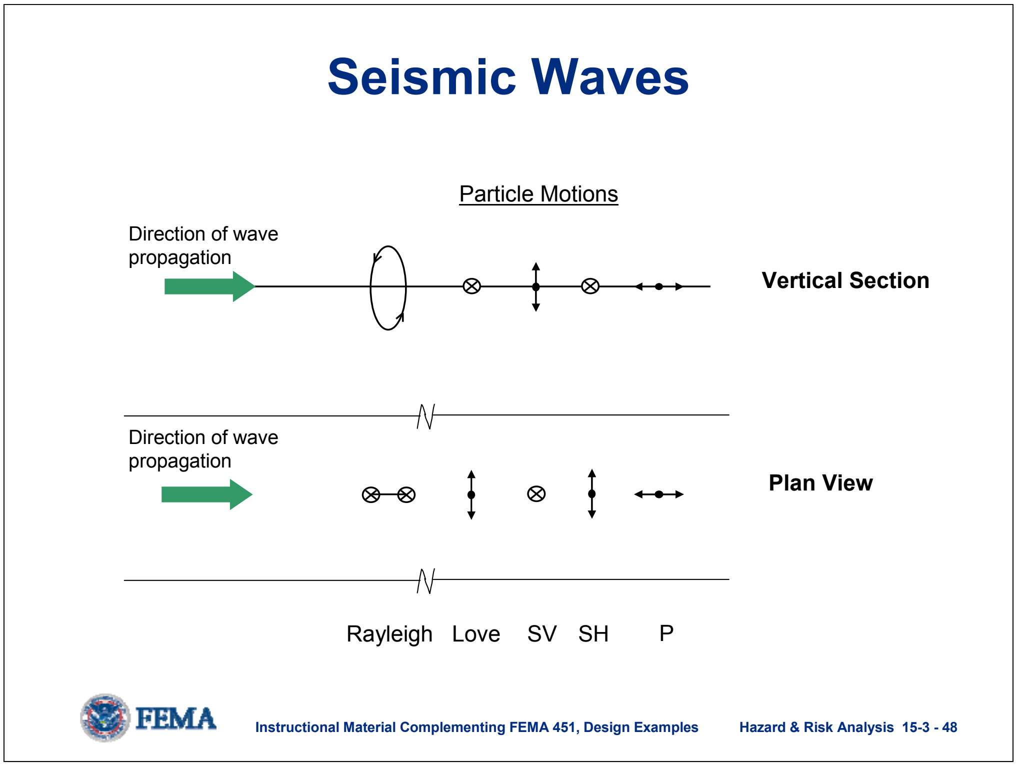


Earthquake Source and Seismic Waves

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

Body waves are generated at the source and they radiate in all directions as they go through layers, they are *reflected*, *refracted* and *transformed.* As per Snell's Law, the wave path is nearly vertical by the time they reach the ground surface.



Seismic Waves

Particle Motions

Direction of wave propagation

Vertical Section

Direction of wave propagation

Plan View

Rayleigh Love SV SH P

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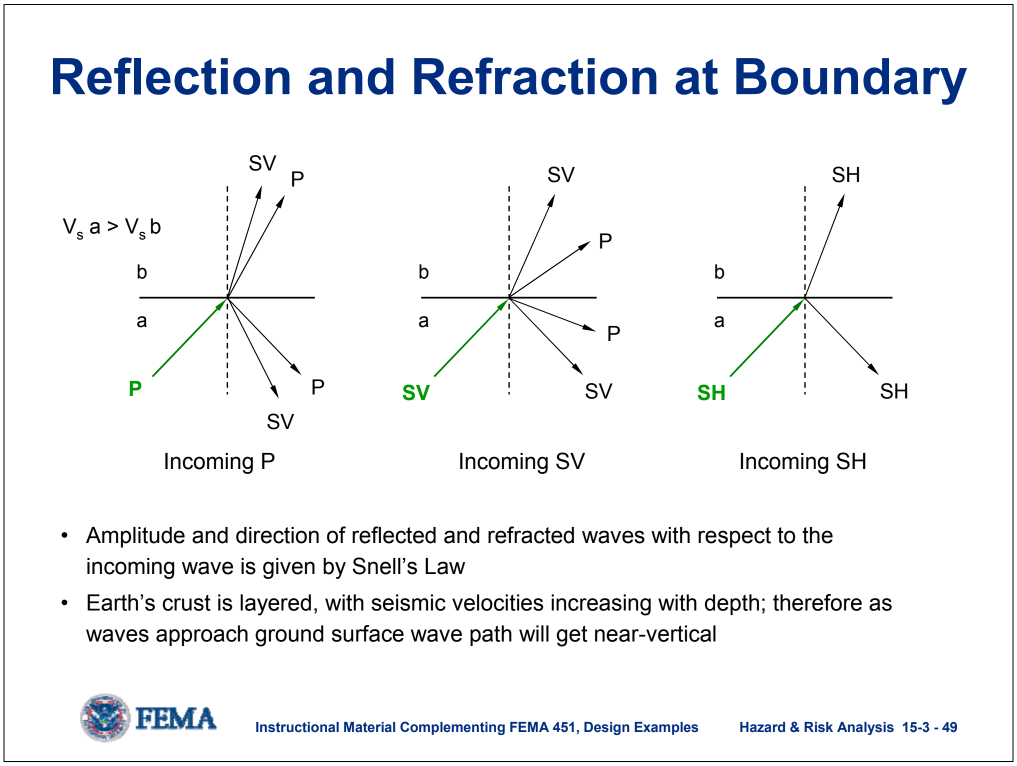
The waves motions of various waves are important, as the horizontally polarized shear wave is our main concern.



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

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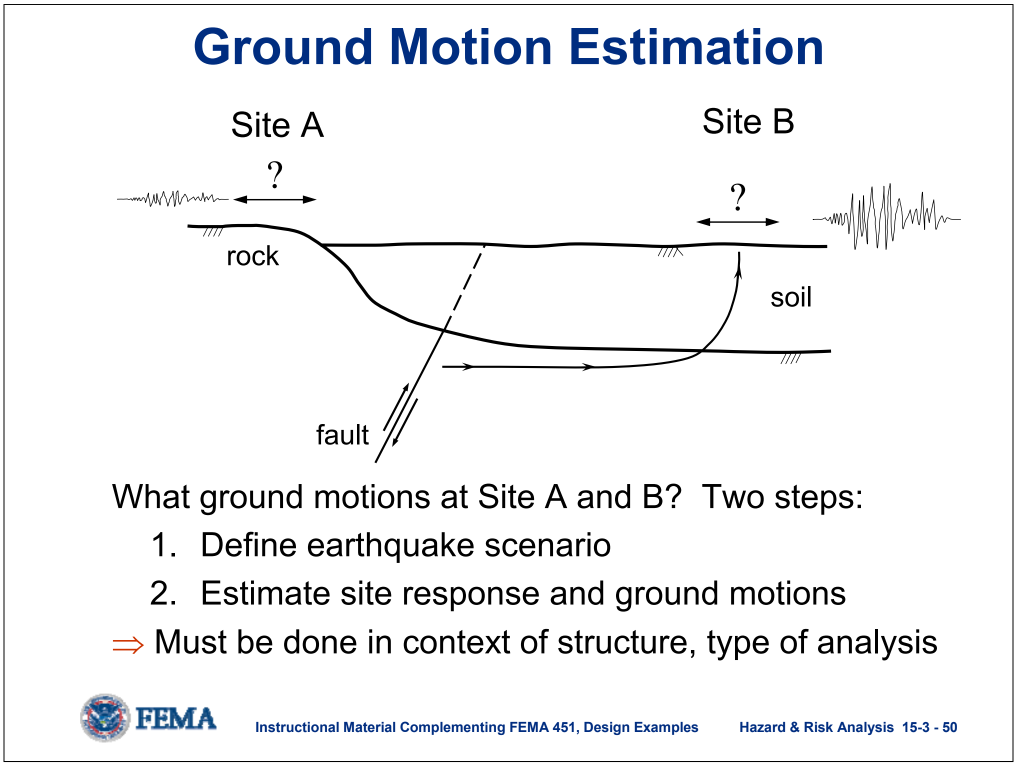
The amplitude and direction of reflected and refracted waves with respect to the incoming wave is given by Snell's law. It can be seen the P and Sv (vertically polarized shear wave) are converted into different wave types at the interfaces, whereas the Sh waves remain Sh waves. This explains the "scattering" that reduces the amount of P wave energy and preserves the Sh waves-- by the time the motions reach the surface the signal is very rich in Sh waves.



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

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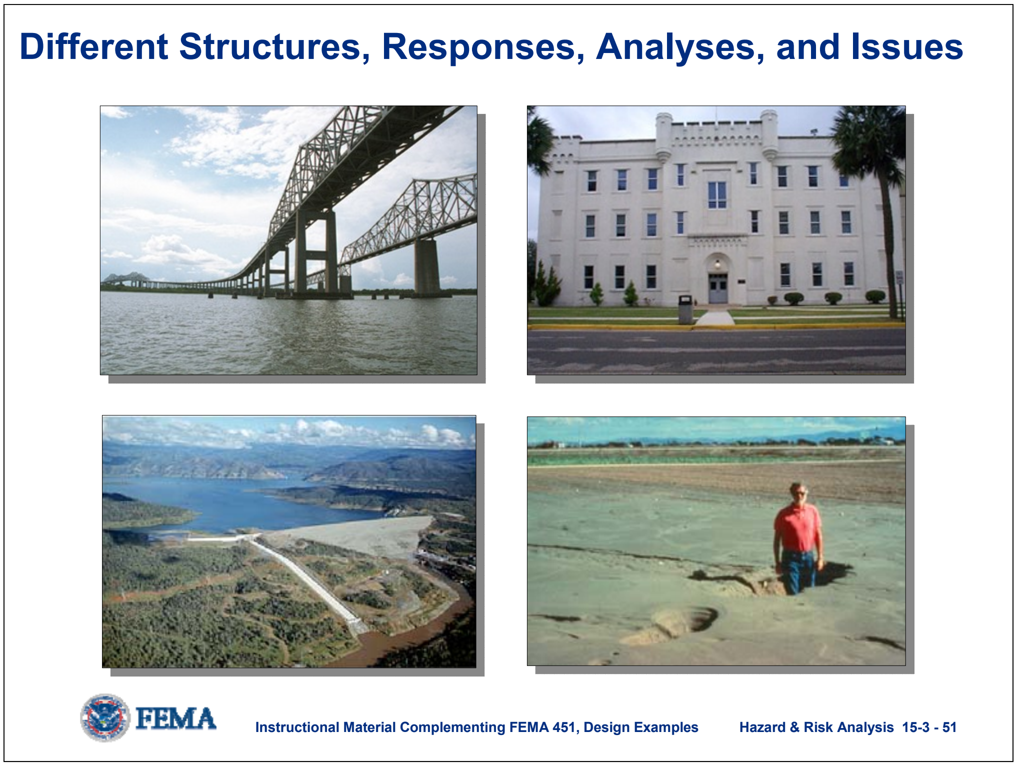
Estimating ground motions is made more difficult by the presence of soil deposits which acts as a “filter,” changing the amplitude and frequency of the resultant surface motions from those that occur in hard rock.



Different Structures, Responses, Analyses, and Issues

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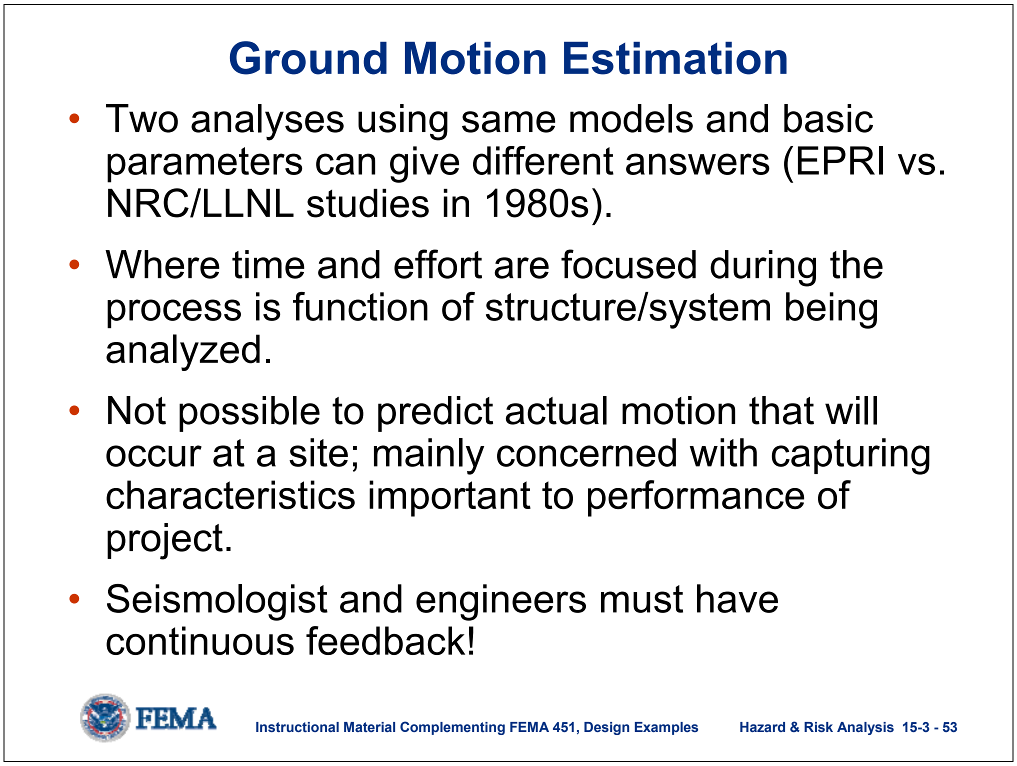
The photographs illustrate a series of different structures and site conditions, all of which would respond differently to a given earthquake motion. Therefore the motions used to analyze these structures should be carefully considered – there is no on universal set of ground motions that can be used to analyze all structures. Remember, the objective is to duplicate the most important characteristics of the potential ground shaking.

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.

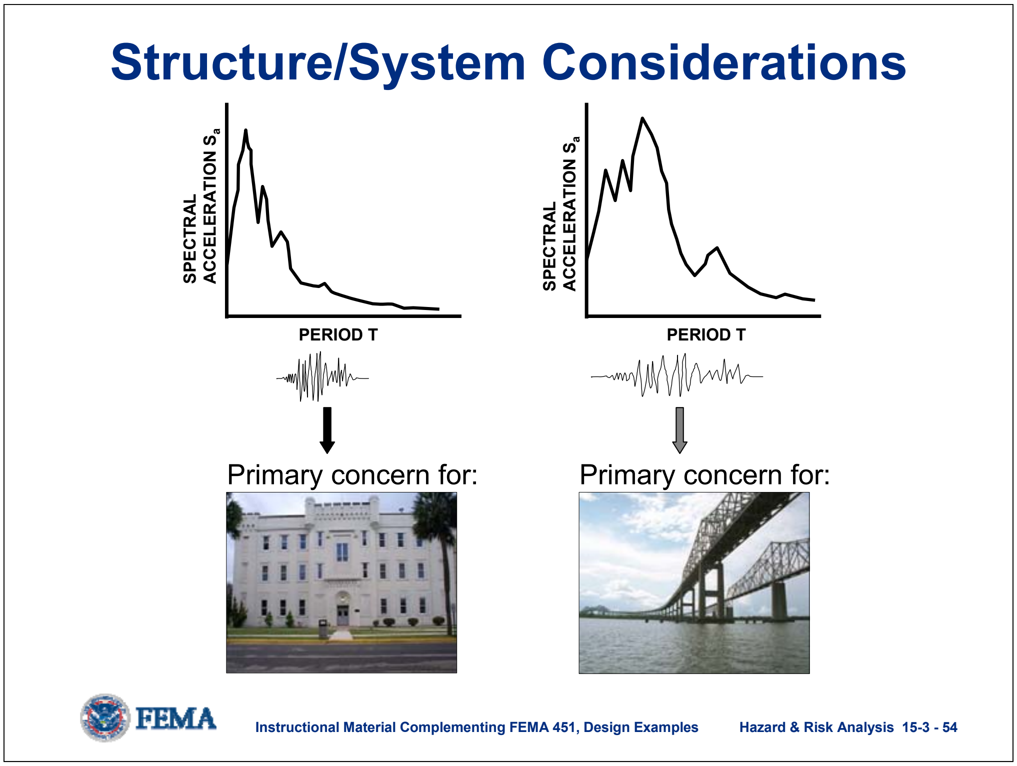
It is important to emphasize that there is no “universal” set of ground motions for any region and that motions to be used will depend upon the specific issue most important to the project (unless of course one can design for all conceivable scenarios, which is economically impossible in most cases).



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!

None.



Structure/System Considerations

Primary concern for:

Primary concern for:

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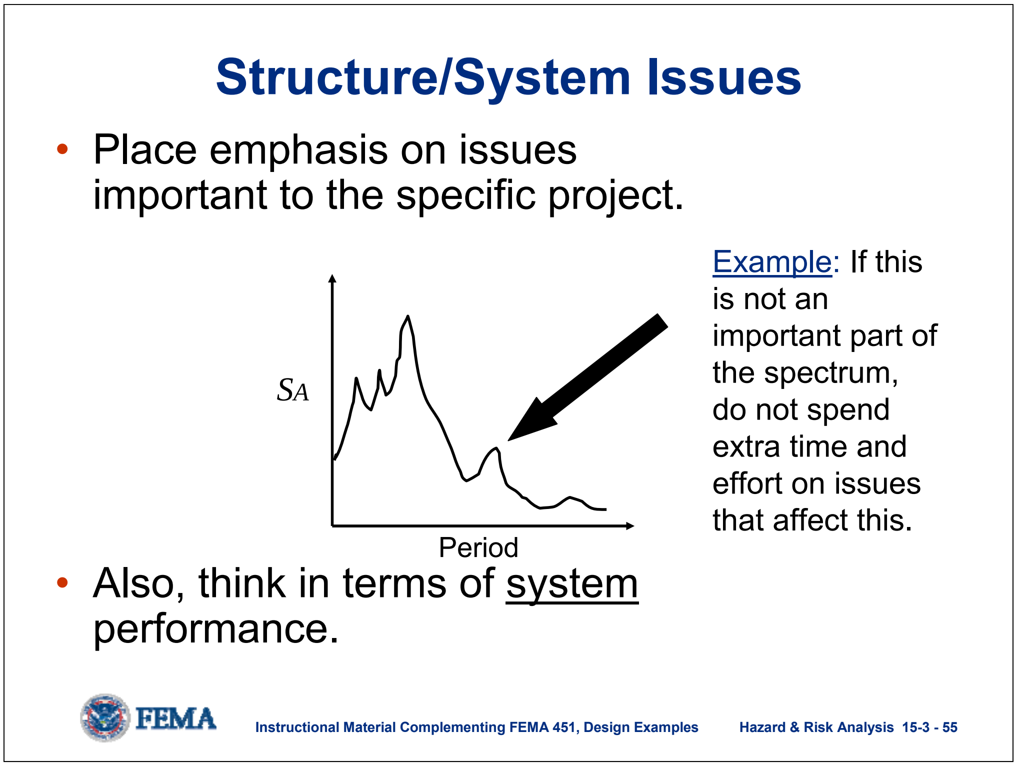
The short stiff building would be more concerned with the low-period (high-frequency motions) portion of the spectrum, whereas the bridge would be more affected by the energy in the high-period (low frequency motions) portion of the spectrum.



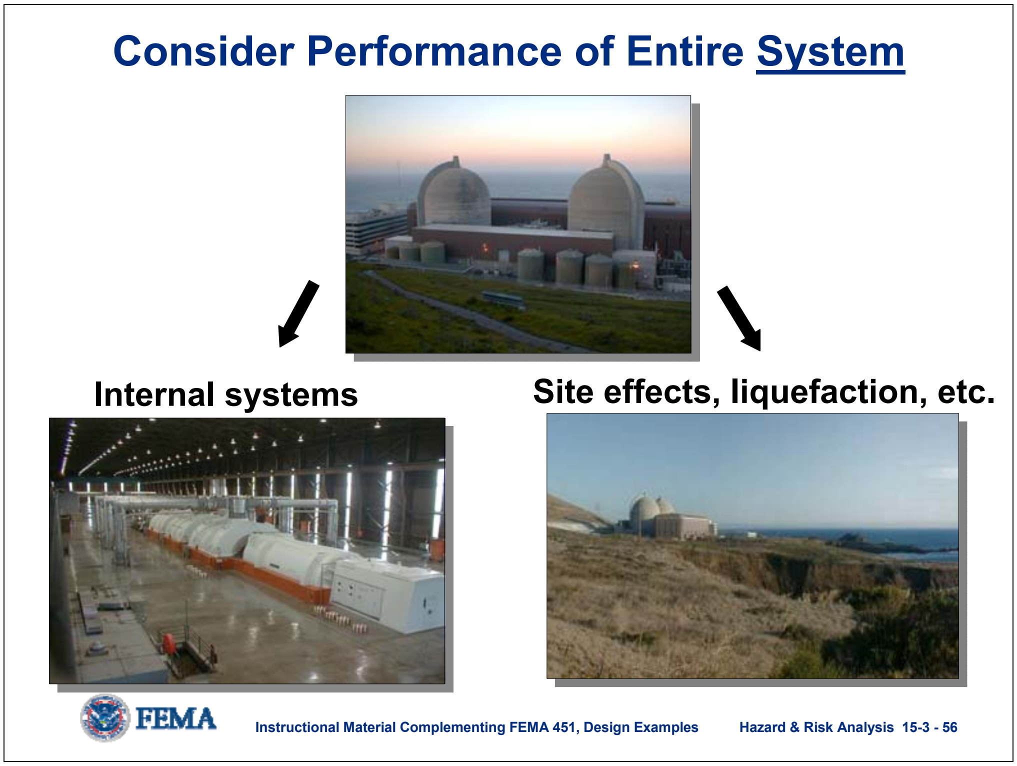
Structure/System Issues

- 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.

It important to place emphasis on the portion of the spectrum that will most affect the structure and its contents.



Consider Performance of Entire System

Internal systems

Site effects, liquefaction, etc.

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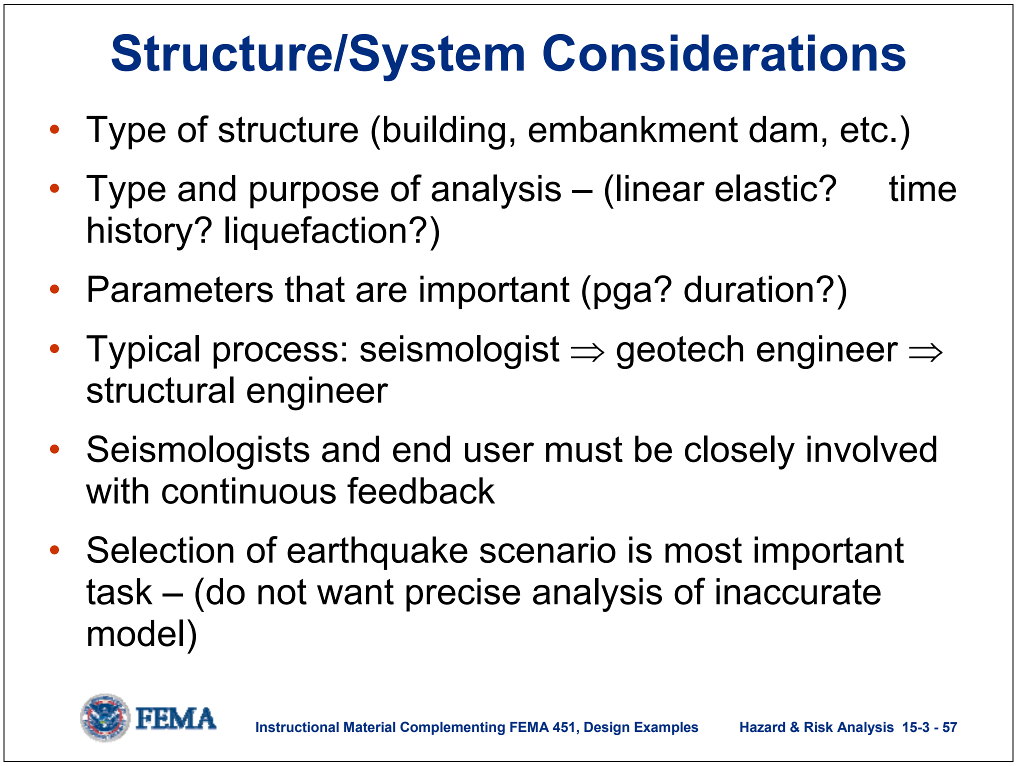
The overall performance of the nuclear power facility above would depend upon the performance of each of the major components. Each aspect would be concerned with different characteristics of the ground motion.



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)

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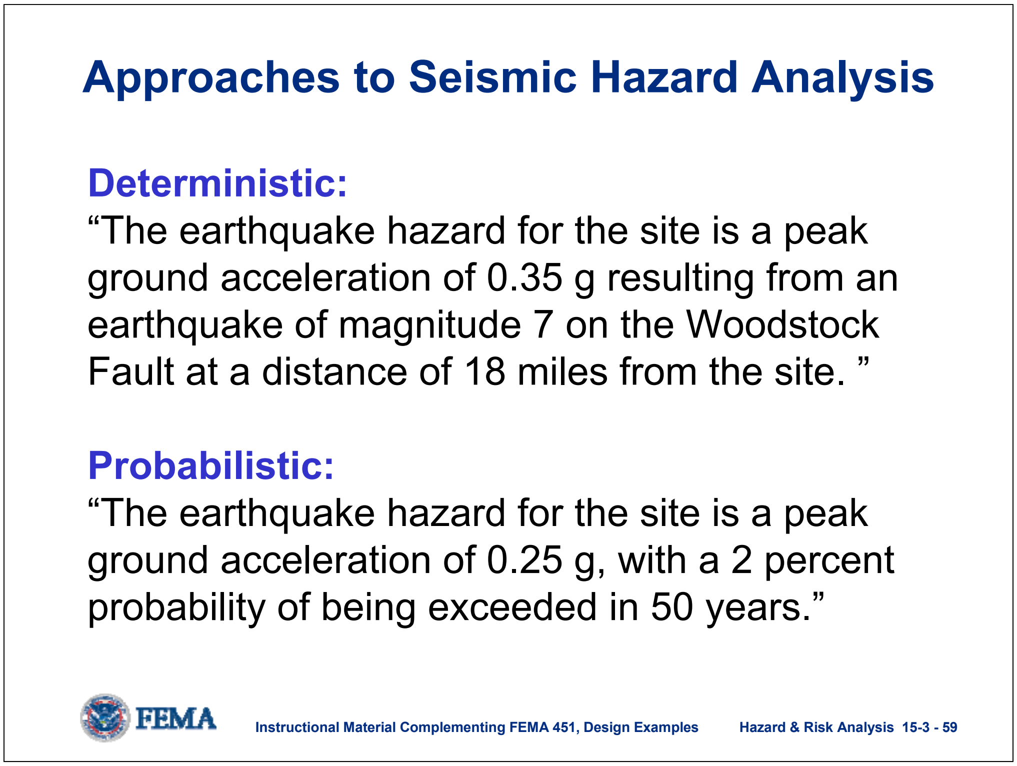
None.

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

None.



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. ”

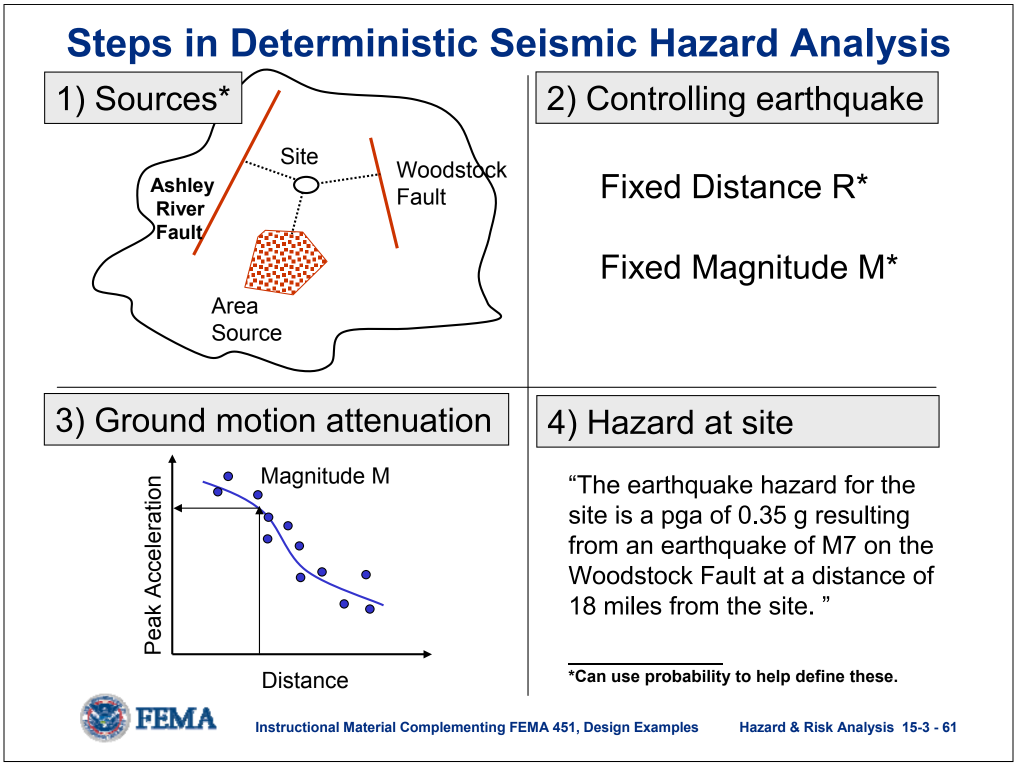
Probabilistic:
“The earthquake hazard for the site is a peak ground acceleration of 0.25 g, with a 2 percent probability of being exceeded in 50 years.”

None.

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

None.



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.

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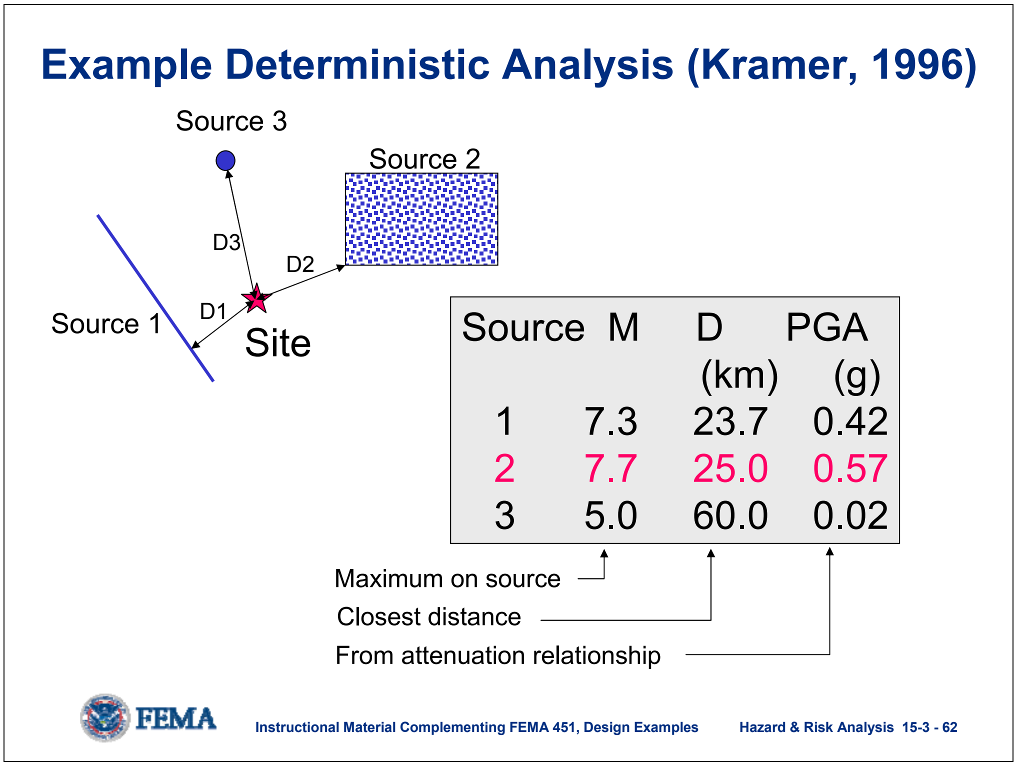
The main advantage of the deterministic approach is that it is relatively simple, and relatively “transparent” such that the effects of individual elements can be understood and judged more readily. Of course, the likelihood of various scenarios and uncertainty in the data cannot be considered in a purely deterministic analysis.



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

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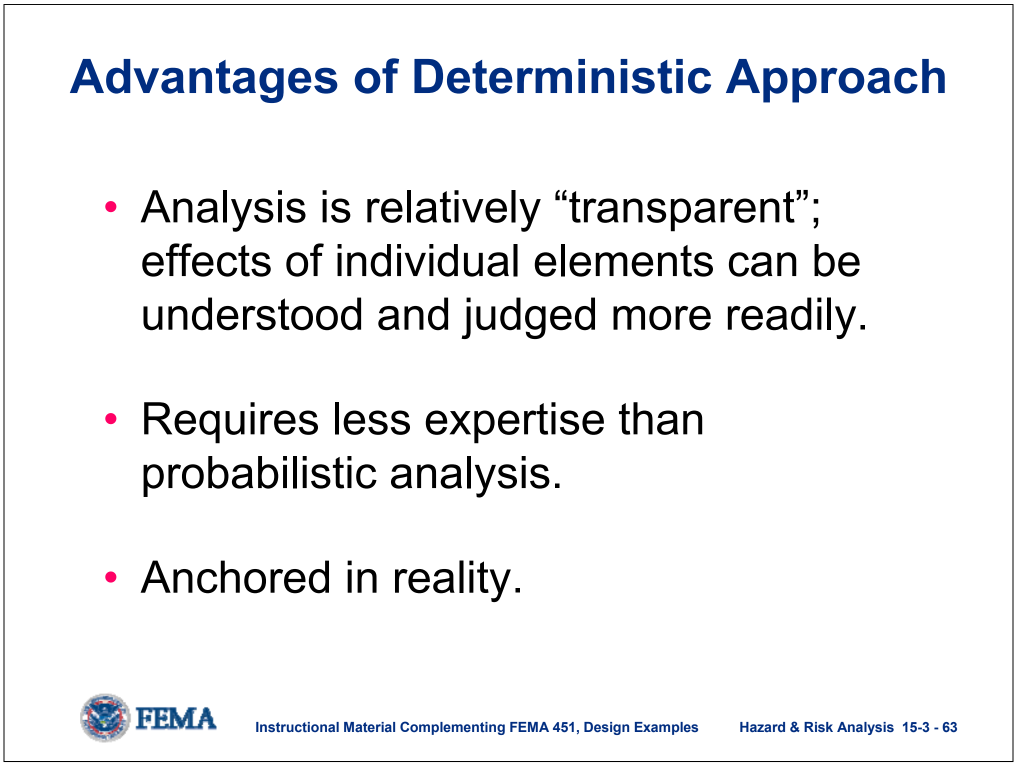
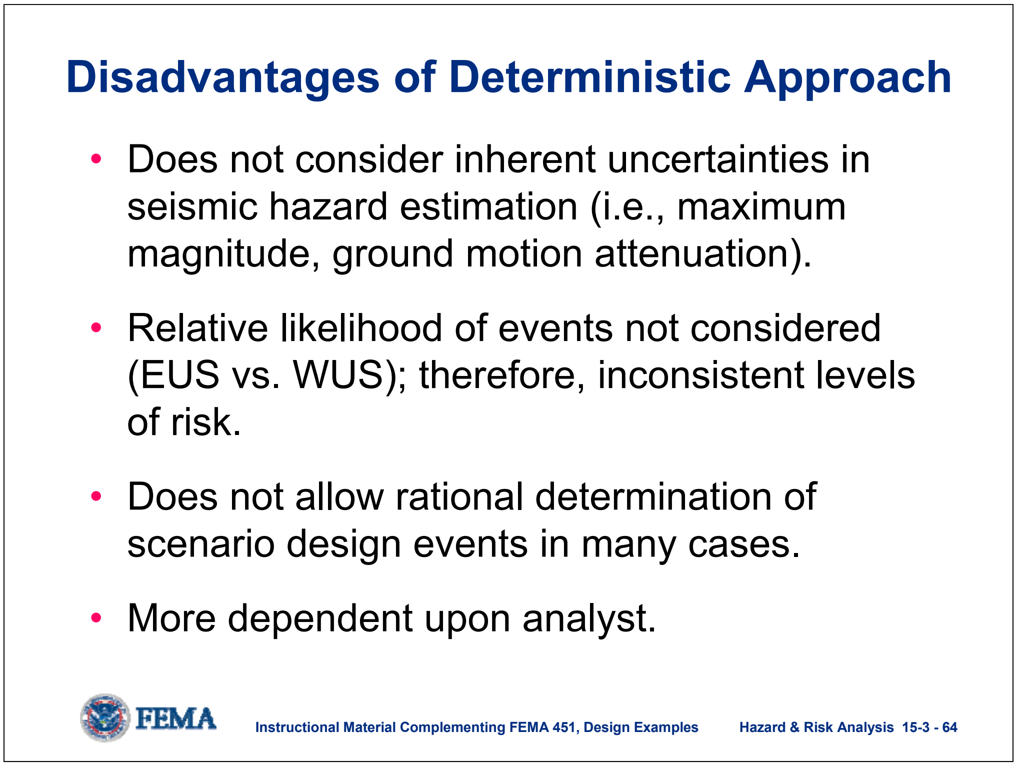
The motions at the site are based on the source magnitude and distance.



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.

Anchored in reality refers to the fact that the scenarios considered by this approach are based on real physical sources (as opposed to some of the results of probabilistic analyses which can correspond to scenarios not physically possible based on fault locations, etc.



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.

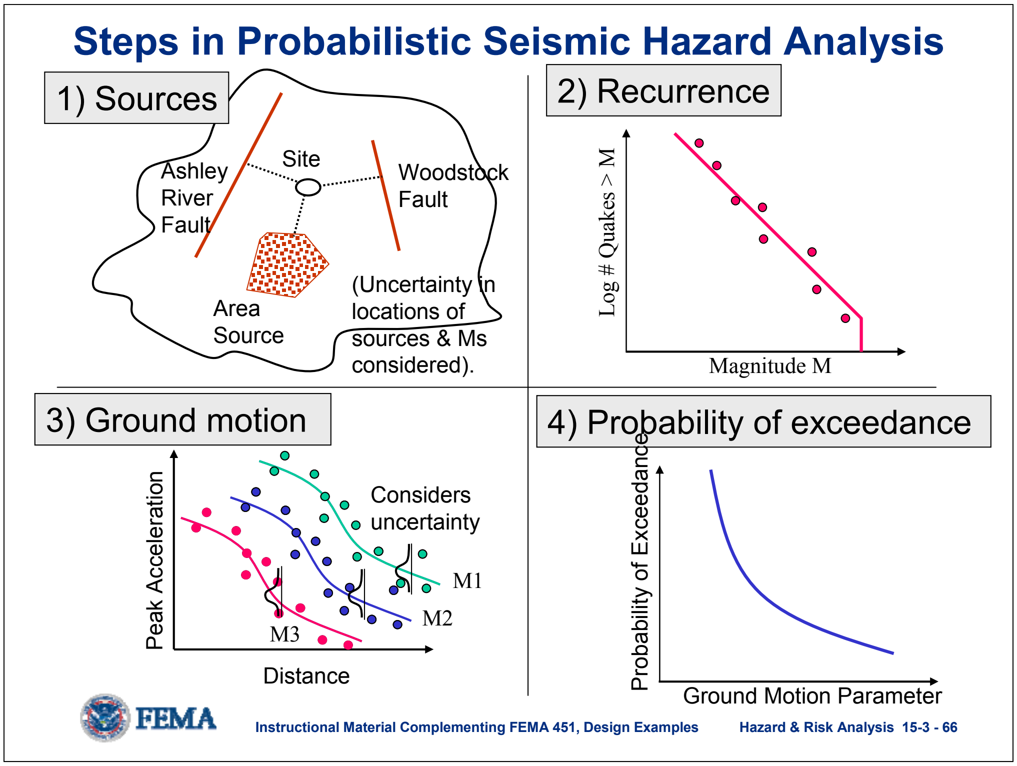
None.

Probabilistic Seismic Hazard Analysis

⇒ Considers where, how big, and how often.

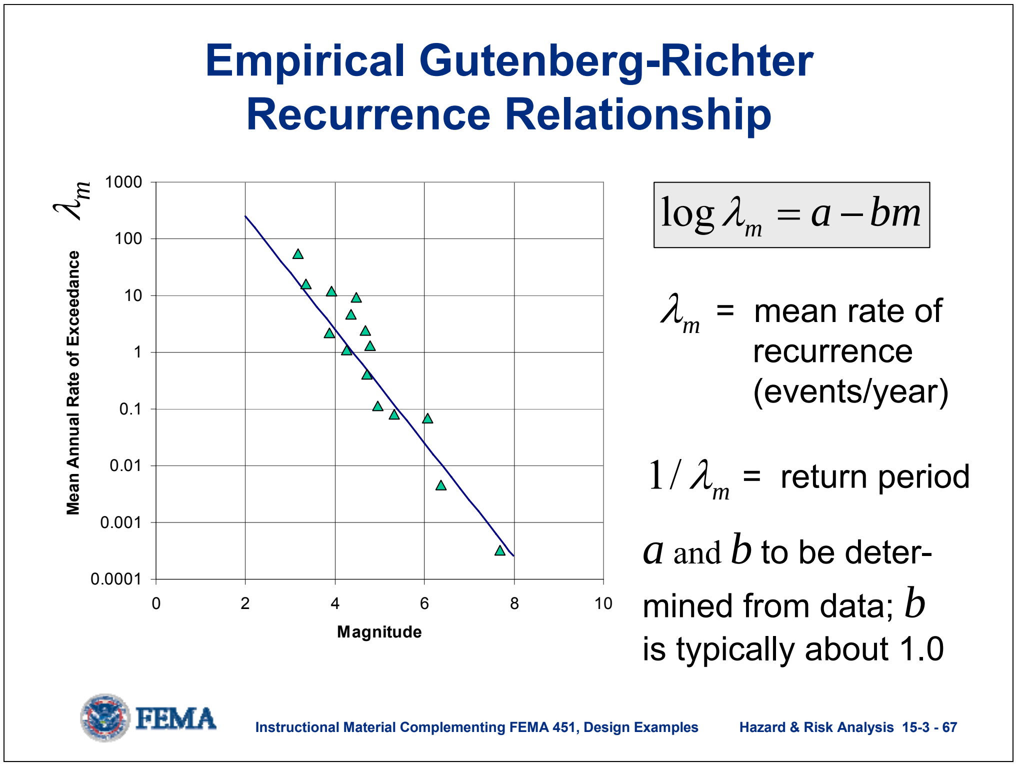
- Identify and characterize source zones that may produce significant ground shaking at the site including the spatial distribution and probability of eq's in each zone.
- Characterize the temporal distribution and probability of earthquakes in each source zone via a recurrence relationship and probability 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.

Probability basically considers the probability of earthquake of a given magnitude occurring at a given point along a fault multiplied by the probability that the earthquake motions produced by the event will be a certain value at a given location– we thus end up with the probabilistic ground motion for a given site. In the nomenclature of probability theory, the probability of events depends on the probability density distribution that is sampled and the sampling method. For earthquakes, we know neither because we do not understand the physics of earthquake recurrence, so we pick a distribution based on the earthquake history which for most faults is short (only a few recurrences) and complicated. As a result, various distributions consistent with the earthquake history can produce quite different estimates.



Steps in Probabilistic Seismic Hazard Analysis

Probability basically considers the probability of earthquake of a given magnitude occurring at a given point along a fault multiplied by the probability that the earthquake motions produced by the event will be a certain value at a given location– we thus end up with the probabilistic ground motion for a given site. A hazard curve tells you what the probability is of any particular strength of ground shaking. It doesn't tell you which value you should choose to design your building against. Do you want to be 95% safe, 99% safe, or 99.9% safe? These are really economic or political decisions, not seismological ones. Also, one has to bear in mind that low probability events do happen. The Maharashtra earthquake of 1993 is a good case in point. If a seismologist had been assessing the hazard in this part of India in 1992, he would have concluded that the probability of a damaging earthquake was extremely low. And he would have been right. Unfortunately, that very small probability came up next year.



Empirical Gutenberg-Richter Recurrence Relationship

$$\boxed{\log \lambda_m = a - bm}$$

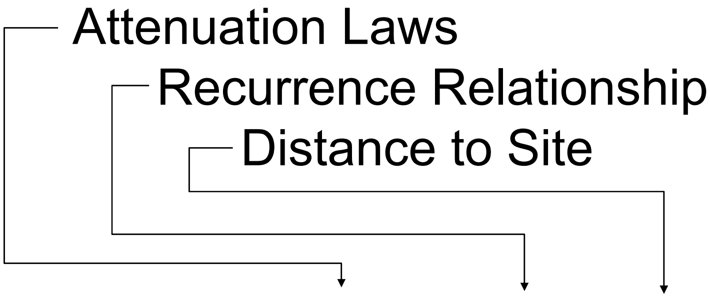
λ_m = mean rate of recurrence (events/year)

$1/\lambda_m$ = return period

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

The number of earthquake of a given magnitude, based on seismic network monitoring, are used to determine recurrence relationships and/or or the rate of earthquake of various magnitudes. The number of small earthquakes is much greater than the number of large earthquakes. The number of frequent small events is used to estimate the probable rate of large events.

Uncertainties Included in Probabilistic Analysis

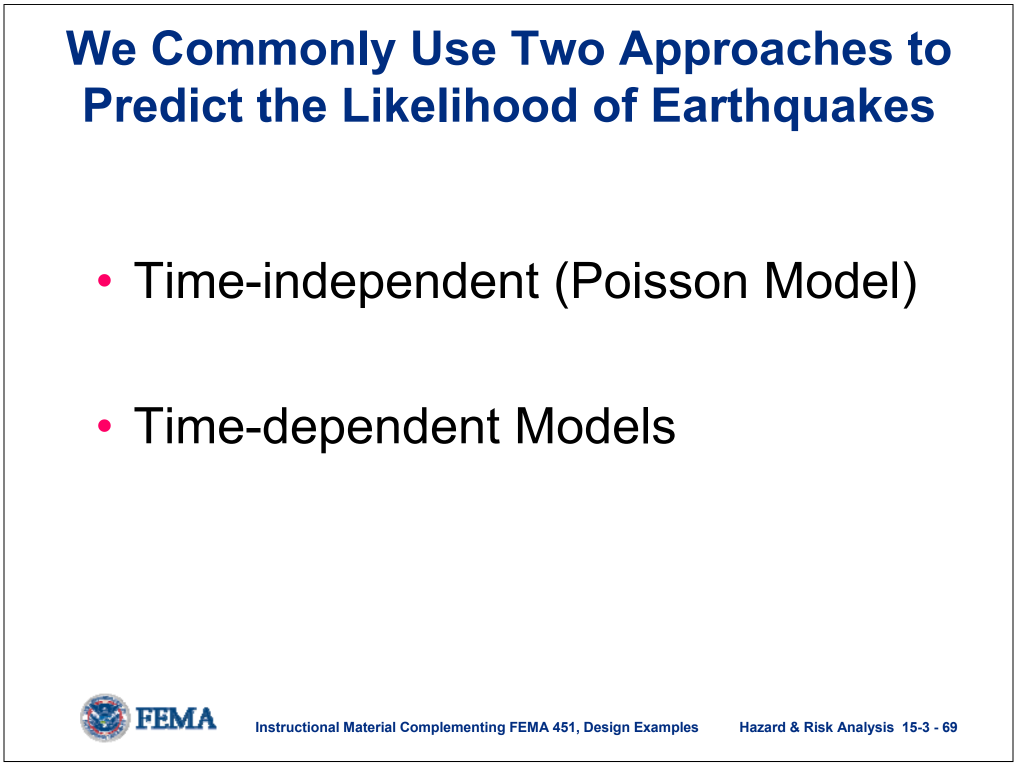

Attenuation Laws

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 do not really know with confidence many of the input parameters required for seismic hazard analysis in CEUS. The above equation is complicated, but the equation simply result in the determination of one parameter– the mean annual rate of earthquakes, λ. This is used in the Poisson model to estimate the probability of earthquakes shaking exceeding a certain value. Note that a ground shaking level (i.e., PGA) is assumed and the probability of exceeding this value is computed. Thus, the ground motion is actually the independent variable, while the probability is the dependent variable. After many probability-ground motions pairs are determined, the results are typically plotted in map form with contours of ground motions for a given probability of exceedance; see current USGS maps. On a given seismic hazard map for a given probability of exceedance (PE), locations shaken more frequently will have larger ground motions. Plotted in this manner, the maps suggest that the ground motion is the dependent variable; however, the probability is actually the dependent variable. Note the rate parameter above is used in the Poisson model in several of the following slides.



