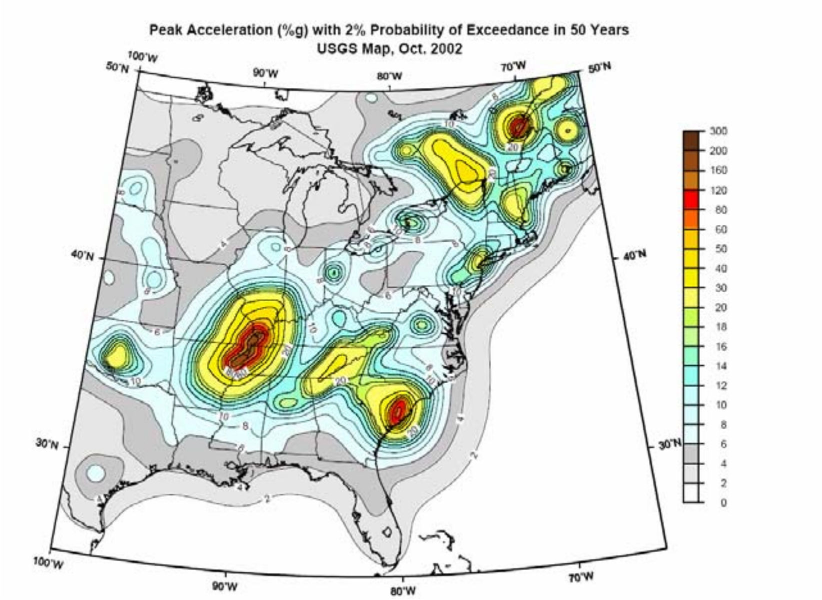
## SEISMIC HAZARD ANALYSIS

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This topic addresses deterministic and probabilistic seismic hazard analysis, ground motion attenuation relationships, the U.S. Geological Survey (USGS) seismic hazard maps, the *NEHRP Recommended Provisions* seismic design maps, site effects, directionality effects, and the *NEHRP Recommended Provisions* response spectrum.

# Seismic Hazard Analysis

- Deterministic procedures
- Probabilistic procedures
- USGS hazard maps
- 2003 *NEHRP Provisions* design maps
- Site amplification
- *NEHRP Provisions* response spectrum
- UBC response spectrum

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Before pursuing this topic, study the topics that address earthquake mechanics and effects and the dynamics of single-degree-of-freedom systems. Note that the principal references for the topic are Reiter (1990) and Kramer (1996).

Although this topic is lengthy (and might not be of great interest to structural engineers), it is necessary to proceed through the material to learn where the USGS seismic hazard maps come from because the *NEHRP Recommended Provisions* maps use the USGS maps as a “starting point.”

I

## Hazard vs Risk

*Seismic hazard analysis*
describes the potential for dangerous, earthquake-related natural phenomena such as ground shaking, fault rupture, or soil liquefaction.

*Seismic risk analysis*
assesses the probability of occurrence of losses (human, social, economic) associated with the seismic hazards.

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The purpose of this slide is to clarify the differences between the terms "hazard" and "risk." The terms are often used interchangeably, and should not be. In this topic we address the hazard and do not talk about risk (except in the most general sense).

For example, a *hazard* associated with earthquakes is ground shaking. The *risk* is structural collapse and, possibly, loss of life.

## Approaches to Seismic Hazard Analysis

**Deterministic**
"The earthquake hazard for the site is a peak ground acceleration of 0.35g resulting from an earthquake of magnitude 6.0 on the Balcones Fault at a distance of 12 miles from the site. "

**Probabilistic**
"The earthquake hazard for the site is a peak ground acceleration of 0.28g with a 2 percent probability of being exceeded in a 50-year period."