We Commonly Use Two Approaches to Predict the Likelihood of Earthquakes

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

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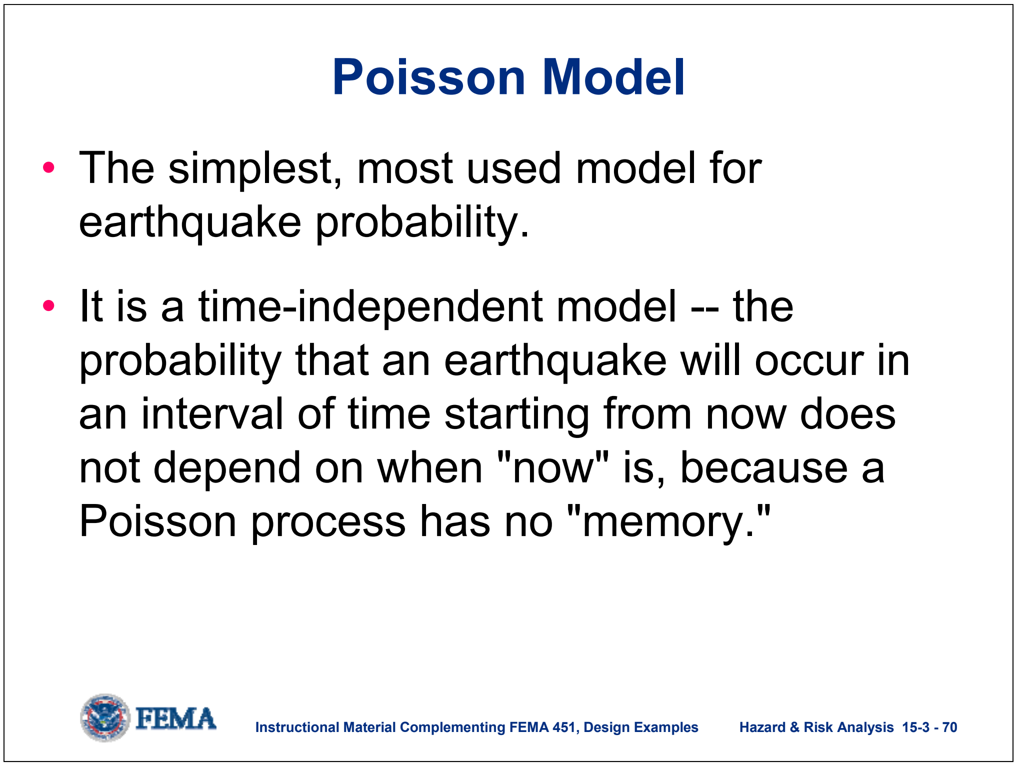
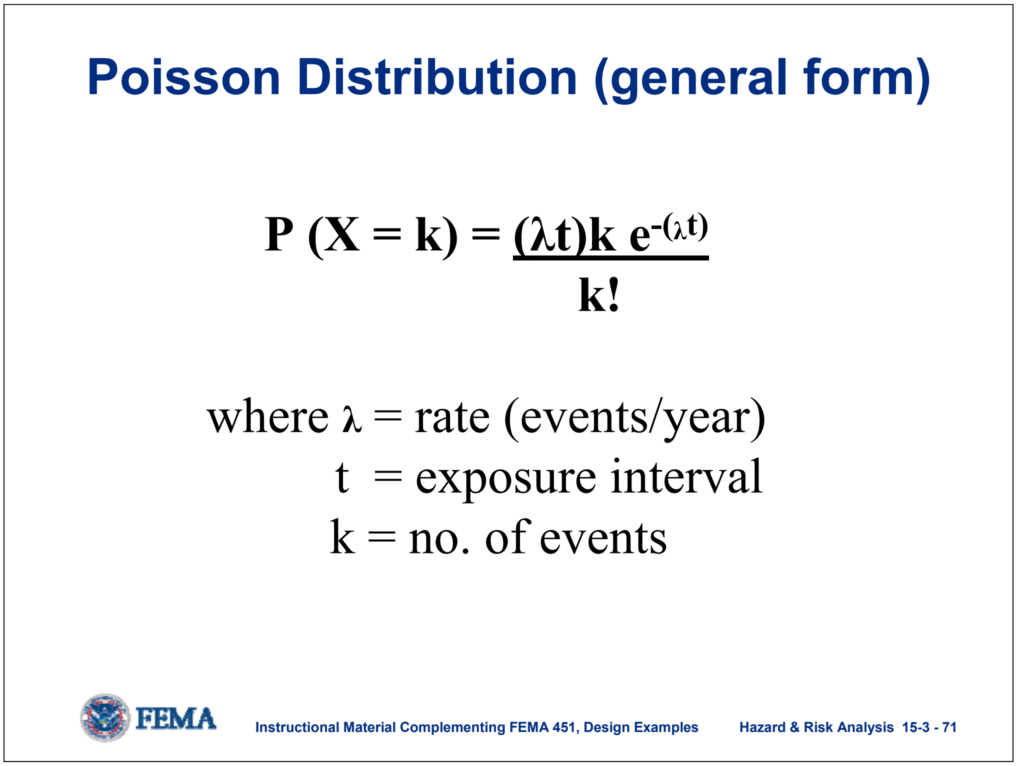
The difference is that for times since the previous earthquake less than about 2/3 of the assumed recurrence interval, the Poisson model predicts higher probabilities. At later times a Gaussian model predicts progressively greater probabilities. For example, consider estimating the probability of a major New Madrid earthquake in the next 20 years, assuming that the past one occurred in 1812. If we assume these earthquakes have a mean recurrence of 500 years with standard deviation 100 years, the time dependant (Gaussian) probability is 0.1%, whereas the time independent probability is 4%. If instead we assume mean recurrence of 750 years and standard deviation 100 years, the probabilities are 0.3% and 3%. Weibull and log-normal distributions would give other values. Hence the probability we estimate depends on the distribution we chose and the numerical parameters we chose for that distribution. We pick what we want, and get the answer we wish. The tendency in the Midwest has been to use Poisson models, which give higher earthquake probabilities than the time-dependant models because we're still close to 1812. Conversely in California, most applications use time-dependant models. Even with good paleoseismic data, one gets quite a range of probability estimates. For example at Pallet Creek on the San Andreas the most recent five major earthquakes yield recurrence with a mean and standard deviation of 194 and 58 years, whereas the past ten earthquakes yield 132 and 105. Thus in 1989 the range of probabilities for a major earthquake before 2019 was estimated as about 7-51%. If this is what 10 earthquake cycles give, the implications for New Madrid where we have only 3 or 4 are obvious.



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."

The simplest model for earthquake occurrence is a time-independent Poisson model, in which 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".

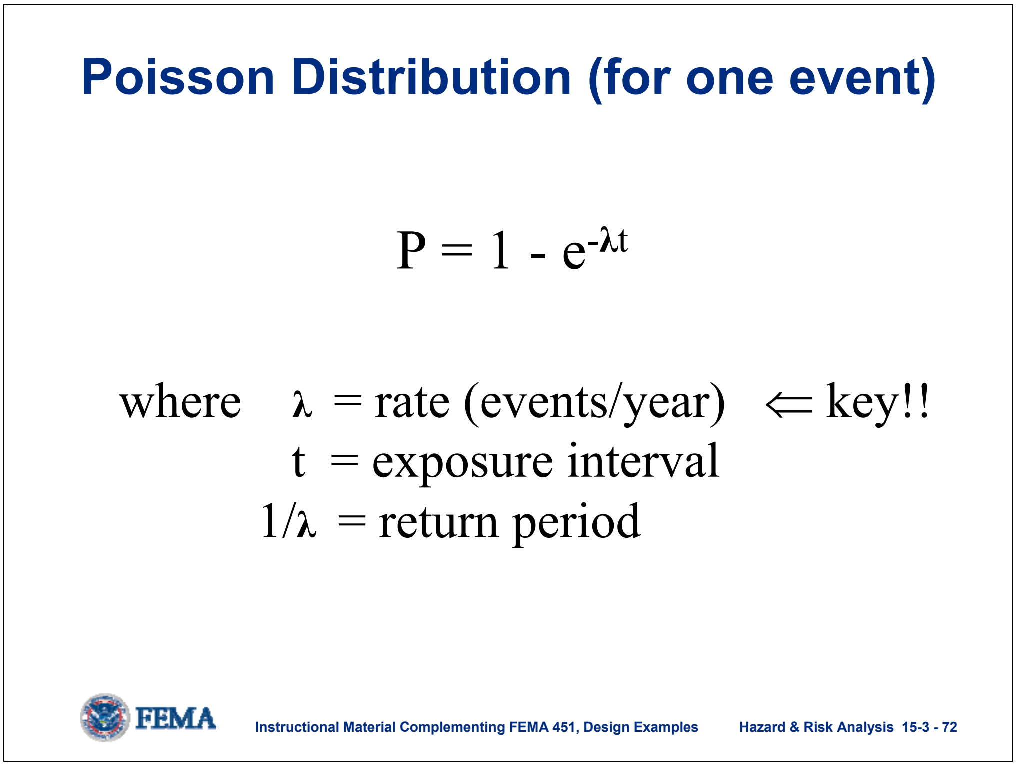


Poisson Distribution (general form)

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

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

The simplest model for earthquake occurrence is a time-independent Poisson model, in which 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". This method is used in probabilistic analysis of both earthquake, floods, and other natural disasters.



Poisson Distribution (for one event)

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

where λ = rate (events/year) ⇐ key!!

t = exposure interval

$1/\lambda$ = return period

We are usually concerned with estimating the probability of just one event occurring, so we solve the Poisson equation in terms of one event; this results in the exponential distribution shown above (as opposed to the general form shown on the previous slide). This equation predicts the probability of having at least one event occur in a given time period, based on the mean rate of events, ν. The model assumes each event is independent. This is a fairly good model for earthquake occurrence, especially if the region considered is large enough. Probably not good model for localized area of faults because in reality these areas have interactions involving stress transfer, etc. between successive events. This is the equation used to develop the national seismic hazard maps, the main unknown and most important input parameter being the rate of seismicity for each area of the country.

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, **λ**t, is small, then P ≈ **λ**t.

Note that for low probabilities (or long return periods), the return period is approximately t/PE such that T is about = 50/0.02 = 2,500 years. This approximation works fine for low probabilities or long return periods, but does not work well for higher probabilities. For instance, the actual return period of 50% PE in 50 Years is 72 years, not 100 years as suggested by the approximate formula.

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.

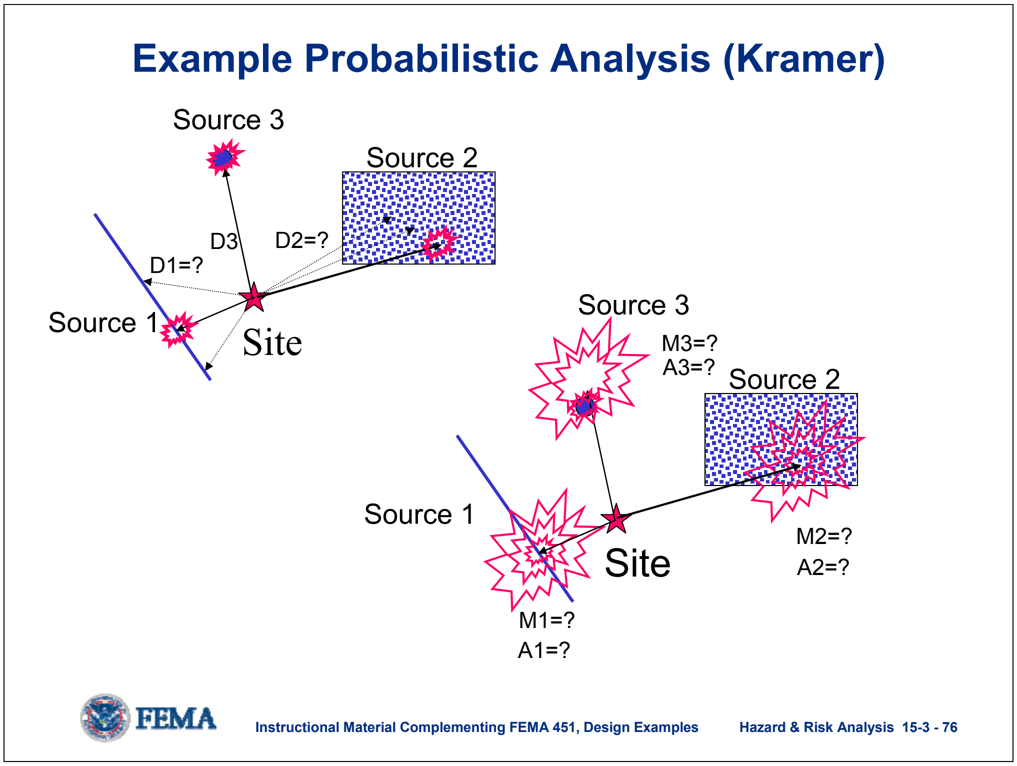
None.

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.

Alternative models are time-dependant, in which 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. These include Gaussian, log- normal, and Weibull distributions, each of which give different numbers.

Again, as mentioned in the previous slide, the difference is that for times since the previous earthquake less than about 2/3 of the assumed recurrence interval, the Poisson model predicts higher probabilities. At later times a Gaussian model predicts progressively greater probabilities. For example, consider estimating the probability of a major New Madrid earthquake in the next 20 years, assuming that the past one occurred in 1812. If we assume these earthquakes have a mean recurrence of 500 years with standard deviation 100 years, the time dependant (Gaussian) probability is 0.1%, whereas the time independent probability is 4%. If instead we assume mean recurrence of 750 years and standard deviation 100 years, the probabilities are 0.3% and 3%. Weibull and log-normal distributions would give other values. Hence the probability we estimate depends on the distribution we chose and the numerical parameters we chose for that distribution. We pick what we want, and get the answer we wish. The tendency in the Midwest has been to use Poisson models, which give higher earthquake probabilities than the time-dependant models because we're still close to 1812. Conversely in California, most applications use time-dependant models. Even with good paleoseismic data, one gets quite a range of probability estimates. For example at Pallet Creek on the San Andreas the most recent five major earthquakes yield recurrence with a mean and standard deviation of 194 and 58 years, whereas the past ten earthquakes yield 132 and 105. Thus in 1989 the range of probabilities for a major earthquake before 2019 was estimated as about 7-51%. If this is what 10 earthquake cycles give, the implications for New Madrid where we have only 3 or 4 are obvious.



Example Probabilistic Analysis (Kramer)

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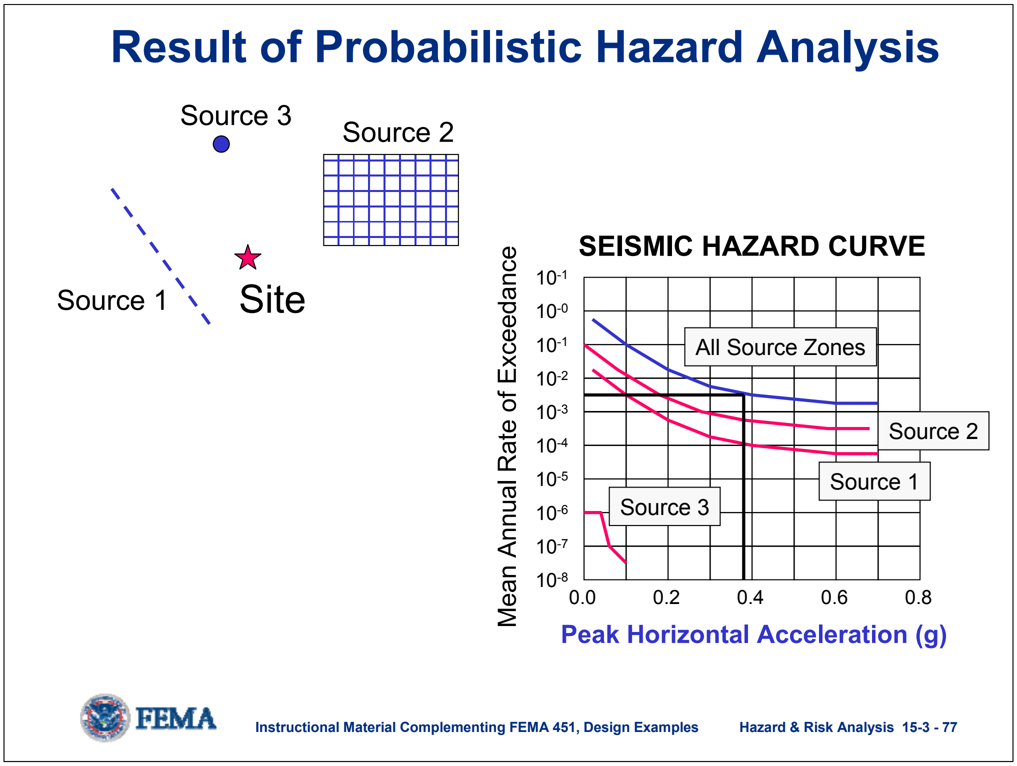
The PSHA analyses consider all magnitudes (large enough to cause damage, typically M5 and above) from all sources at all distances. The sources vary from specific faults to large area sources (box in figure above) or in many case, a background source (the entire region in which it is determined that earthquake could occur anywhere in the general region– such as the Piedmont region of the south east).



Result of Probabilistic Hazard Analysis

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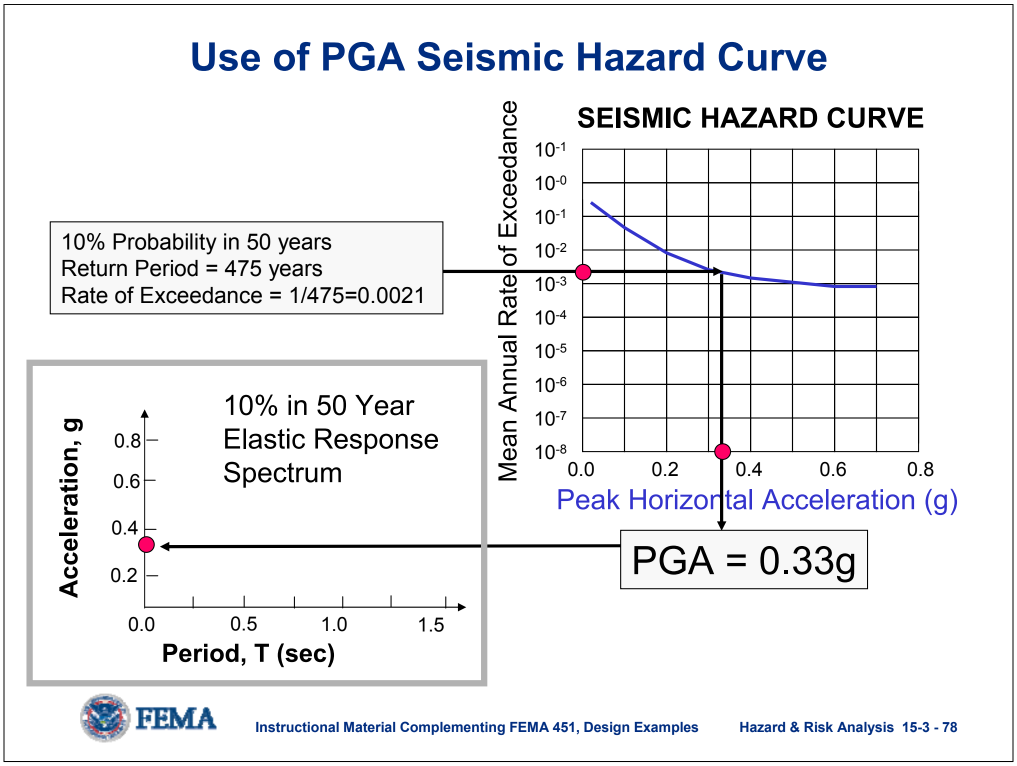
The more sources, the higher the likelihood of exceeding a certain level of shaking.

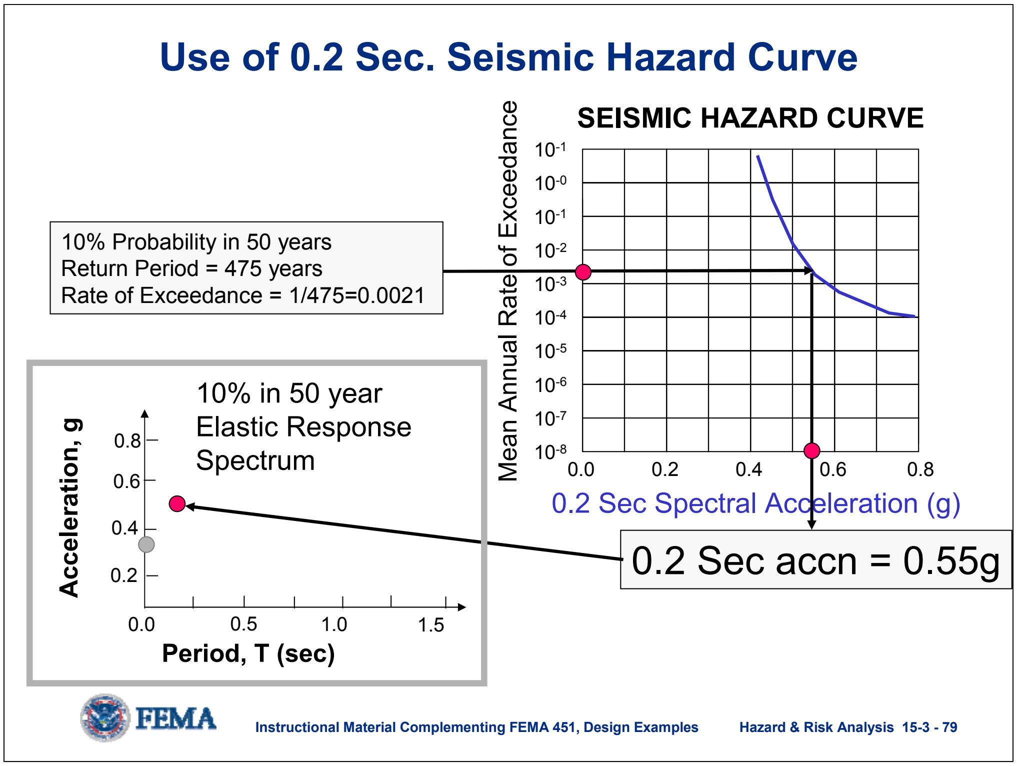


Use of PGA Seismic Hazard Curve

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

PGA = 0.33g

The PGA value for the 500 year EQ is being shown. This is zero period spectral ordinate for the Uniform Hazard Spectrum (UHS).



Use of 0.2 Sec. Seismic Hazard Curve

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

0.2 Sec accn = 0.55g

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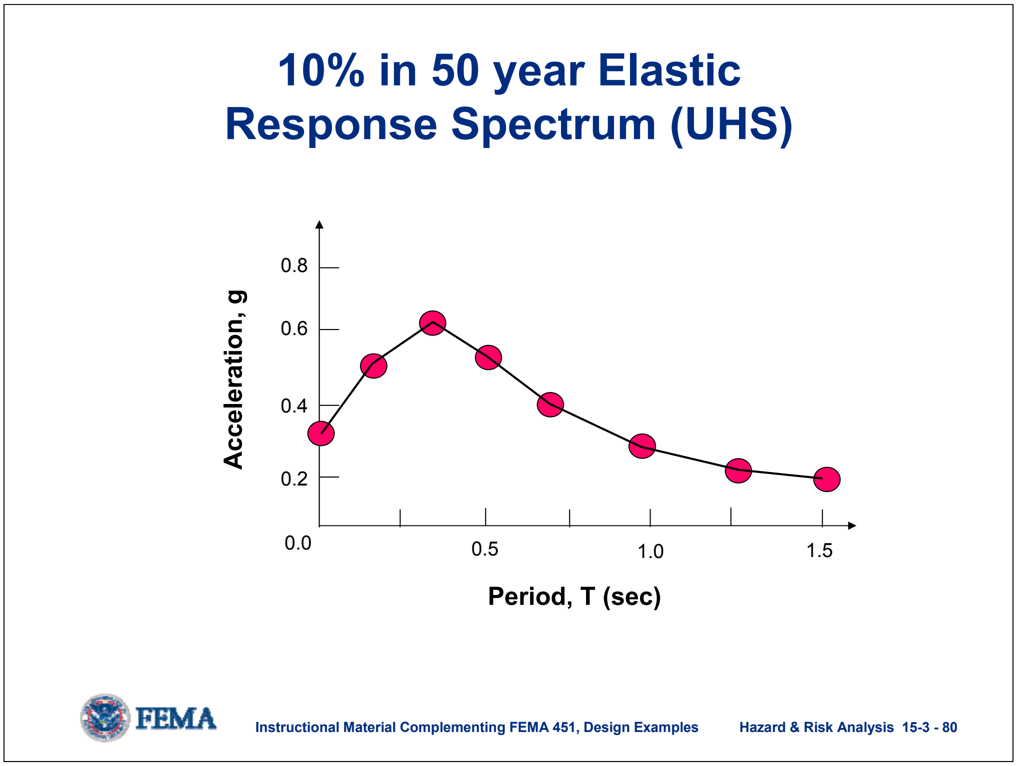
The 0.2 second spectral ordinate for the 500 year EQ is being shown. This is o.2 secpond spectral ordinate for the Uniform Hazard Spectrum (UHS).



10% in 50 year Elastic Response Spectrum (UHS)

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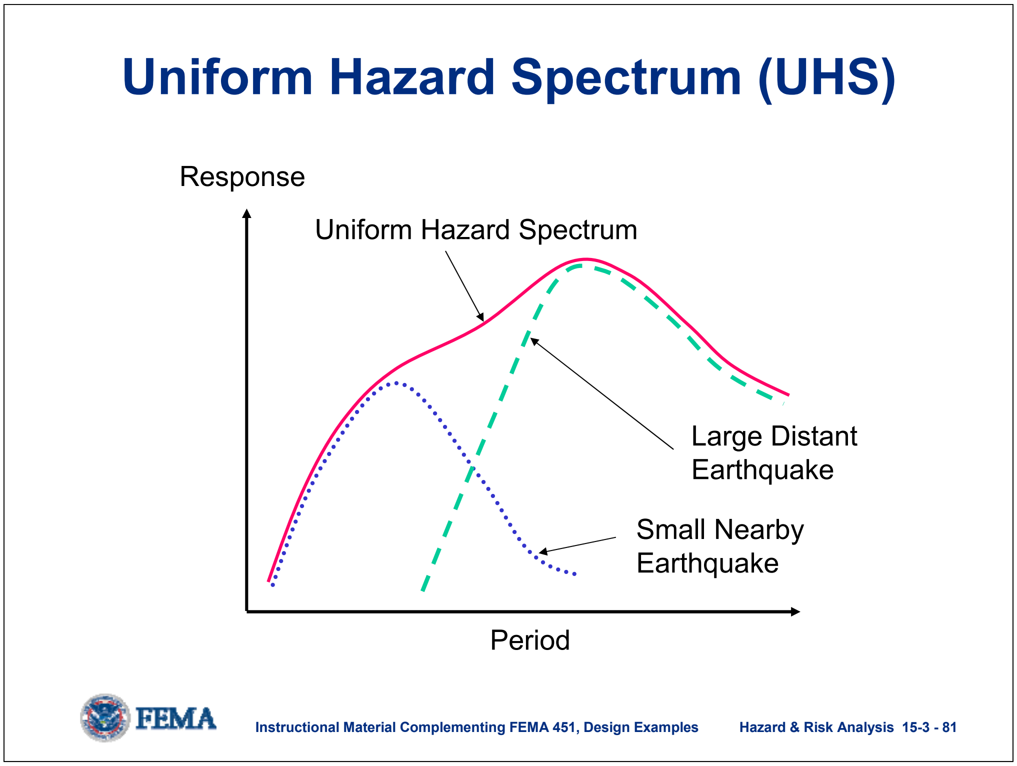
10% in 50 year elastic response spectrum developed from the curves shown in the previous slides and additional points.



Uniform Hazard Spectrum (UHS)

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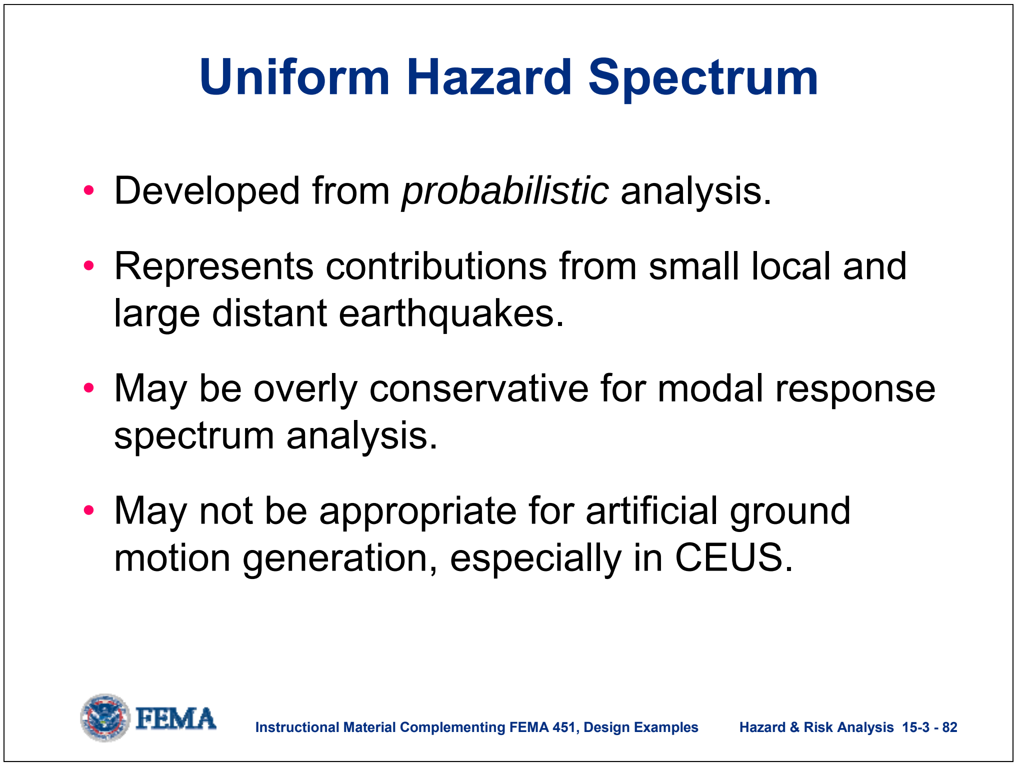
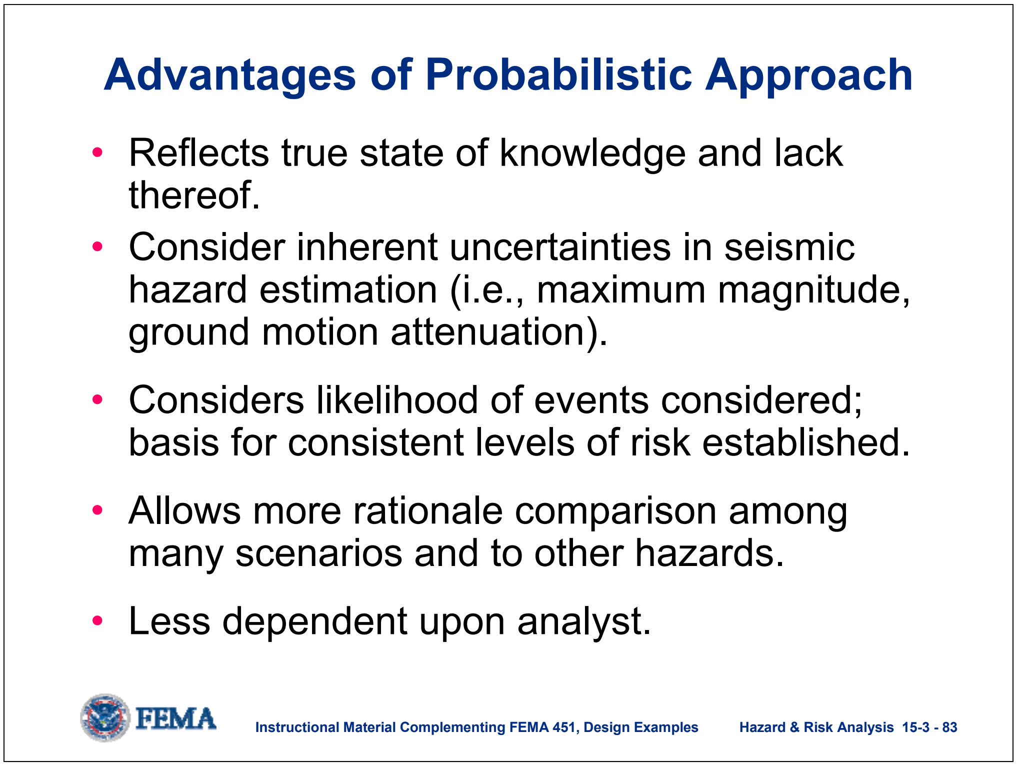
Using the UHS as a basis for spectrum matching to establish a single earthquake motion is incorrect; the extent of the issues associated with this procedures depends upon the depends upon the specifics of the analysis, such as the region of the country. That is, in northern California where the seismicity in San Francisco is dominated by the nearby San Andreas fault, the UHS and the deterministic spectra will probably be very similar because the hazard is so dominated by a single event.



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.

None.



Advantages of Probabilistic Approach

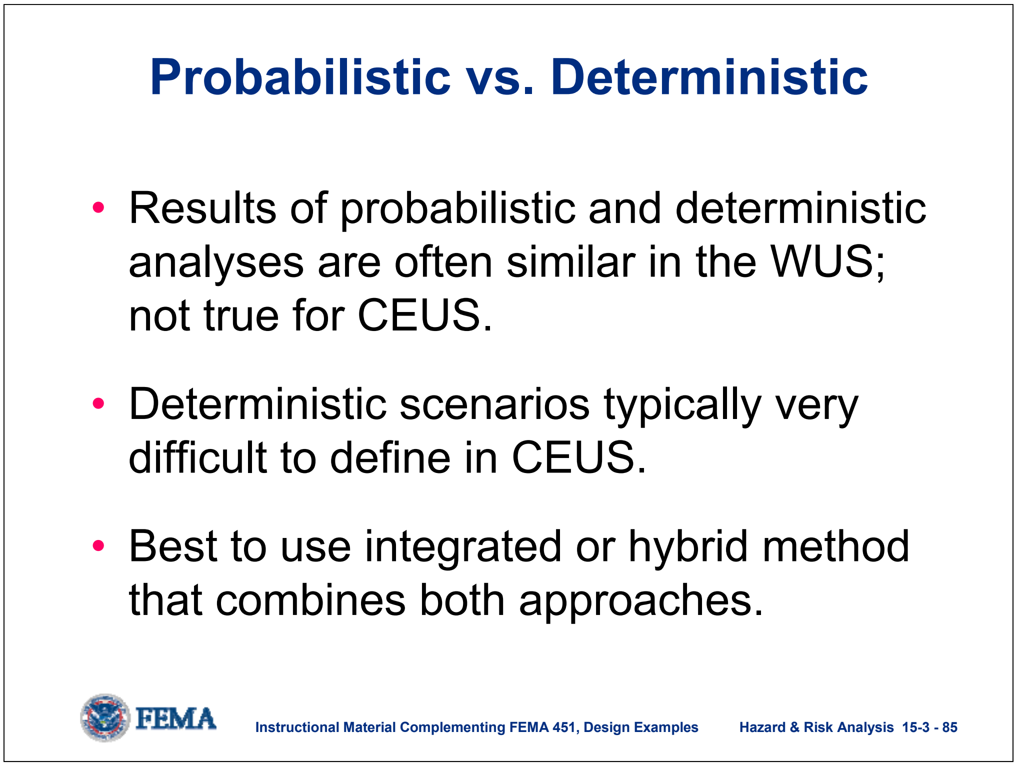
- Reflects true state of knowledge and lack thereof.
- Consider inherent uncertainties in seismic hazard estimation (i.e., maximum magnitude, ground motion attenuation).
- Considers likelihood of events considered; basis for consistent levels of risk established.
- Allows more rationale comparison among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

None.

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.).

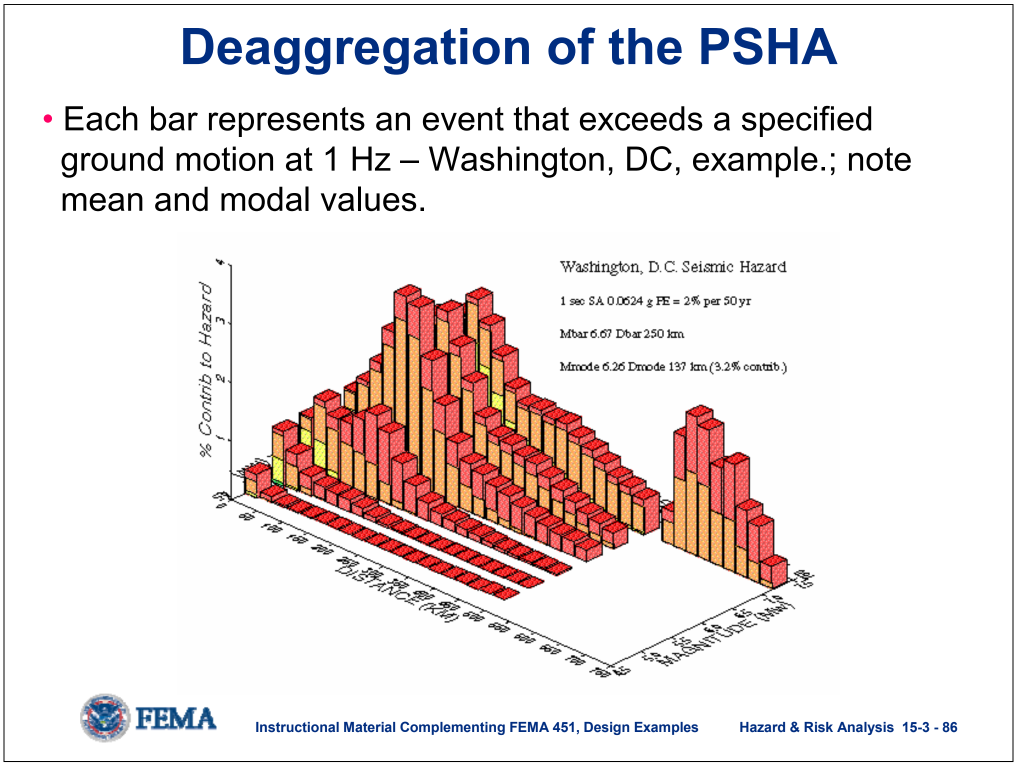
Since the probabilities we estimate depend on many choices, it may no be wise to focus on specific numbers. It may make more sense to quote probabilities in broad ranges, such as low (<10%), intermediate (10-90%), or high (>90%).



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.

Both approaches can be combined to take advantage of the best attributes of both. This approach is used in the example project in central IL and IN shown in the following slides.



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.

Washington, D.C. Seismic Hazard

1 sec SA 0.0624 g PE = 2% per 50 yr

Mbar 6.67 Dbar 250 km

Mmode 6.26 Dmode 137 km (3.2% contrib.)

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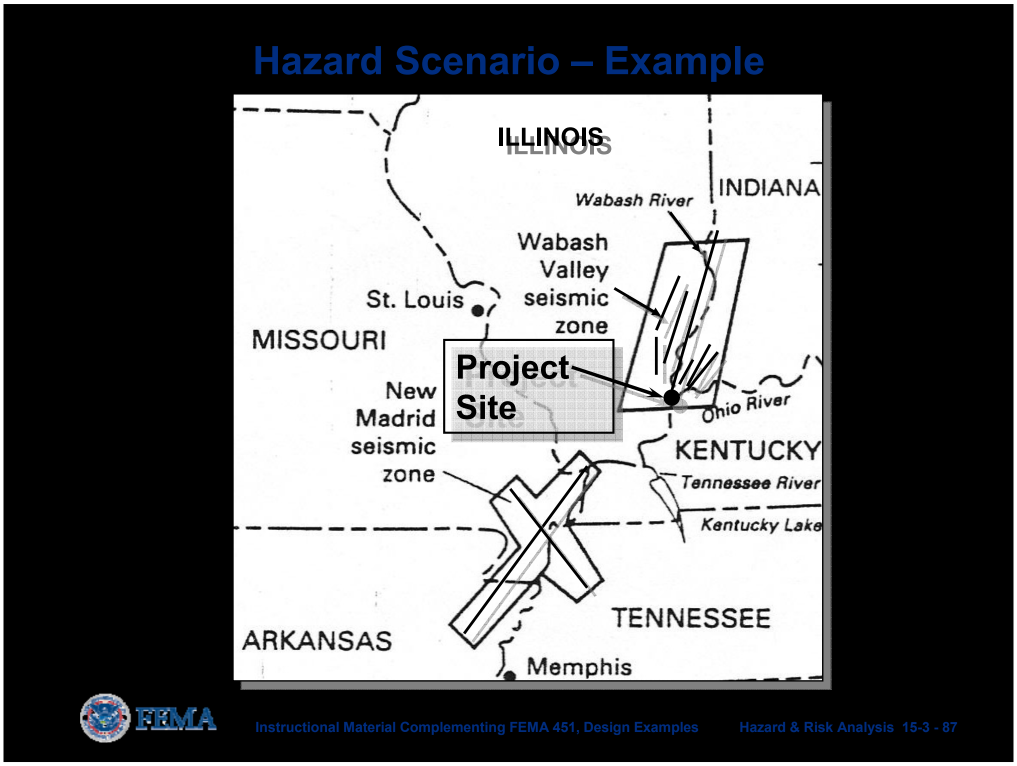
The deaggregation plot above indicates the relative contribution of different earthquakes of different sizes at different distances in the Washington, DC area. The values reflect the relative contribution toward the spectral acceleration value of the UHS at 1 Hz. It is important to understand the significance between the mean and the modal events, as the modal event is the most likely event and the mean reflects the average scenario.



Hazard Scenario – Example

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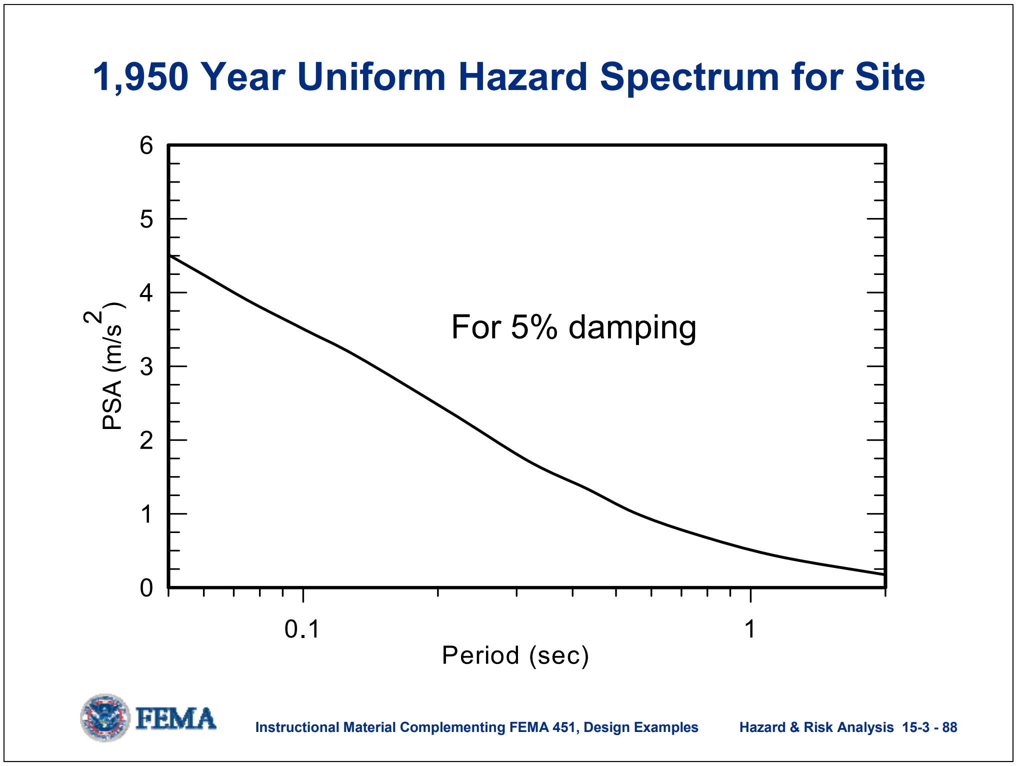
The figure above illustrates two different sources zones that can affect the project site. Each of the source zones contain multiple faults that can generate earthquakes of different sizes. For a site such as that above where there are many different sources at different distances and of different magnitudes, probability is best tool to use to determine which earthquake scenarios are most critical to design for. The primary end objective was to develop an appropriate set of acceleration time histories for the design of the facility.



1,950 Year Uniform Hazard Spectrum for Site

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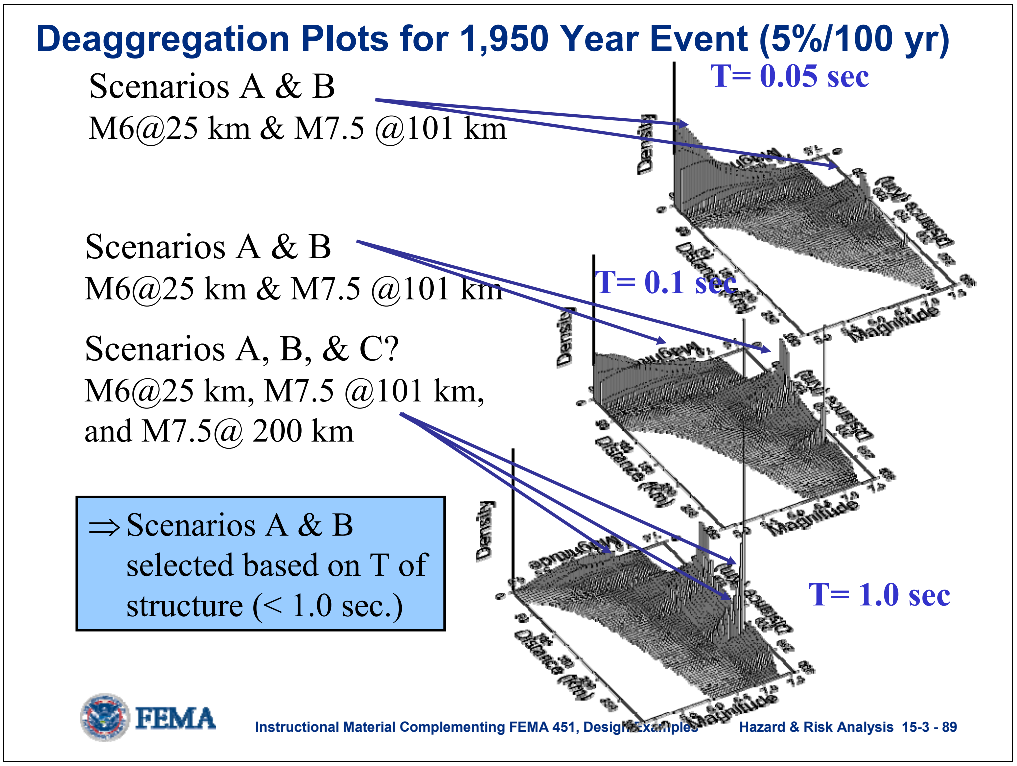
1,950-year uniform hazard spectrum for site; elastic spectrum for 5% damping. This curve was developed from the probabilistic seismic hazard analysis of the site shown in the previous slide.



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

T= 1.0 sec

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

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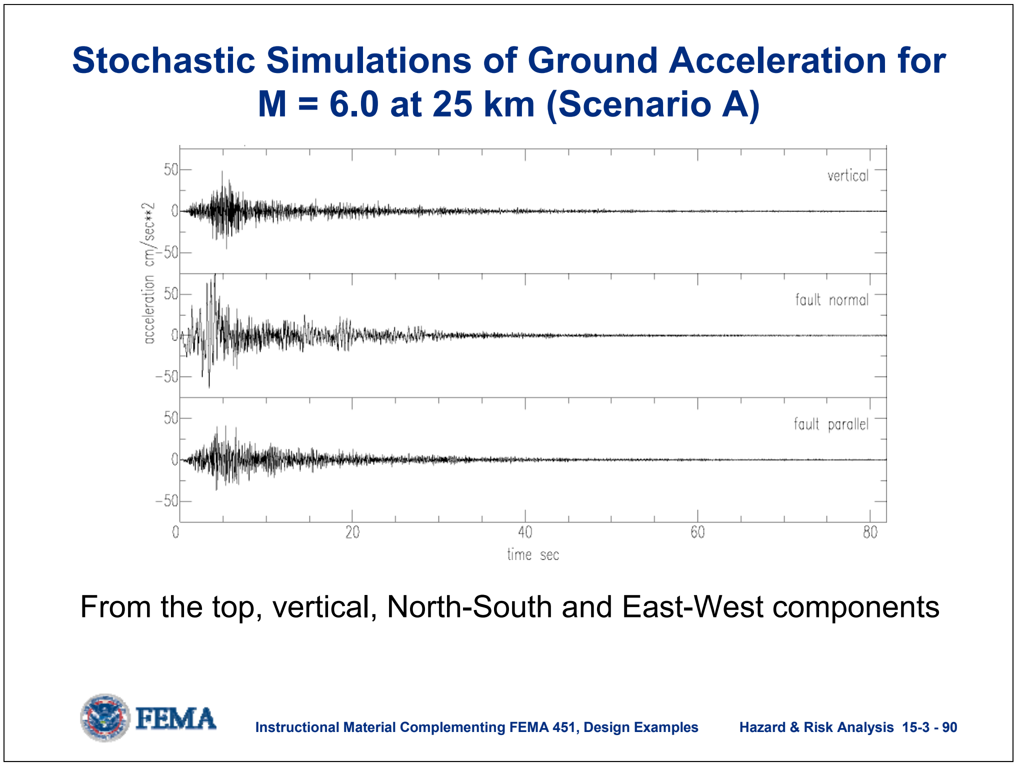
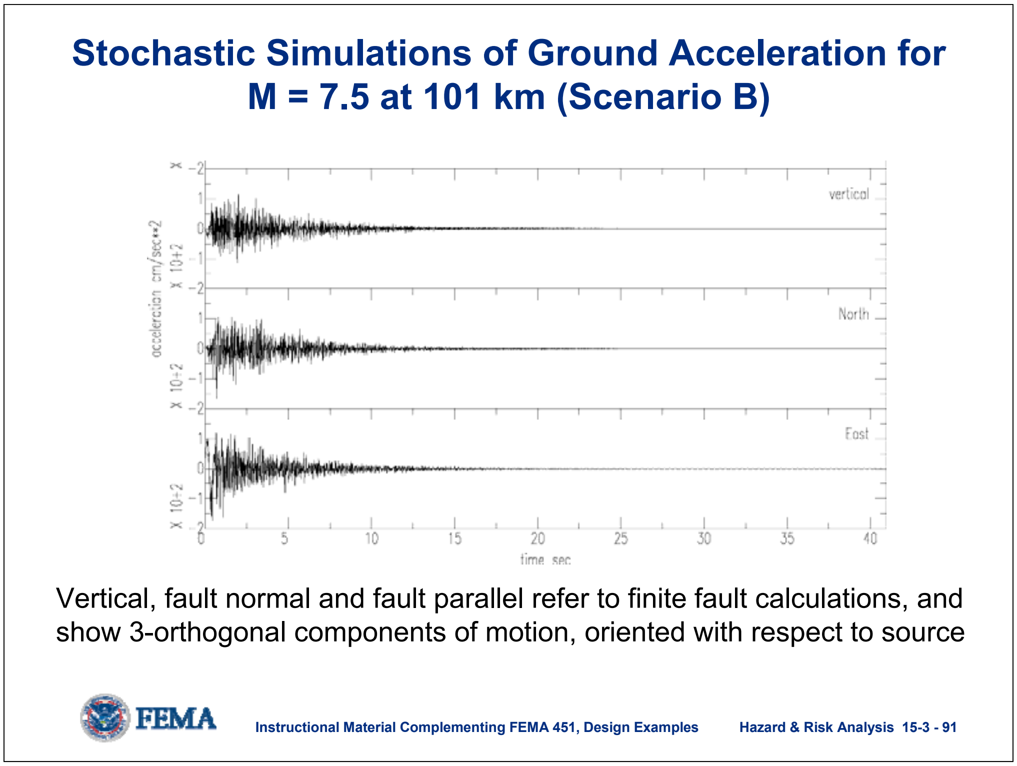
Deaggregation plots showing the relative contribution of various earthquake events for various periods on the UHS. From these plots, a number of earthquake scenarios (magnitudes and distances) need to be considered such that appropriate time histories can be developed for analysis of the project.