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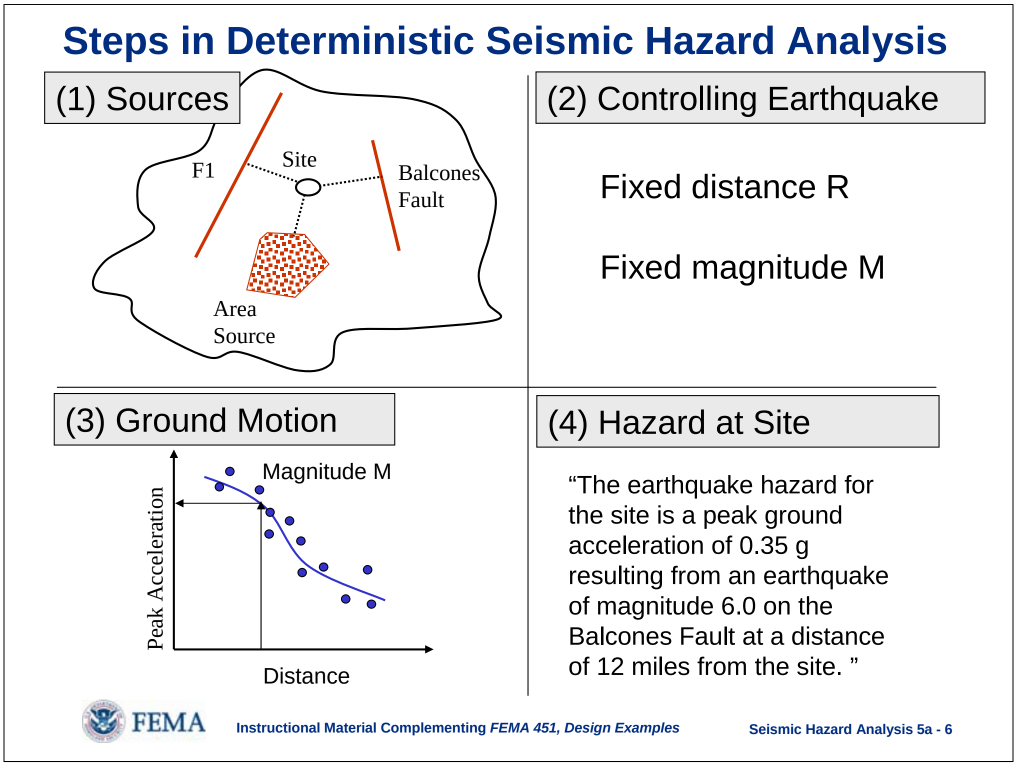
There are two basic approaches to seismic hazard analysis. Both use the same basic body of information to determine what the "design earthquake" should be. The main difference is that the probabilistic approach systematically examines the uncertainties and includes the likelihood of an actual earthquake exceeding the design ground motion. All of the elements of a deterministic analysis are included in the probabilistic approach.

## Probabilistic Seismic Hazard Analysis

First addressed in 1968 by C. Allin Cornell in "Engineering Seismic Risk Analysis," and article in the *Bulletin of the Seismological Society* (Vol. 58, No. 5, October).

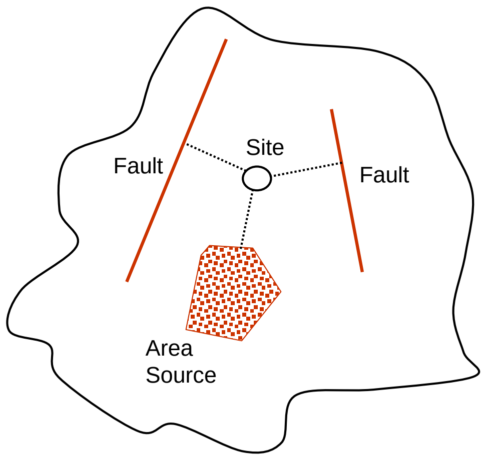


This is the reference that first described probabilistic seismic hazard analysis. It is not easy reading, particularly if one is not familiar with engineering probability. Cornell still teaches at Stanford.




These are the basic steps in the deterministic analysis. The first step is to identify all the possible sources of ground motion. Some of these will be easy to identify (e.g., a known active fault); others may be more difficult to describe. Next, the controlling earthquake needs to be defined and this involves engineering judgment. Do you want to design for the largest earthquake that could ever occur at the site (using perhaps an estimate of seismic moment) or only the largest motion that has occurred, say, within the past 200 years. Note that nothing is being said about probability of occurrence. As the known earthquakes will have occurred at a distance that is not likely to be the same as the distance to the site, some correction needs to be made. This is done through the use of attenuation relationships that have been established. In deterministic analysis, it is traditional to use the closest distance from a source to a site. It is very important to use attenuation relationships that are characteristic to the local geology. The resulting hazard statement is basically a scenario.

# Source Types




- Fault
- Localizing structure
- Seismotectonic province



This slide introduces the source types. Faults were already been discussed in the topic on earthquake mechanics and effects. The other two source types are defined on the next slide.

## Source Types

***Localizing structure***: An identifiable geological structure that is assumed to generate or “localize” earthquakes. This is generally a concentration of known or unknown active faults.

***Seismotectonic province****:* A region where there is a known seismic hazard but where there are no identifiable active faults or localizing structures.

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Definitions of the more vague source types. The blind thrust Northridge earthquake might be classified as being originated in a localizing structure. It is known from deep drilling that a network of such faults exists in the Los Angeles area. The New Madrid seismic zone may be classified as a seismotectonic province – that is, we know that earthquakes have occurred there, but we are still unsure as to the source. While it may be relatively easy to establish magnitudes from known faults, the process is somewhat less exact when localizing structures and seismotectonic provinces are involved. This is particularly true when major earthquakes are infrequent and where there is not a strong instrument database.

## Maximum Earthquake

**Maximum possible earthquake:** An upper bound to size (however unlikely) determined by earthquake processes (e.g., maximum seismic moment).

**Maximum credible earthquake:** The maximum reasonable earthquake size based on earthquake processes (but does not imply likely occurrence).

**Maximum historic earthquake:** The maximum historic or instrumented earthquake that is often a lower bound on maximum possible or maximum credible earthquake.

**Maximum considered earthquake:** Described later.

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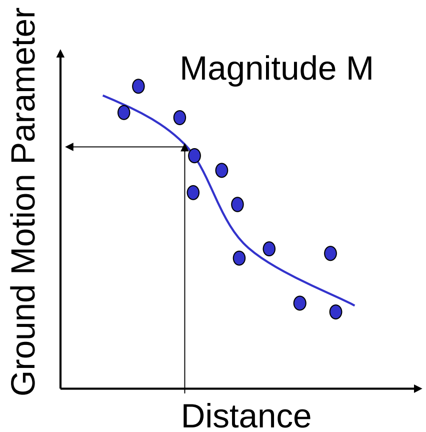
In order to establish the magnitude of the controlling earthquake, one needs to make a decision regarding the *maximum earthquake*. Listed here are a few possible choices in order of decreasing possible magnitude.

The "maximum considered earthquake" (shown in gray) is used in the *NEHRP Recommended Provisions* and will be described in more detail later in the topic. The maximum considered earthquake is more of a philosophy that it is a specific ground motion.

## Ground Motion Attenuation




Reasons:

- Geometric spreading
- Absorption (damping)

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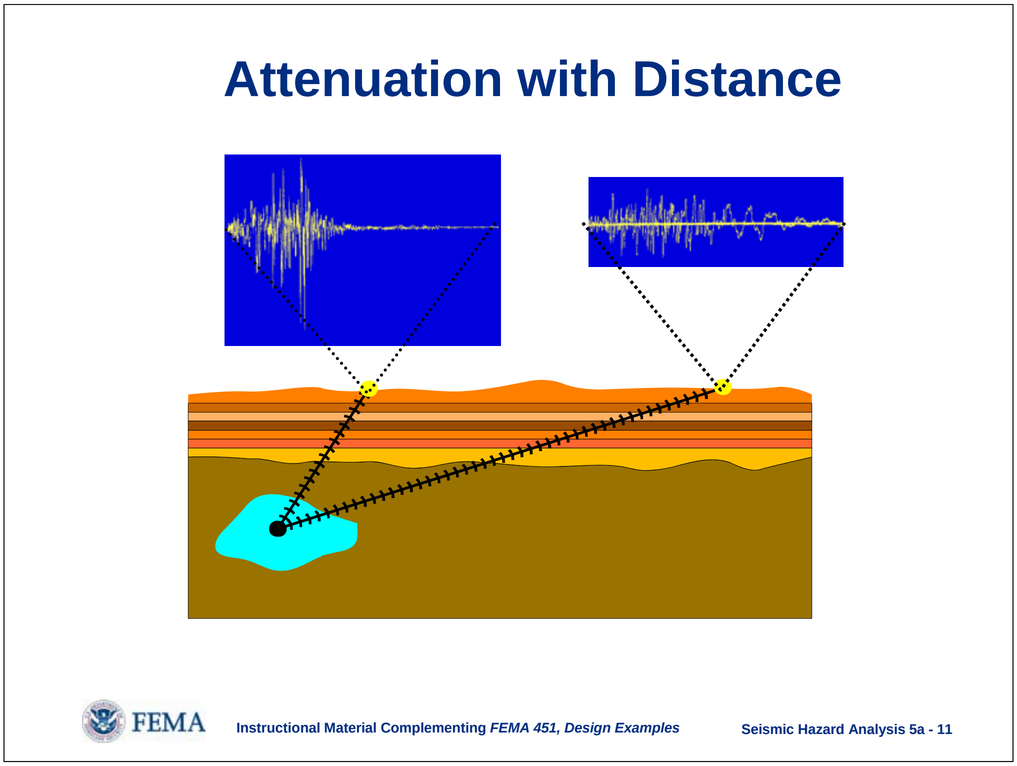
Attenuation has been described previously.  In both deterministic and probabilistic seismic hazard analysis (SHA), empirical attenuation relationships are utilized.  The seismologist must be careful to use attenuation relationships that are characteristic of the site.  The ground motion parameter may be anything that characterizes the shaking;  peak ground acceleration, spectral acceleration (at a specific period), and so on.