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 = 6.0 at 25 km (Scenario A); this was one of the two scenarios considered for the design of the facility.



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

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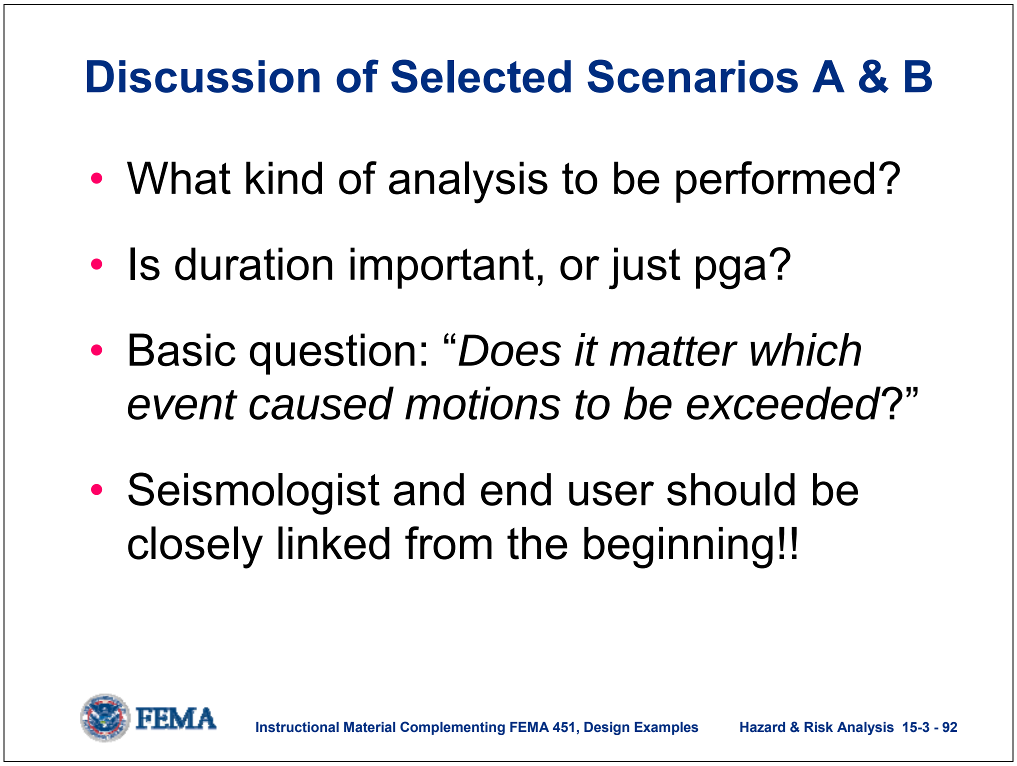
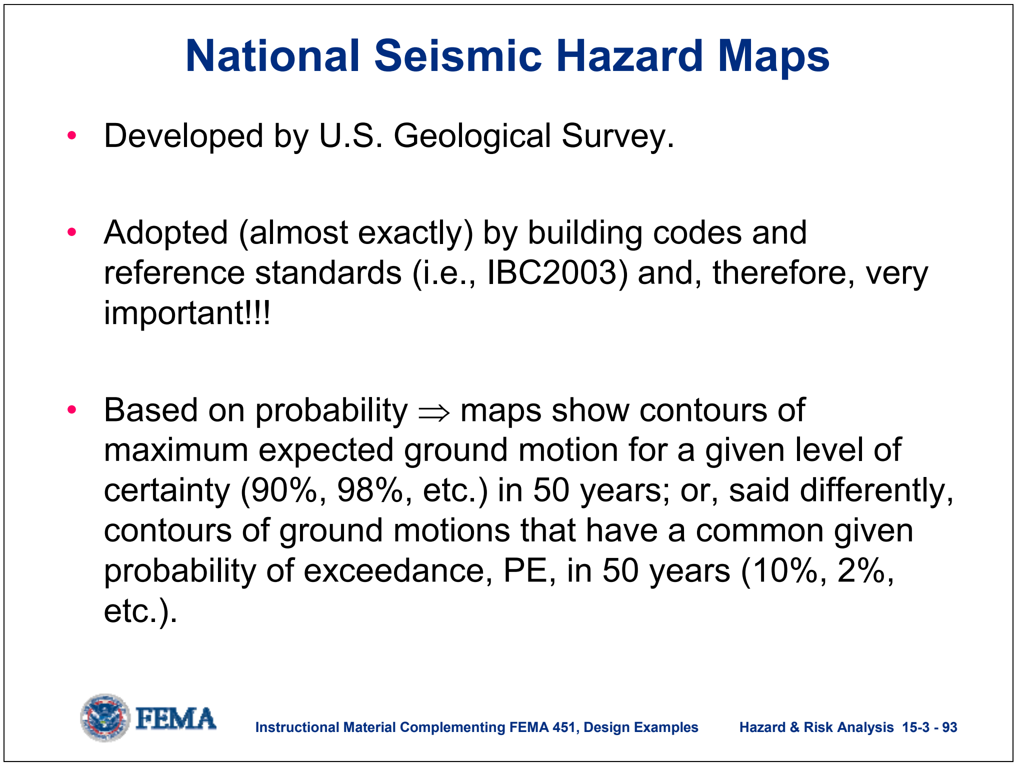
Stochastic simulations of ground acceleration for M = 7.5 at 101 km (Scenario B); this was one of the two scenarios considered for the design of the facility.



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!!

It is possible to perform analyses for all possible sources and distances, but often there is too little budget. It must be determined which scenario is the most critical. Which event is most critical depends upon many issues, such as whether duration as well as PGA is important (most geotechnical analyses), or whether PGA is the main consideration (most structural analyses).



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.).

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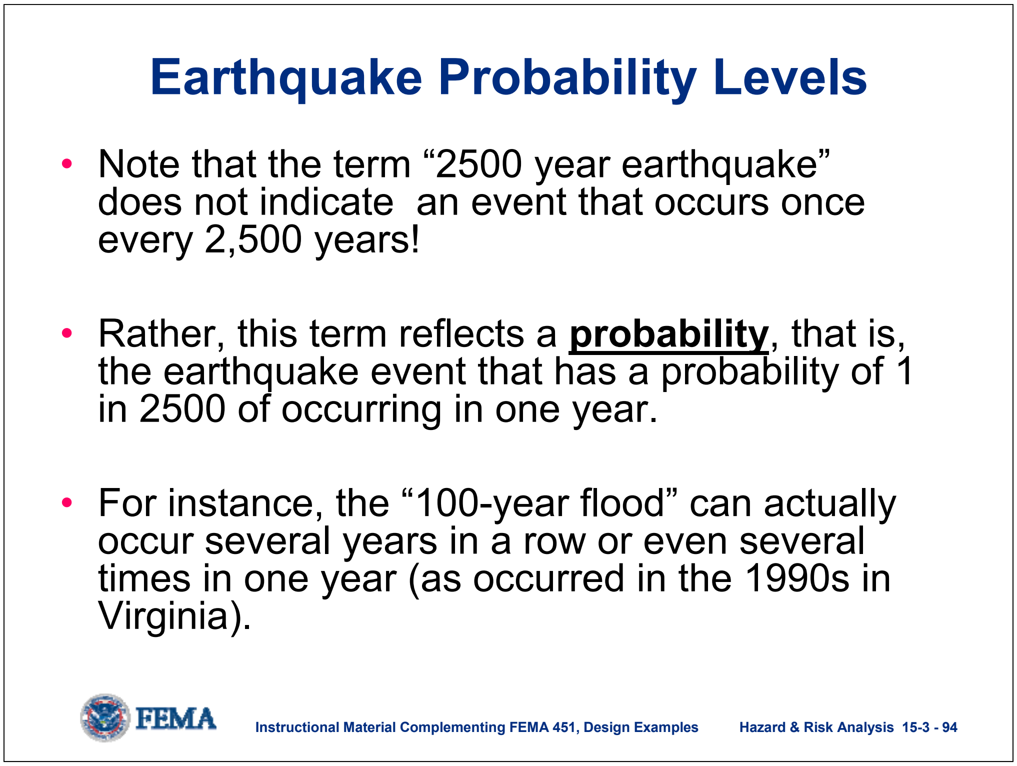
The specific basis for originally selecting these three specific probability levels for mapping and use in engineering design is somewhat moot and is probably a remnant of the first series of seismic safety analyses performed for nuclear power facilities in the late 1960s and 1970s when probabilistic seismic hazard analysis techniques were being originally developed. These probabilities have become the “standard” probability levels frequently referred to and used in seismic design. The 2%/50-year map is used as the basis for structural design in most regions



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).

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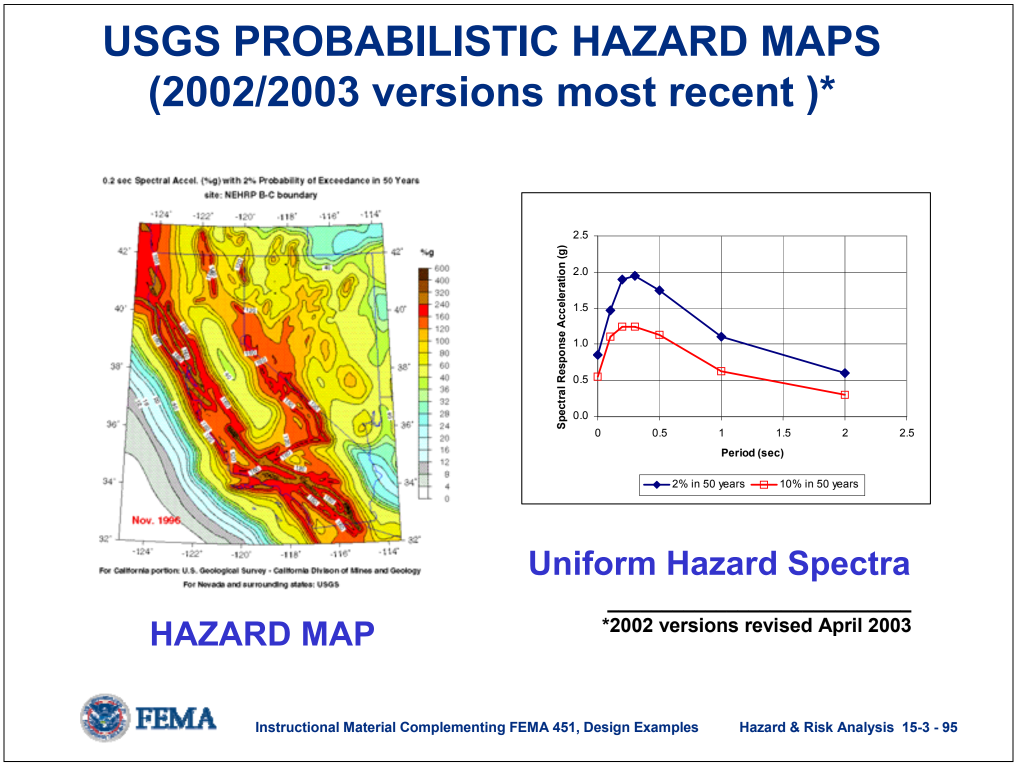
This term is commonly misunderstood and misinterpreted. The term “2500 year earthquake” does not indicate that an event that occurs once every 2,500 years! Rather, this term reflects a **probability**, that is, the earthquake event that has a probability of 1 in 2500 of occurring in one year. For instance, 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). The Poisson model is used to predict the probability of earthquakes based on the average rate of earthquakes of a given size that occur in a region—hence the importance of seismic monitoring networks that record earthquakes, including the frequent small events that are not felt. A statically representative data catalog of the number of earthquakes of various size forms the basis for estimating the likelihood of future events, including large damaging earthquakes. The more data available, the better the predictions (at least statistically). For more on the discussion of probability associated with the maps, see FAQs at: http://geohazards.cr.usgs.gov/eq/html/faq.html and/or: “Info for the Layman” at http://geohazards.cr.usgs.gov/eq/



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

0.2 sec Spectral Accel. (%g) with 2% Probability of Exceedance in 50 Years
site: NEHRP B-C boundary

For California portion: U.S. Geological Survey - California Divison of Mines and Geology
For Nevada and surrounding states: USGS

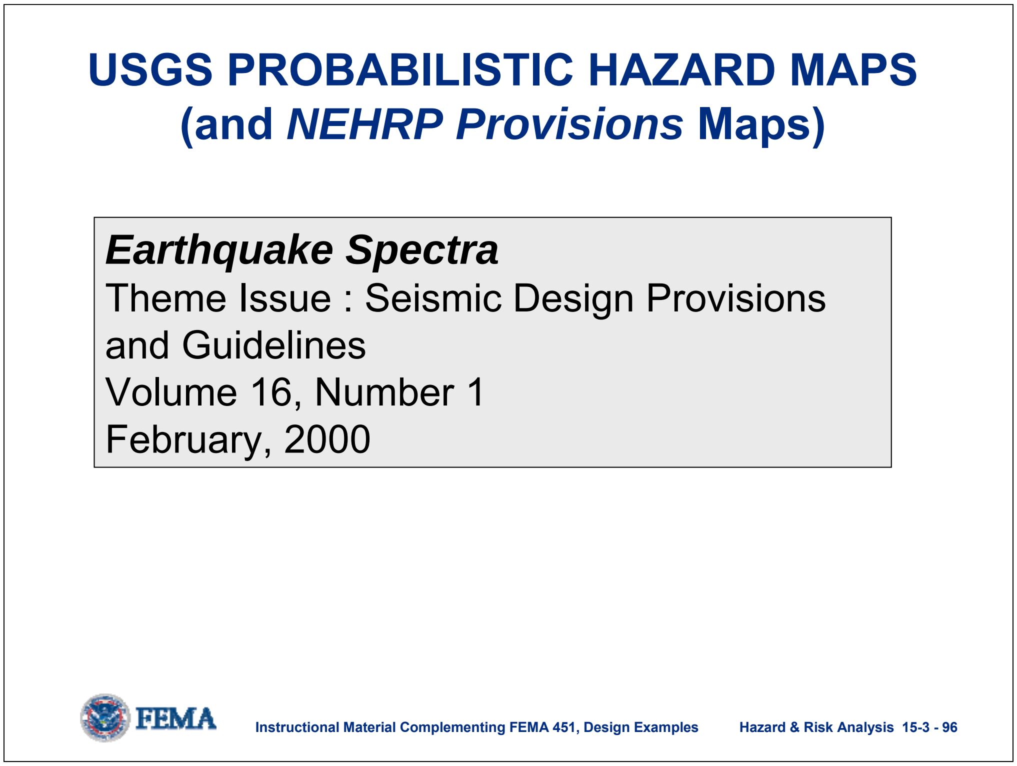
HAZARD MAP

Uniform Hazard Spectra

*2002 versions revised April 2003

USGS maps are available on-line at web address: http://eqhazmaps.usgs.gov/

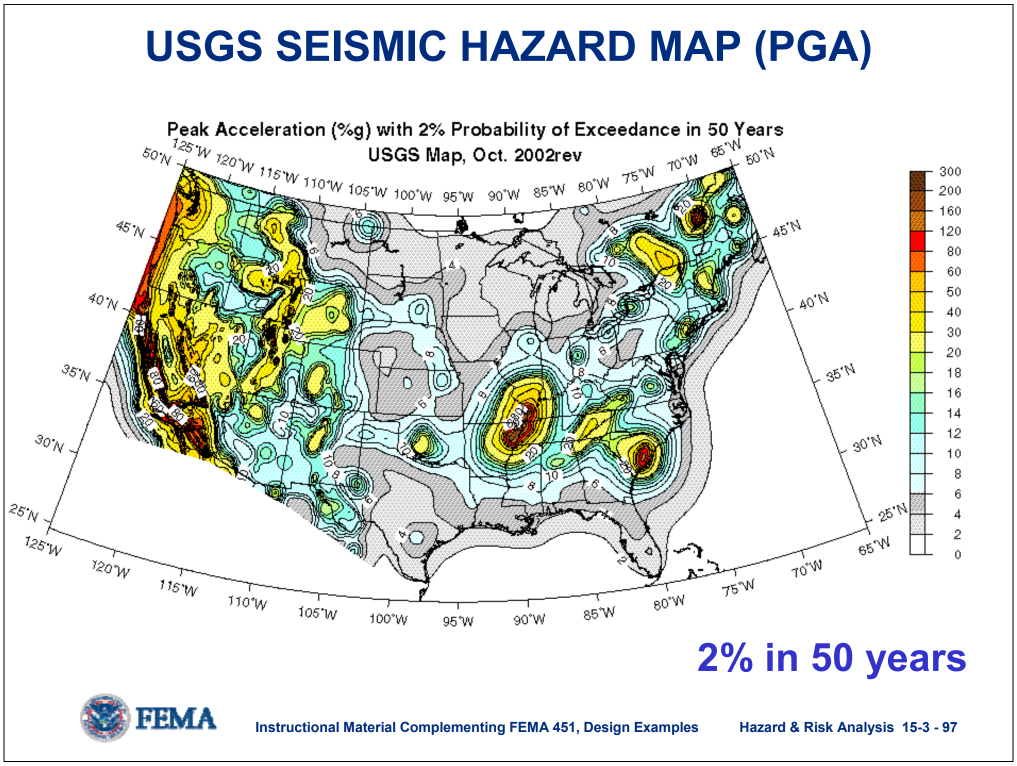
Maps are provided for three different probability levels and four different ground motion parameters, peak acceleration and spectral acceleration at 0.2, 0.3, and 1.0 sec. periods. (These values are mapped for a given geologic site condition. Other site conditions may increase or decrease the hazard. Also, other things being equal, older buildings are more vulnerable than new ones.) The maps can be used to determine (a) the relative probability of a given critical level of earthquake ground motion from one part of the country to another; (b) the relative demand on structures from one part of the country to another, at a given probability level. In addition, (c) building codes use one or more of these maps to determine the resistance required by buildings to resist damaging levels of ground motion. The different levels of probability are those of interest in the protection of buildings against earthquake ground motion. The ground motion parameters are proportional to the hazard faced by a particular kind of building.



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

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

The Earthquake Engineering Research Institute (EERI) reference provide many important details involved in the development of the USGS maps.



USGS SEISMIC HAZARD MAP (PGA)

2% in 50 years

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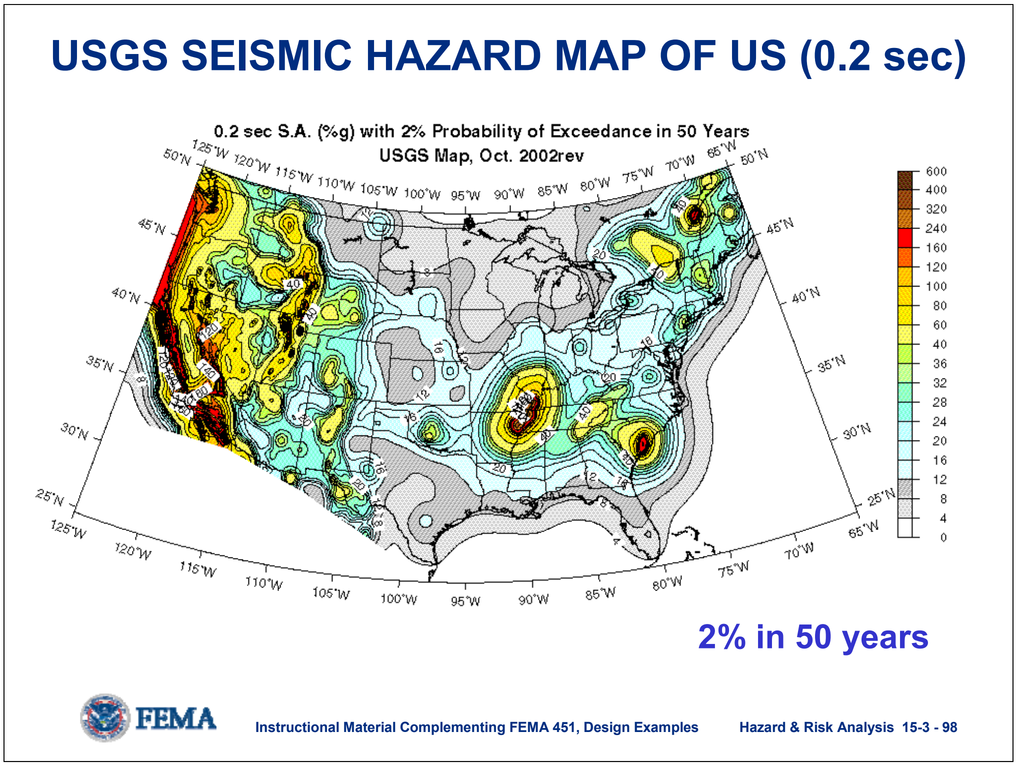
This map depicts earthquake hazard by showing, by contour values, the earthquake ground motions that have a common given probability of being exceeded in 50 years. The motions on the map above are PGAs with a 2% probability of being exceeded in 50 years ("2,500 year event"). The ground motions being considered at a given location are those from all future possible earthquake magnitudes at all possible distances from that location. The ground motion coming from a particular magnitude and distance is assigned an annual probability equal to the annual probability of occurrence of the causative magnitude and distance. The method assumes a reasonable future catalog of earthquakes, based upon historical earthquake locations and geological information on the recurrence rate of fault ruptures.

When all the possible earthquakes and magnitudes have been considered, one can find a ground motion value such that the annual rate of its being exceeded has a certain value. Hence, on a given map, for a given probability of exceedance, PE, locations shaken more frequently, will have larger ground motions. For a LARGE exceedance probability, the map will show the relatively likely ground motions, which are LOW ground motions, because small magnitude earthquakes are much more likely to occur than are large magnitude earthquakes. For a SMALL exceedance probability, the map will emphasize the effect of less likely events: larger-magnitude and/or closer-distance events, producing overall LARGE ground motions on the map. The maps have this format, because they are designed to be useful in building codes, in which we assume that, for the most part, all buildings would be built to the same level of safety. For other applications, maps of another format might be more useful. For instance, many buildings across the US are built more or less the same, regardless of earthquake hazard. If we knew that a particular type of building was likely to fail at a particular ground motion level, we could make a map showing contours of the likelihood of that ground motion value being exceeded, due to earthquakes.



USGS SEISMIC HAZARD MAP OF US (0.2 sec)

0.2 sec S.A. (%g) with 2% Probability of Exceedance in 50 Years
USGS Map, Oct. 2002rev

2% in 50 years

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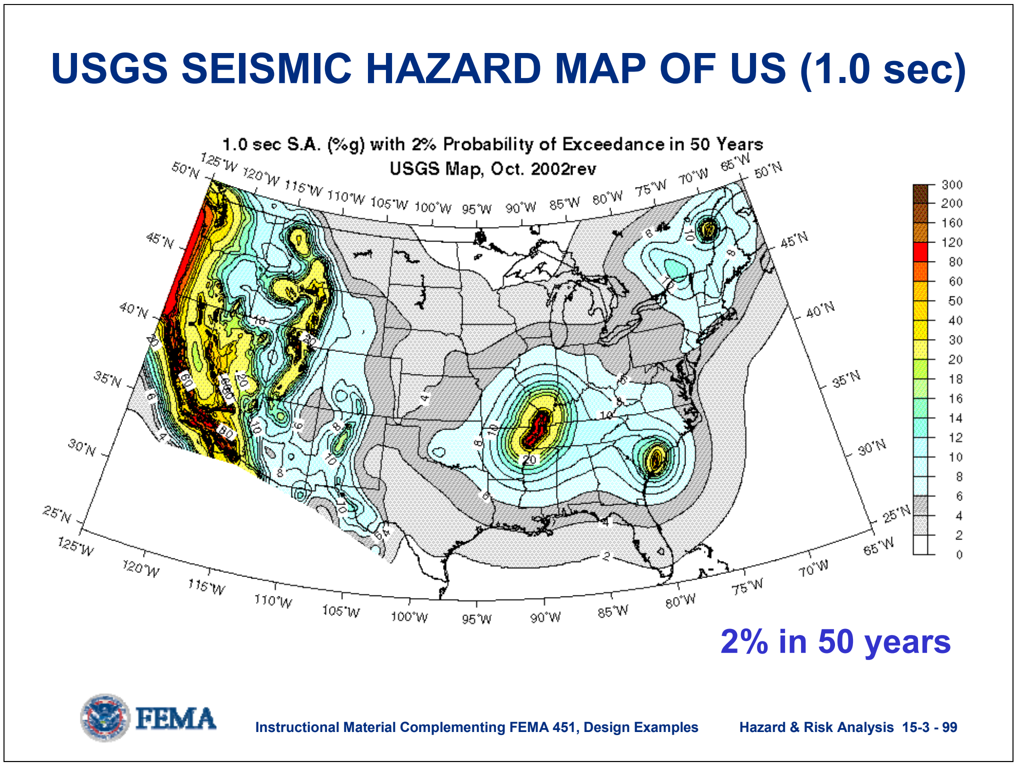
Hazard & Risk Analysis 15-3 - 98

This map depicts earthquake hazard by showing, by contour values, the earthquake ground motions that have a common given probability of being exceeded in 50 years. The motions on the map above are spectral accelerations for the 0.2 sec ordinate with a 2% probability of being exceeded in 50 years ("2,500 year event"). The ground motions being considered at a given location are those from all future possible earthquake magnitudes at all possible distances from that location. The ground motion coming from a particular magnitude and distance is assigned an annual probability equal to the annual probability of occurrence of the causative magnitude and distance. The method assumes a reasonable future catalog of earthquakes, based upon historical earthquake locations and geological information on the recurrence rate of fault ruptures.

When all the possible earthquakes and magnitudes have been considered, one can find a ground motion value such that the annual rate of its being exceeded has a certain value. Hence, on a given map, for a given probability of exceedance, **PE**, locations shaken more frequently, will have larger ground motions. For a LARGE exceedance probability, the map will show the relatively likely ground motions, which are LOW ground motions, because small magnitude earthquakes are much more likely to occur than are large magnitude earthquakes. For a SMALL exceedance probability, the map will emphasize the effect of less likely events: larger-magnitude and/or closer-distance events, producing overall LARGE ground motions on the map. The maps have this format, because they are designed to be useful in building codes, in which we assume that, for the most part, all buildings would be built to the same level of safety. For other applications, maps of another format might be more useful. For instance, many buildings across the US are built more or less the same, regardless of earthquake hazard. If we knew that a particular type of building was likely to fail at a particular ground motion level, we could make a map showing contours of the likelihood of that ground motion value being exceeded, due to earthquakes.



USGS SEISMIC HAZARD MAP OF US (1.0 sec)

2% in 50 years

FEMA

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Hazard & Risk Analysis 15-3 - 99

This map depicts earthquake hazard by showing, by contour values, the earthquake ground motions that have a common given probability of being exceeded in 50 years. The motions on the map above are spectral accelerations for the 1.0 sec ordinate with a 2% probability of being exceeded in 50 years (“2,500 year event”). The ground motions being considered at a given location are those from all future possible earthquake magnitudes at all possible distances from that location. The ground motion coming from a particular magnitude and distance is assigned an annual probability equal to the annual probability of occurrence of the causative magnitude and distance. The method assumes a reasonable future catalog of earthquakes, based upon historical earthquake locations and geological information on the recurrence rate of fault ruptures.

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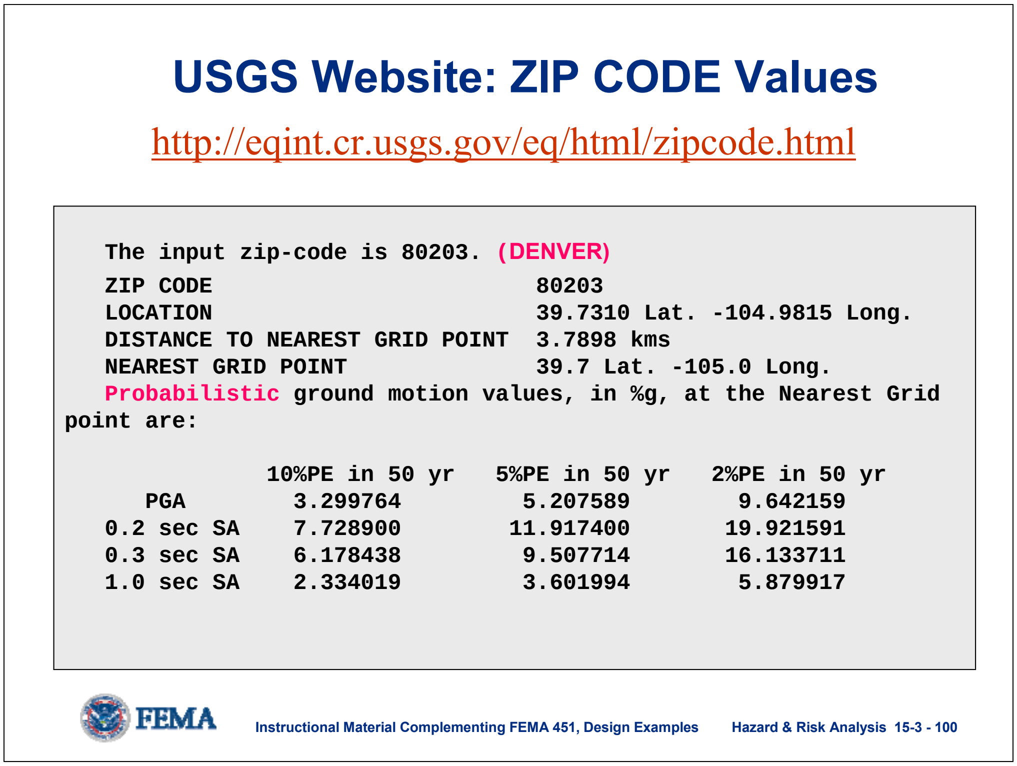