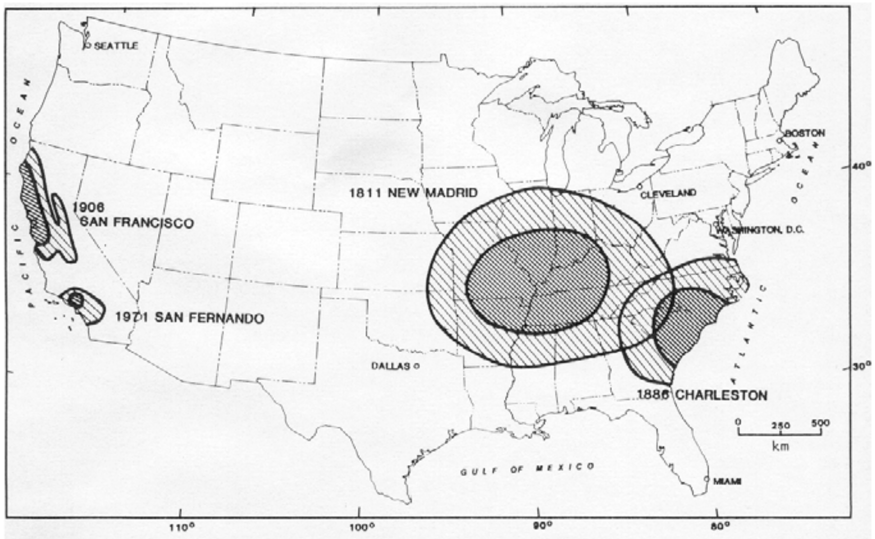

Note the difference between site amplification and attenuation. These are quite different phenomena.

The following two paragraphs are a paraphrase from Kramer (1996):

Seismic wave attenuation can be considered of two major elements -- geometric spreading and absorption (damping). Geometric spreading results from conservation of energy as waves and wave fronts occupy more area as they spread from the seismic source. (Without absorption, waves would still attenuate.)

Absorption is controlled by loss mechanisms such as friction across cracks, internal friction, and inhomogeneities along the travel path.

## Comparison of Attenuation for Four Earthquakes

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This map shows isoseismal maps for several (nonconcurrent) earthquakes. The minimum modified Mercalli intensity (MMI) value shown on the maps is approximately VI (boundaries of felt regions would be significantly greater). The extent of the isoseismal boundary VI is much greater in the eastern United States than in the western states. This is because the crustal region of the western United States, being located near a plate boundary, is much more internally fractured and is less homogenous than the relatively less fractured eastern United States. A good analogy is a bell. An uncracked bell will ring much more clearly and loudly than a cracked one.

## Ground Motion Attenuation
## Steps to Obtain Empirical Relationship

1. Obtain catalog of appropriate ground motion records
2. Correct for aftershocks, foreshocks
3. Correct for consistent magnitude measure
4. Fit data to empirical relationship of type:

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

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This is the basic form of an attenuation relationship. The equation is the result of a regression analysis of several variables, as shown. Y overline is some parameter, such as peak ground acceleration, spectral acceleration, or some other entity.

# 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 |
| $\varepsilon$ | Error term |

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More detail on the “ingredients” in the regression analysis.

## Ground Motion Attenuation Relationships for Different Conditions

- Central and eastern United States
- Subduction zone earthquakes
- Shallow crustal earthquakes
- Near-source attenuation
- Extensional tectonic regions
- Many others

May be developed for any desired quantity (PGA, PGV, spectral response).