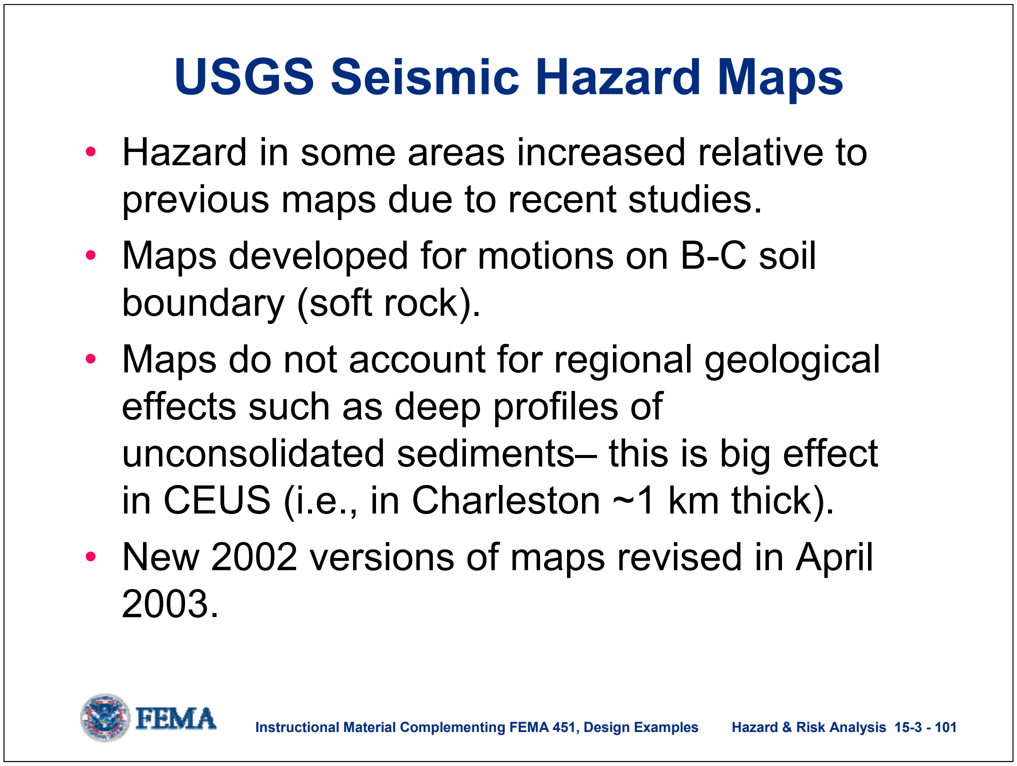
USGS Website: ZIP CODE Values

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
```

The Zipcode Lookup tool is an extremely useful tool for determining mapped values but its use for actual design is discouraged. Use of the actual lat-long for a site is the appropriate way of determining the map values for design.



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.

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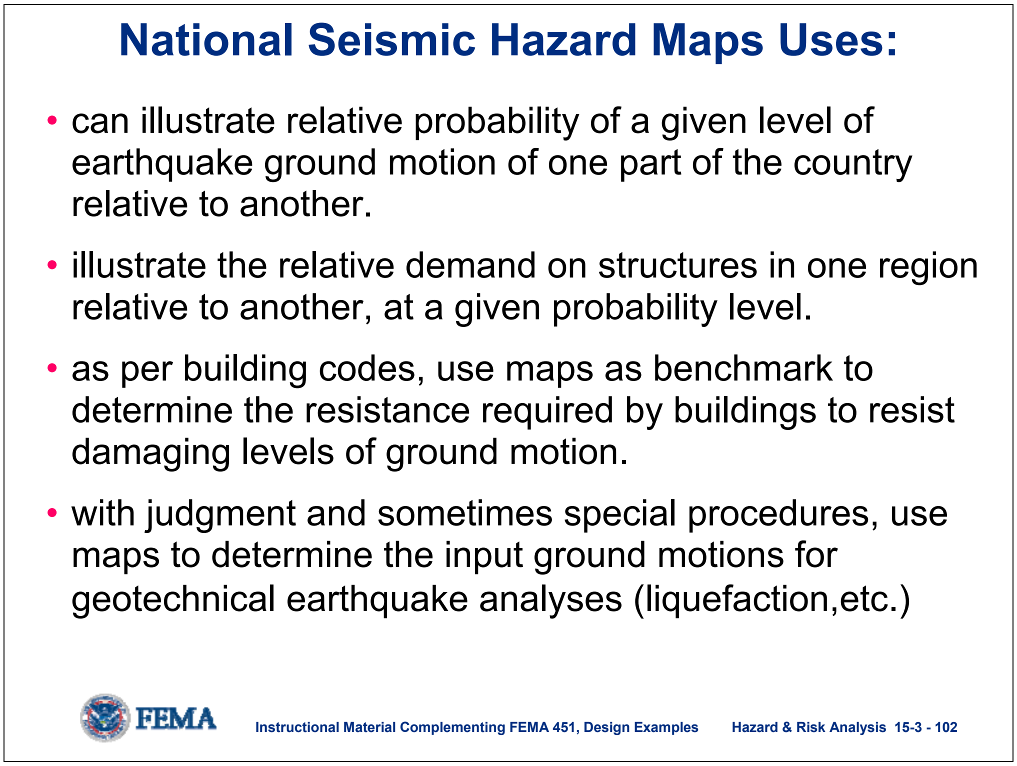
None.



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.)

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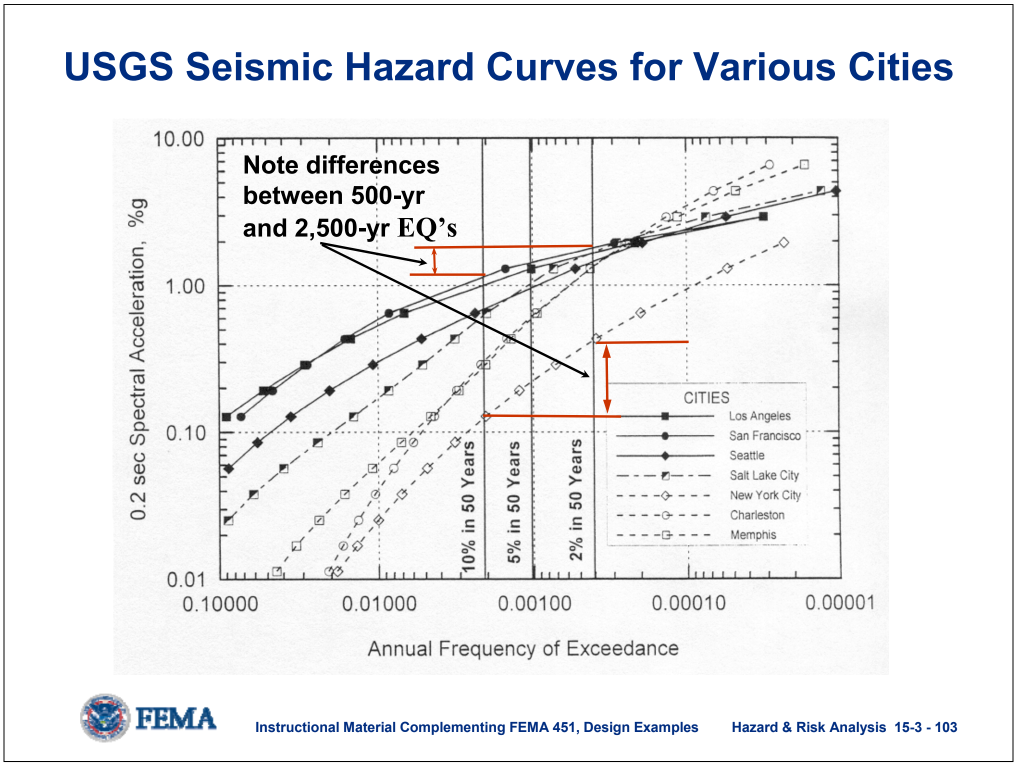
Hazard & Risk Analysis 15-3 - 102

None.



USGS Seismic Hazard Curves for Various Cities

Note differences between 500-yr and 2,500-yr EQ's

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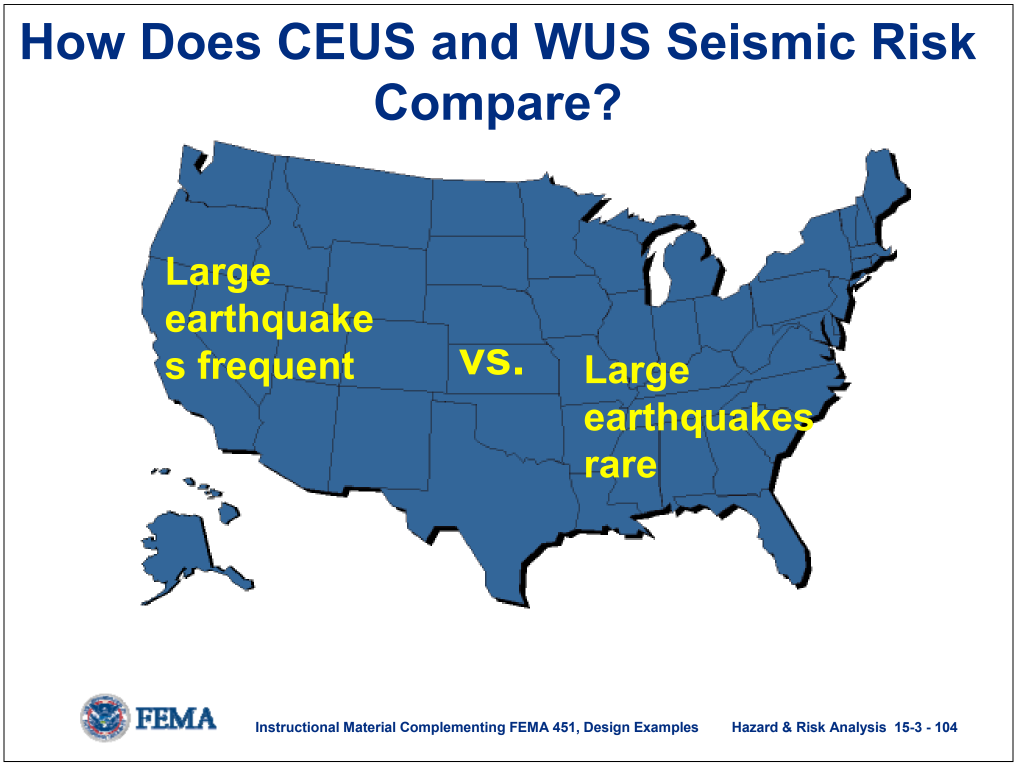
Hazard & Risk Analysis 15-3 - 103

Due to the shape of the hazard curves, it can be seen that in the EUS, there is great difference between the 500 and 2,500-year event. Thus, this left many buildings in the CEUS designed for the 500-year event vulnerable to collapse in a large, rare earthquake (i.e., 2500-year event). New IBC2003 Code provisions account for this by using 2,500-year event (MCE) as the basis for design in all regions.



How Does CEUS and WUS Seismic Risk Compare?

Large earthquake s frequent

vs.

Large earthquakes rare

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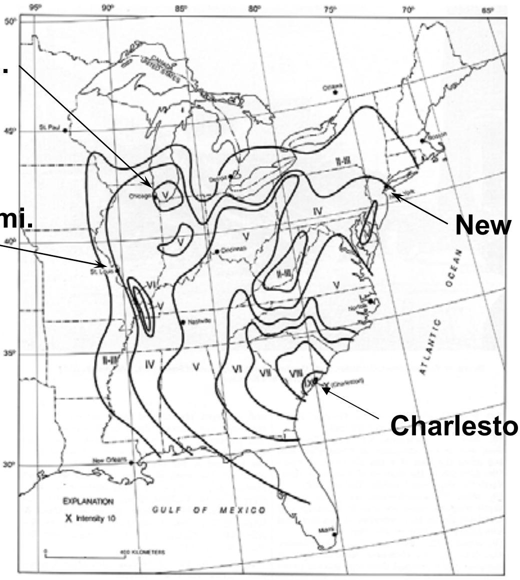
Hazard & Risk Analysis 15-3 - 104

People are different, so what about earthquakes? Large, damaging earthquakes occur more frequently in the western US and thus the seismic hazard is higher there, but this is not true for the overall seismic risk because the consequences of such an event are much greater in the eastern US due to the weaker infrastructure and lower attenuation.

Large, damaging earthquakes occur more frequently in the western US and thus the seismic hazard is higher there, but this is not true for the overall seismic risk because the consequences of such an event are much greater in the eastern US due to the weaker infrastructure and lower attenuation.

1886 Charleston Earthquake Felt Over EUS!



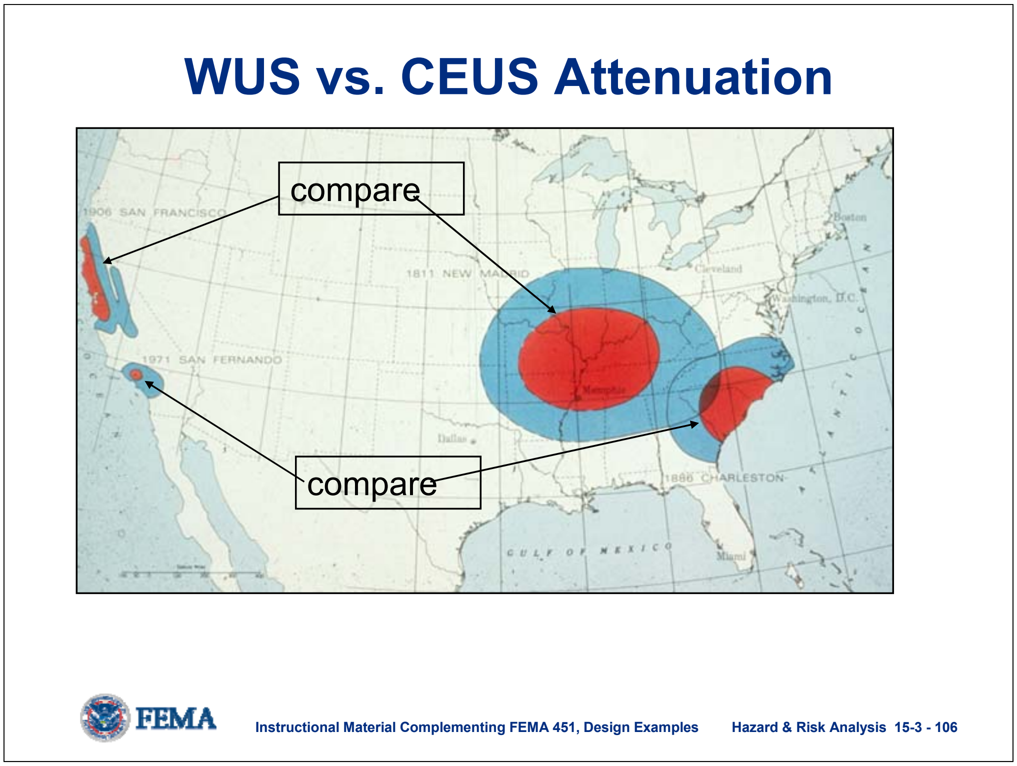
Chicago > 700 mi.

St. Louis > 650 mi.

New York >600 mi.

Charleston

The 1886 Charleston earthquake was felt over an unusually long distance (relative to west-coast standards). Again, this reflects the lower attenuation in this region due to harder rock.

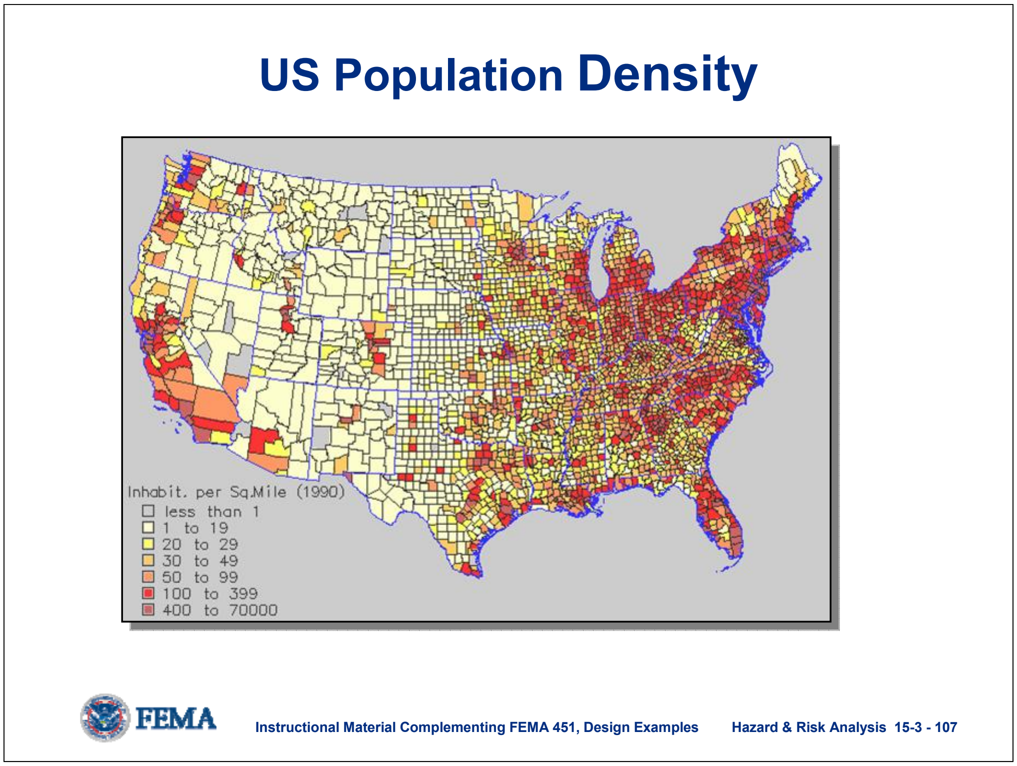


WUS vs. CEUS Attenuation

compare

compare

Attenuation is lower in CEUS because of location in the middle of plate. Crust is older, colder, and much harder than in the WUS.



US Population Density

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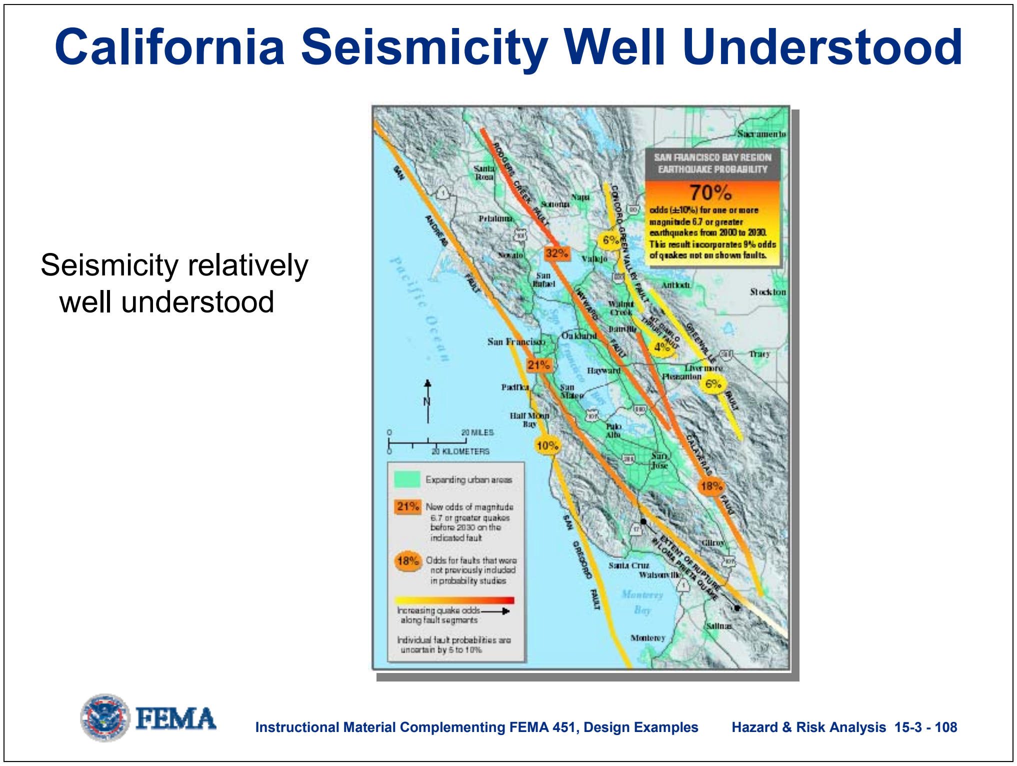
On the average, population density is higher in the EUS than in the WUS; as per the map above. Thus given the same magnitude earthquake, there is a higher likelihood of affecting a larger number of people.



California Seismicity Well Understood

Seismicity relatively well understood

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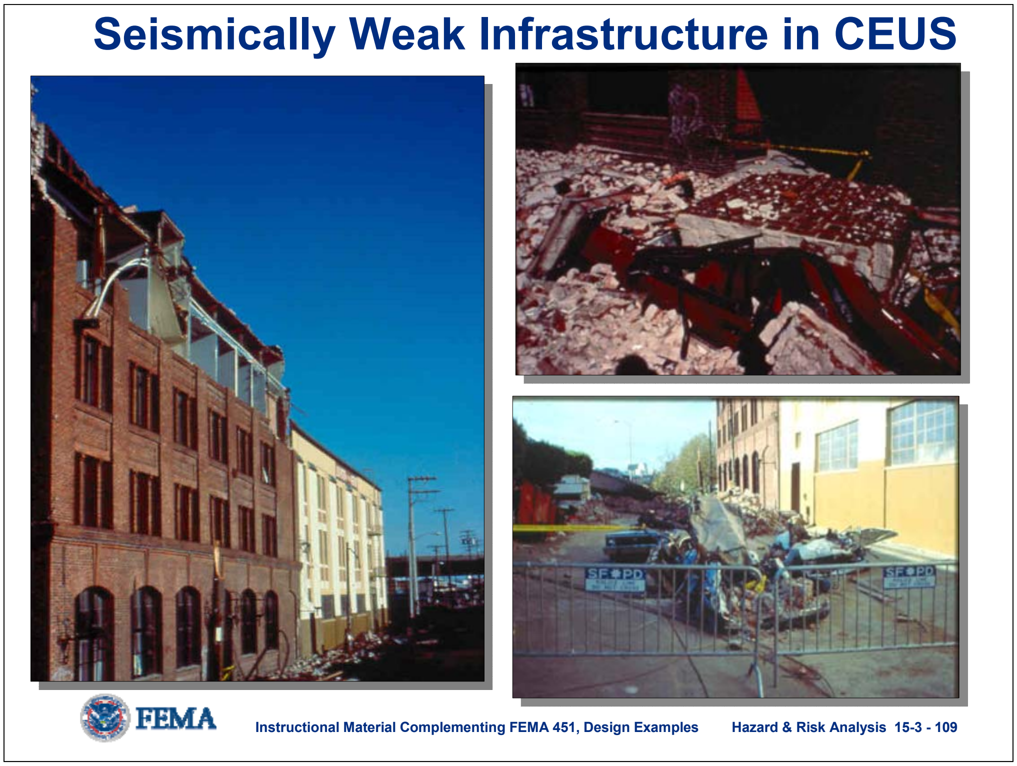
Seismicity in California is generally well understood and the major faults are clearly identified– the map above even has data that shows the likelihood of future events for specific faults. This is not the case in the eastern US where the seismic sources and mechanisms are poorly defined.



Seismically Weak Infrastructure in CEUS

FEMA

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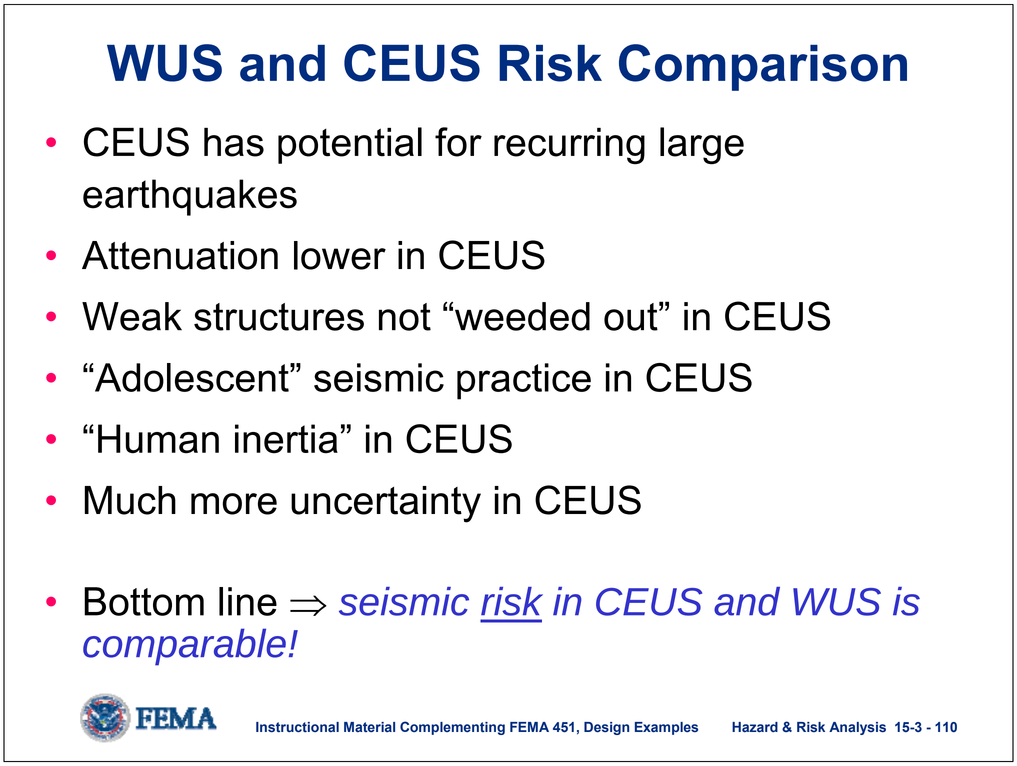
There is an abundance of seismically weak infrastructure in the CEUS. Figure above shows damage to an unreinforced masonry structure near 6th and Townsend Streets during the 1989 Loma Prieta earthquake. Close-up photos on the right show cars that were crushed leading to the death of five people. This building was located in the western US, but similar construction is abundant in the central and eastern US.



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!*

The seismic risk is higher in the WUS due to the higher frequency of earthquakes, but the risk in the EUS is comparable.

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

Cypress Overpass

The damaged Cypress Overpass is an exampled of nonductile behavior.

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The poor performance of the Cypress Structure prompted the decision to tear down the rest of the structure following the 1989 Loma Prieta earthquake.

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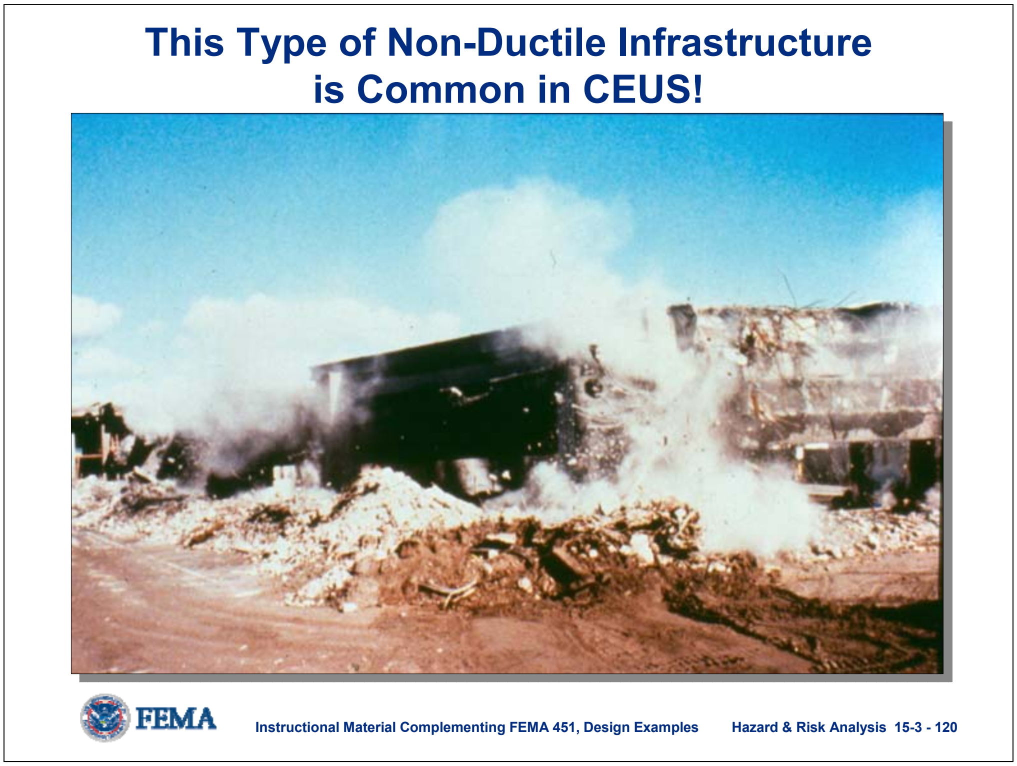
Instructional Material Complementing FEMA 451, Design Examples



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

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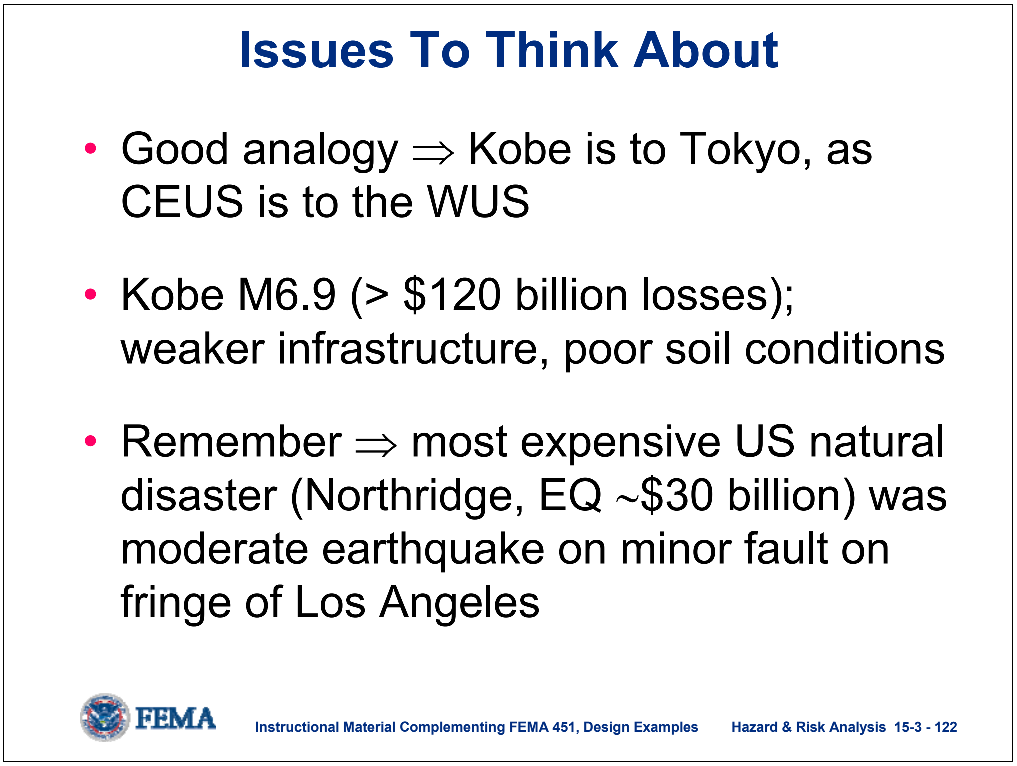
This collapse was cause by <u>one</u> impact of the wrecking ball! Again, classic nonductile behavior.

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 risk in CEUS and WUS is comparable!***

The comparable seismic risks between WUS and CEUS are surprising to many.



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

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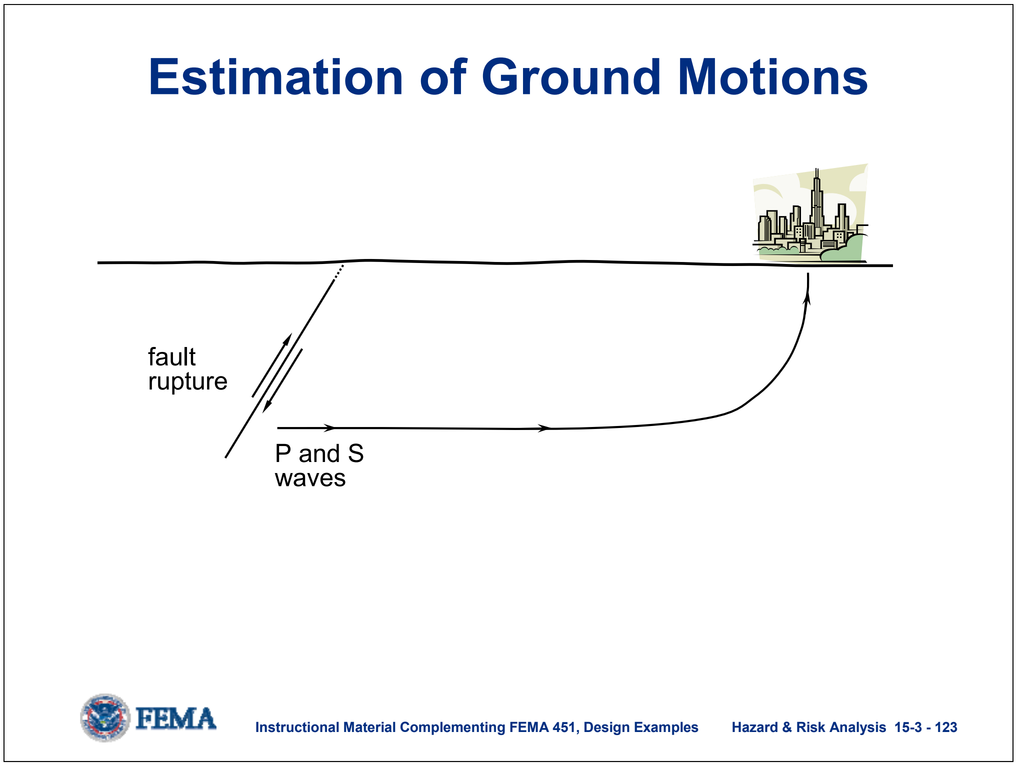
The fact that the most expensive US natural disaster (Northridge, California, earthquake ~$30 billion) was a moderate earthquake on minor fault on the fringe of Los Angeles is alarming in terms of demonstrating the damage potential of earthquakes.



Estimation of Ground Motions

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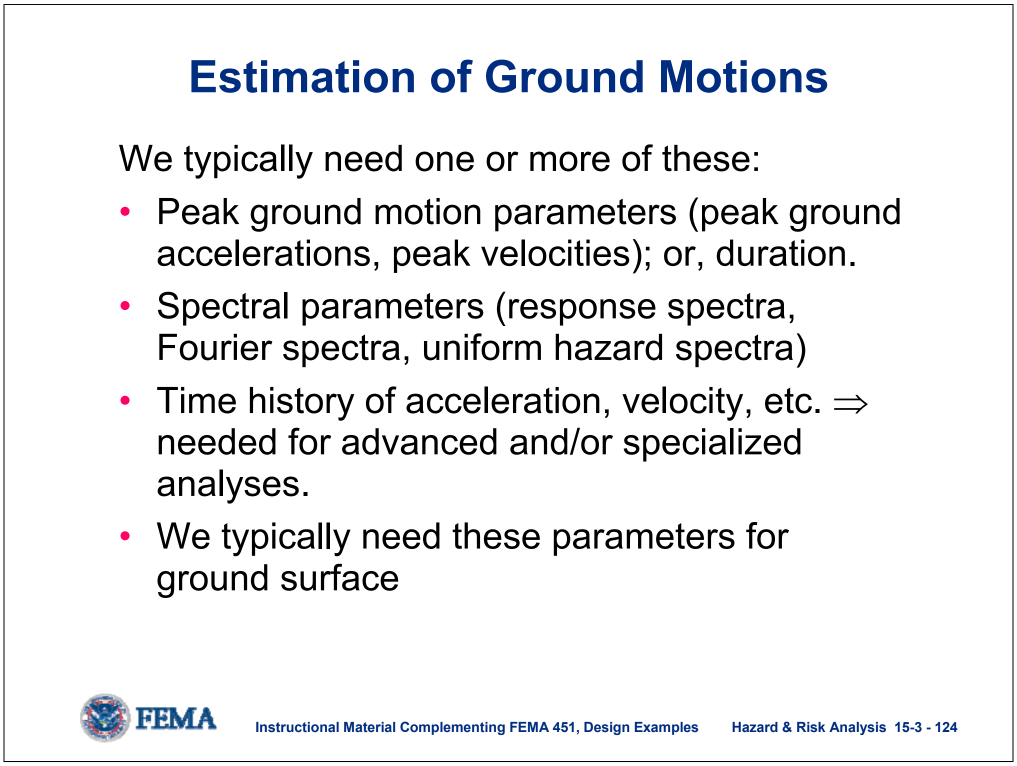
Ground motions at a site are related to source conditions, path effects, and site effects.



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

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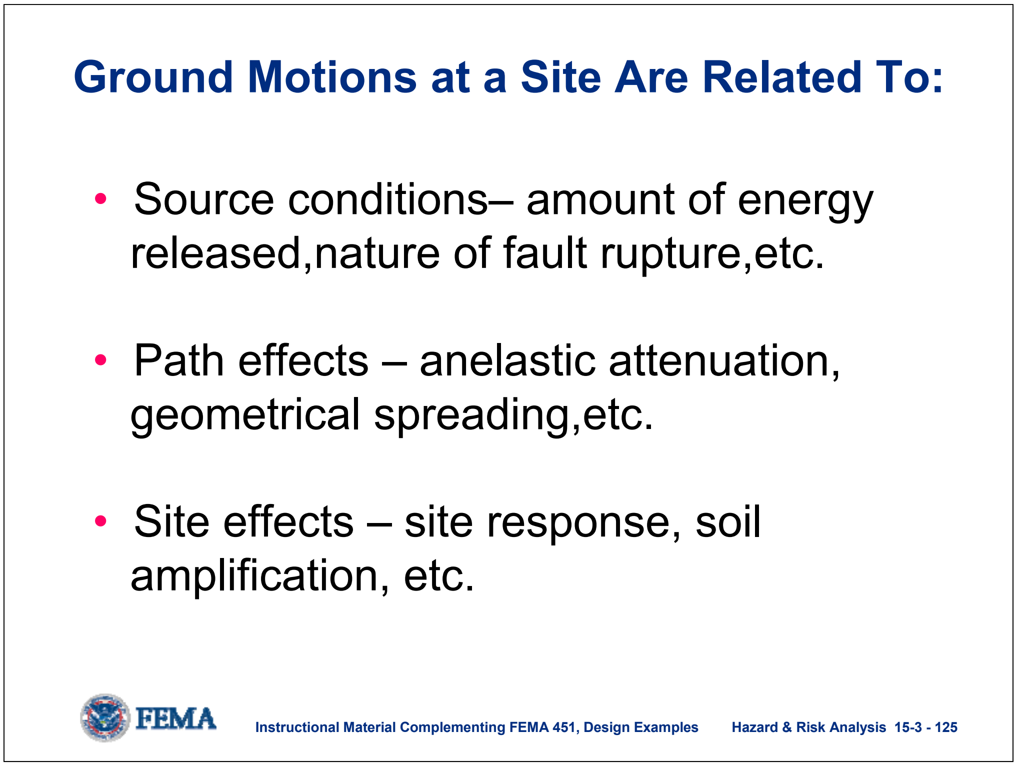
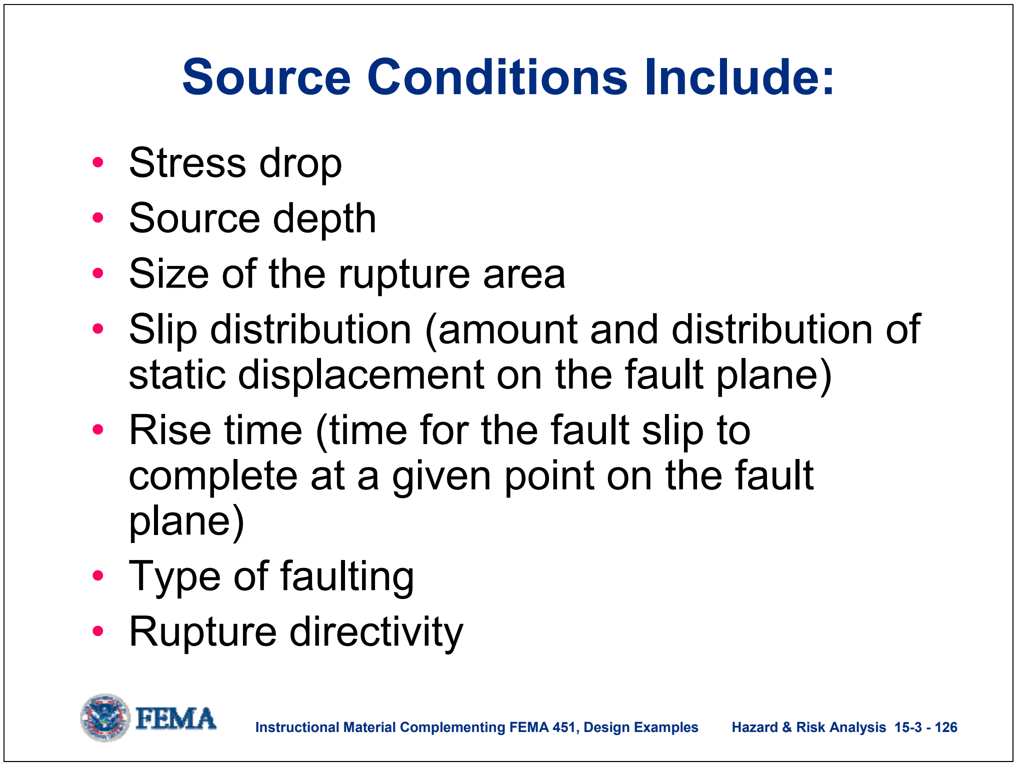
None.



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.

None.



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

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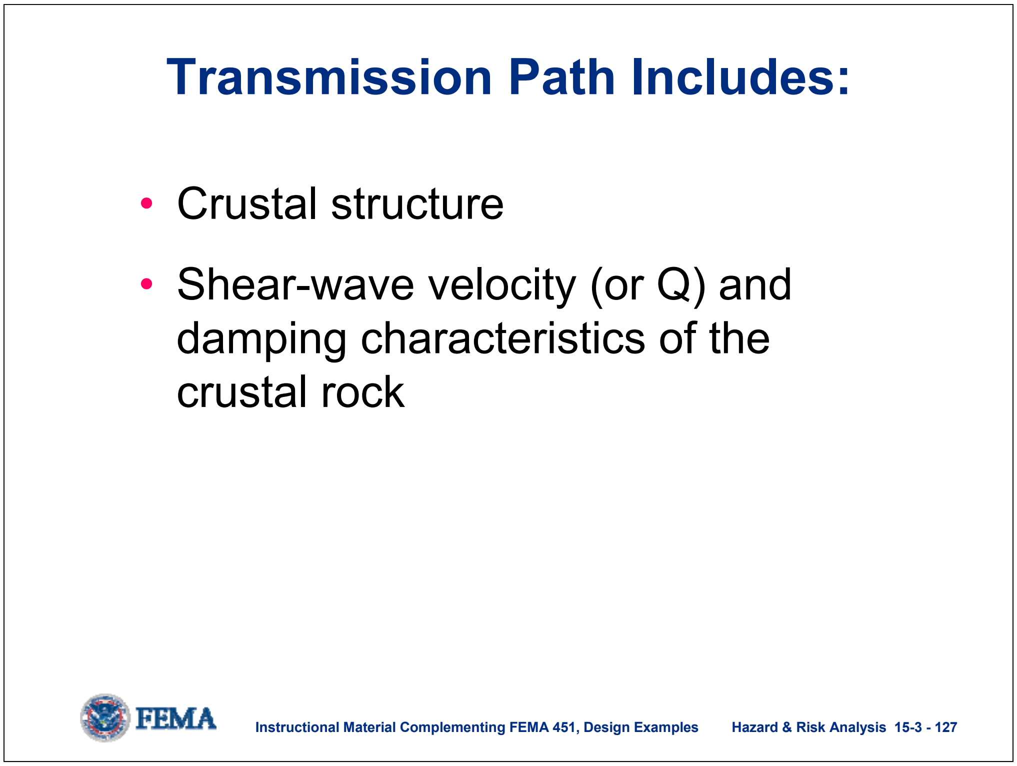
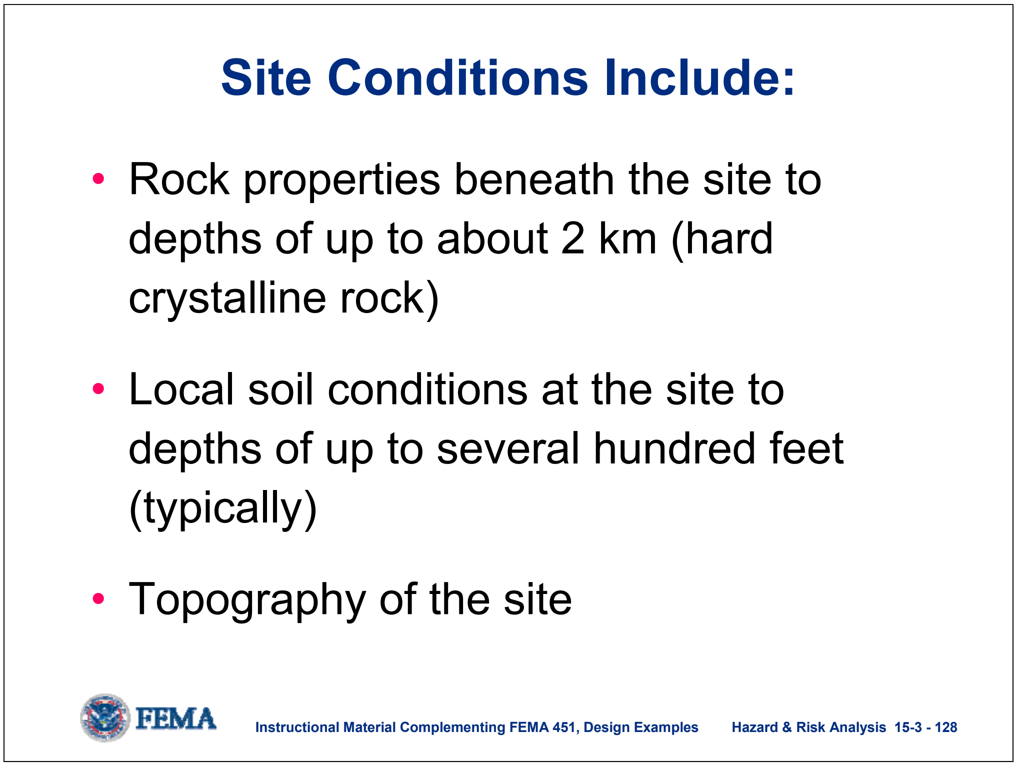
None.



Transmission Path Includes:

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

None.



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

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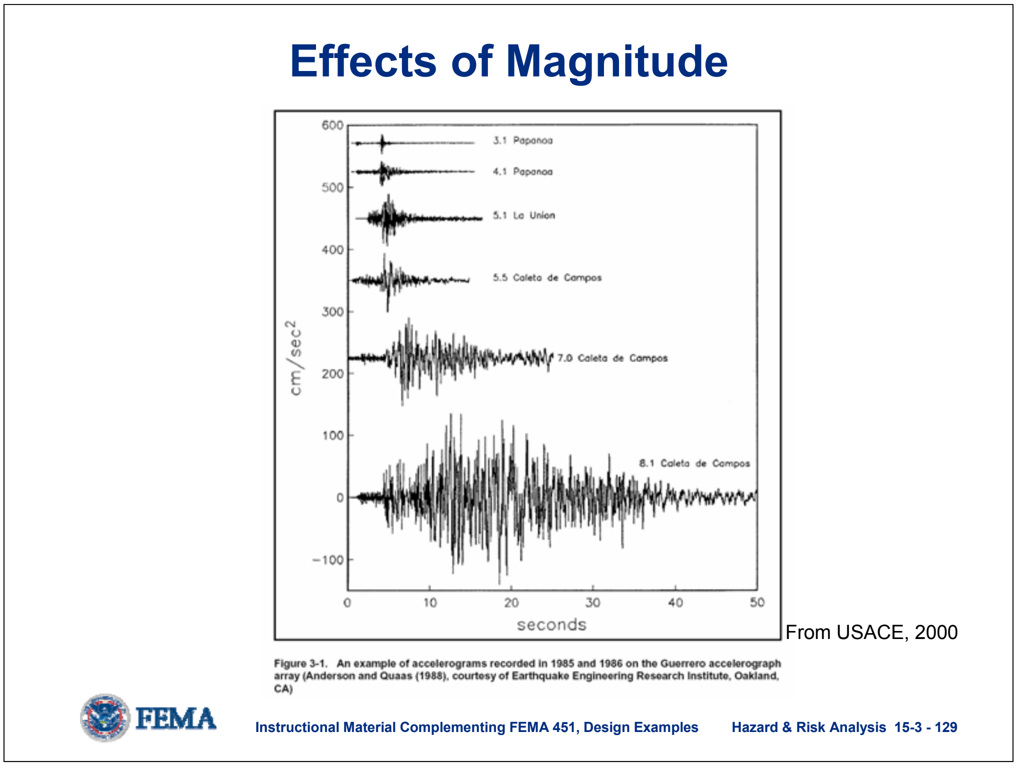
Local soil conditions at a site usually involves material with depths of up to several hundred feet (typically) – 30 m is more or less common value.

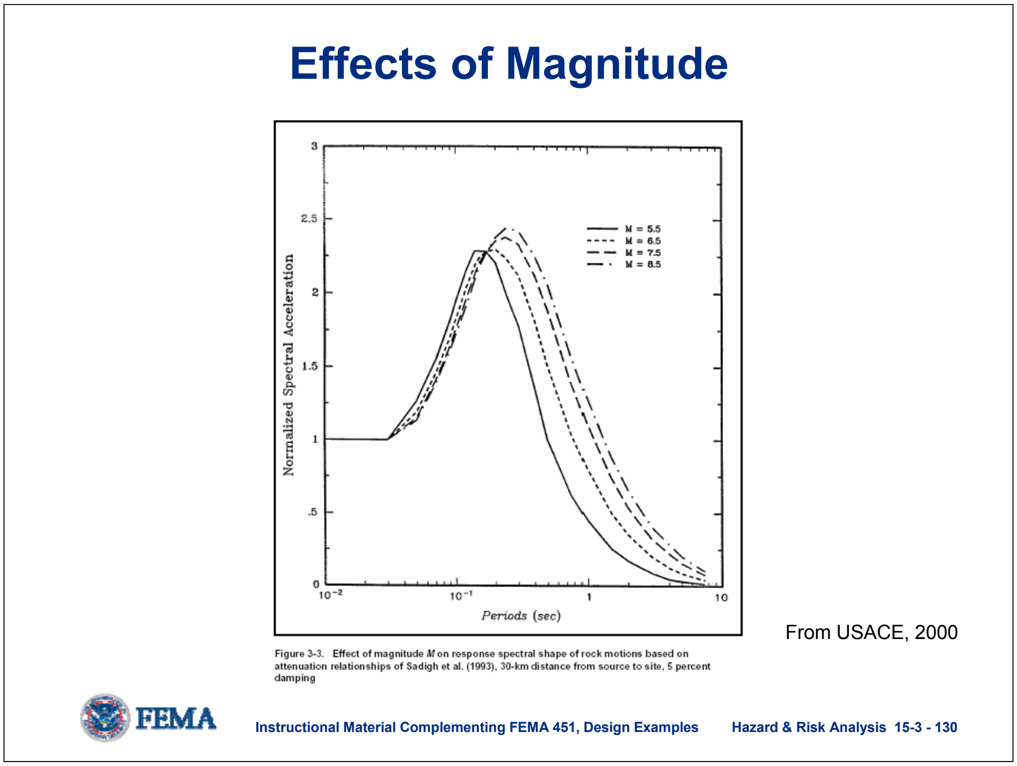


Effects of Magnitude

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)

The larger the magnitude, the longer the duration of motion and the larger the amplitude of motion (up to a point). United States Army Corps of Engineers (USACE) (2000). “Time history of dynamic analsyis of concrete hydraulic structures,” *Engineering Circular (EC) 1110-2-6051*, Department of the Army, Washington, D.C.



Effects of Magnitude

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

From USACE, 2000

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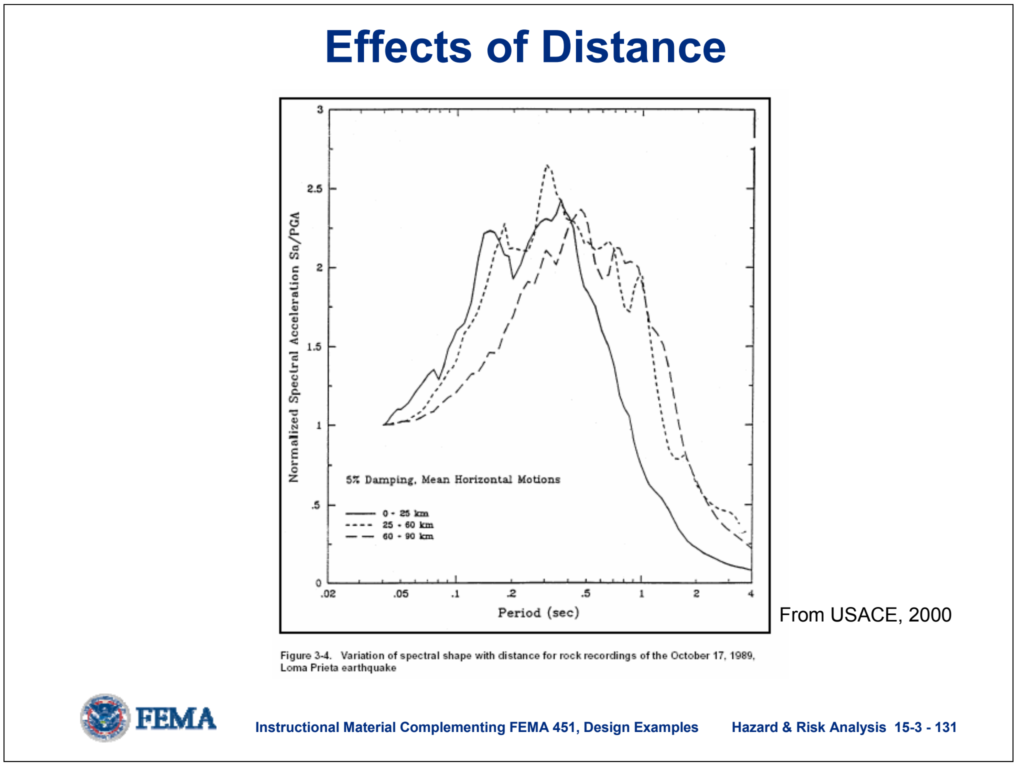
Hazard & Risk Analysis 15-3 - 130

Larger magnitude earthquakes have broader spectra and more energy in lower frequency range. United States Army Corps of Engineers (USACE) (2000). “Time history of dynamic analsyis of concrete hydraulic structures,” *Engineering Circular (EC) 1110-2-6051*, Department of the Army, Washington, D.C.



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

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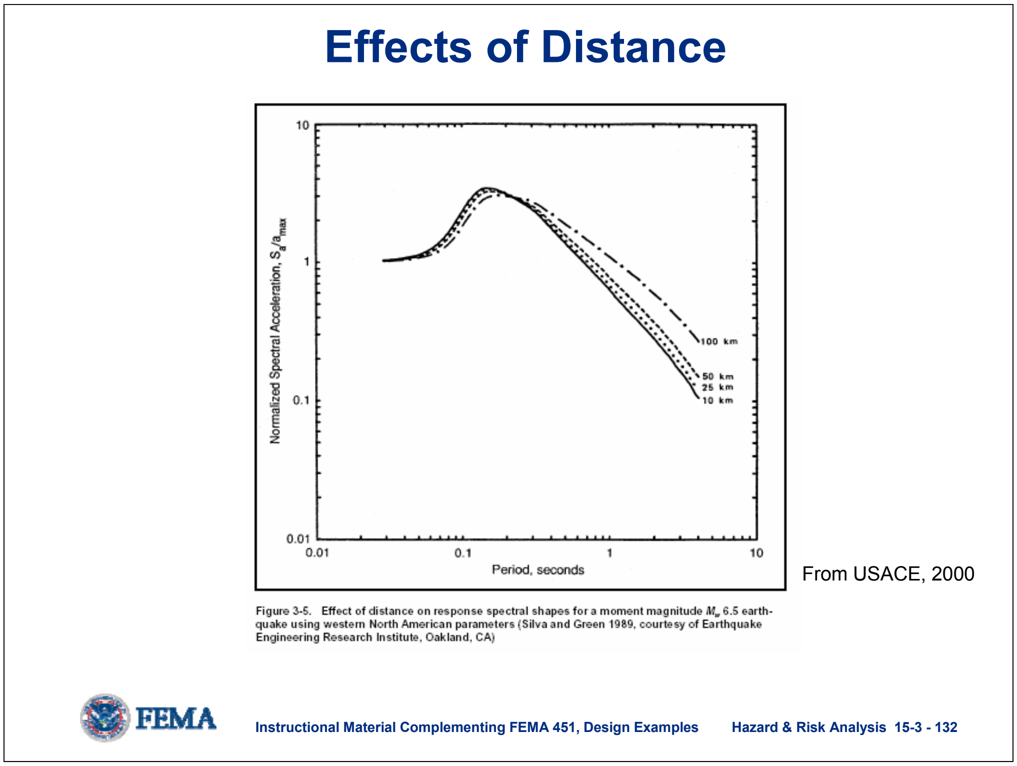
Motions decrease in high-frequency energy and increase in low-frequency energy as distance increases. United States Army Corps of Engineers (USACE) (2000). “Time history of dynamic analsyis of concrete hydraulic structures,” *Engineering Circular (EC) 1110-2-6051*, Department of the Army, Washington, D.C.



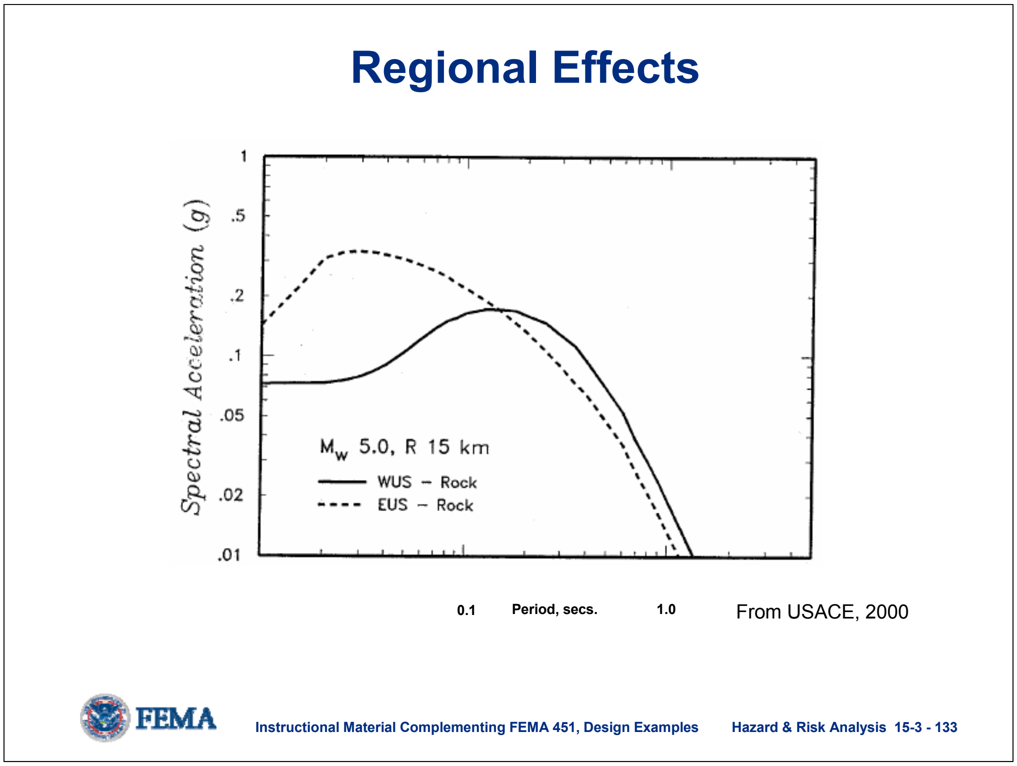
Effects of Distance

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)

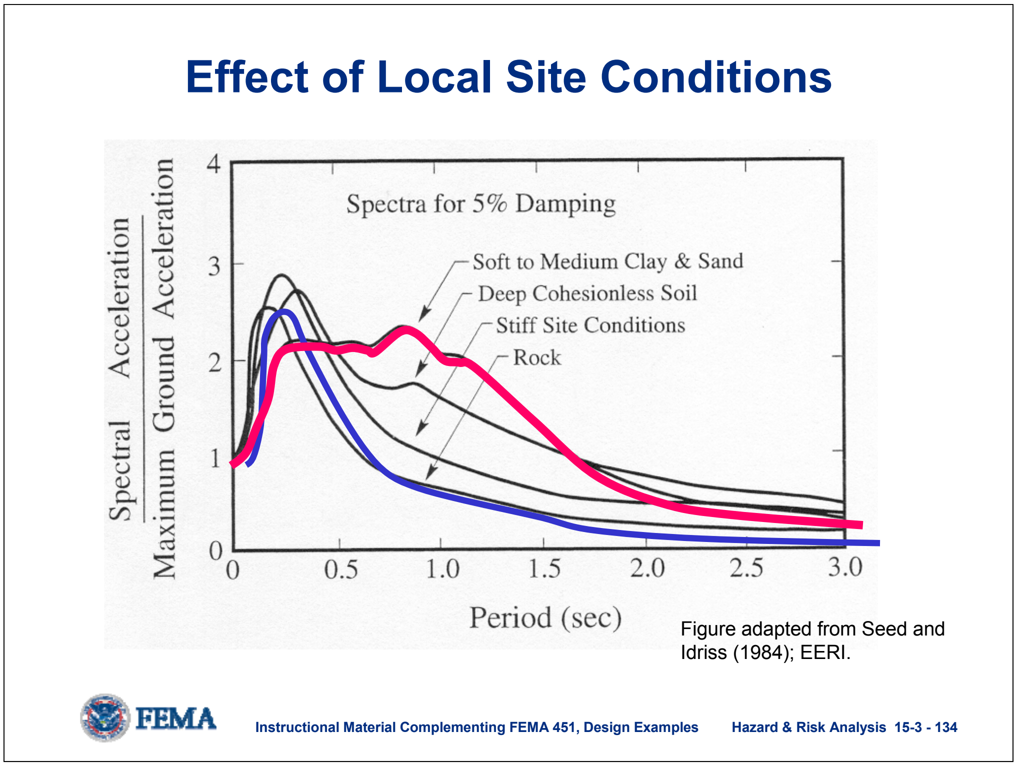
Motions decrease in high-frequency energy and increase in low-frequency energy as distance increases. United States Army Corps of Engineers (USACE) (2000). “Time history of dynamic analsyis of concrete hydraulic structures,” *Engineering Circular (EC) 1110-2-6051*, Department of the Army, Washington, D.C.

Regional Effects



From USACE, 2000

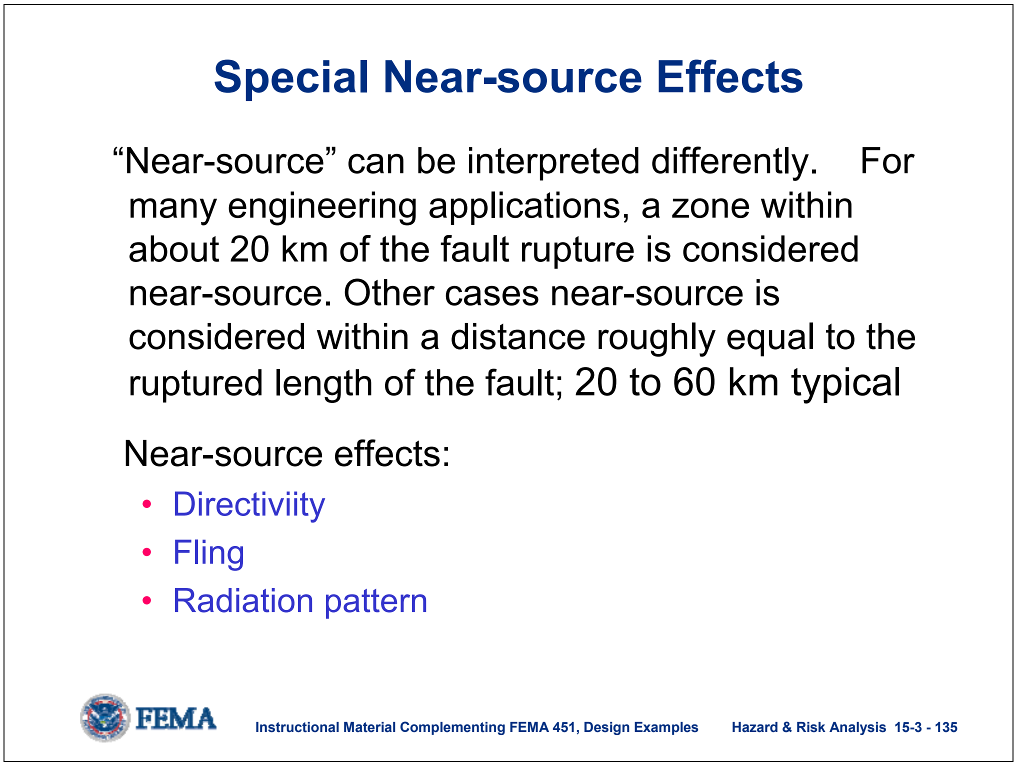
EUS events typically contain more high frequency energy than comparable WUS events. United States Army Corps of Engineers (USACE) (2000). “Time history of dynamic analsyis of concrete hydraulic structures,” *Engineering Circular (EC) 1110-2-6051*, Department of the Army, Washington, D.C.



Effect of Local Site Conditions

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

Soft soils decrease the spectral response relative to some stiff soils, but the range over which the motions are near their maximum is broadened.



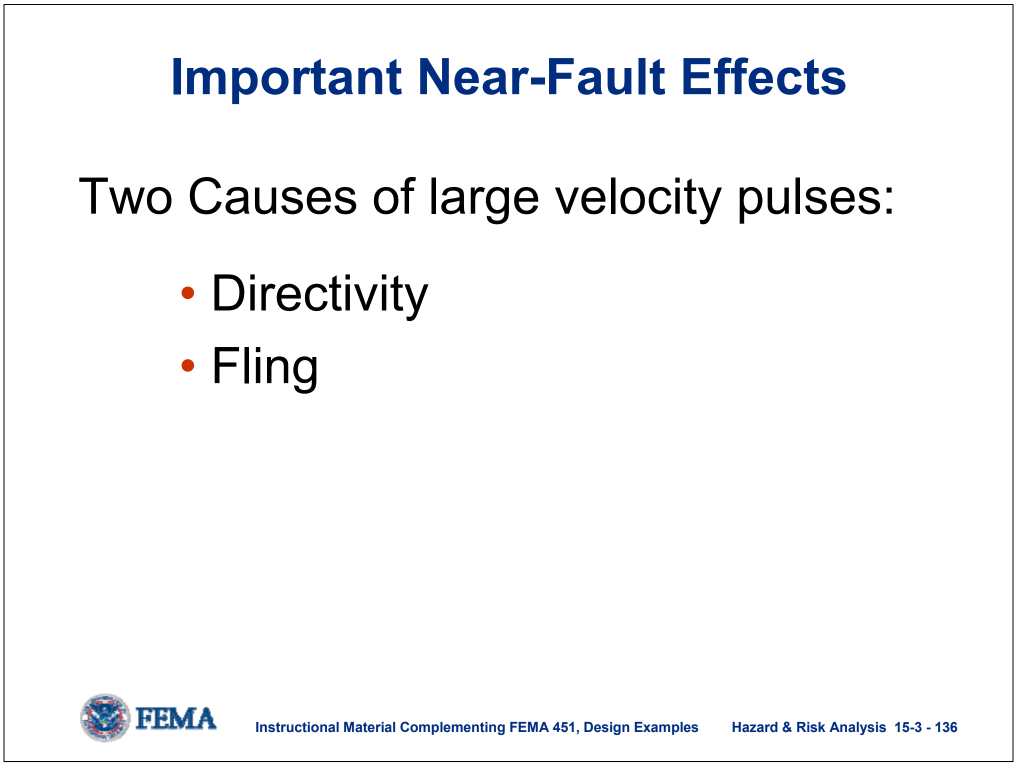
Special Near-source Effects

"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

"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

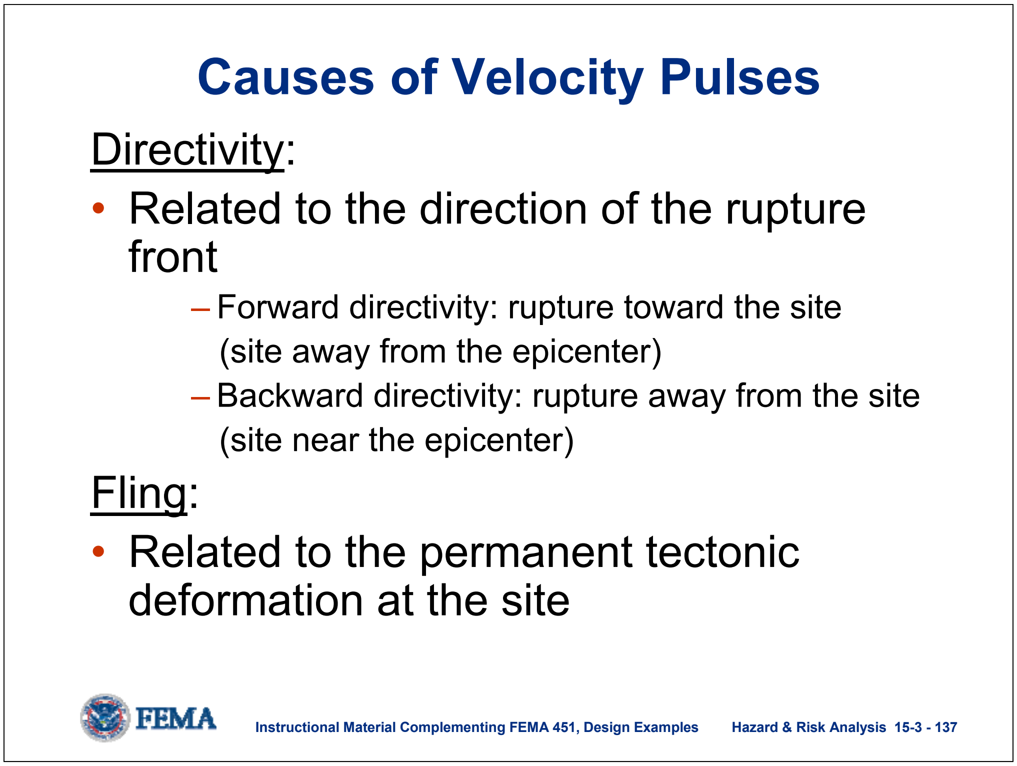


Important Near-Fault Effects

Two Causes of large velocity pulses:

- Directivity
- Fling

Directivity is related to the direction of the rupture front and fling is related to permanent tectonic deformation.



Causes of Velocity Pulses

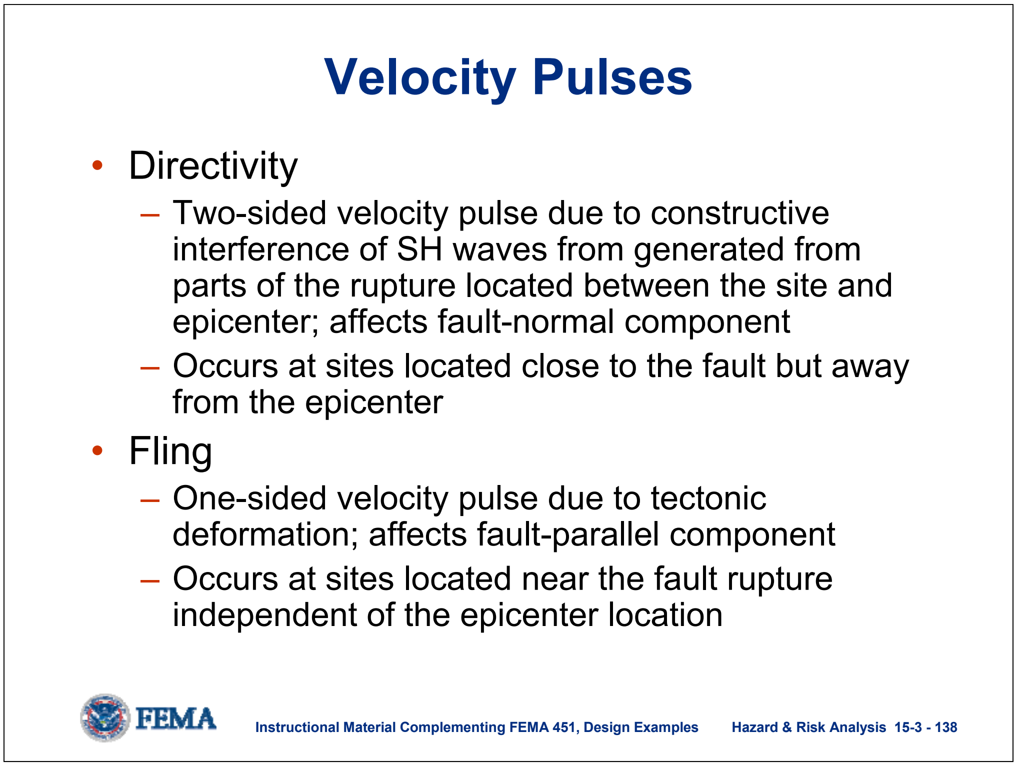
Directivity:

- 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

None.



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

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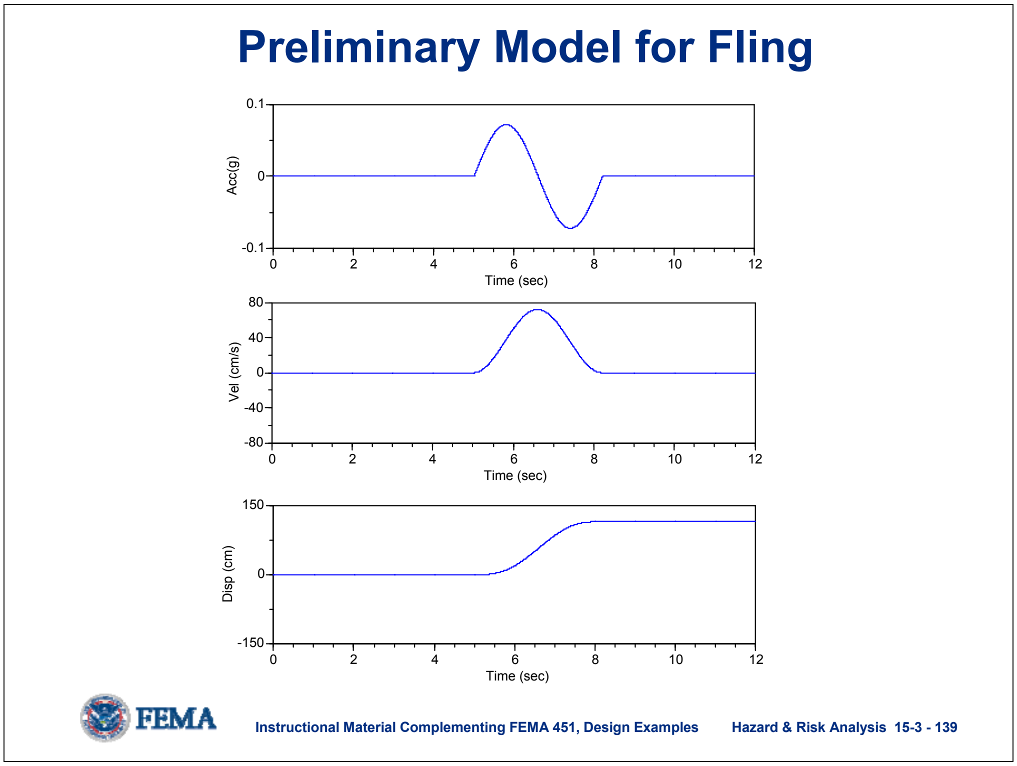
Both directivity and fling increase ground motions and seismic demand on structures.



Preliminary Model for Fling

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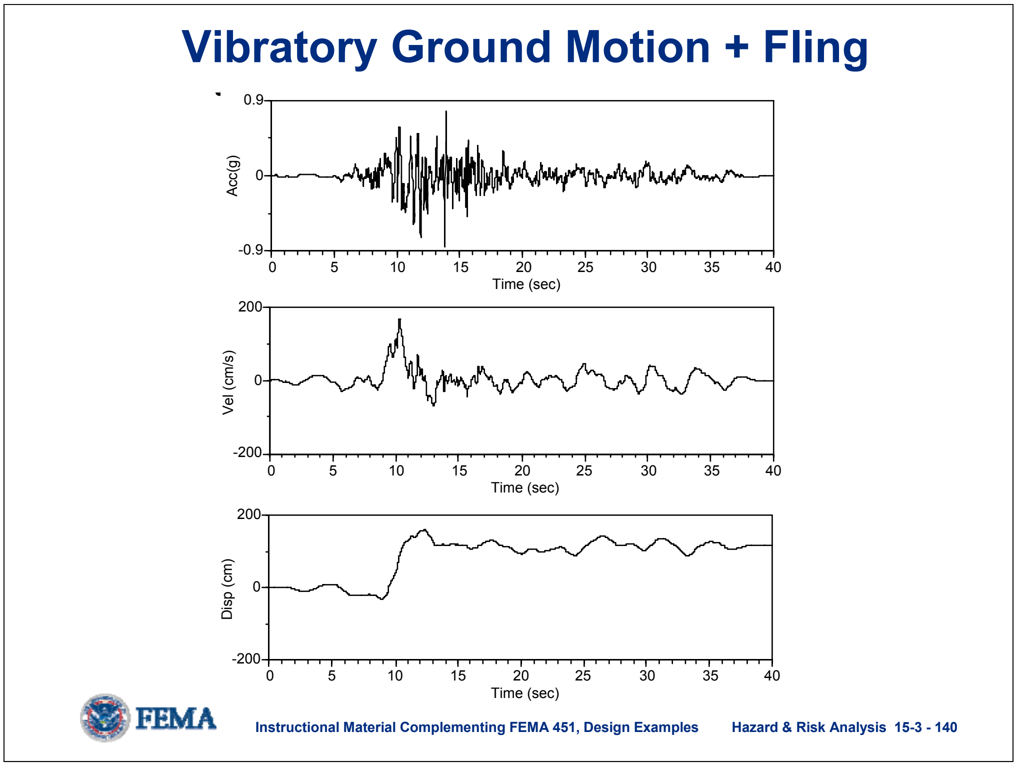
Figure adapted from Abrahamson at
http://civil.eng.buffalo.edu/webcast/abrahamson/presentation_files/frame.htm

The large displacement (static) shown at about 6 seconds (bottom) corresponds to the large velocity (and acceleration) pulse that occurs in the record motions.



Vibratory Ground Motion + Fling

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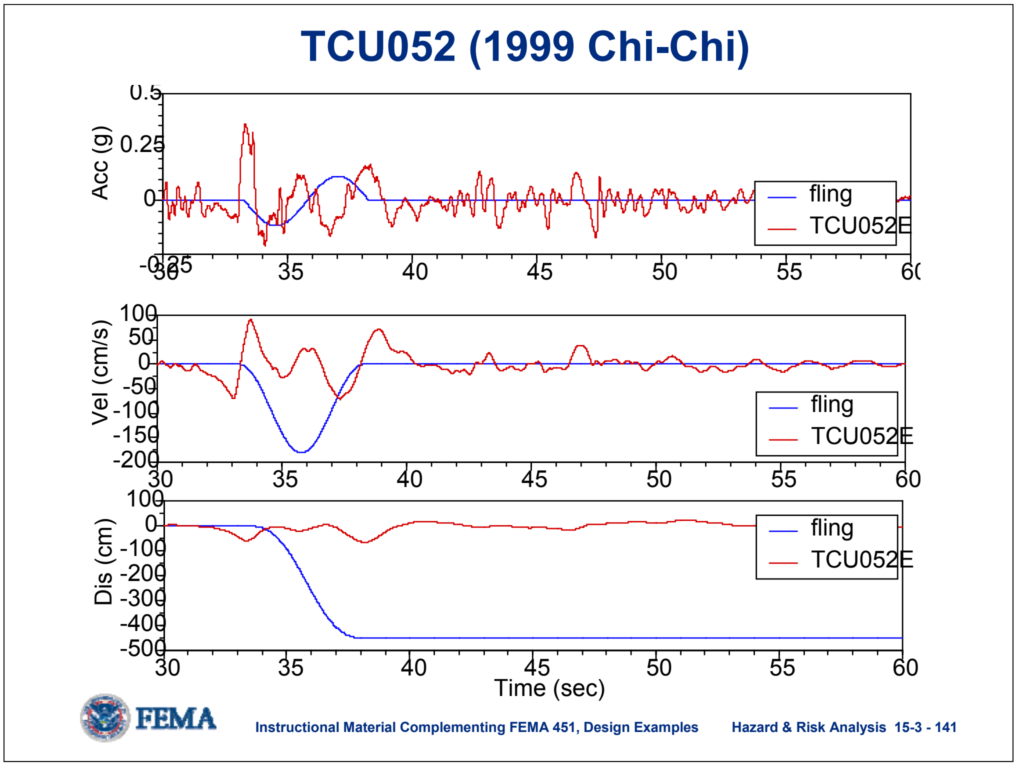
Figure adapted from Abrahamson at http://civil.eng.buffalo.edu/webcast/abrahamson/presentation_files/frame.htm

The large displacement shown at about 10 seconds (bottom) corresponds to the large velocity (and acceleration) pulse that occurs in the record motions.



TCU052 (1999 Chi-Chi)

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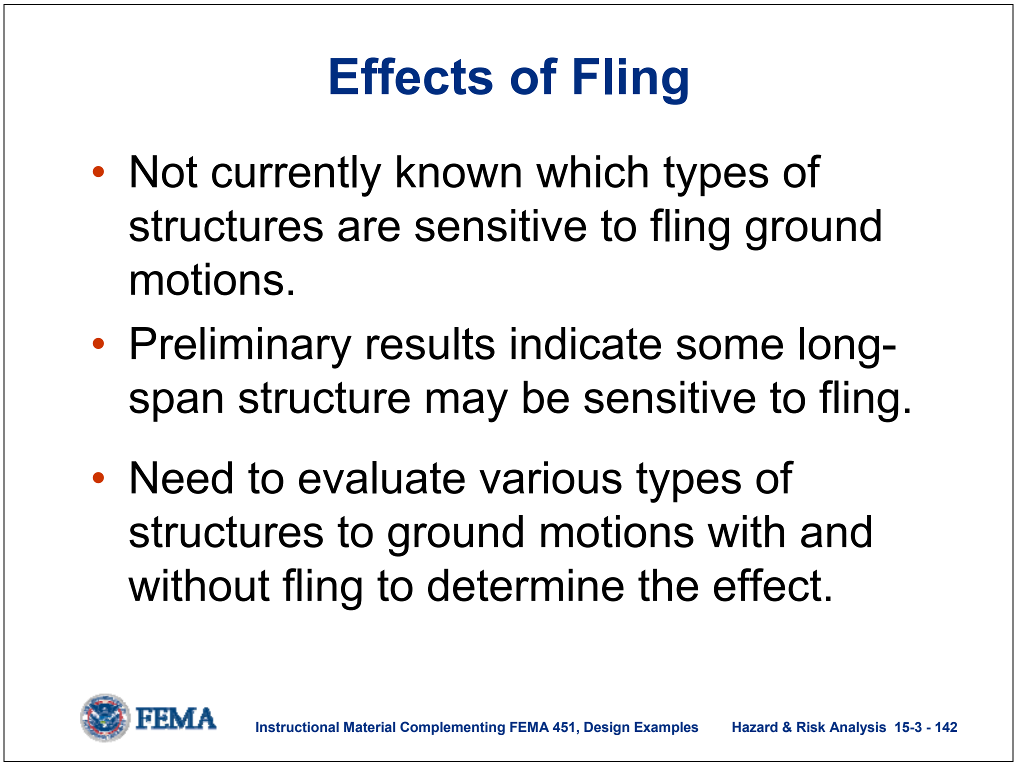
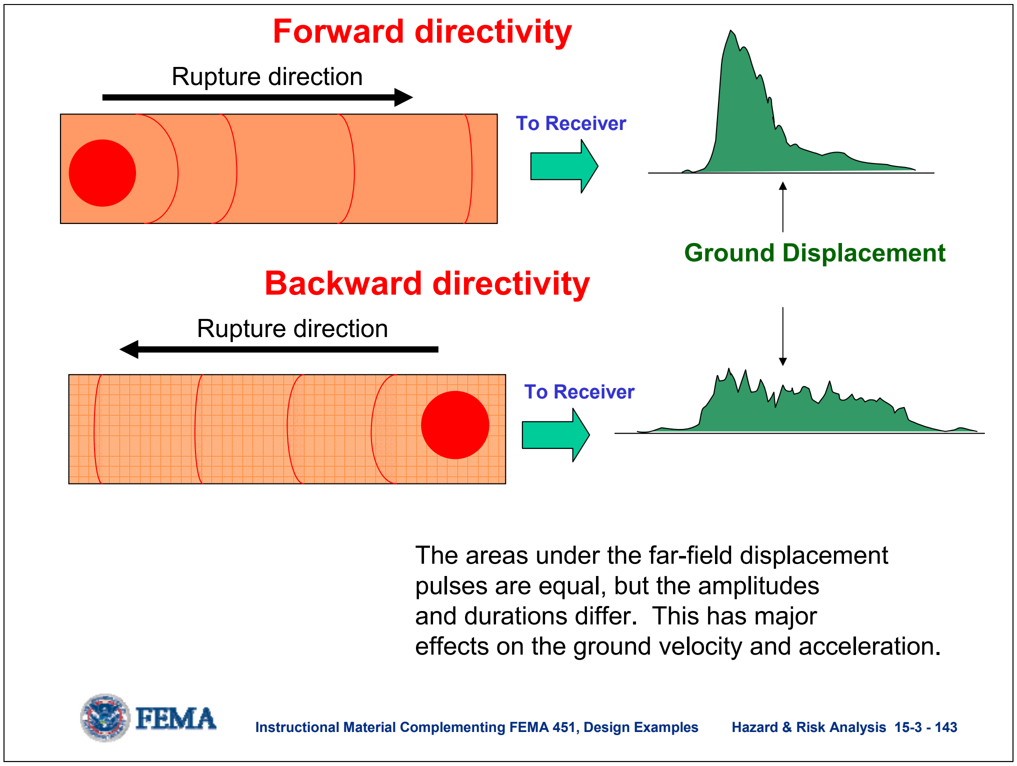
Figure adapted from Abrahamson at
http://civil.eng.buffalo.edu/webcast/abrahamson/presentation_files/frame.htm



Effects of Fling

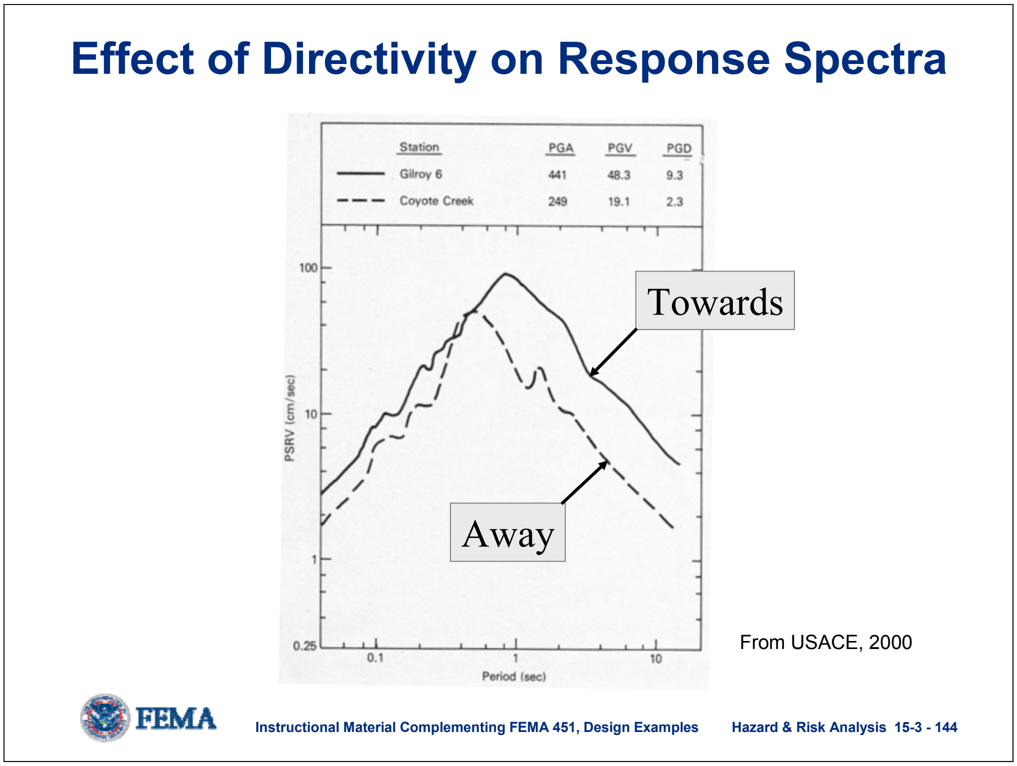
- Not currently known which types of structures are sensitive to fling ground motions.
- Preliminary results indicate some long-span structure may be sensitive to fling.
- Need to evaluate various types of structures to ground motions with and without fling to determine the effect.

In strike slip faulting, the fling affects the strike-parallel component of ground motion.



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.

Figure above adapted from Martin Chapman, Virginia Tech Department of Geological Sciences. The effect of directivity is prominent in the fault parallel direction (i.e., in direction of fault rupture) but affects the fault perpendicular component of the ground motion. For instance, in strike slip faulting, the directivity pulse occurs on the strike normal component.

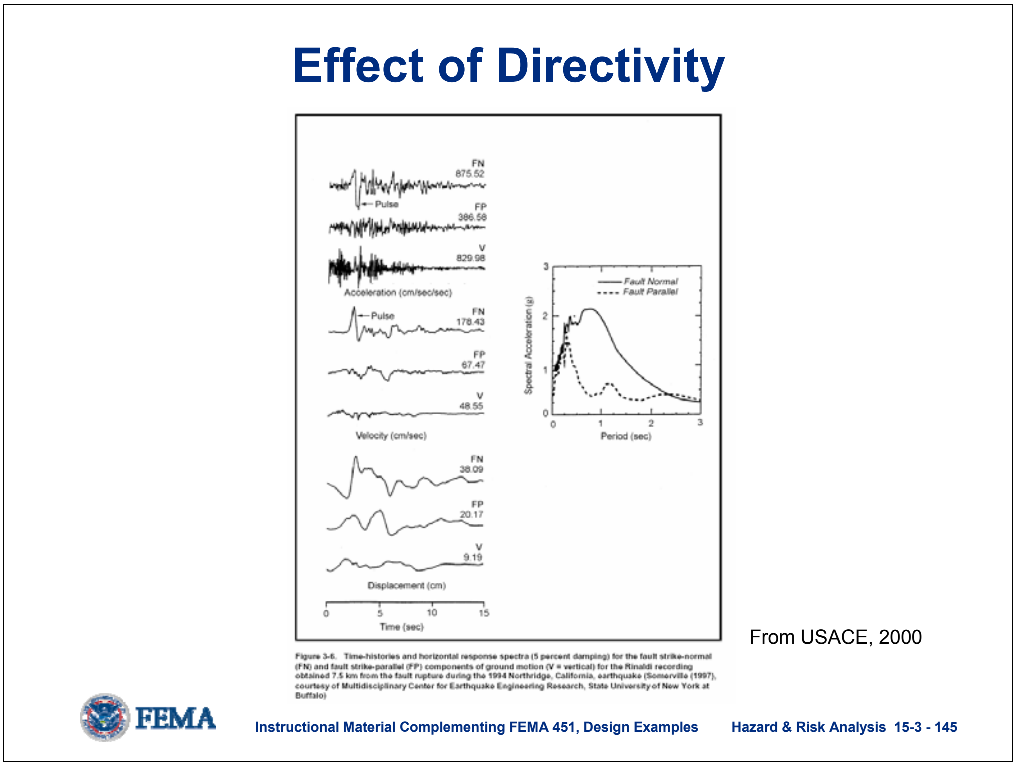


Effect of Directivity on Response Spectra

Station	PGA	PGV	PGD
Gilroy 6	441	48.3	9.3
Coyote Creek	249	19.1	2.3

From USACE, 2000

Receiver positioned in the direction of the fault rupture indicates stronger ground shaking.



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

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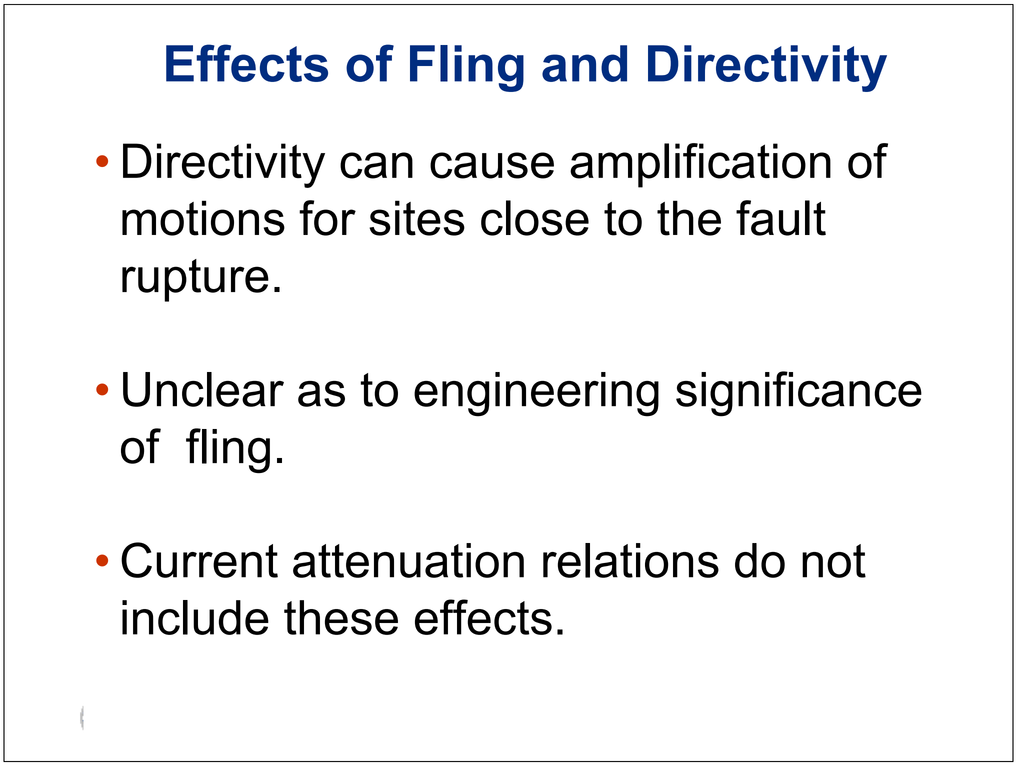
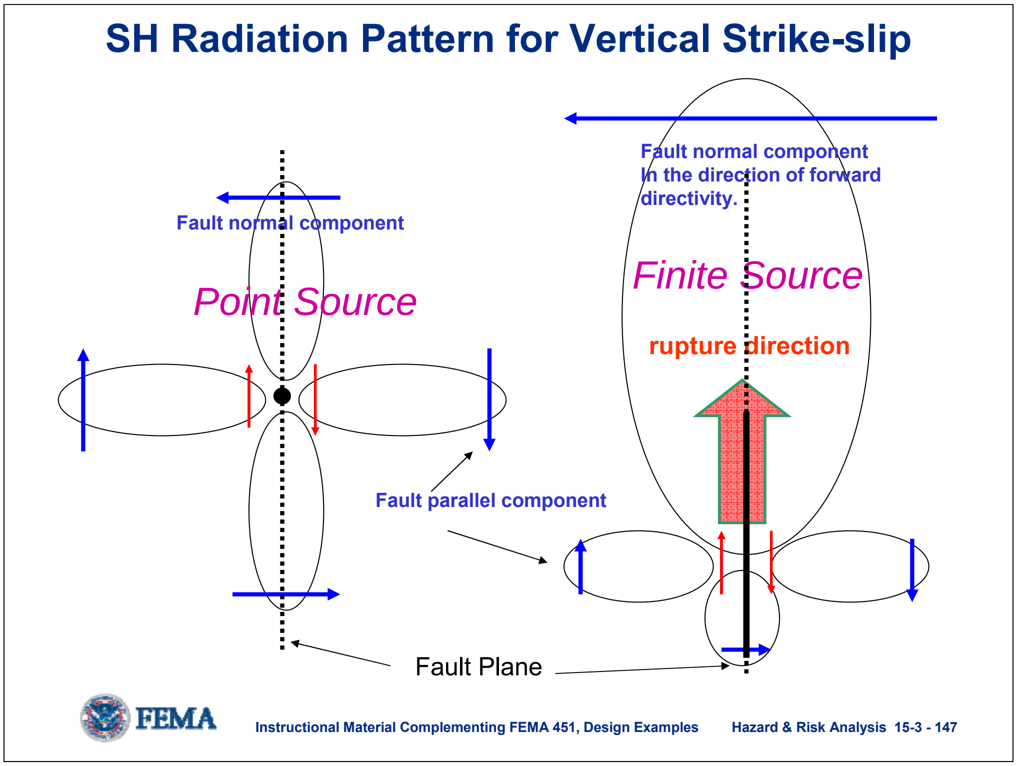
Directivity affect dependent upon fault type, direction and manner of slip, and position of site relative to the fault (i.e., in maximum or minimum nodes). Typically strike-slip faulting produces maximum motions in the fault normal direction and less in the fault parallel direction.



Effects of Fling and Directivity

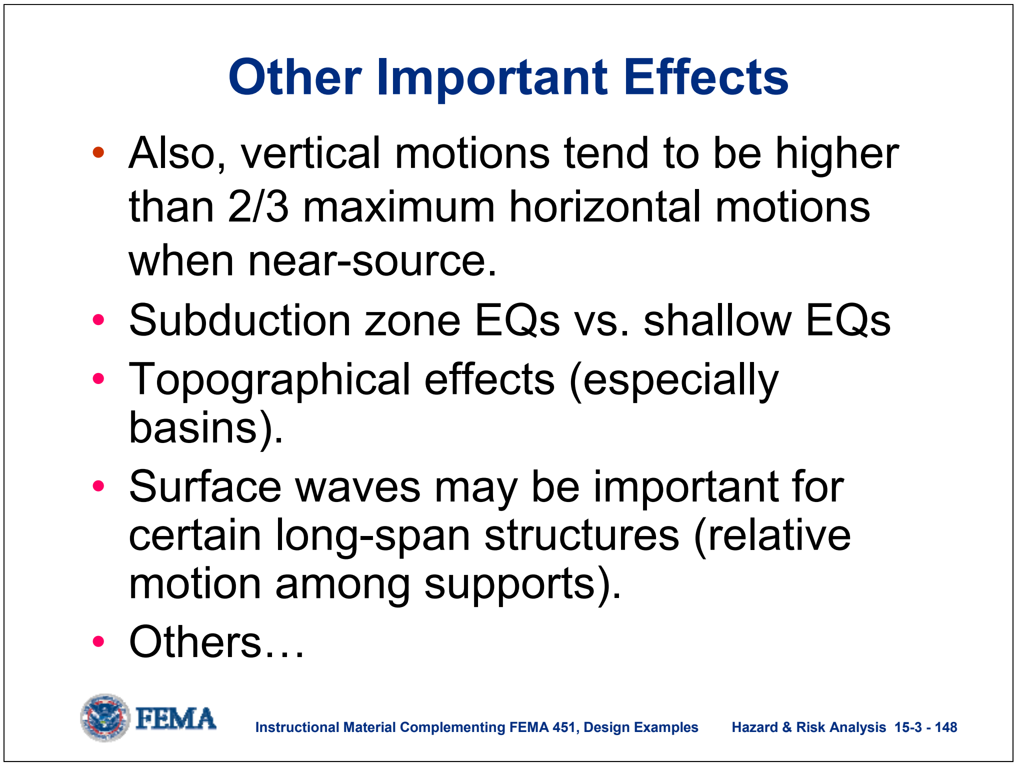
- Directivity can cause amplification of motions for sites close to the fault rupture.
- Unclear as to engineering significance of fling.
- Current attenuation relations do not include these effects.

Both directivity and fling are difficult to predict precise and design for using simplified methods.



SH Radiation Pattern for Vertical Strike-slip

Illustration of directivity effects. Figure indicates type of energy radiation associated with each point along the fault. Lobes of energy radiation indicates predicted motions along the fault in direction of rupture. The pattern of energy radiation shown for a point along the fault is same as what overall energy pattern looks like when the fault is view from a very large scale such that it look like a point source.



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…

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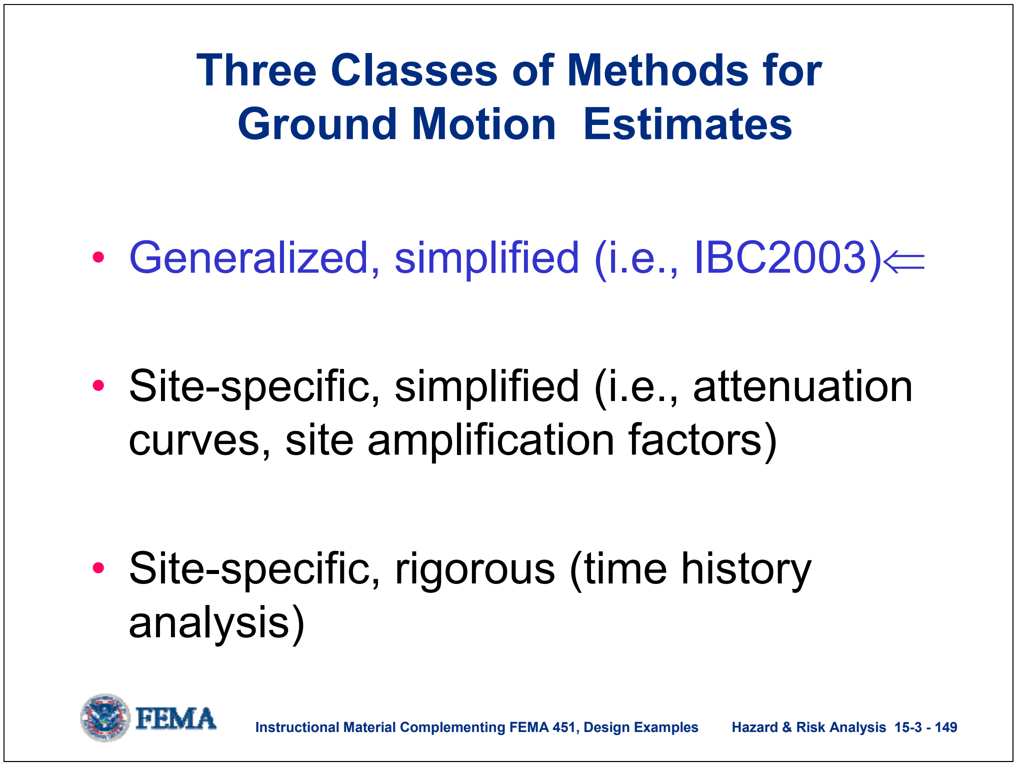
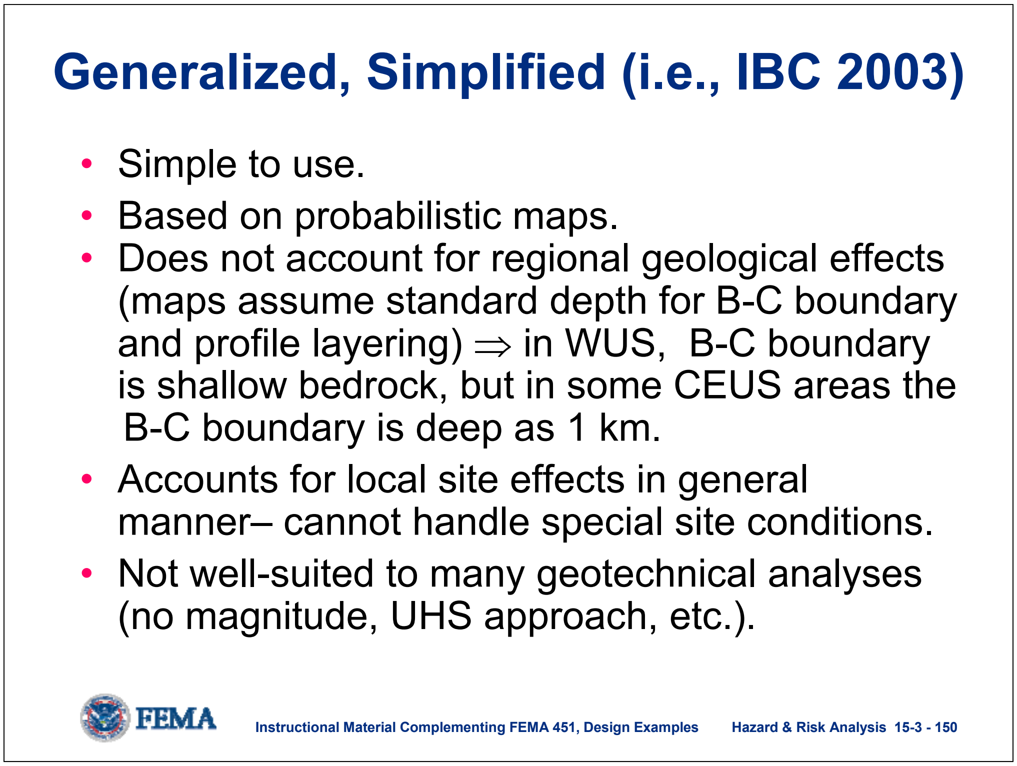
Other special situations require more advanced analyses (rather than simplified without careful consideration).



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)

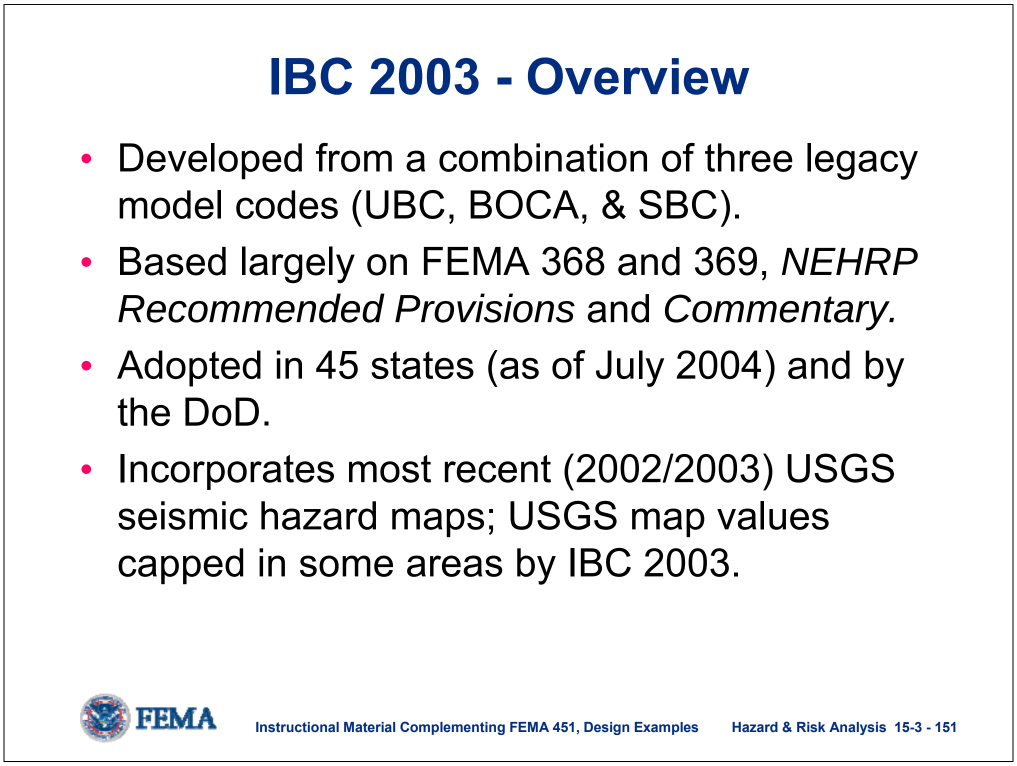
None.



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.).

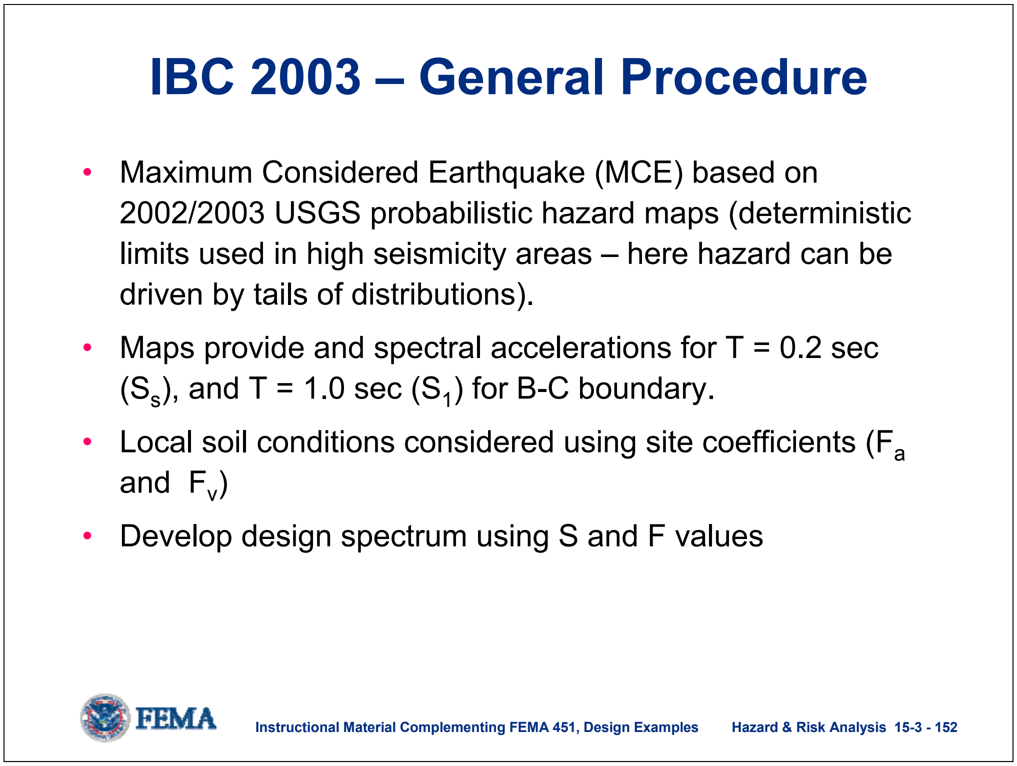
Most generalized methods, such as those used by building codes do not account for regional geological effects (maps assume standard depth for B-C boundary and profile layering)⇒ in WUS, B-C boundary is typically shallow bedrock, but in some CEUS areas the B-C boundary is deep as 1 km.



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.

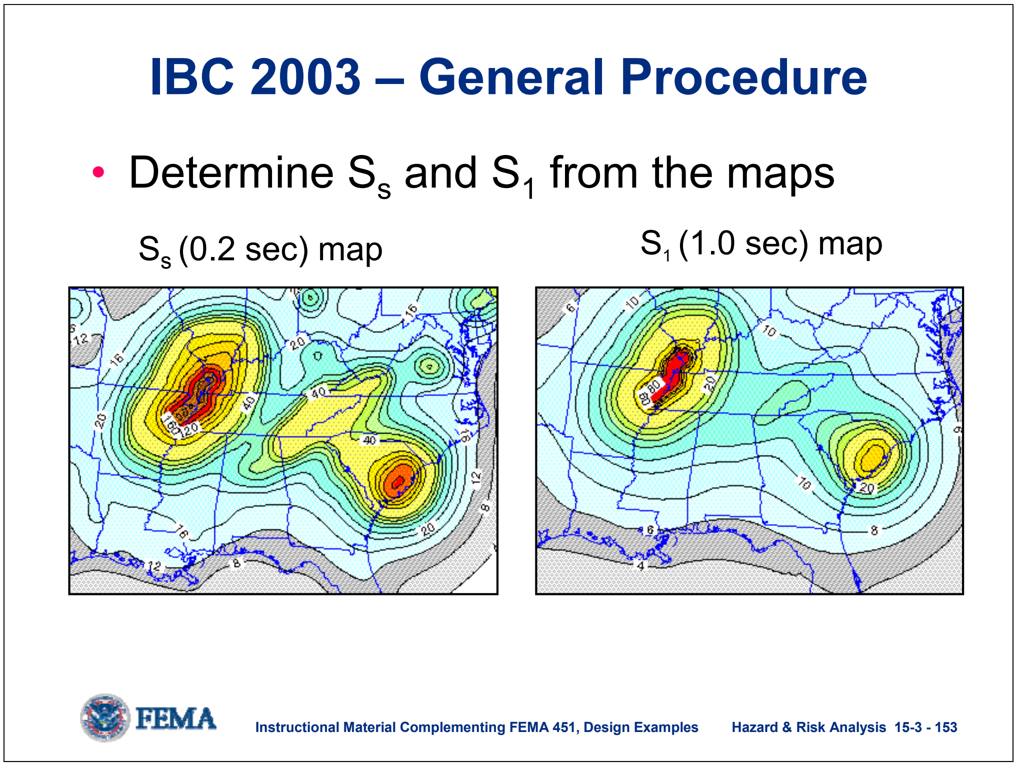
IBC2003 incorporates the most recent (2002/2003) USGS seismic hazard maps, but the IBC caps the USGS map values in some areas (i.e., southern California) so the IBC2003 values are lower than the USGS maps. In most other states, the USGS and IBC maps are exact.



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

Maximum Considered Earthquake (MCE) is based on 2003 USGS probabilistic hazard study. Maps in building codes are identical to the building code maps in IBC2003 with the primary exception of California.



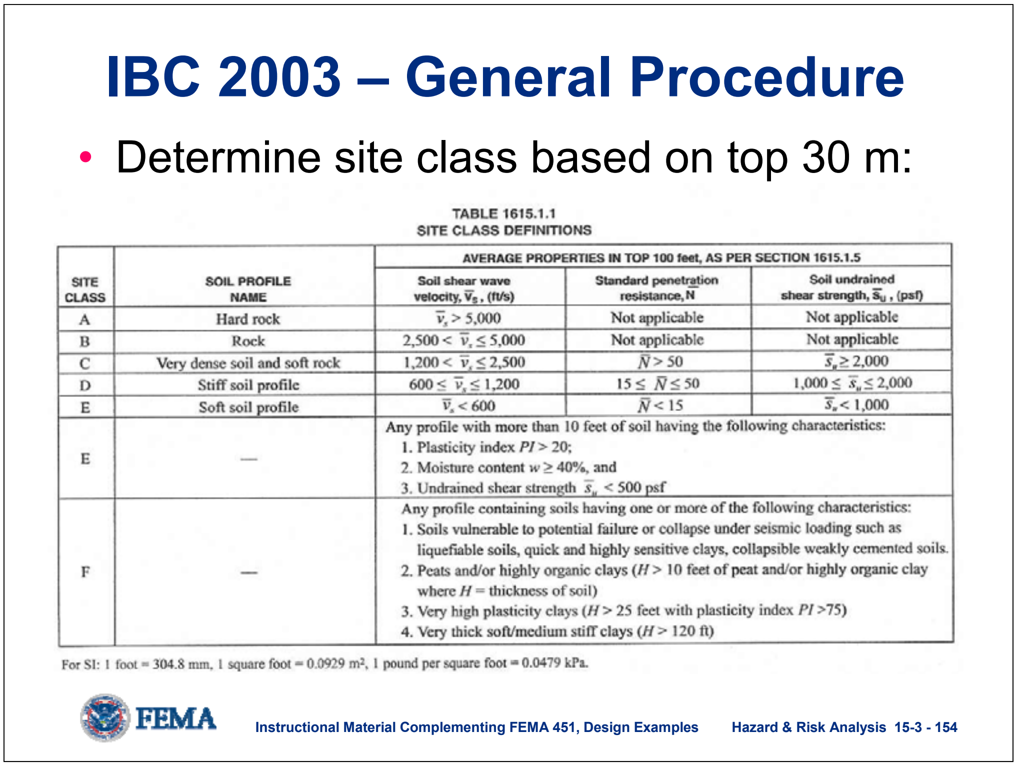
IBC 2003 – General Procedure

- Determine S_s and S_1 from the maps

S_s (0.2 sec) map

S_1 (1.0 sec) map

The IBC 2003 procedure require Ss and S1 be determined from IBC/USGS maps. Again, the USGS maps are the same as building code maps in most regions outside California.