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When performing a seismic hazard analysis, it is very important to use attenuation relationships that have been derived for the region of interest. It would be totally inappropriate to use a shallow crustal relationship (San Andreas) in a subduction zone (Alaska).

## Ground Motion Attenuation Relationships

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

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This is a edition of the *Seismological Research Letters* that contains write-ups and coefficients for a variety of attenuation relationships. (Note that a membership in the Seismological Society of America can be had for an additional $50 over the cost of an EERI membership. The main benefit to the membership in SSA is a subscription to *Letters*.)

Note that "new generation attenuations" (NGAs) have been developed over the past year (or two) at the PEER center. The NGAs will be the predominant relations used for the next issue of the USGS hazard maps, at least for the regions where they apply.

## Earthquake Catalog for Shallow Crustal Earthquakes

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

TABLE 1
List of Earthquakes Used to Develop Attenuation Relationships

| Earthquake | Date | M | Fault Type[1] | Distance Range (km) | No. of Records[2] R | No. of Records[2] DS |
|---|---|---|---|---|---|---|
| Kern County,CA | 1952/07/21 | 7.4 | RV | 120.5–224.0 | 0 | 3 |
| Port Hueneme, CA | 1957/03/18 | 4.7 | RV | 14.1–14.1 | 0 | 1 |
| Daly City, CA | 1957/03/22 | 5.3 | RV | 9.5–9.5 | 1 | 0 |
| Parkfield, CA | 1966/06/27 | 6.1 | SS | 0.1–230.0 | 1 | 6 |
| Borrego Mtn., CA | 1968/04/09 | 6.6 | SS | 113.0–261.0 | 5 | 3 |
| Santa Rosa, CA (A) | 1969/10/02 | 5.6 | SS | 80.0–113.0 | 1 | 2 |
| Santa Rosa, CA (B) | 1969/10/02 | 5.7 | SS | 78.9–112.0 | 1 | 2 |
| Lytle Creek, CA | 1970/09/12 | 5.3 | RV | 19.7–76.0 | 5 | 2 |
| San Fernando, CA | 1971/02/09 | 6.6 | RV | 2.8–305.0 | 11 | 14 |
| Lake Isabella, CA | 1971/03/08 | 4.1 | SS | 8.9–8.9 | 1 | 0 |
| Bear Valley, CA | 1972/02/24 | 4.7 | SS | 2.5–2.5 | 1 | 0 |
| Point Mugu, CA | 1973/02/21 | 5.6 | RV | 25.0–25.0 | 0 | 1 |
| Hollister, CA | 1974/11/28 | 5.2 | SS | 39.0–39.0 | 1 | 0 |
| Oroville, CA | 1975/08/01 | 5.9 | SS | 9.5–35.8 | 2 | 2 |
| Oroville, CA (R) | 1975/08/02 | 5.1 | SS | 12.7–14.6 | 0 | 2 |
| Oroville, CA (S) | 1975/08/02 | 5.2 | SS | 12.4–15.0 | 0 | 2 |
| Oroville, CA (A) | 1975/08/03 | 4.6 | SS | 8.4–14.9 | 1 | 6 |