IBC 2003 – General Procedure

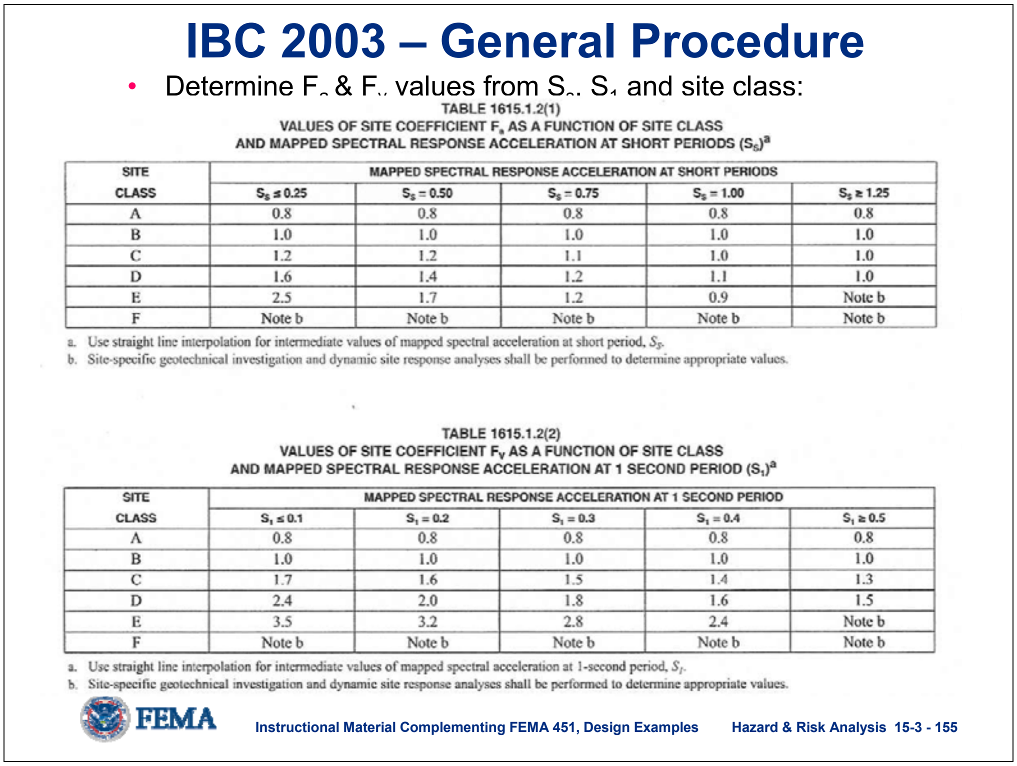
- Determine site class based on top 30 m:

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	$2{,}500 < \bar{v}_s \leq 5{,}000$	Not applicable	Not applicable
C	Very dense soil and soft rock	$1{,}200 < \bar{v}_s \leq 2{,}500$	$\bar{N} > 50$	$\bar{s}_u \geq 2{,}000$
D	Stiff soil profile	$600 \leq \bar{v}_s \leq 1{,}200$	$15 \leq \bar{N} \leq 50$	$1{,}000 \leq \bar{s}_u \leq 2{,}000$
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 $w \geq 40\%$, 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.

Note special provisions for “F” sites. These site conditions are of particular concern for seismic analysis. F site involved soft soils that can greatly amplify ground motions, such as in Mexico City in 1985 or Loma Prieta in 1989 or liquefiable soils.



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.

FEMA

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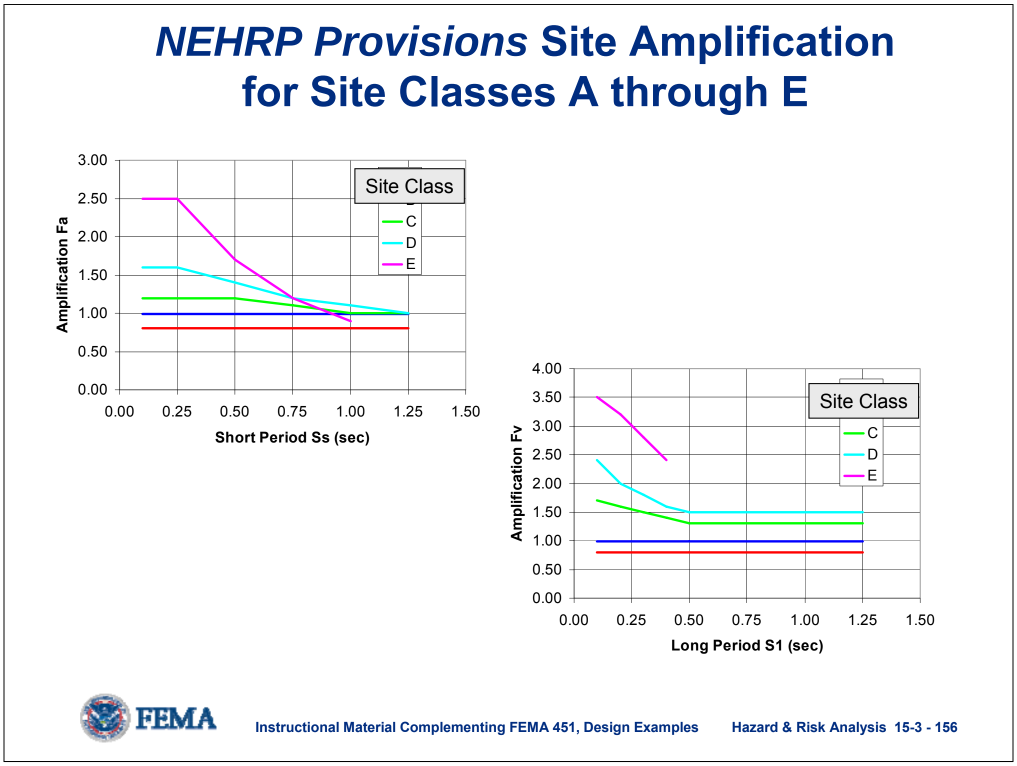
Note special site-specific analysis required for F sites.



NEHRP Provisions Site Amplification for Site Classes A through E

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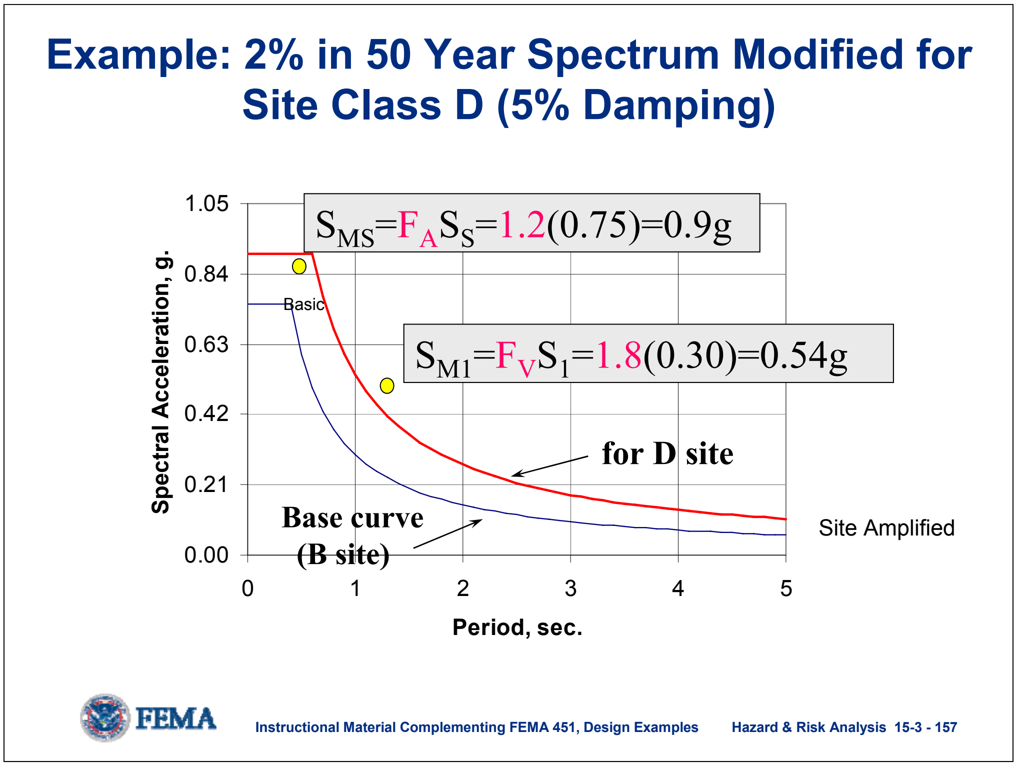
Graphical representation of soil amplification factors. The poorer soil sites show higher amplifications. Note special provisions for F sites. These site conditions are of particular concern for seismic analysis. F site involved soft soils that can greatly amplify ground motions, such as in Mexico City in 1985 or Loma Prieta in 1989 or liquefiable soils.



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

$S_{MS}=F_A S_S=1.2(0.75)=0.9g$

$S_{M1}=F_V S_1=1.8(0.30)=0.54g$

Slide showing amplification of curve for soil conditions.

IBC 2003 - General Procedure

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

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

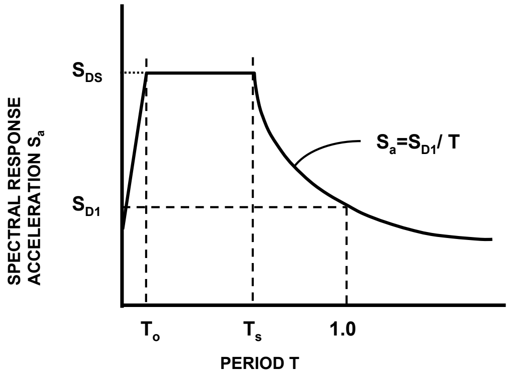
- Calculate the spectral design values S_{DS} and S_{D1}:

$$S_{DS} = 2/3 \bullet S_{MS} \quad S_{D1} = 2/3 \bullet S_{M1}$$

Note the 2/3 multiplier to reduce the motions from the MCE level.

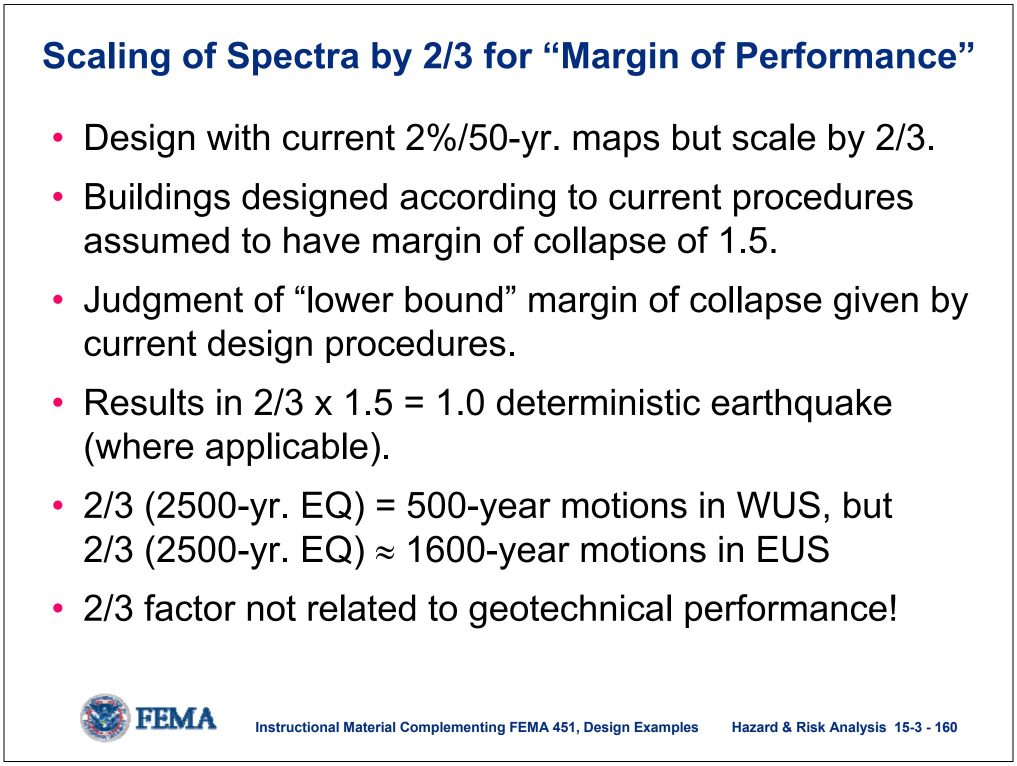
IBC2003 – General Procedure

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



DESIGN RESPONSE SPECTRUM

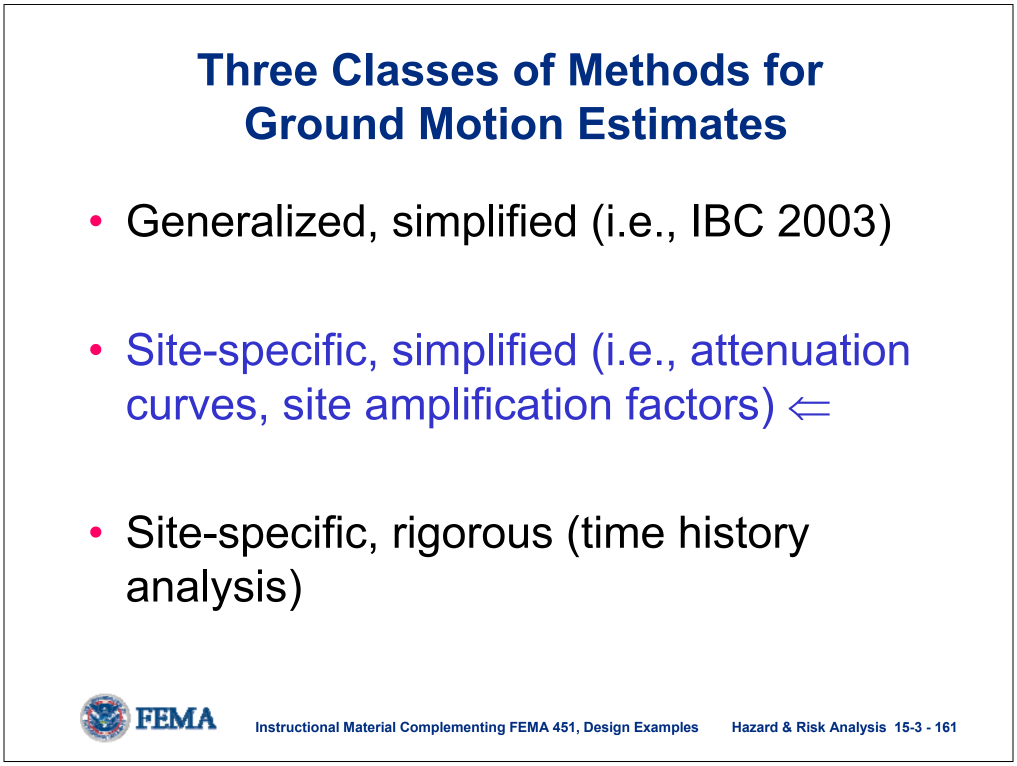
Smoothed spectrum used for design. Spectrum anchored by USGS/IBC map values at short (To) and long (T = 1 sec) period.



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!

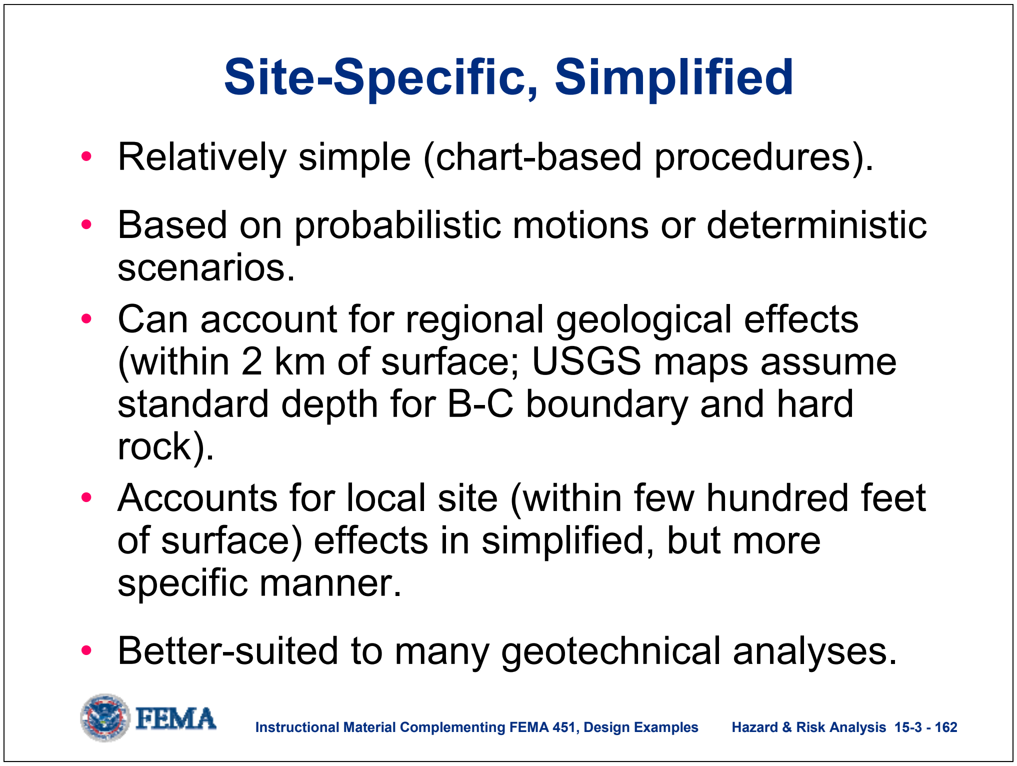
IBC 2003 maps do not provide same earthquake design levels in EUS vs. WUS, as 2/3 MCE in EUS is not equal to 2/3 MCE in WUC. Also, maps are not well-suited to geotechnical performance (2/3 is not for geotechnical performance and magnitude/duration is not directly provided).



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)

None.



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.

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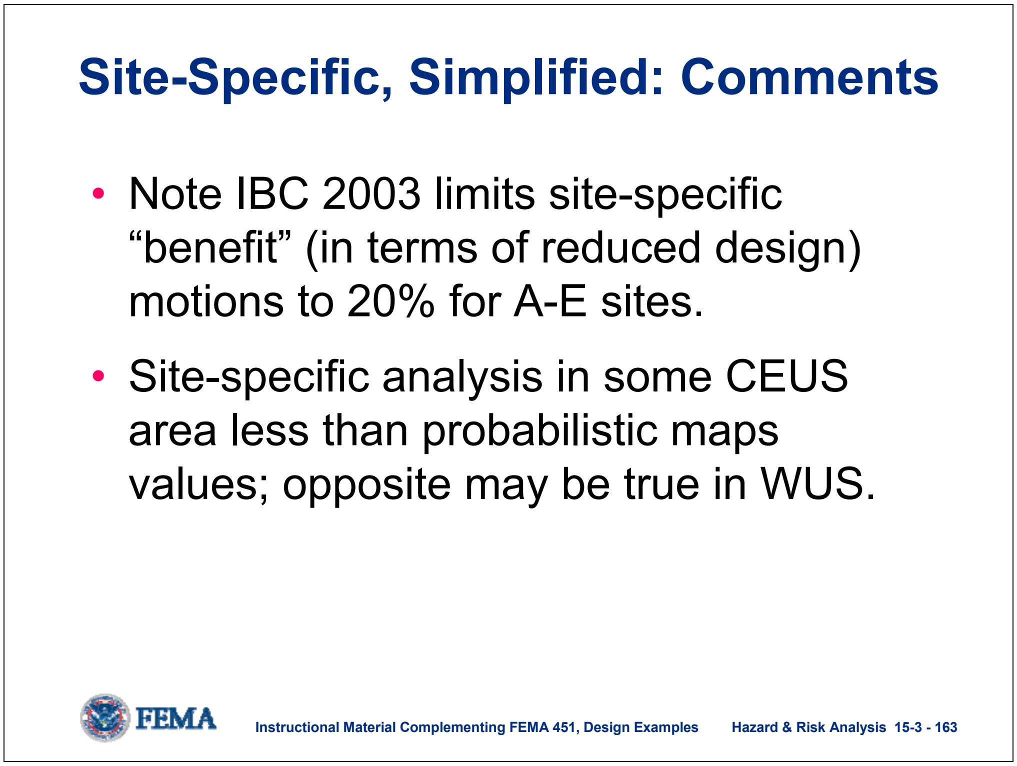
Relatively simple (chart-based procedures) are used for may preliminary and approximate analysis.



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.

None.

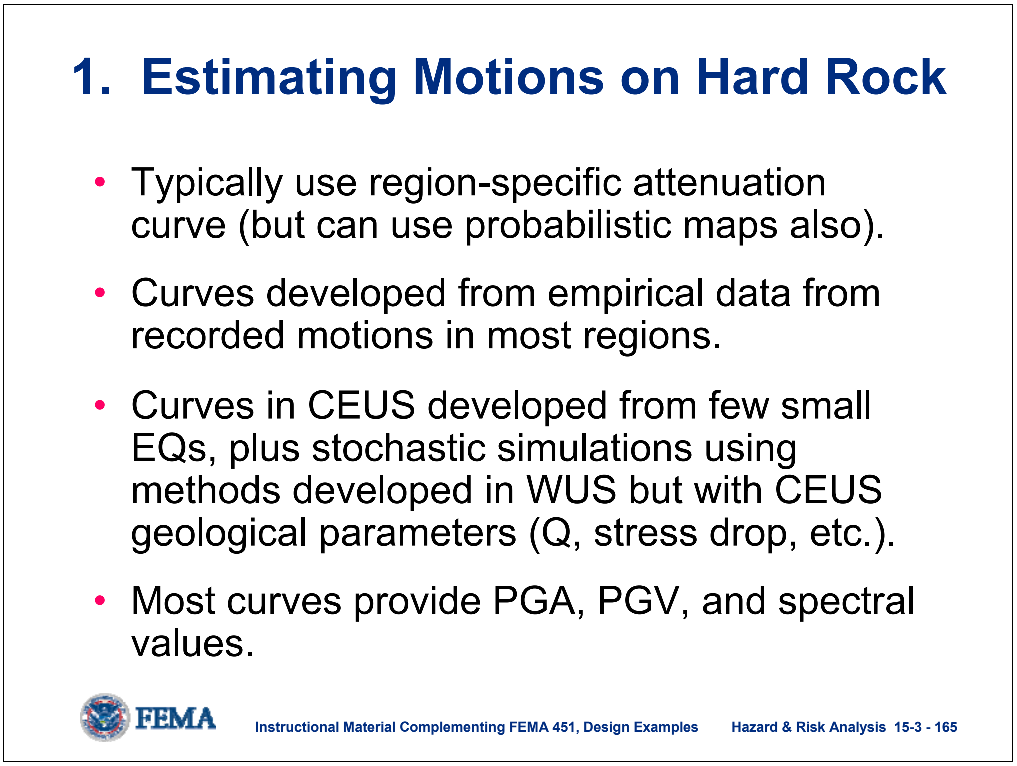
Site-Specific Simplified Procedures

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.

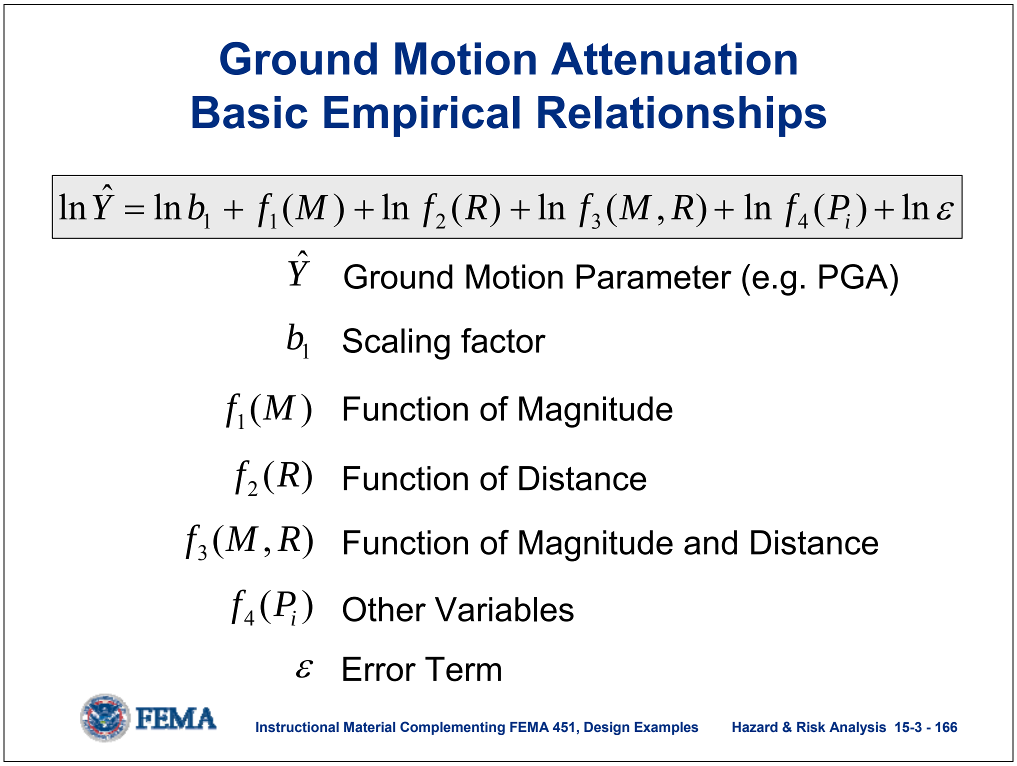
None.



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.

None.



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

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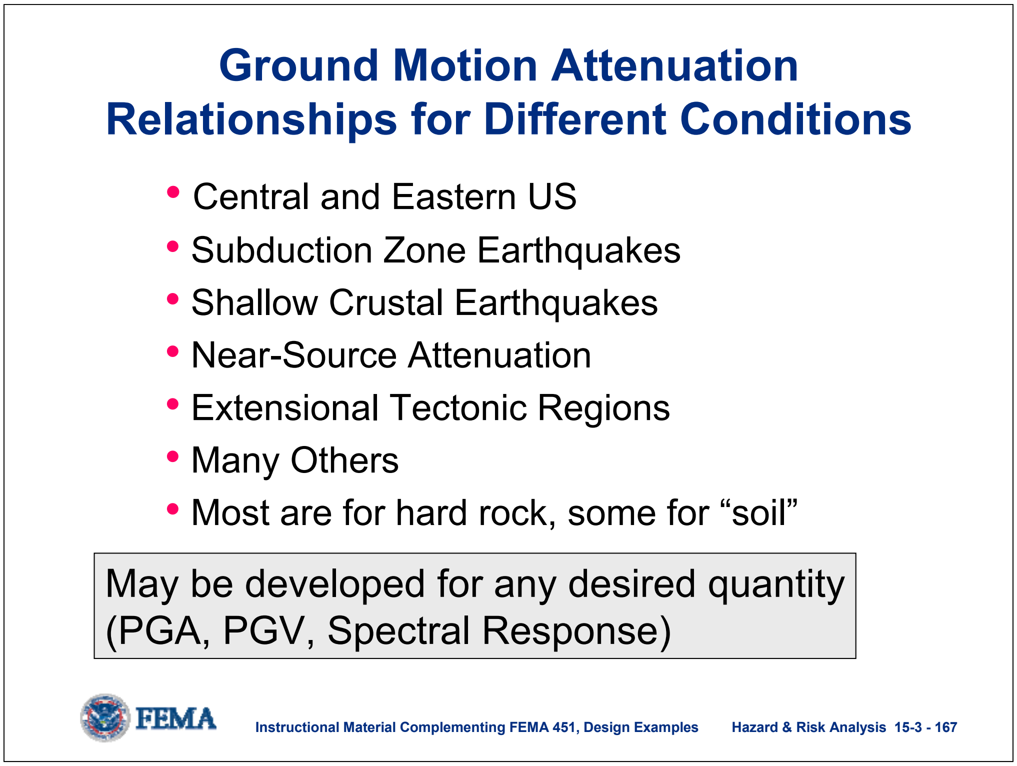
This relationship show the typical form of attenuation curves based on regression analyses form empirical data.



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”

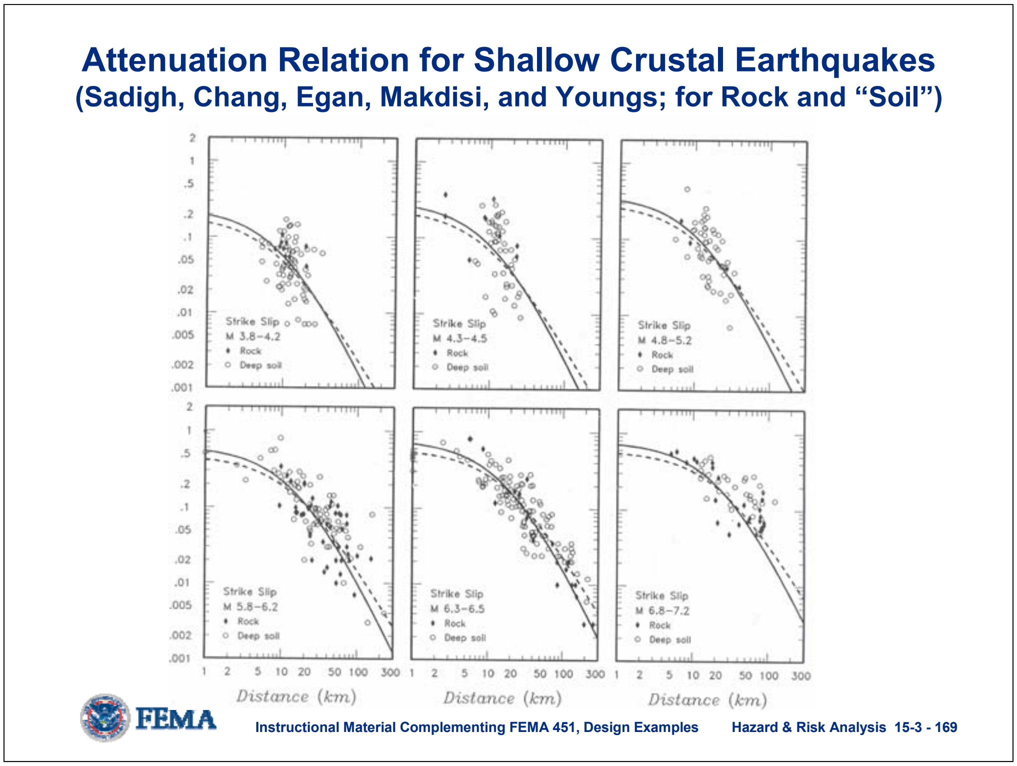
May be developed for any desired quantity (PGA, PGV, Spectral Response)

A number of attenuation curves are available for specific source and site conditions.

Ground Motion Attenuation Relationships

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

This slide indicates an excellent reference on recent attenuation relationships in the US.



Attenuation Relation for Shallow Crustal Earthquakes

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

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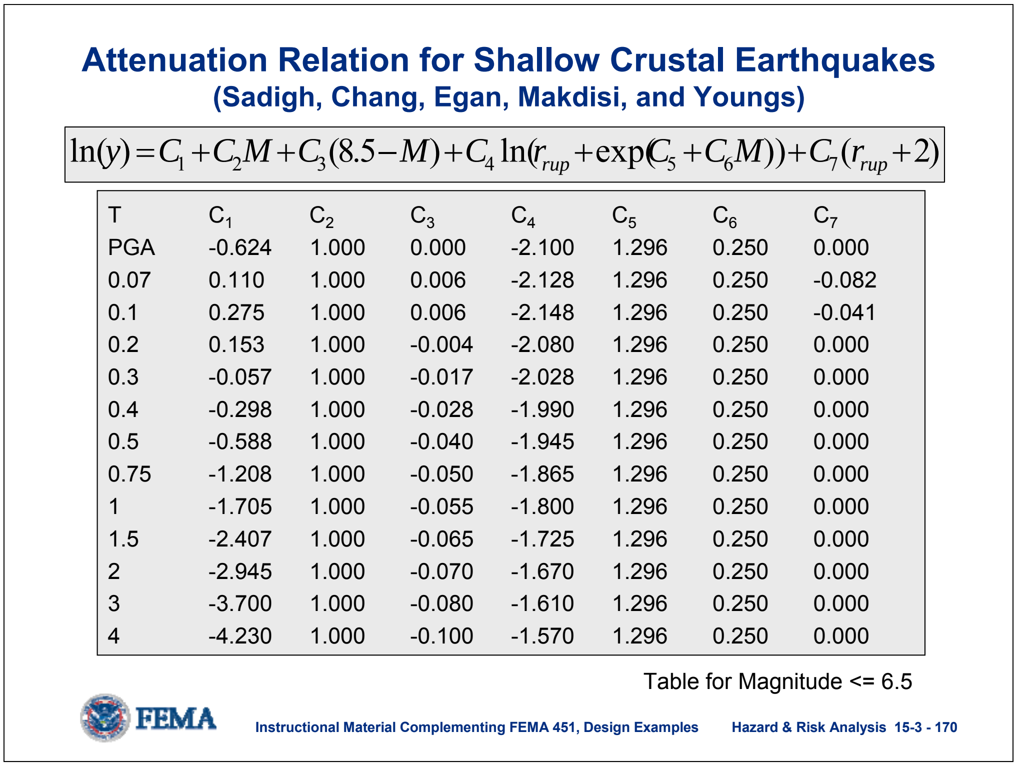
Note that there is high variability in PGAs for various site conditions.



Attenuation Relation for Shallow Crustal Earthquakes

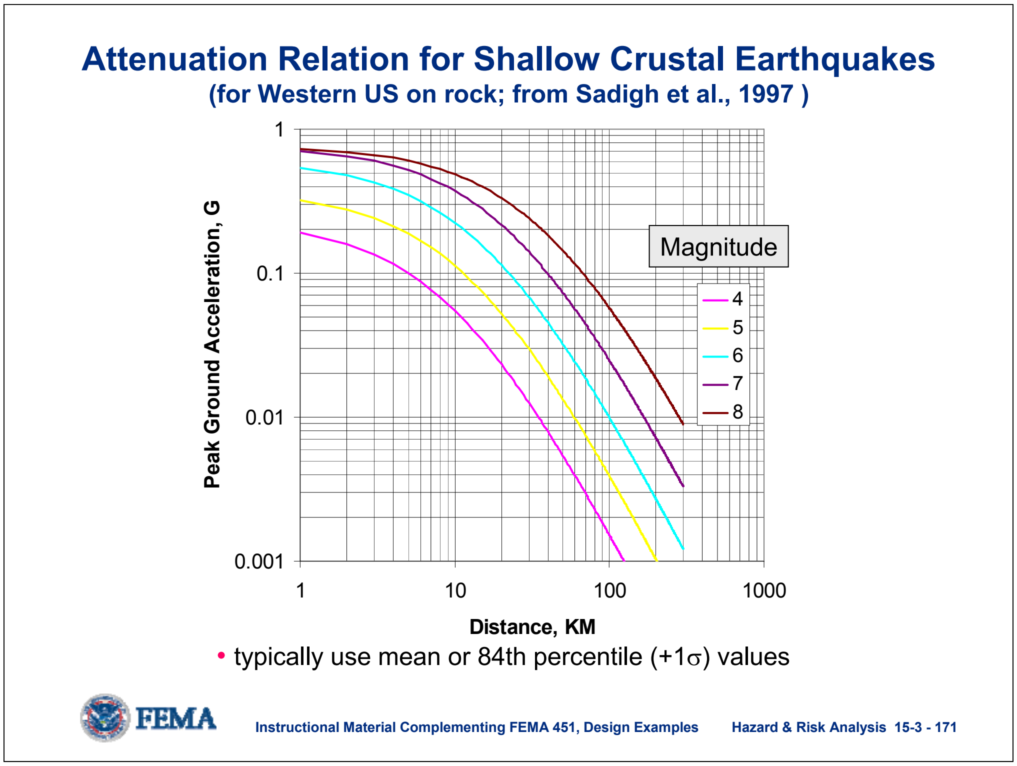
(Sadigh, Chang, Egan, Makdisi, and Youngs)

$$\ln(y) = C_1 + C_2 M + C_3(8.5 - M) + C_4 \ln(r_{rup} + \exp(C_5 + C_6 M)) + C_7(r_{rup} + 2)$$

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

Table of coefficients for use in attenuation equation.

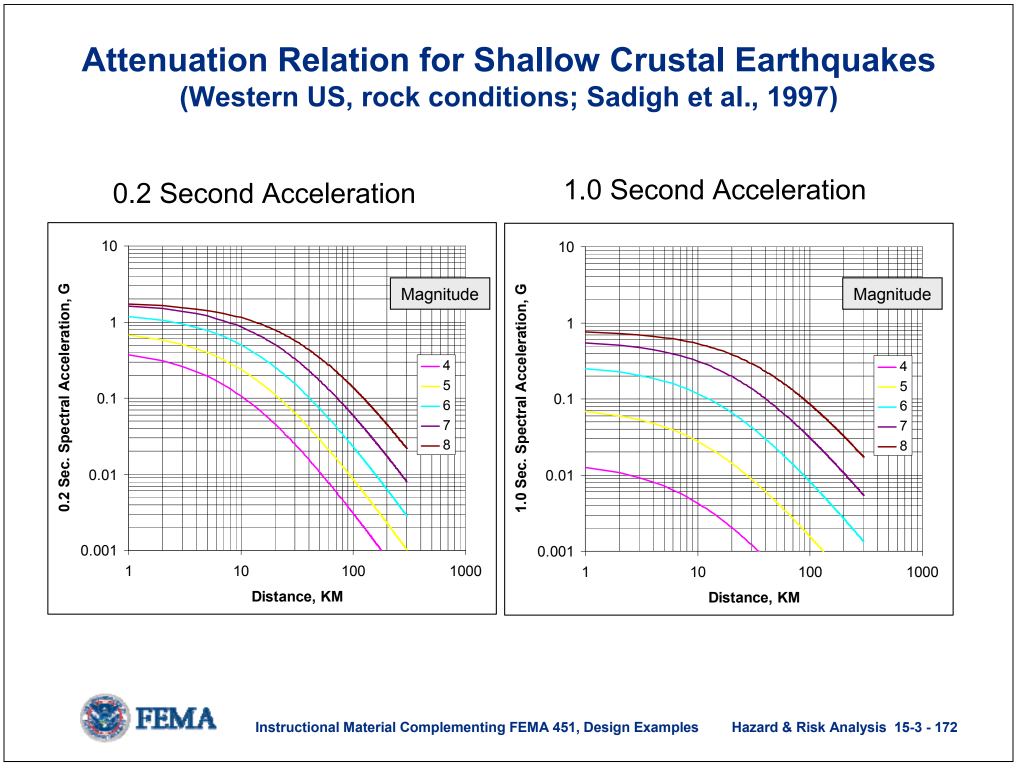


Attenuation Relation for Shallow Crustal Earthquakes

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

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

Attenuation of PGA vs. distance for shallow crustal earthquakes; from "Crustal Earthquakes Based on California Strong Motion Data," by K. Sadigh, C.-Y. Chang, J.A. Egan, F. Makdisi, and R.R. Youngs, *Seismological Research Letters, 68,* January/February, 1997.



Attenuation Relation for Shallow Crustal Earthquakes

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

0.2 Second Acceleration

1.0 Second Acceleration

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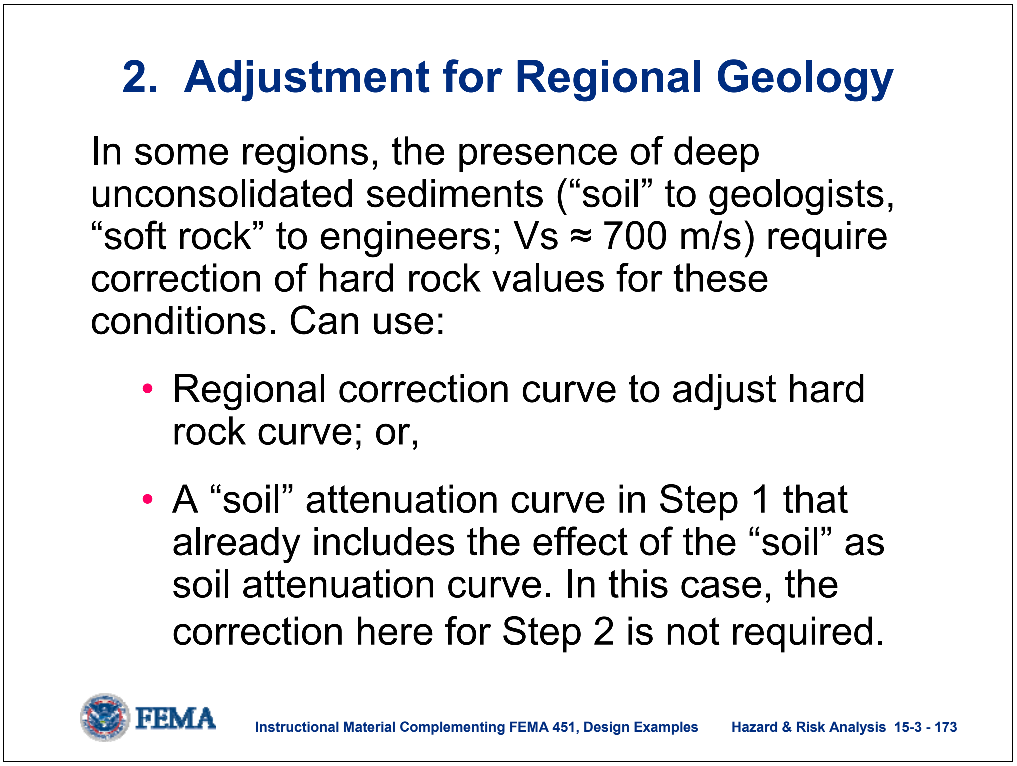
For western US on rock from “Crustal Earthquakes Based on California Strong Motion Data,” by K. Sadigh, C.-Y. Chang, J.A. Egan, F. Makdisi, and R.R. Youngs, *Seismological Research Letters, 68,* January/February, 1997.

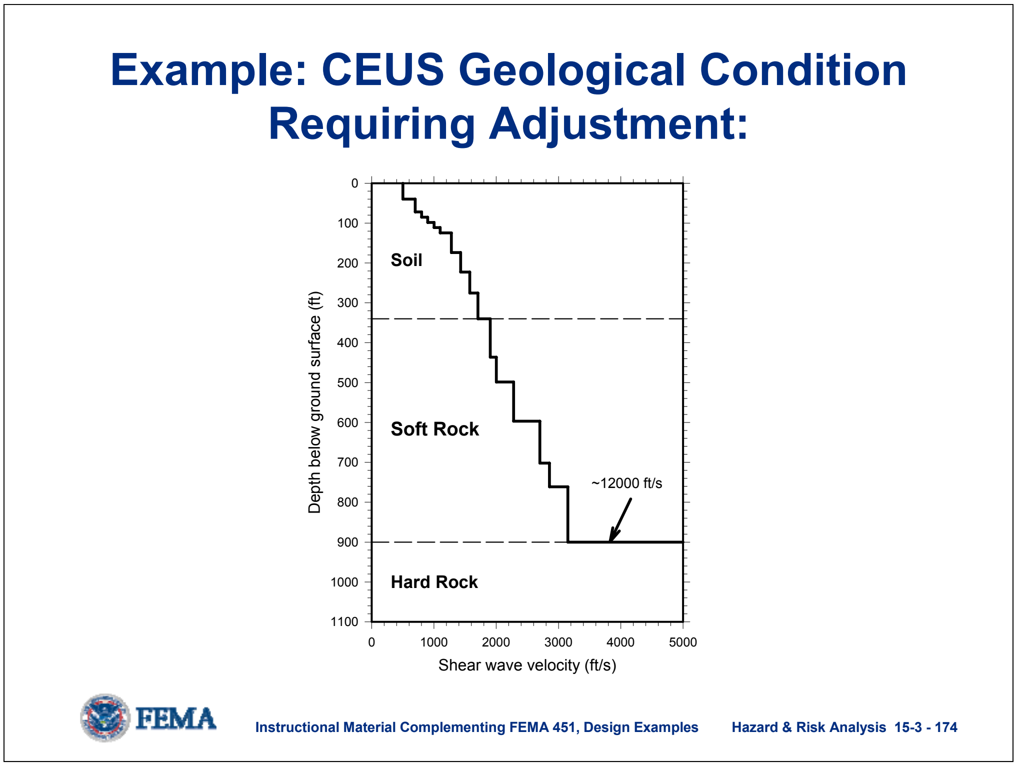


2. Adjustment for Regional Geology

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.

The presence of deep unconsolidated sediments (“soil” to geologists, “soft rock” to engineers; Vs ≈ 700 m/s) require correction of hard rock values as illustrated in the following slides.



Example: CEUS Geological Condition Requiring Adjustment:

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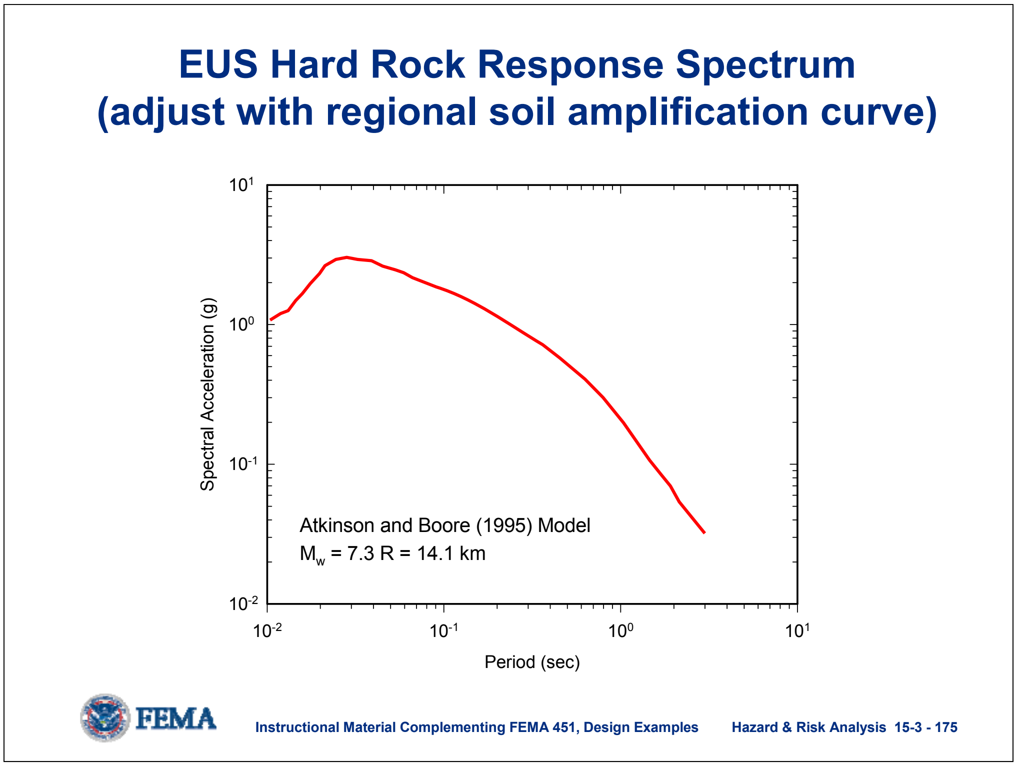
Soil conditions such as those depicted above are common in the central and eastern US such as Memphis and Charleston.



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

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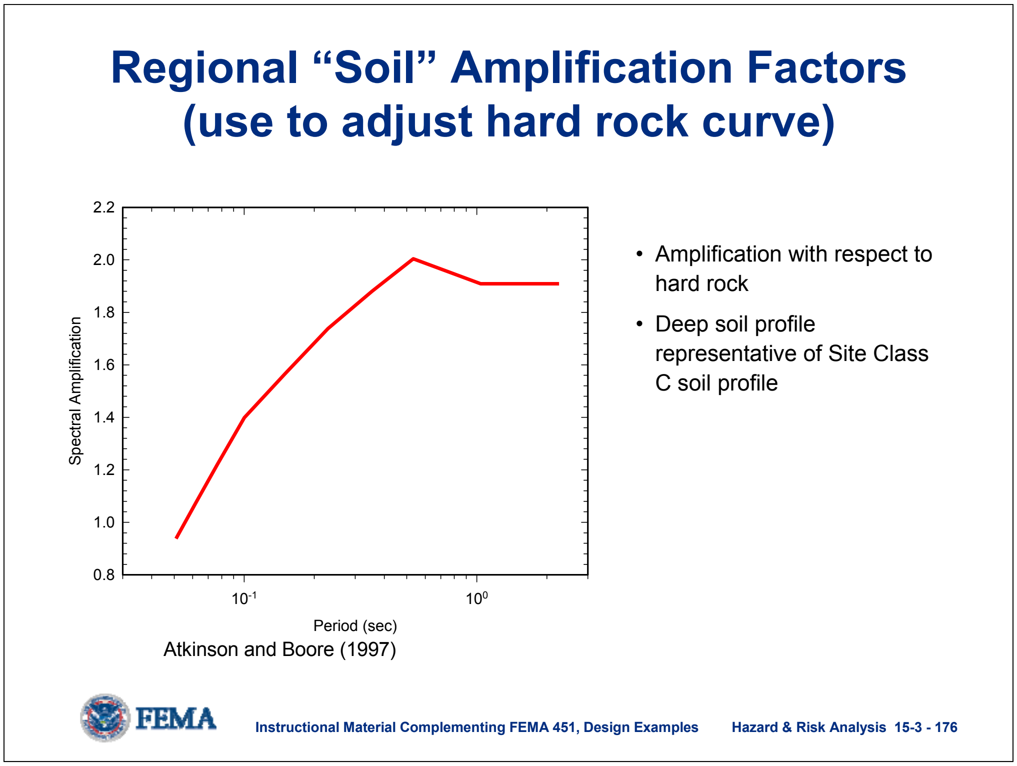
EUS Hard Rock Response Spectrum from Atkinson and Boore (1995) Model for the case where Mw = 7.3, and distance, R, = 14.1 km.



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

Atkinson and Boore (1997)

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

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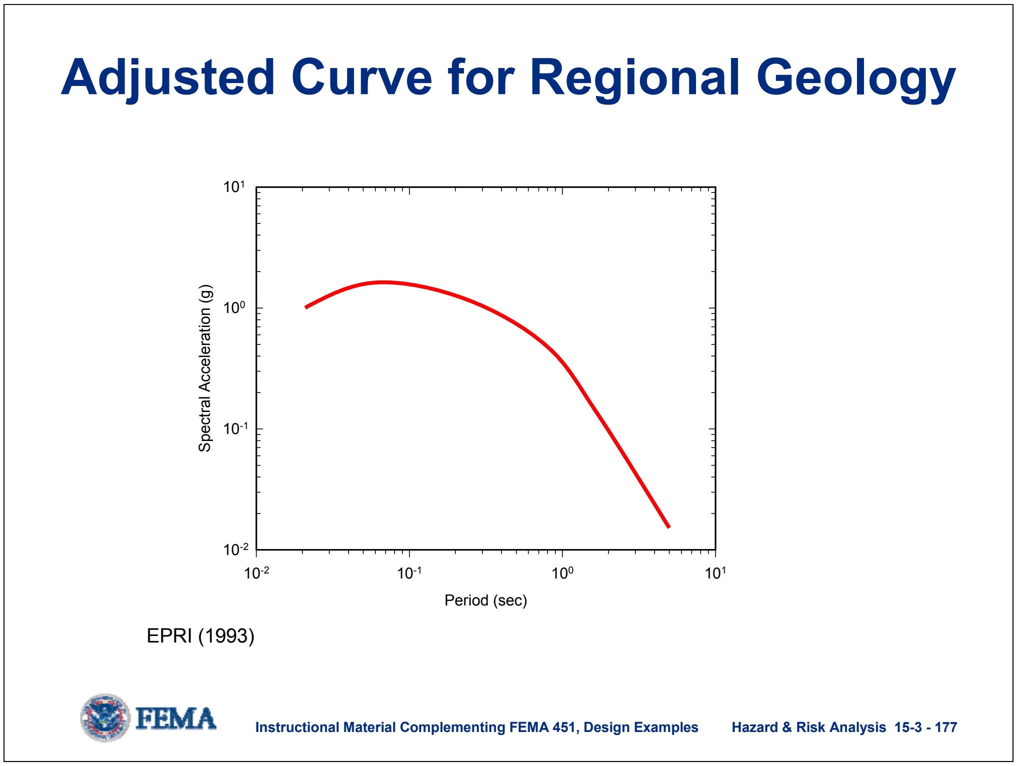
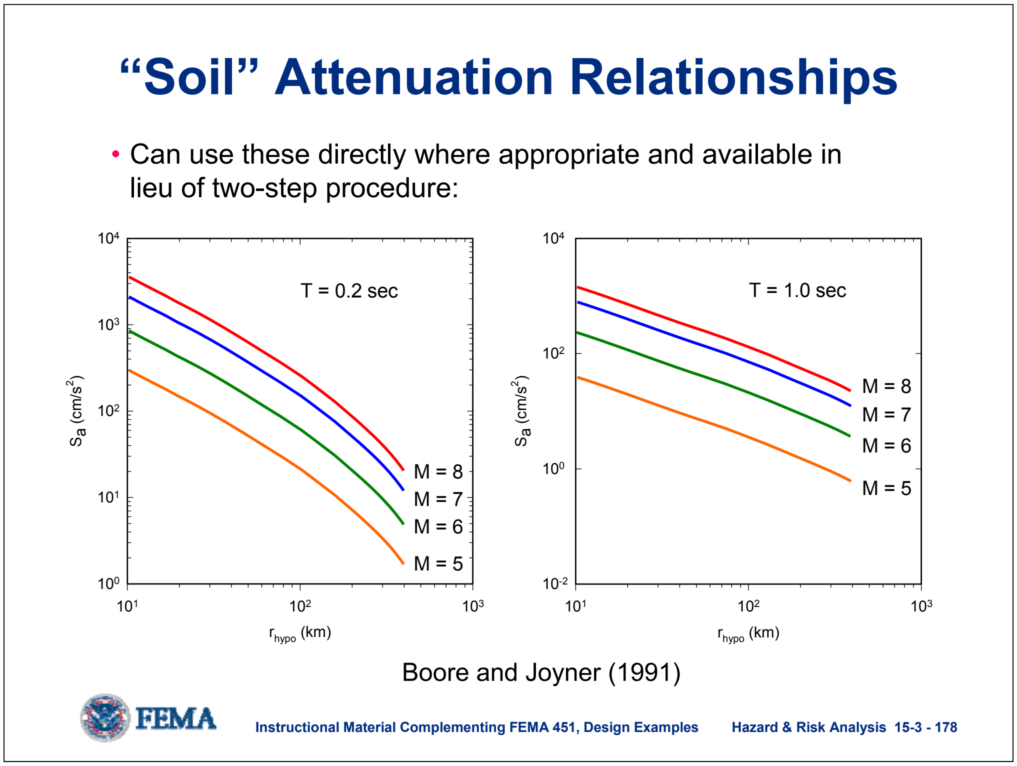
The amplification curve for the deep soil profile with respect to hard rock is shown, and it can be seen that the low periods (high frequencies) will be deamplified and the high periods will be amplified. This is similar to the response expected in Memphis with about 1000 ft. of unconsolidated soil and in Charleston with 800 m of such material.



Adjusted Curve for Regional Geology

EPRI (1993)

Final curve showing ground motions that account for regional source and geology based on combination of previous two slides. The amplification curve for the deep soil profile with respect to hard rock is shown, and it can be seen that the low periods (high frequencies) rock motions were deamplified and the high periods were amplified. This is similar to the response expected in Memphis with about 1000 ft. of unconsolidated soil and in Charleston with 800 m of such material. Still need to adjust for near-surface (typically within 30 m or so) soil conditions.

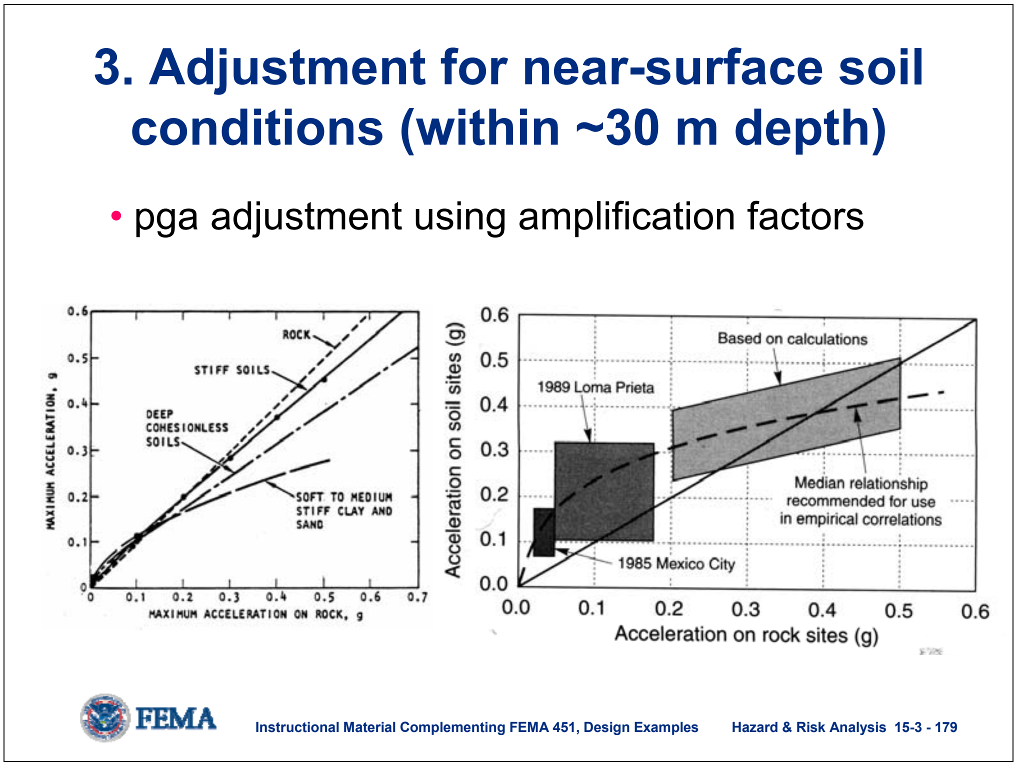


“Soil” Attenuation Relationships

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

Boore and Joyner (1991)

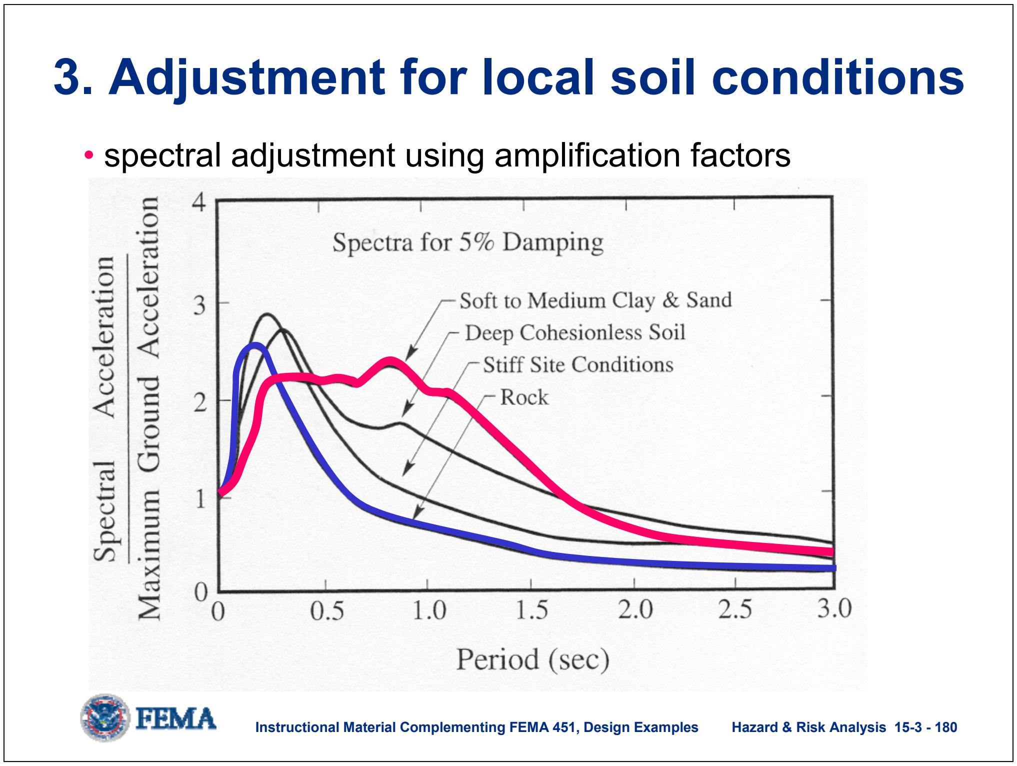
Some relationships are developed for specific regions and already account for the presence of local geological conditions.



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

- pga adjustment using amplification factors

Soft soils can amplify PGAs relative to rock in many cases. Seed and Idriss (1984) and Idriss (1990). Such relationships are very approximate and should be used only when more rigorous methods are unavailable or unwarranted, such as for preliminary analysis.



3. Adjustment for local soil conditions

- spectral adjustment using amplification factors

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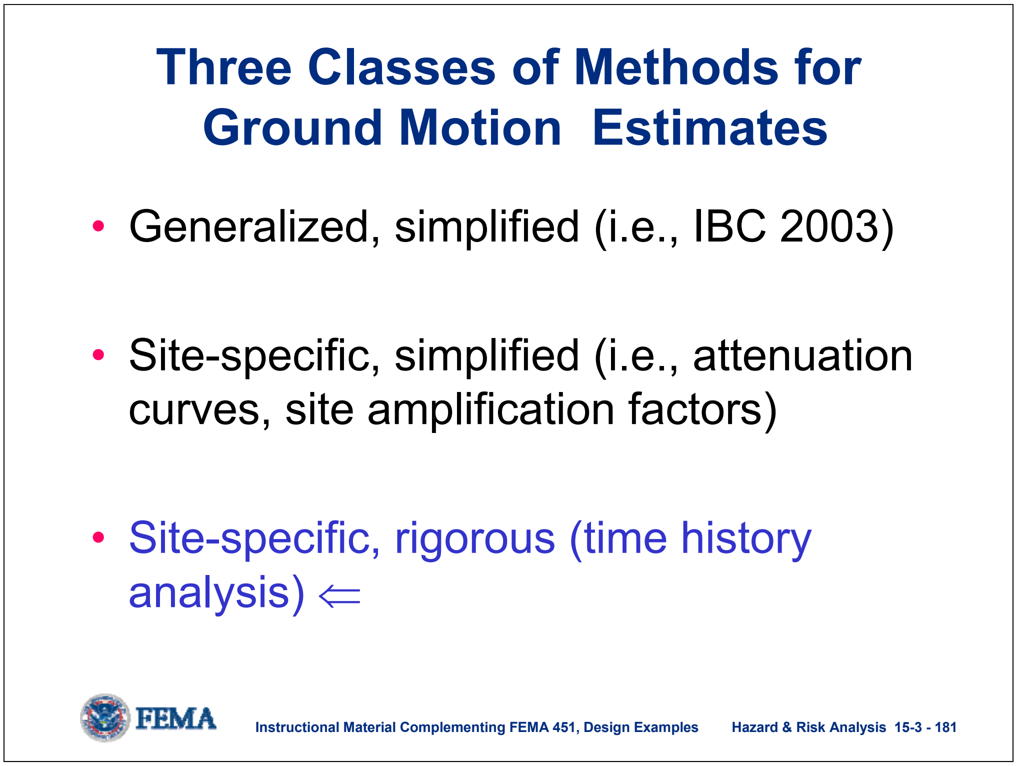
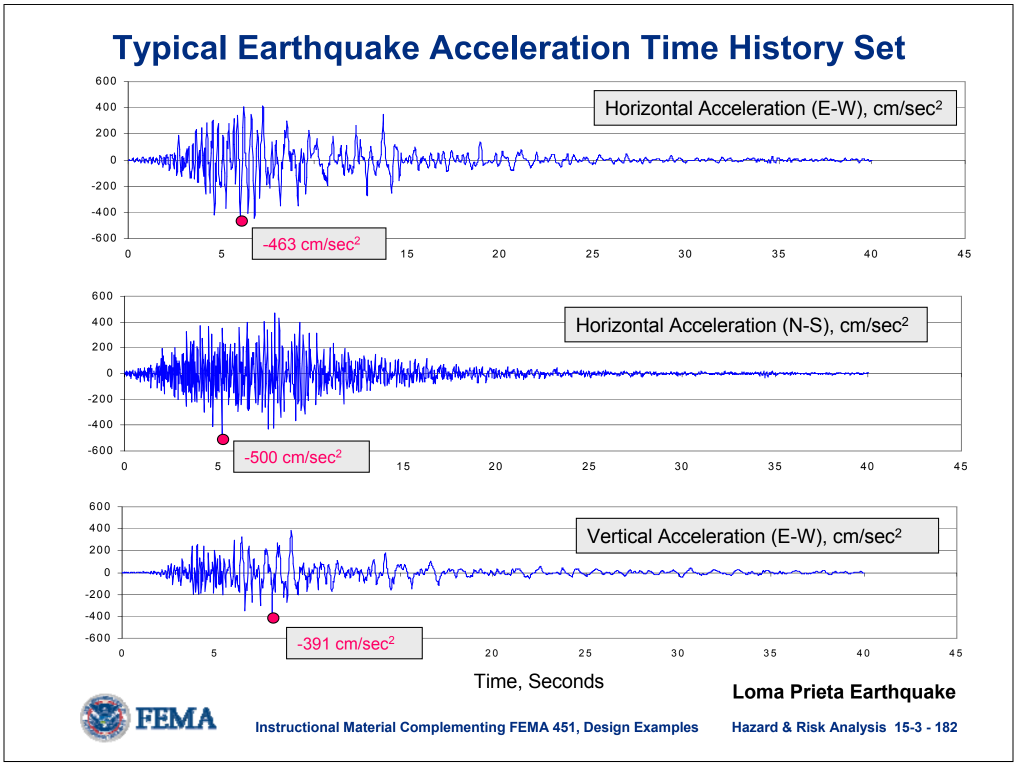
Soft soils affect the shape and ordinate position of the response spectrum, as shown depicted by the red curve.



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) ⇐

None.



Typical Earthquake Acceleration Time History Set

Loma Prieta Earthquake

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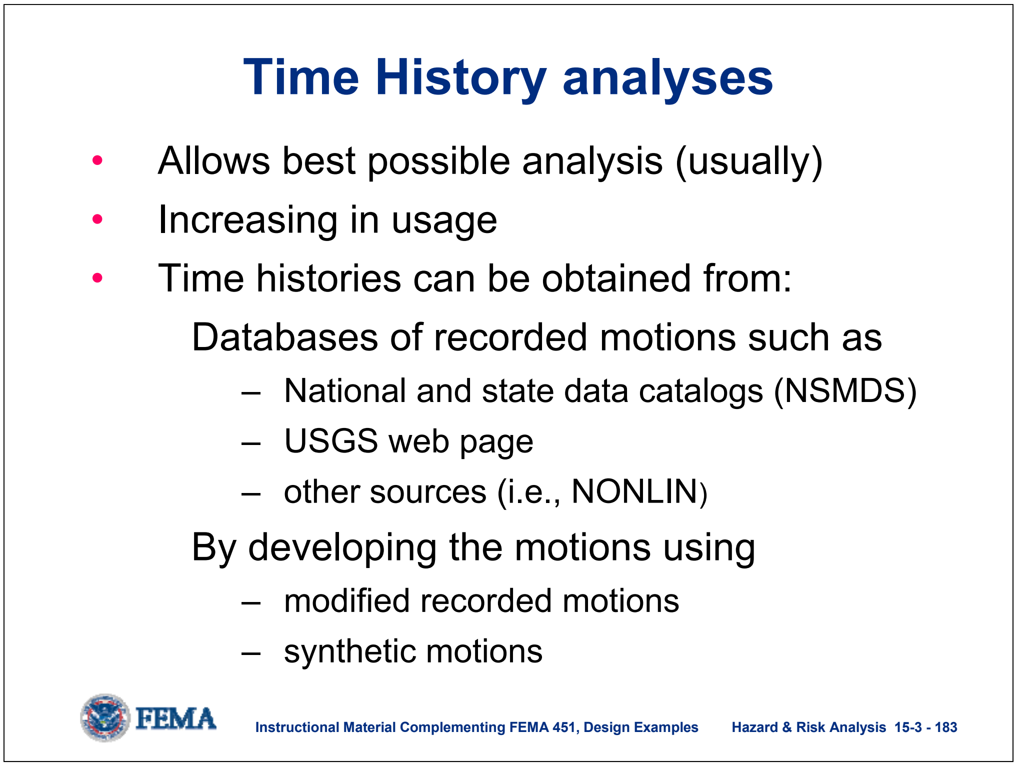
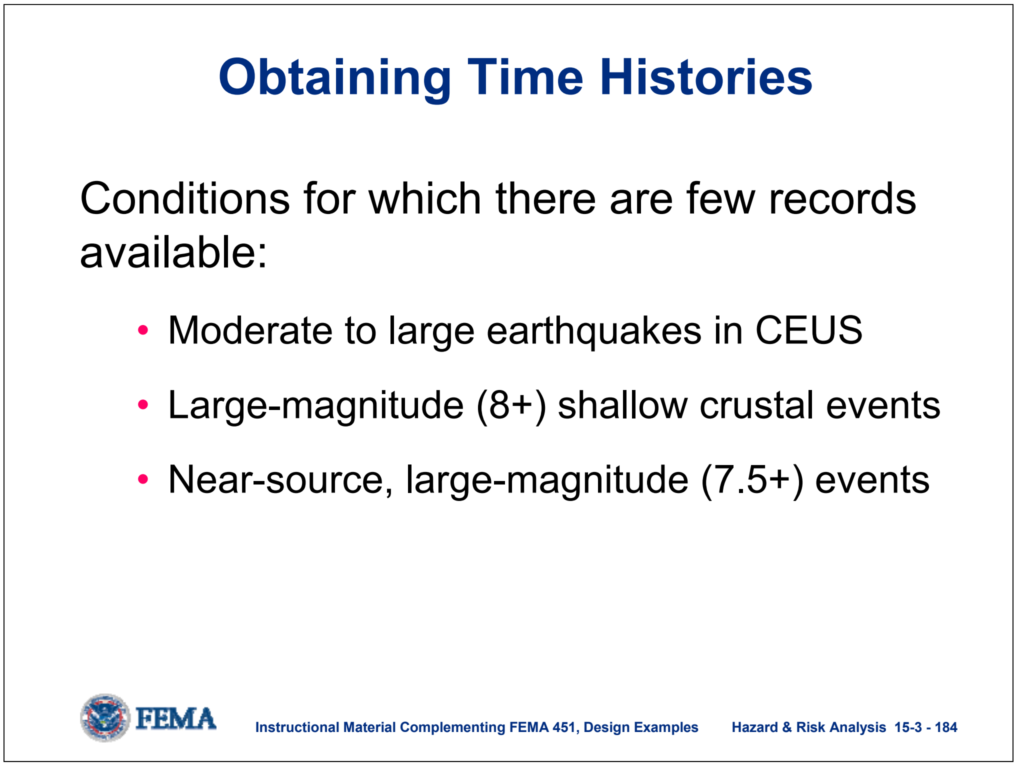
Vertical motions are typically about 2/3 of maximum horizontal shaking, but this ratio is often higher for near-fault conditions.



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

None.

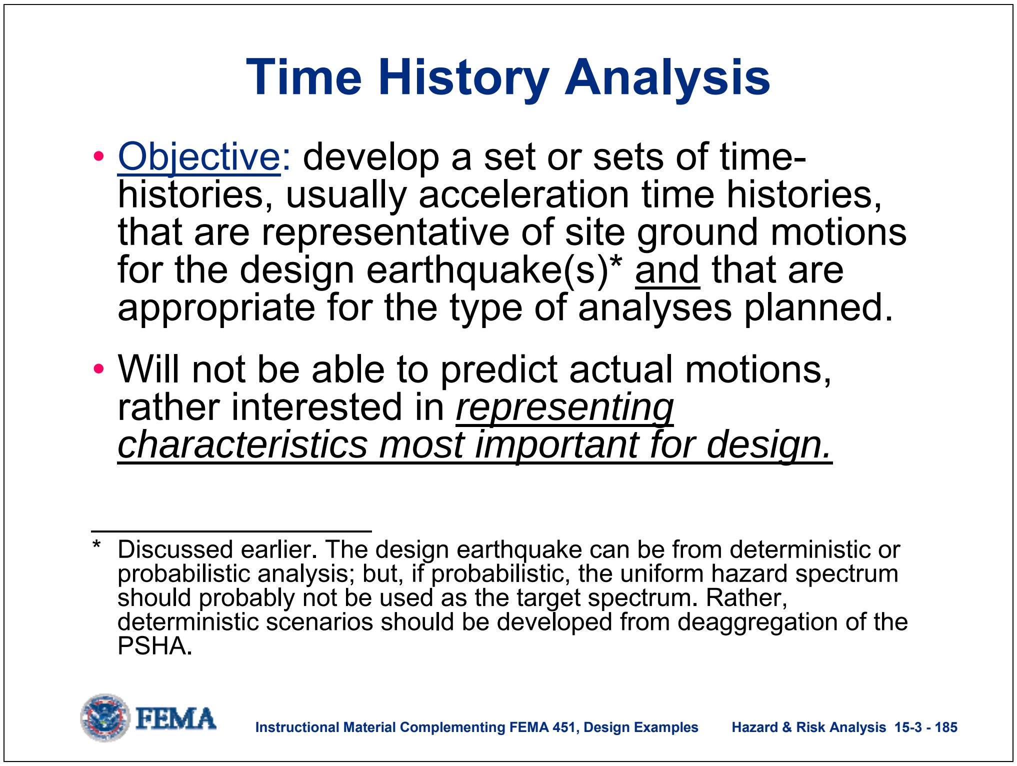


Obtaining Time Histories

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

There are great needs for additional seismic data in the WUS, but especially so for the CEUS.



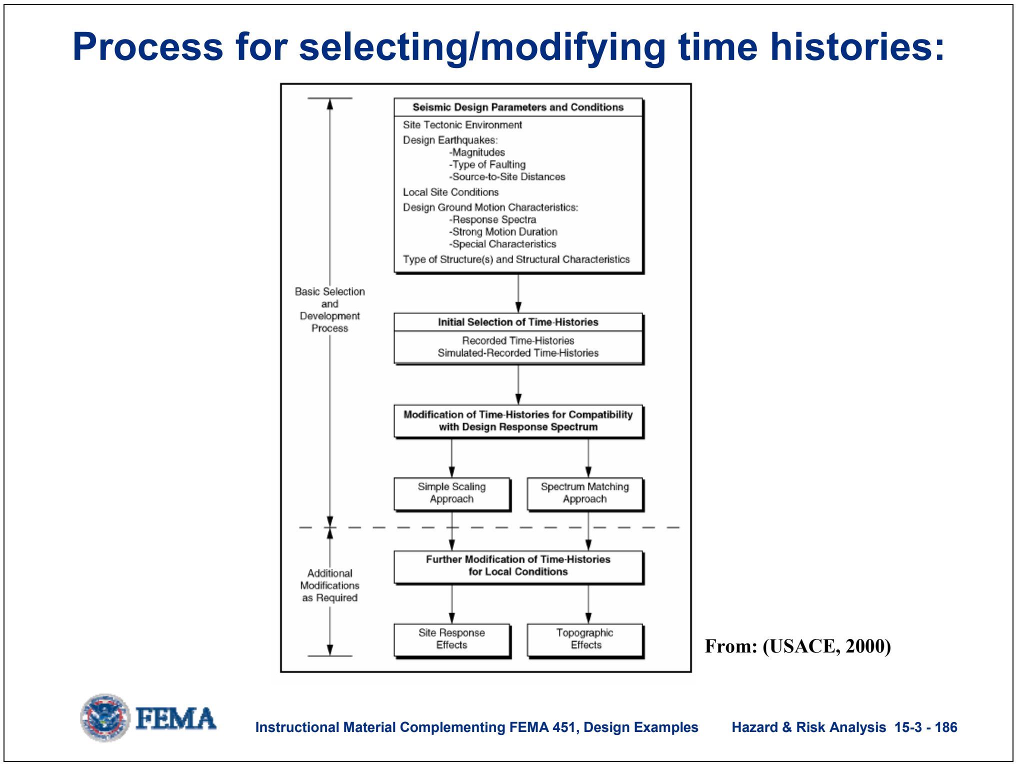
Time History Analysis

- 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.

The design earthquake can be deterministic or probabilistic; 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)

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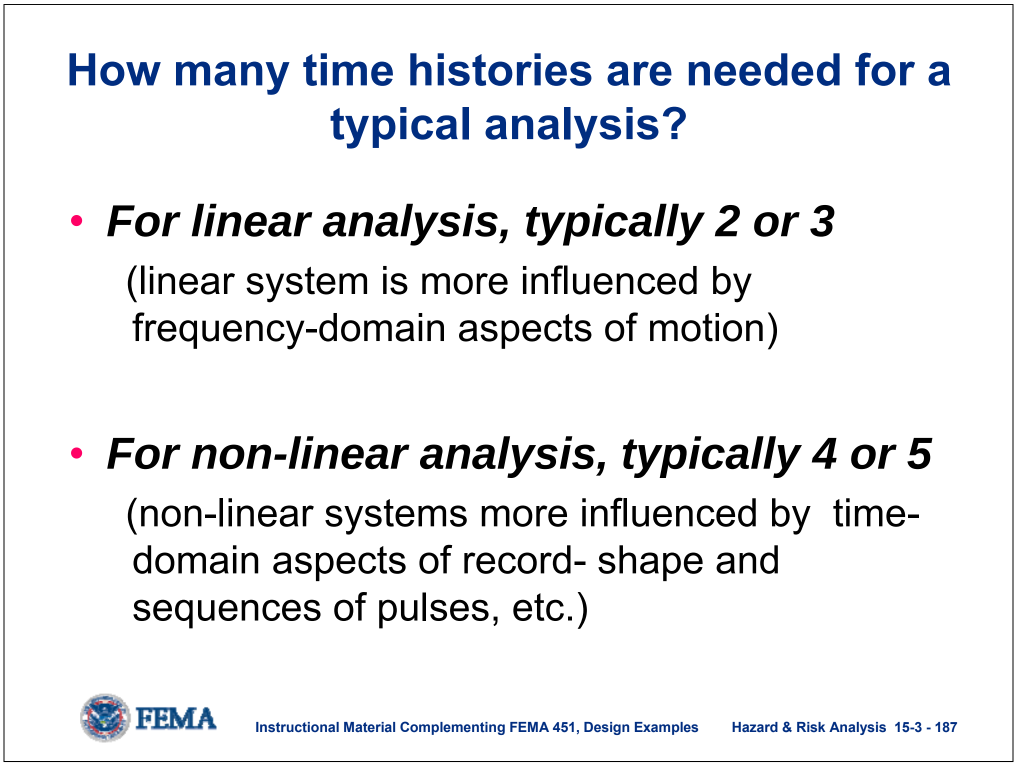
The table above can be used as a guide for the selection of time histories. This was adapted from the United States Army Corps of Engineers (USACE) (2000). “Time history of dynamic analysis of concrete hydraulic structures,” *Engineering Circular (EC) 1110-2-6051*, Department of the Army, Washington, D.C.



How many time histories are needed for a typical analysis?

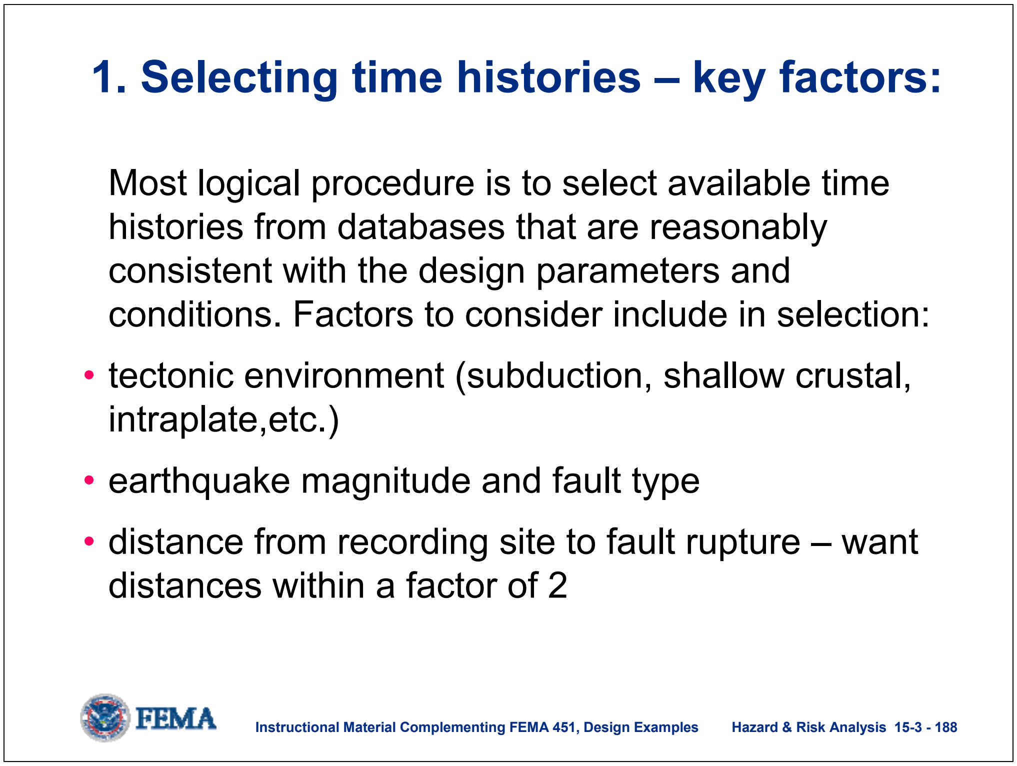
- ***For linear analysis, typically 2 or 3***

  (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.)

The number of time histories to be used in an analysis, depends upon the type of analysis to be performed.

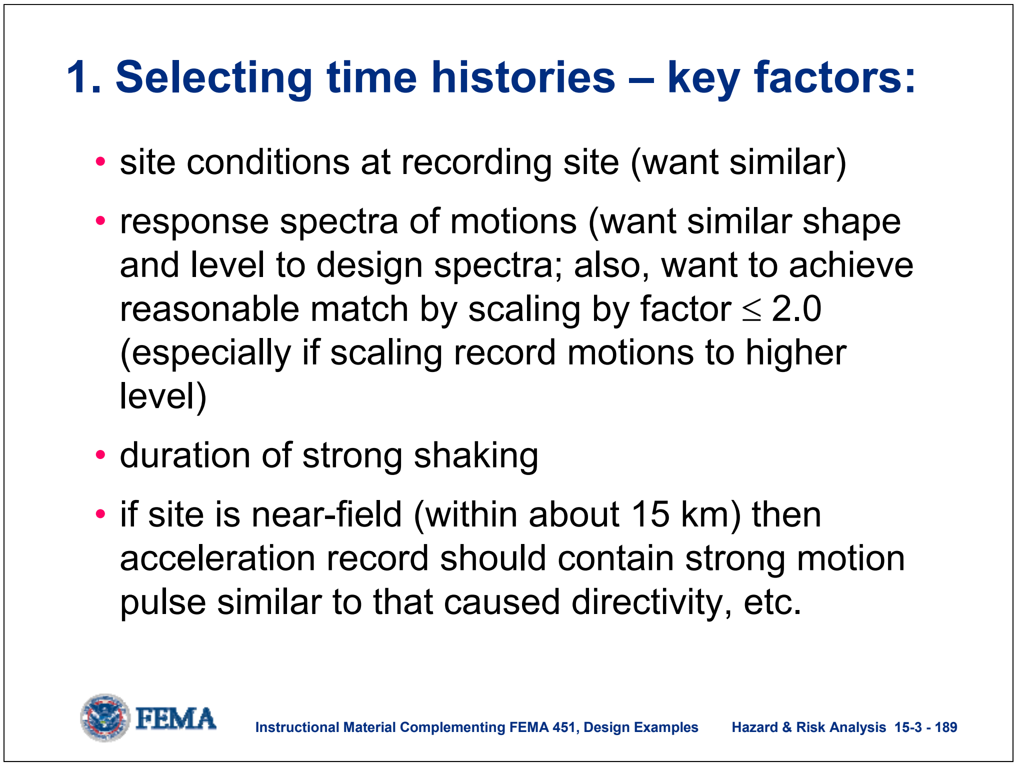


1. Selecting time histories – key factors:

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

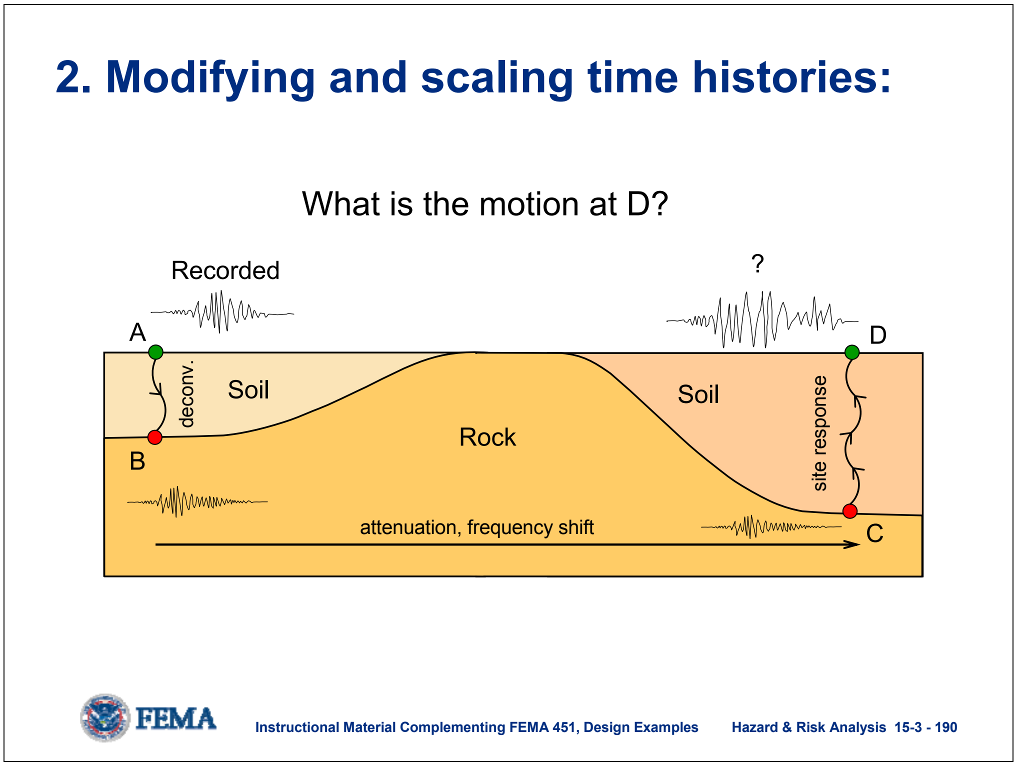
When possible, time histories should be selected from the data base such that they are reasonably consistent with the design parameters and conditions, as discussed more in the following slides.



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.

None.



2. Modifying and scaling time histories:

What is the motion at D?

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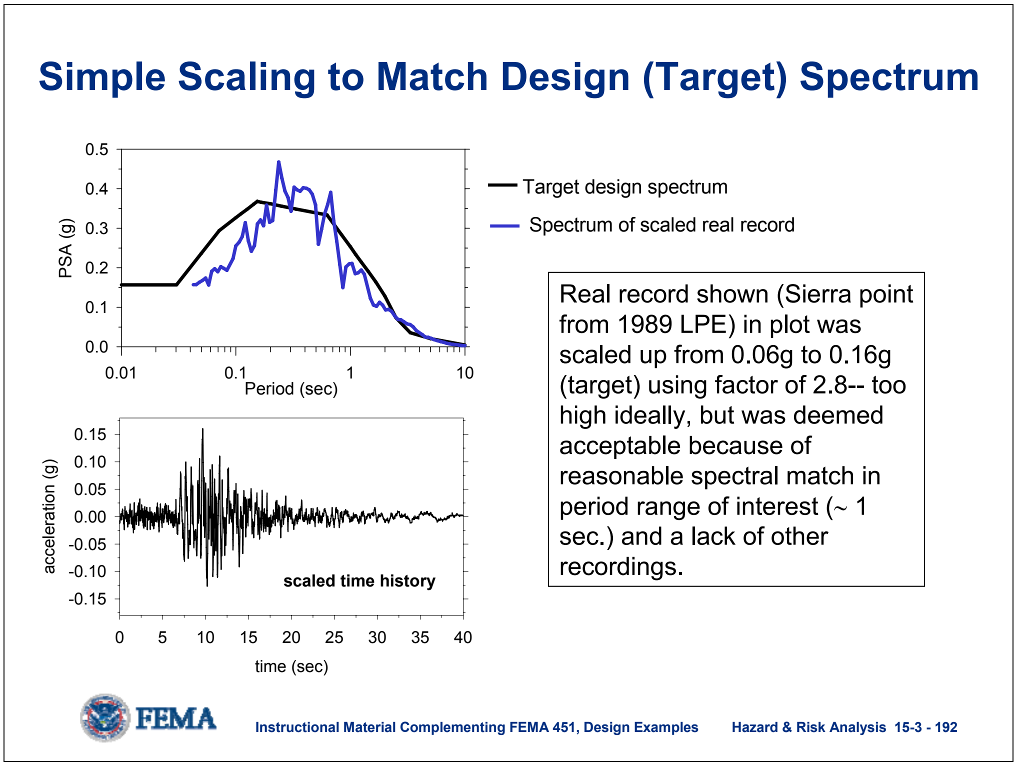
Estimation of time history at D from that recorded at A requires scaling and processing and must account for several factors. The diagram illustrates the general process that is usually involved. SHAKE or a similar site response code is typically used for this analysis. Although possible in theory, the deconvolution step (from A to B) is often difficult to perform and numerically unstable. Care should be taken when performing this step to ensure reasonable results.

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.

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.

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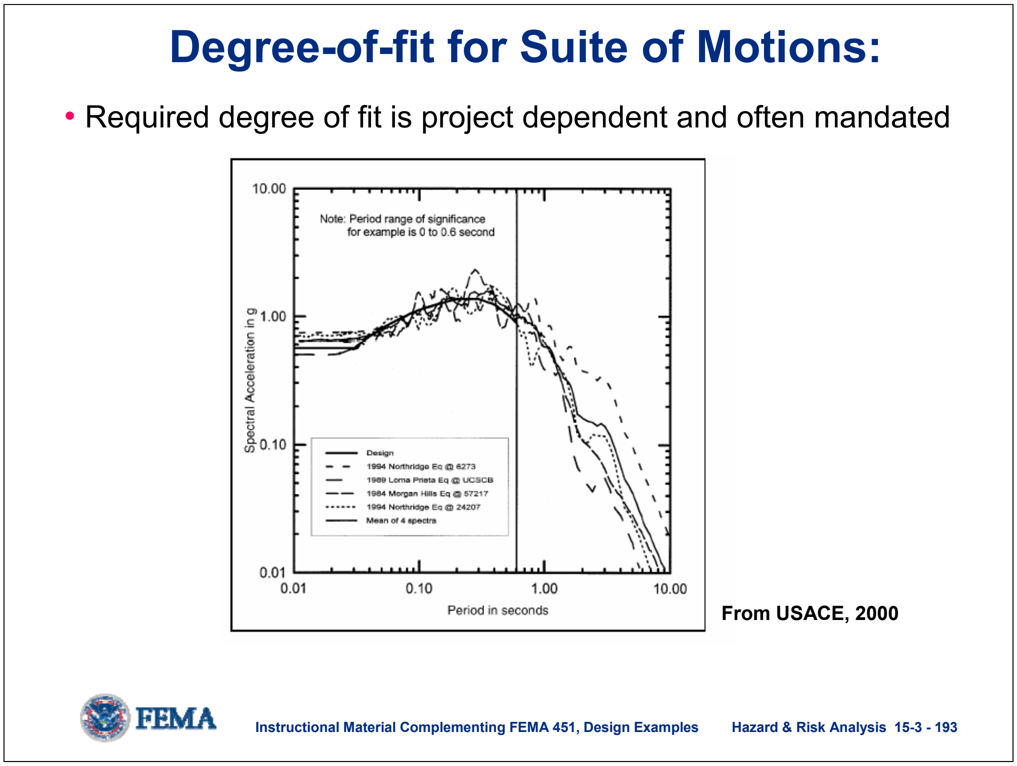
Example of matching target spectrum. It can be seen that the spectral shape of the Sierra Point record matches the target reasonably well, but may not be conservative enough for certain projects, such as nuclear sites that typically require 95% of the points to be equal to higher than the target.



Degree-of-fit for Suite of Motions:

- Required degree of fit is project dependent and often mandated

From USACE, 2000

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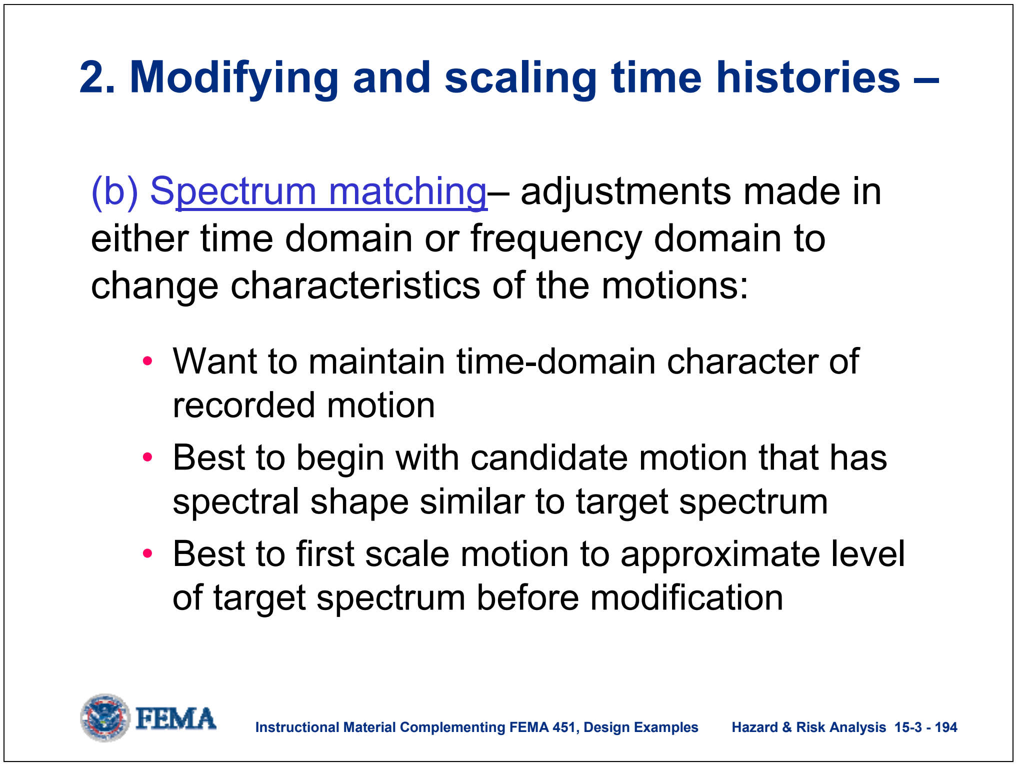
The required degree of fit is project dependent and often mandated by the regulatory agency involved. United States Army Corps of Engineers (USACE) (2000). “Time history of dynamic analysis of concrete hydraulic structures,” *Engineering Circular (EC) 1110-2-6051*, Department of the Army, Washington, D.C.

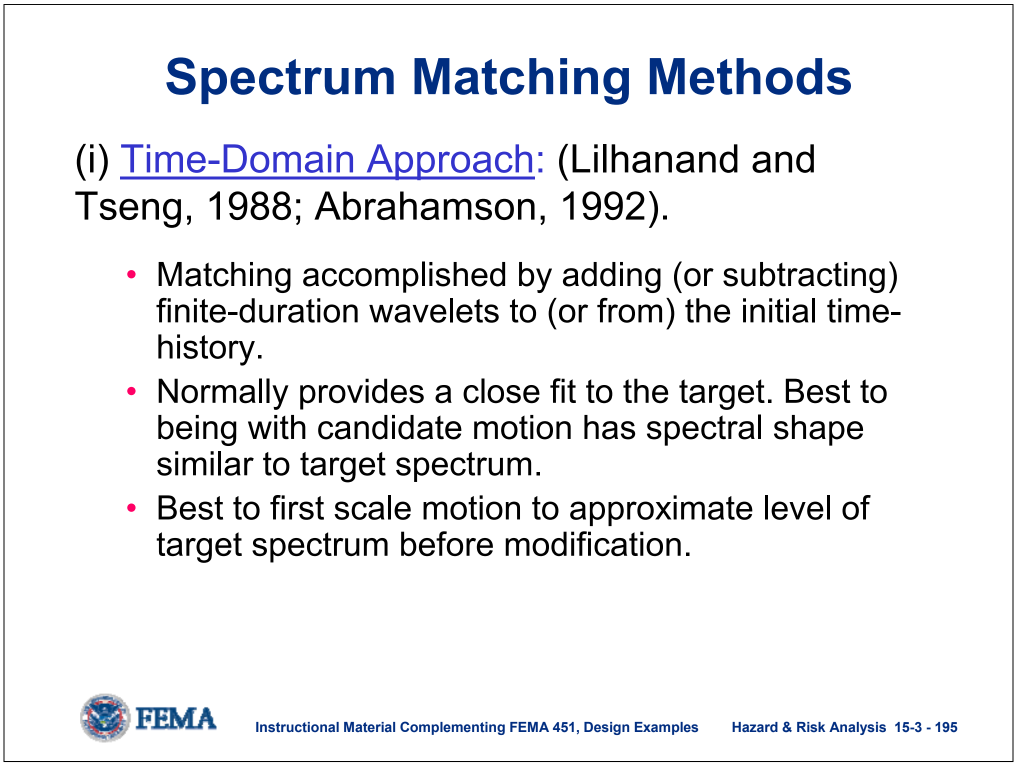


2. Modifying and scaling time histories –

(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

Using the spectrum matching approach, adjustments are made in either time domain or frequency domain to change characteristics of the motions.

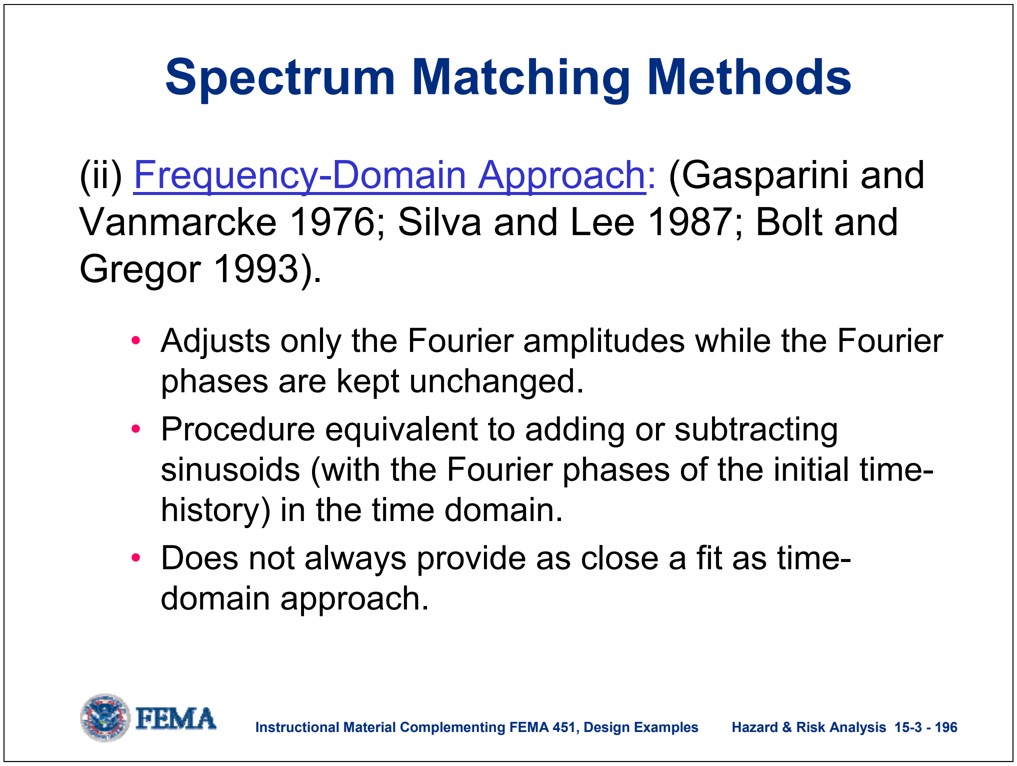


Spectrum Matching Methods

(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.

With the time-domain approach, matching is accomplished by adding (or subtracting) finite-duration wavelets to (or from) the initial time-history.

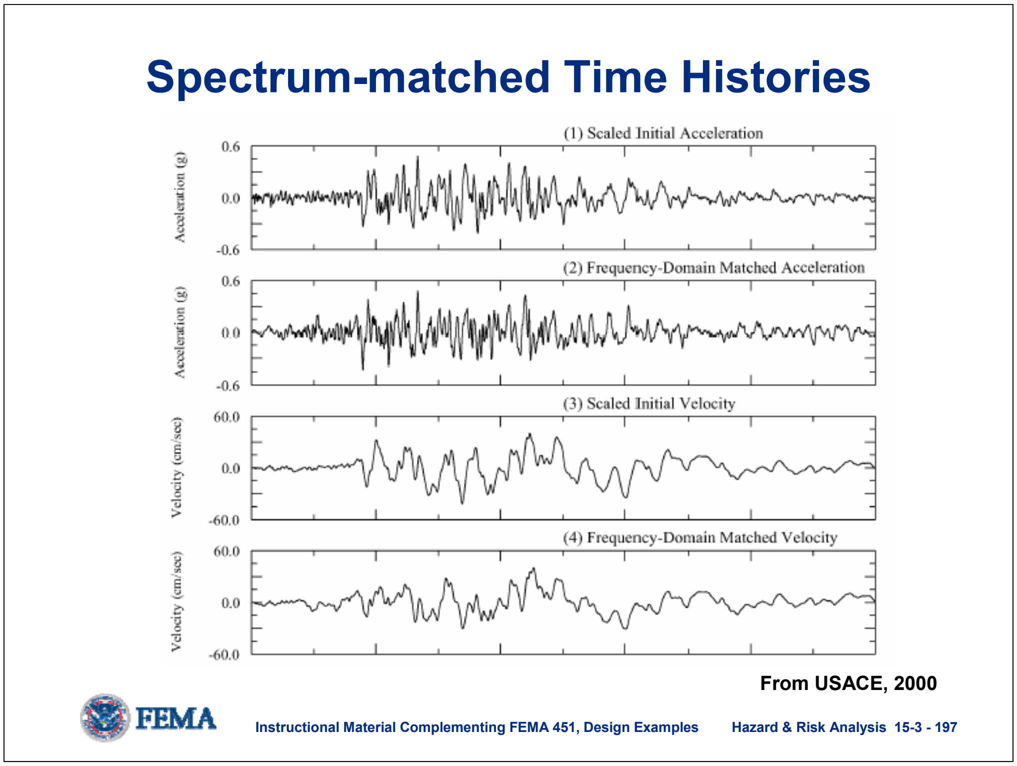


Spectrum Matching Methods

(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.

The frequency-domain approach adjusts only the Fourier amplitudes, while the Fourier phases are kept unchanged.



Spectrum-matched Time Histories

From USACE, 2000

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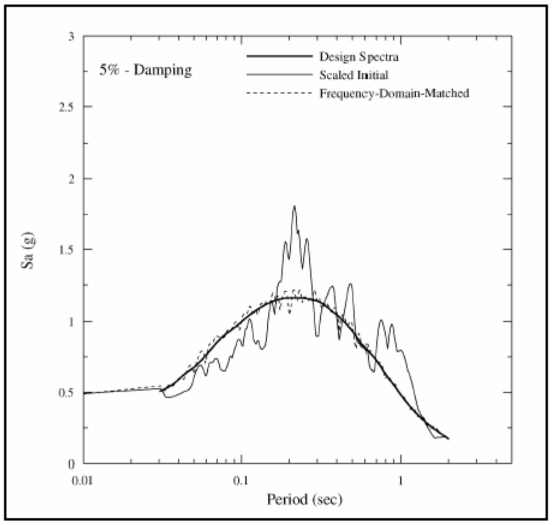
Example of different types of spectrum-matched time histories. Note how the scaling process changed the character of the motions. United States Army Corps of Engineers (USACE) (2000). “Time history of dynamic analysis of concrete hydraulic structures,” *Engineering Circular (EC) 1110-2-6051*, Department of the Army, Washington, D.C.

Spectra of spectrum-matched time histories:



From USACE, 2000

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

Illustration of spectra from different types of spectrum-matched time histories. United States Army Corps of Engineers (USACE) (2000). “Time history of dynamic analysis of concrete hydraulic structures,” *Engineering Circular (EC) 1110-2-6051*, Department of the Army, Washington, D.C.

Other corrections…

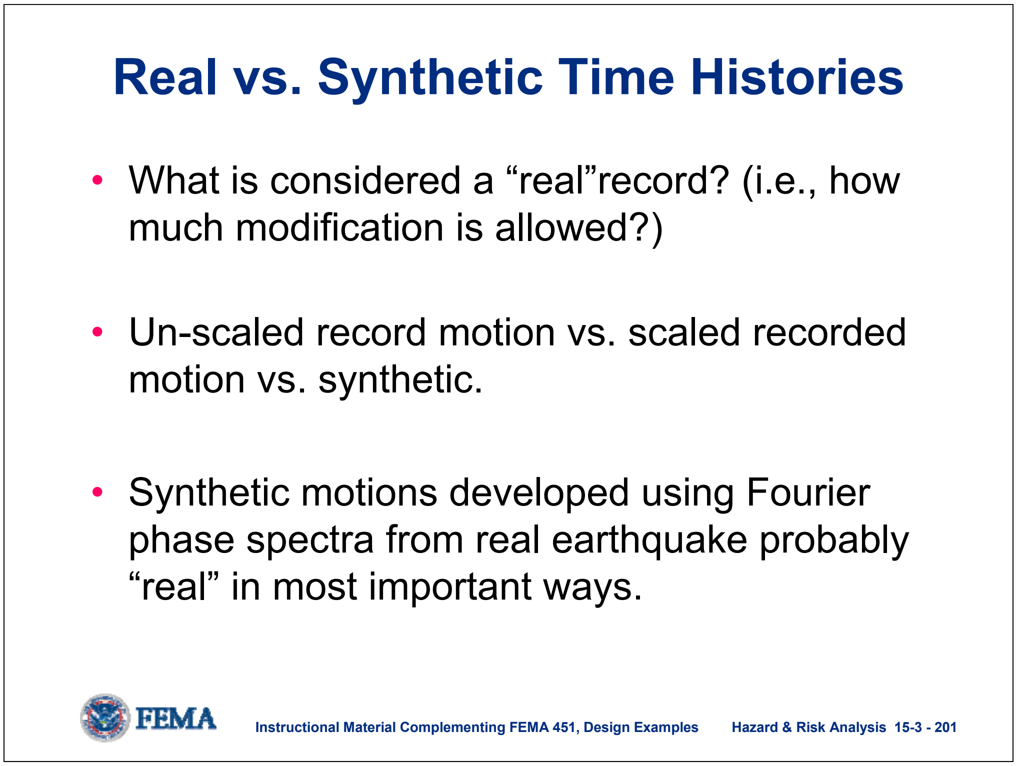
- Ensure records are instrument and base-line corrected, etc.

It is important to ensure that records are instrument- and base-line corrected, especially if displacements are to be calculated.

3. Modification for local site conditions

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

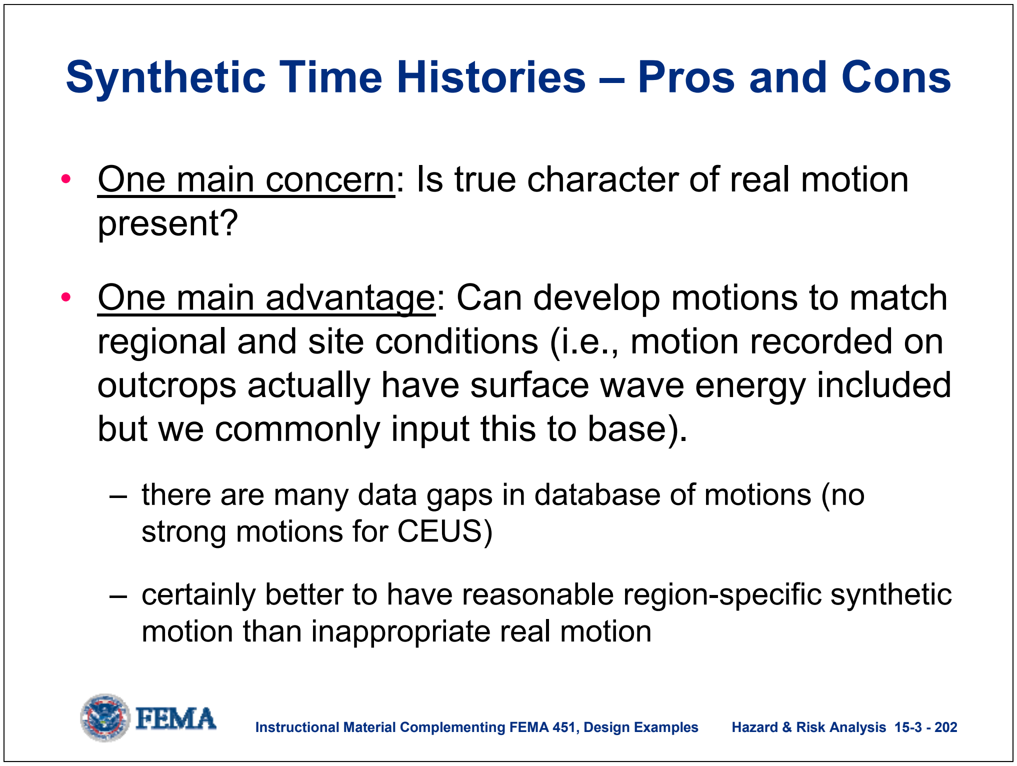
None.



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.

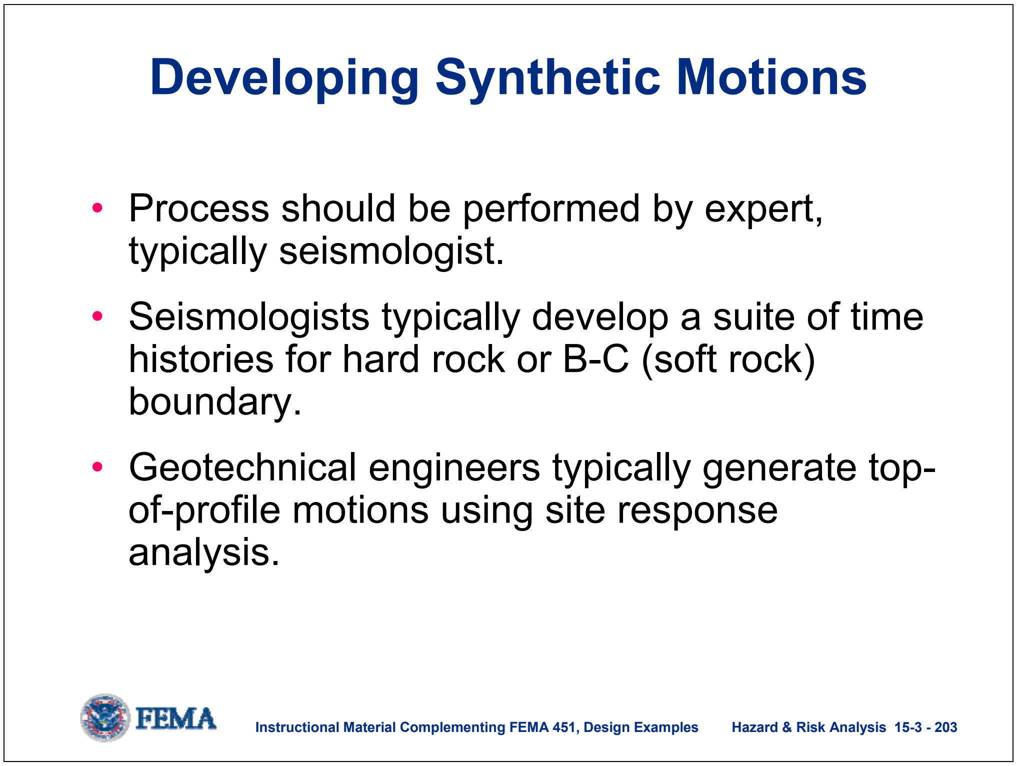
The distinction between real vs. synthetic motions is not always clear– that is, a scaled real motions may be less representative of a real earthquake motions than a carefully generated synthetic motions developed using Fourier phase spectra from a real earthquake.



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

None.



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.