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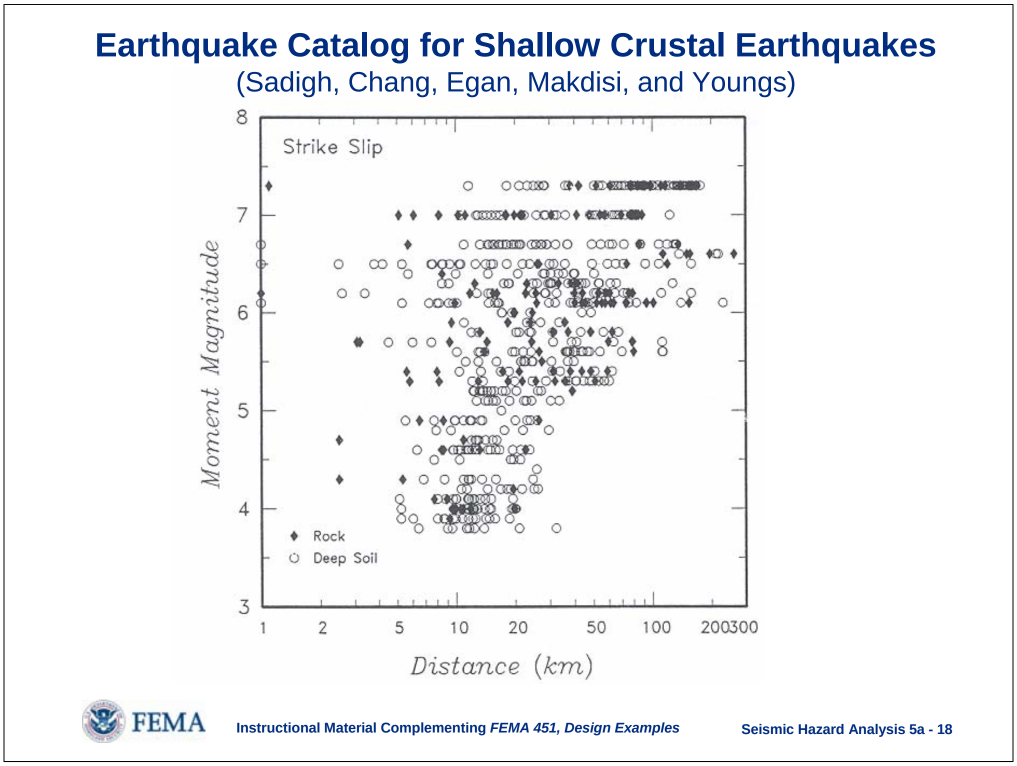
This is partial listing of the earthquake catalog used to determine the attenuation relationships for shallow crustal earthquakes.

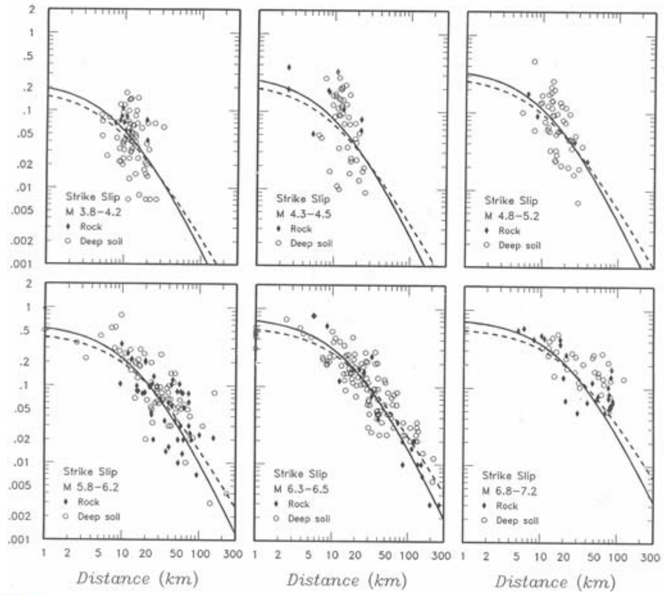
Note the range in magnitudes (recall differences in energy release), different types of fault, and distance to epicenter. In some cases, several records from the same earthquake were used.




This is a plot of moment magnitude vs distance for all earthquakes in the catalog.  There does not seem to be a strong trend (looks like a shotgun blast).

## Attenuation Relation for Shallow Crustal Earthquakes

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

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When the catalog is separated into magnitude ranges and when a plot is created of a ground motion parameter (PGA here) vs distance for each magnitude range, patterns begin to emerge. The regression analysis produces the lines shown on the plots. The lines then form the empirical attenuation relationship used in the SHA.

Note that as one gets to higher magnitudes (lower series of plots), there seems to be a clearer trend in the data.

It is important to emphasize the tremendous scatter in the data. For example, in the vicinity of 20 km, the difference between the high and low values is about one order of magnitude. This aspect of deterministic analysis doesn’t get enough discussion – even if we know the magnitude and location of an earthquake, we are in the dark as to the amplitude of the ground motion.