Seismologists typically develop a suite of time histories for hard rock or B-C (soft rock) boundary and geotechnical engineers typically modify this motion based on the soil profile (less than 30 m typically).

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).

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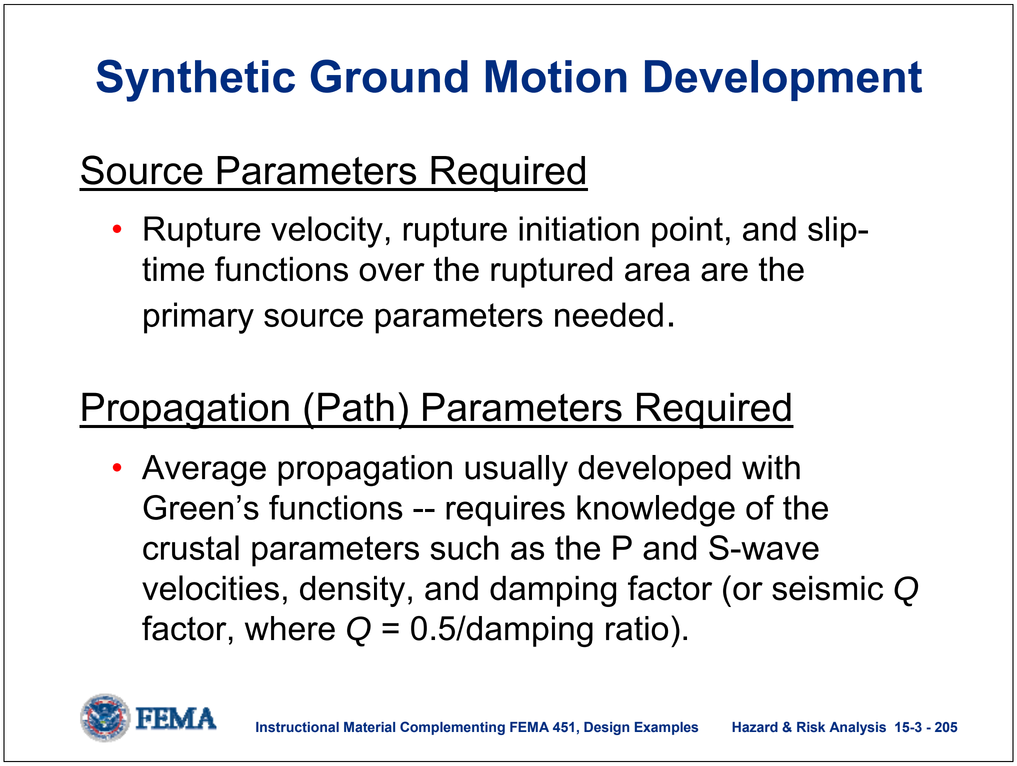
None.



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).

None.

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.

To model complexity of a seismogram, randomness (stochastic model) is often introduced, either in the source process or in the wave propagation. Usually, the high frequency motions (> 2 or 3 Hz) are modeled stochastically and the low frequency motions are modeled deterministically.

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.

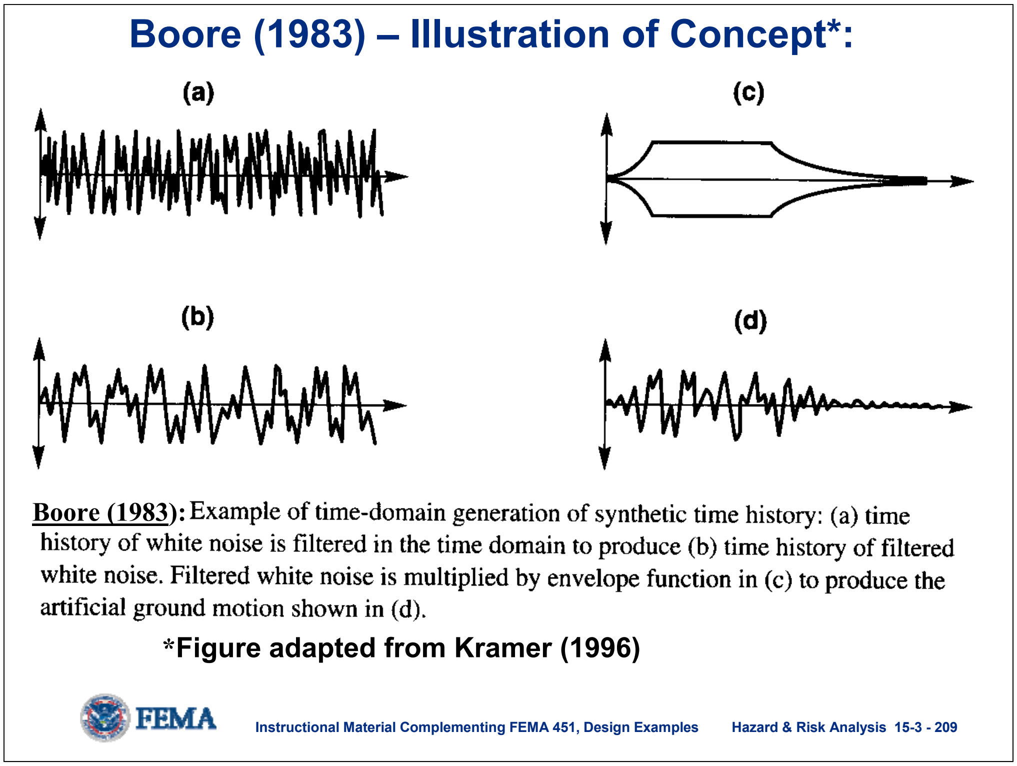
The Green's function that predicts the response at one point in the earth given an action at another point is one of the most important parameters in predicting ground motions. This function contains the effects of the "path" (i.e., geology between site and source).

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.

None.

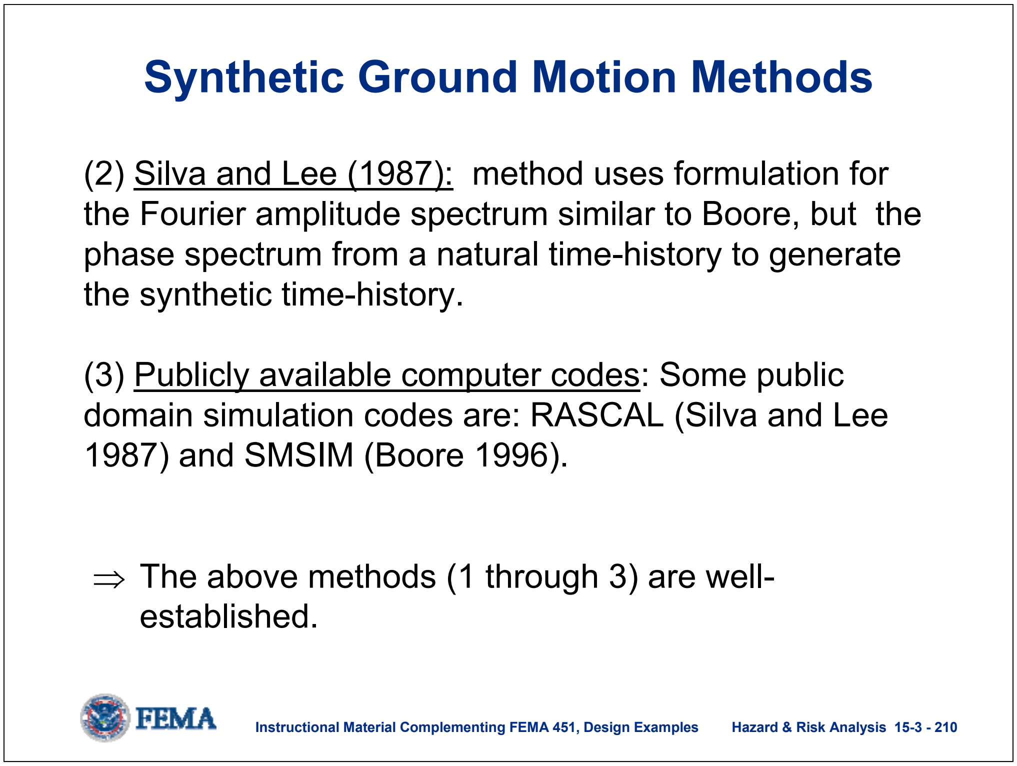


Boore (1983) – Illustration of Concept*:

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)**

Example of the time-domain generation of a synthetic time history. The slide depicts this four-step process.



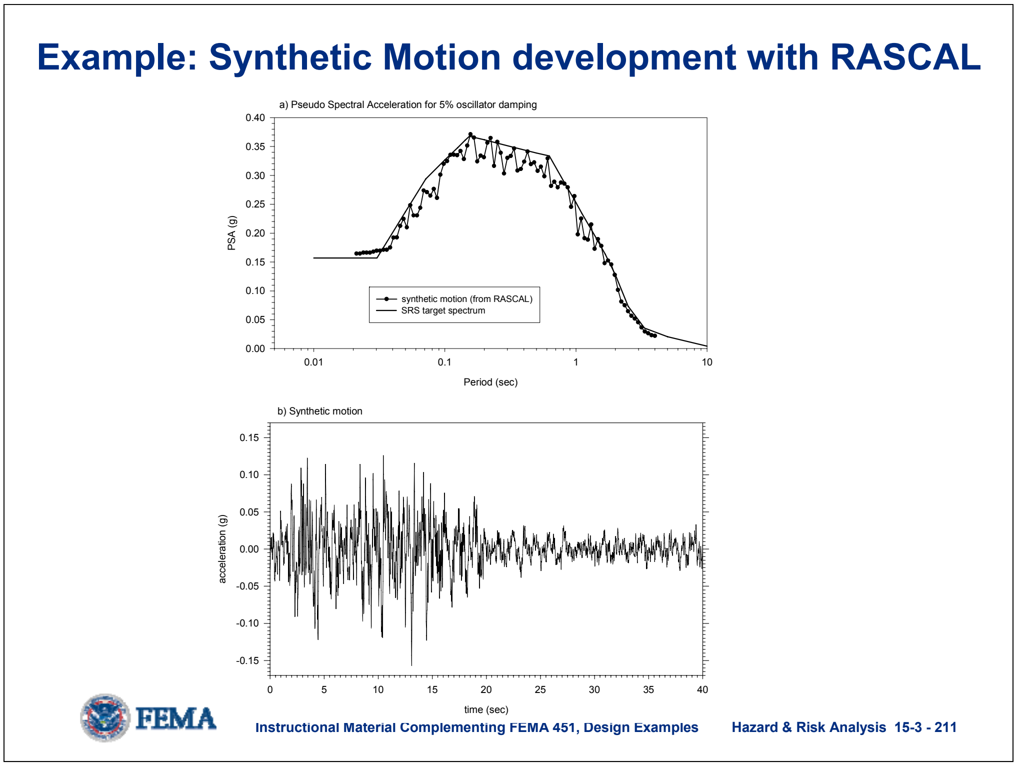
Synthetic Ground Motion Methods

(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.

An exampled using RASCAL will be presented in the following slides.



Example: Synthetic Motion development with RASCAL

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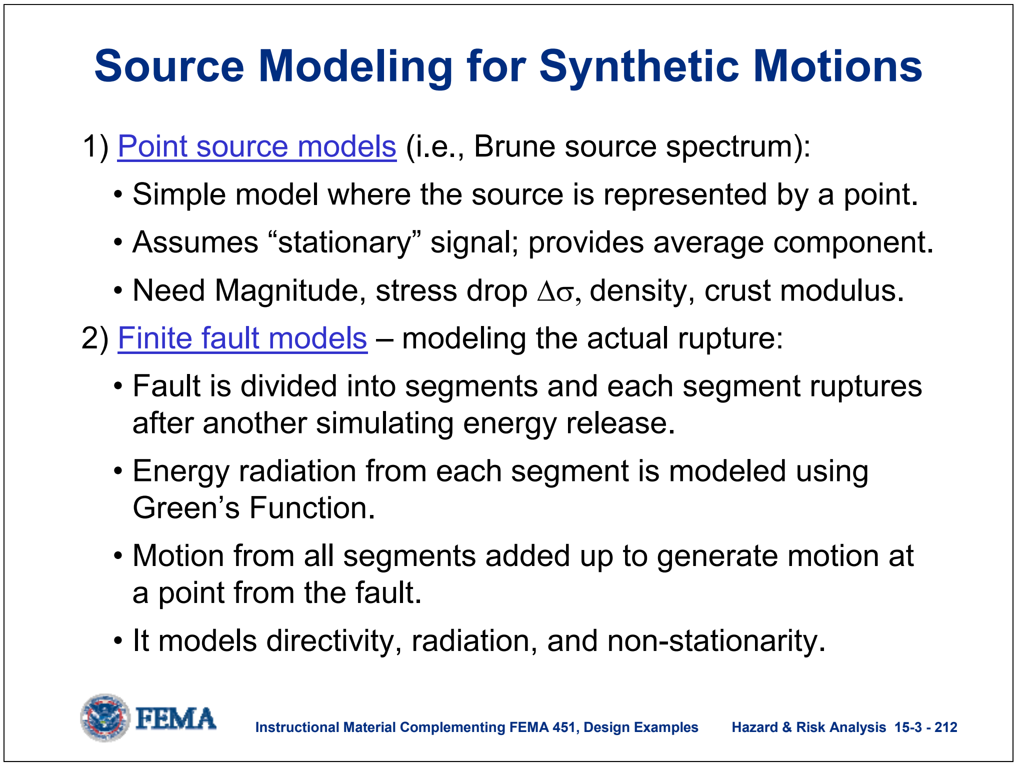
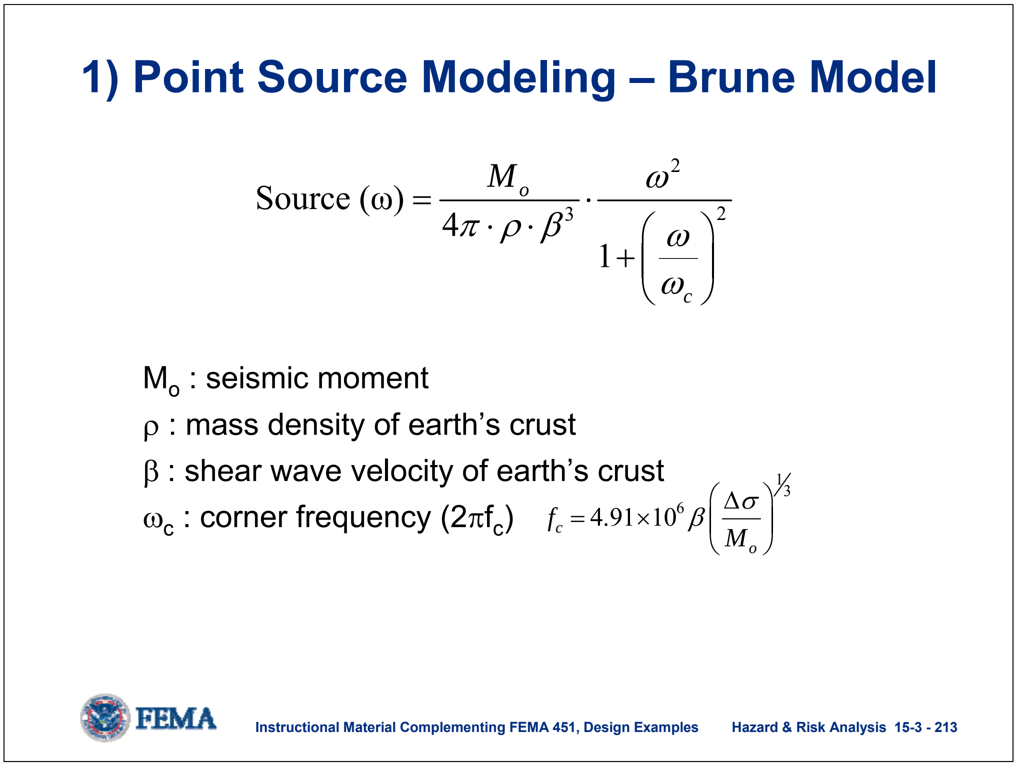
Example of synthetic motion development using RASCAL computer code. The RASCAL code is used to match "target" spectrum at many points. Again, depending upon the project, the closeness of the match is often specified. Nuclear power plant type projects typically require at least 95% of the points equal or exceed the target.



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.

Point source models are simpler to use and more common; finite fault models are for advanced analyses.



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 ($2\pi f_c$) $f_c = 4.91\times10^6 \beta \left(\frac{\Delta\sigma}{M_o}\right)^{1/3}$

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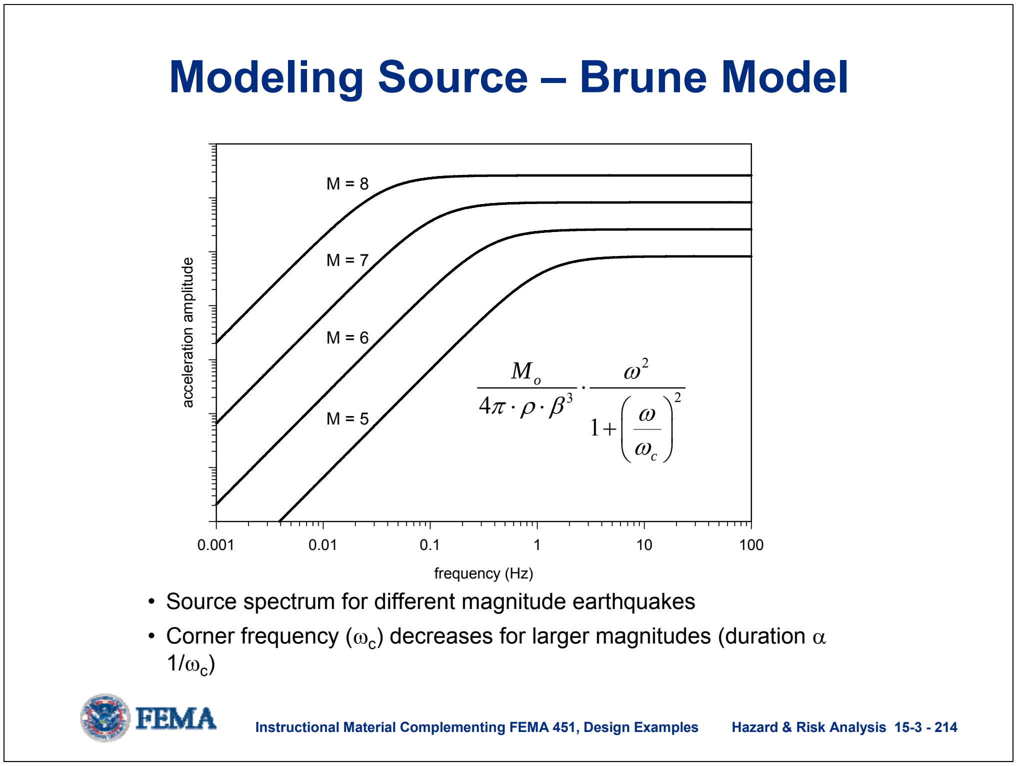
The above equation is used to calculate the displacement amplitude of the motion. This equation is used to develop the source spectrum and from there develop time histories. From: Brune, J., (1970). Tectonic stress and the spectra of seismic shear waves from earthquakes, *Journal of Geophysics Research*, Vol. 75, 4997-5009.

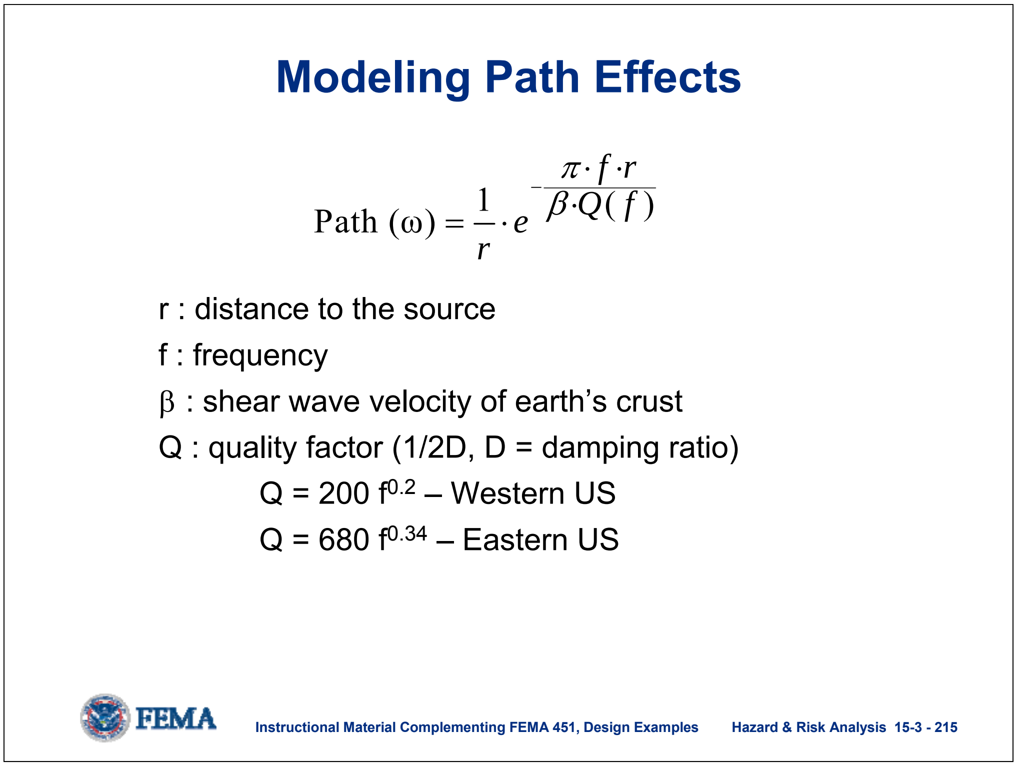


Modeling Source – Brune Model

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

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

The Brune model is a basic source modeling scheme commonly used for many applications. This assumes an ideal, symmetrical earthquake source per se, and is much simpler than finite fault modeling. The inaccuracy of this approach is minimized with distance from the source. From: Brune, J., (1970). Tectonic stress and the spectra of seismic shear waves from earthquakes, *Journal of Geophysics Research*, Vol. 75, 4997-5009.



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

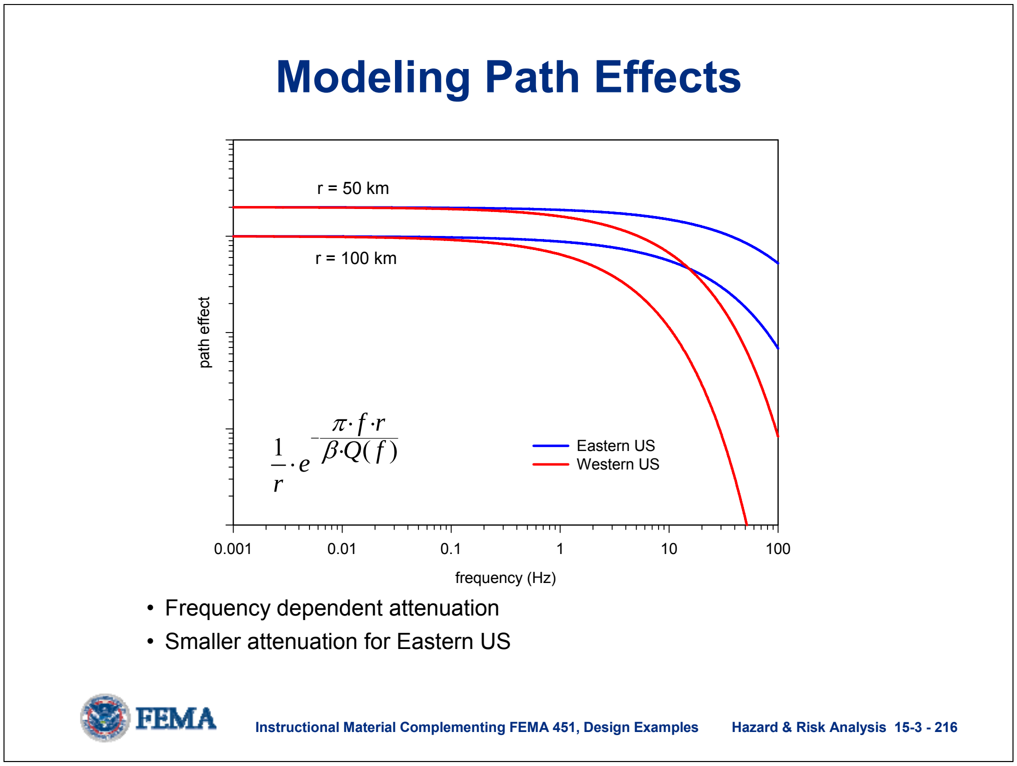
β : shear wave velocity of earth's crust

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

$Q = 200\ f^{0.2}$ – Western US

$Q = 680\ f^{0.34}$ – Eastern US

One the source spectrum is established, the motions are modified for attenuation through the earth's crust. The motions are attenuated as a function of frequency.



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

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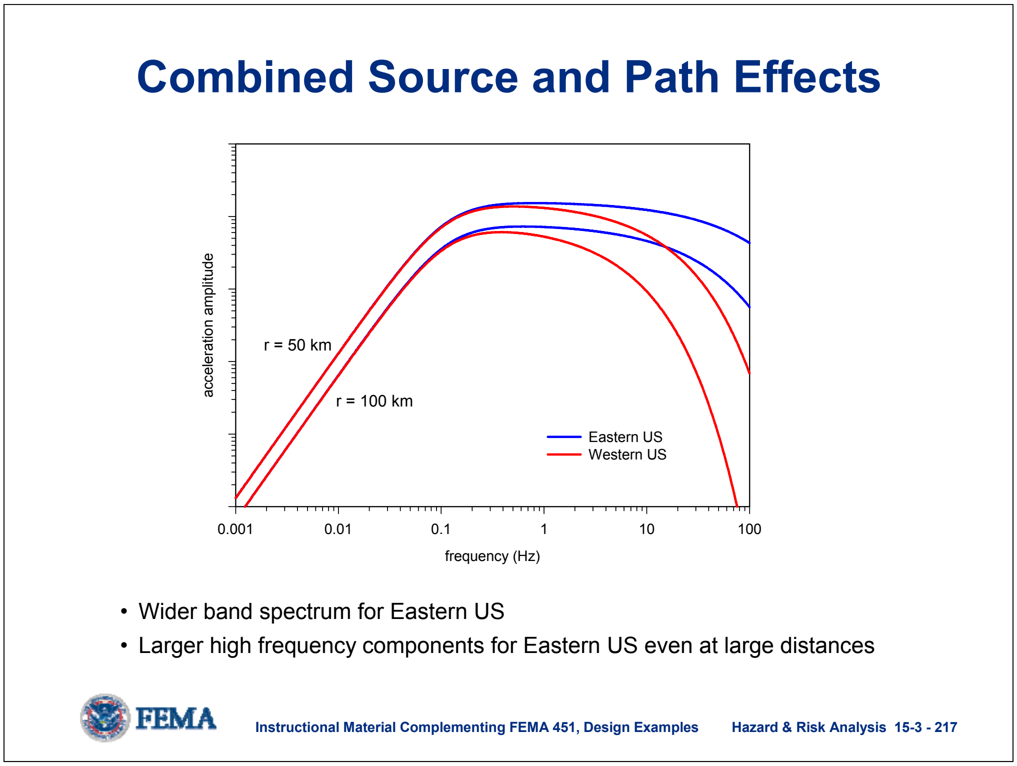
Effects of different crustal conditions (EUS vs. WUS.) and path effects. Use this spectrum to multiply the Brune source spectrum to establish the spectrum for a particular distance from the assumed point source. We can superimpose easily in the frequency domain and thus we multiply spectra together– more efficient and elegant that trying to do this in the time domain. Thus we combine all of the effects in the frequency domain to establish a final spectrum and from there we establish a time history to match the spectrum.



Combined Source and Path Effects

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

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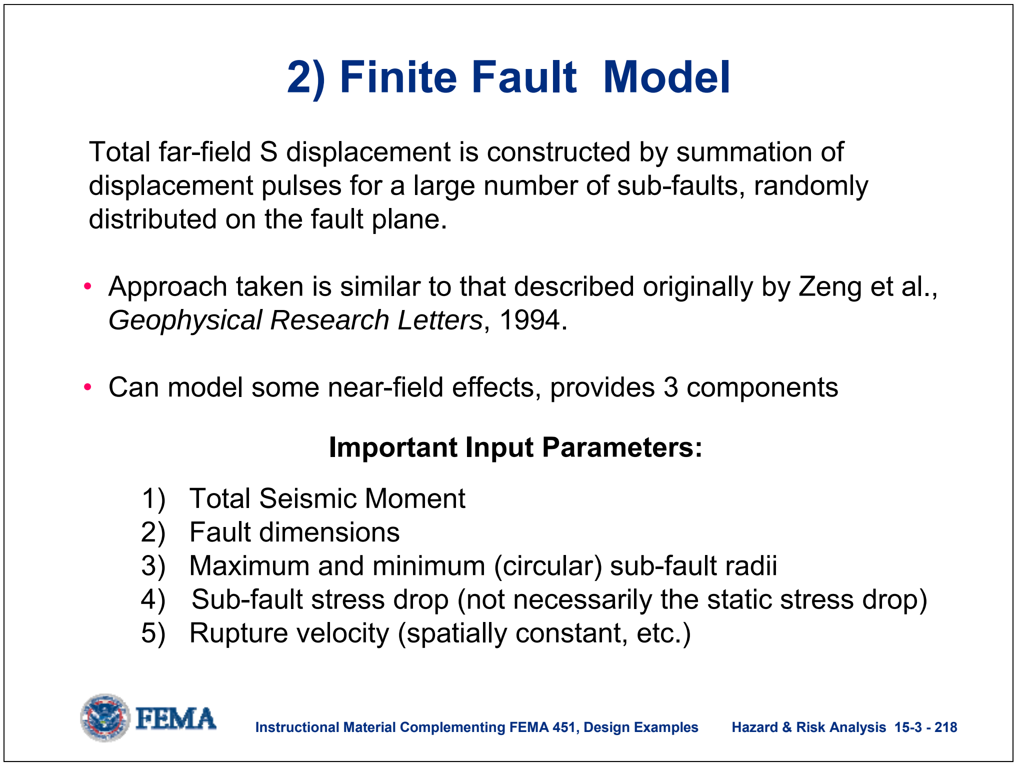
This spectrum represents the combined effect both the source and path effects. This spectrum is used as the “target” spectrum to generate the time histories for this particular location. If local site effects are to be included, then consider this using site response analysis. Note the higher motions in the high-frequency range in the EUS due to the higher Q factor (stiffer rock, lower anelastic attenuation).



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.)

FEMA

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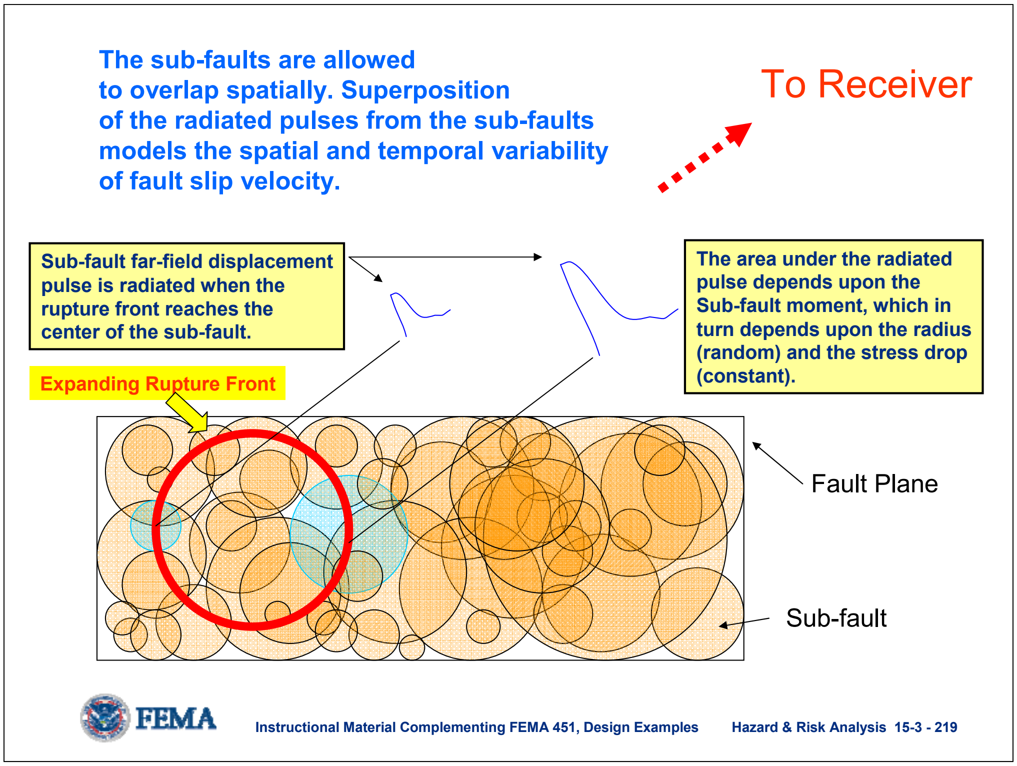
The finite fault model is an advanced modeling technique that should be used only for the case where a reasonable amount of information is known about the relevant fault mechanisms. Otherwise, the added sophistication is unwarranted.



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

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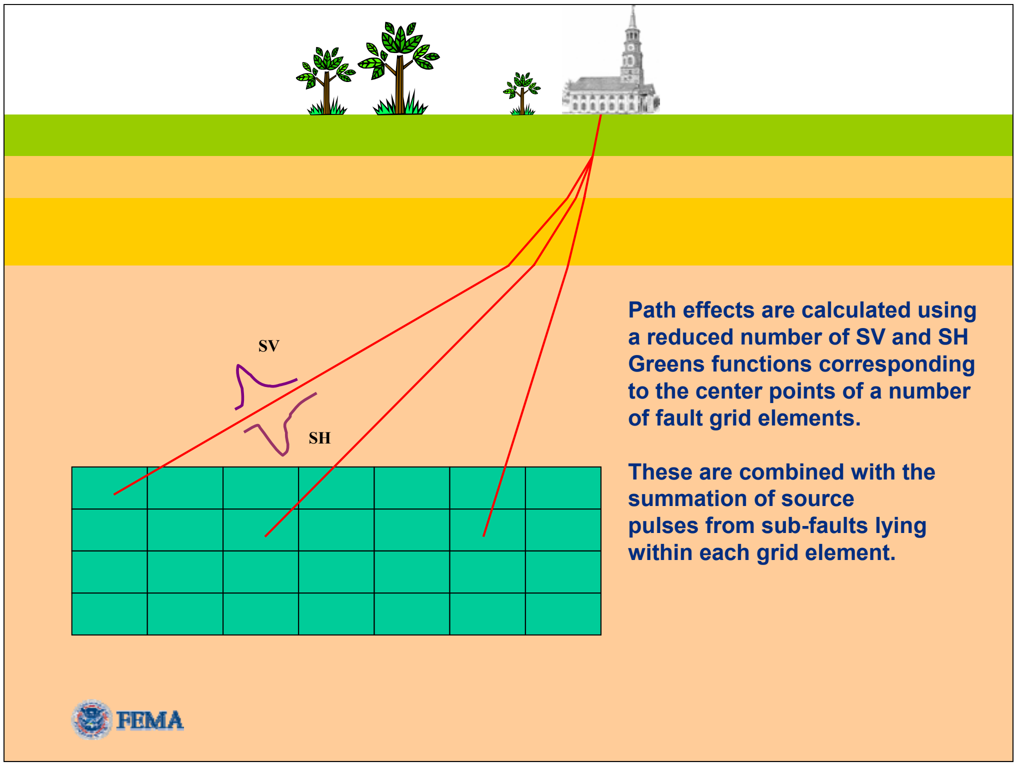
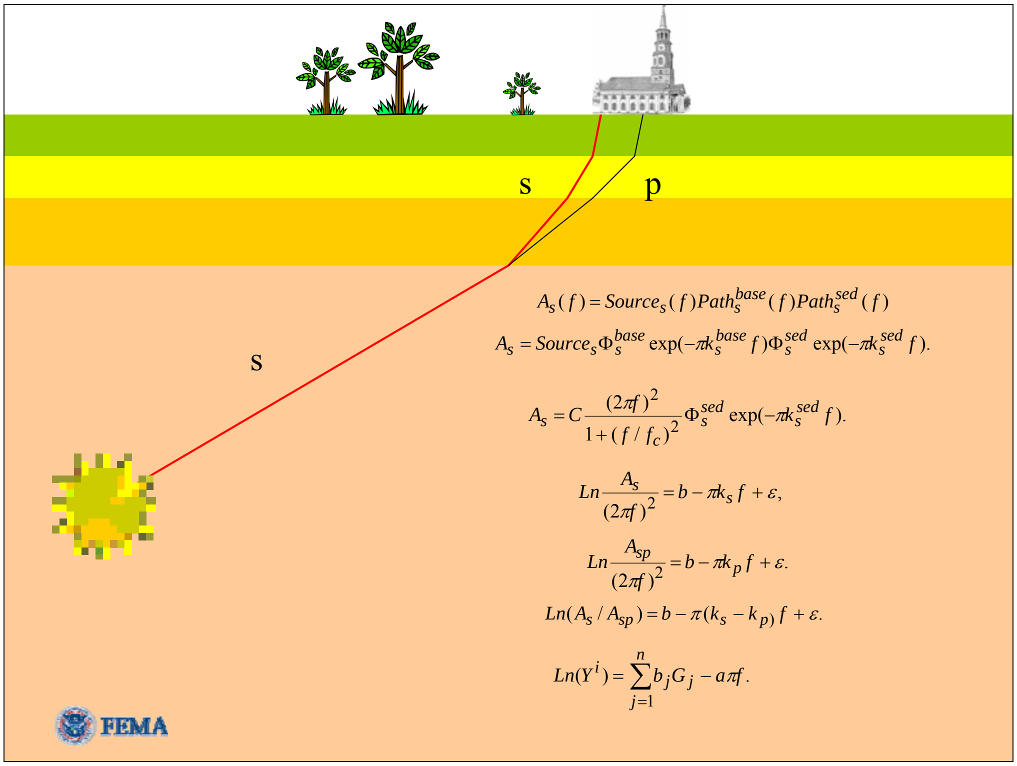
Figure above adapted from Martin Chapman, Virginia Tech department of Geological Sciences. The sub-faults are allowed to overlap spatially. Superposition of the radiated pulses from the sub-faults models the spatial and temporal variability of fault slip velocity.



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.

Figure above adapted from Martin Chapman, Virginia Tech department of Geological Sciences. A larger earthquake is quite simply the superposition of many small earthquakes and this approach is used for modeling. The earthquake 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.



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

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

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

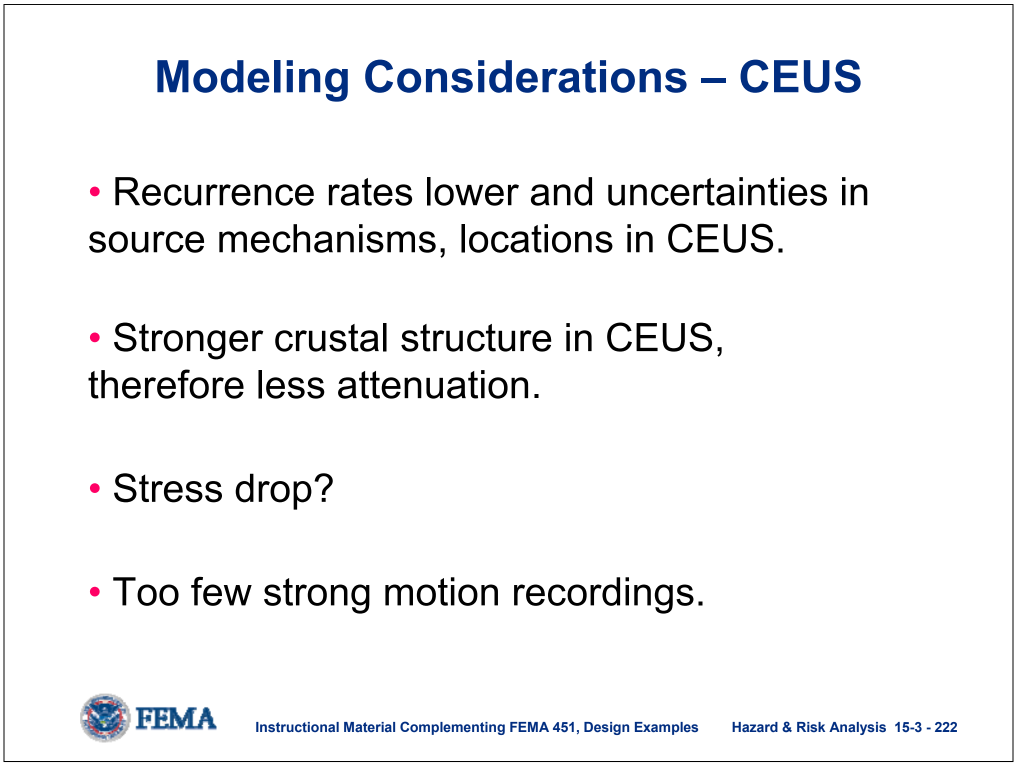
$$Ln \frac{A_s}{(2\pi f)^2} = b - \pi k_s f + \varepsilon,$$

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

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

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

Figure above adapted from Martin Chapman, Virginia Tech department of Geological Sciences. The Green’s function that predicts the response at one point in the earth given an action at another point is one of the most important parameters in predicting ground motions. This function contains the effects of the “path” (i.e., geology between site and source).



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.

Modeling in the CEUS faces a number of challenges, mostly related to a lack of seismological data. A number of good references are available on this specialized area of engineering seismology such as: Boore, D. M., Joyner, W. B., and Fumal, T. E. 1997. “Equations for Estimating Horizontal Response Spectra and Peak Acceleration from Western North American Earthquakes: A Summary of Recent Work,” *Seismological Research Letters,* Vol 68, No. 1, pp 128-153.