## Attenuation Relation for Shallow Crustal Earthquakes

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

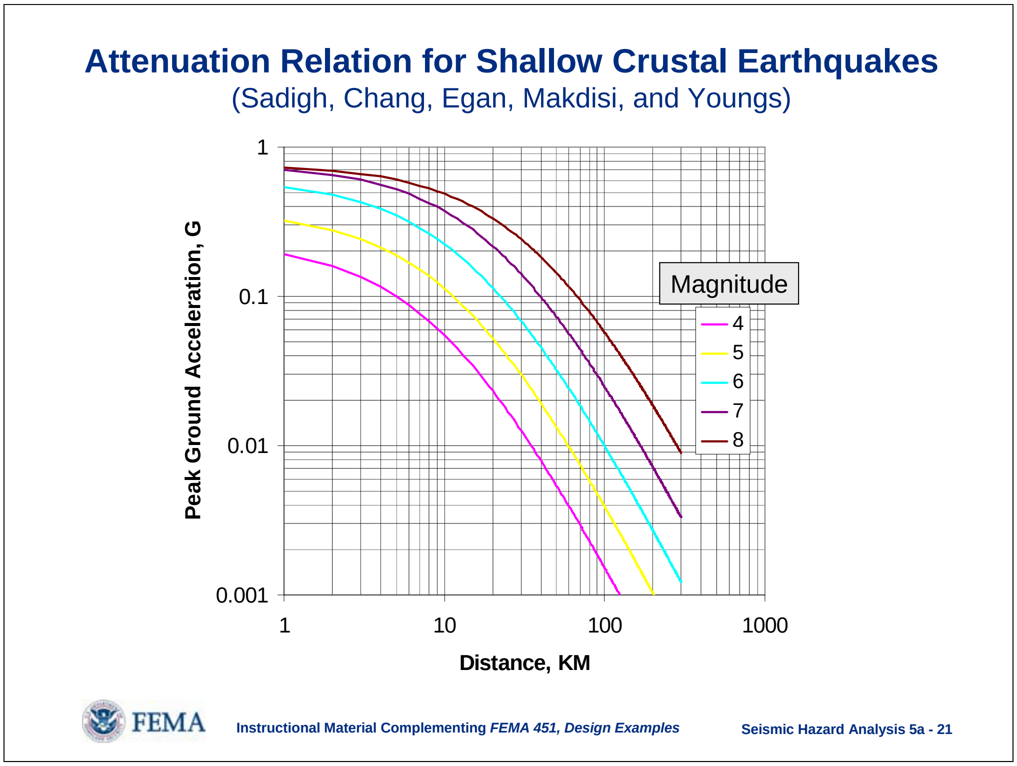
$$\ln(y) = C_1 + C_2 M + C_3(8.5 - M) + C_4 \ln(r_{rup} + \exp(C_5 + C_6 M)) + C_7(r_{rup} + 2)$$

| 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 |

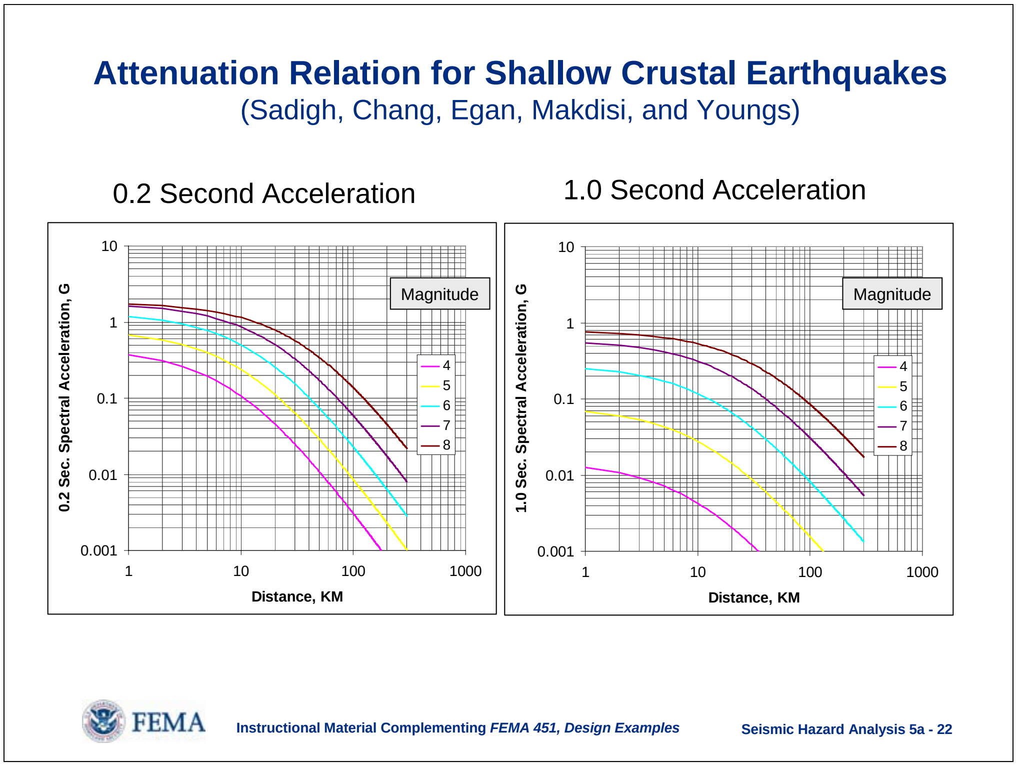
Table for Magnitude <= 6.5



Once the regression analysis has been performed, the empirical attenuation relationship is obtained from the published coefficients. Note that (aside from the *C* coefficients), the data plugged into the equation are magnitude and distance. Hence, a single curve is obtained for a given magnitude.

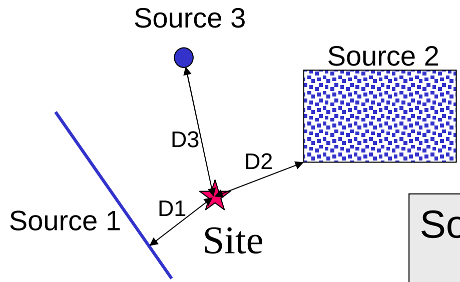



These curves were created in Excel by plotting the data on the previous page for a range of magnitudes. In this case, the parameter being determined at a given distance and magnitude is PGA.




These curves are similar to those in the previous slide except that the items of interest are the 0.2 second and 1.0 second spectral acceleration.

## Example Deterministic Analysis (Kramer)




| 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 (M)
Closest distance (D)
From attenuation relationship (PGA)

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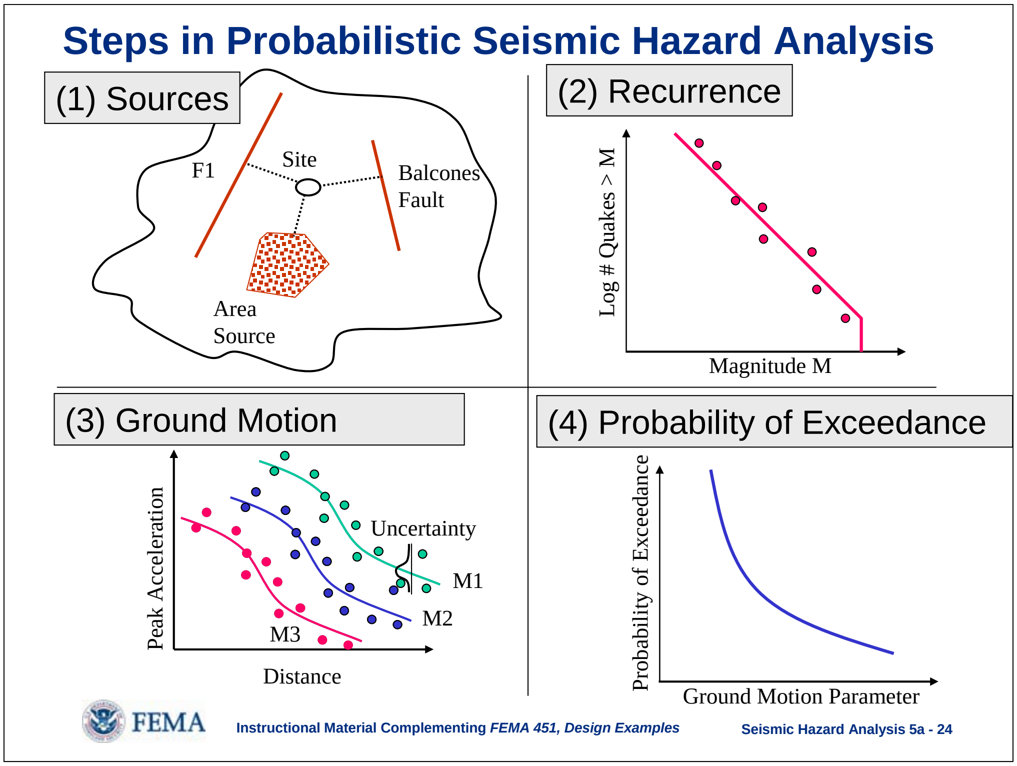
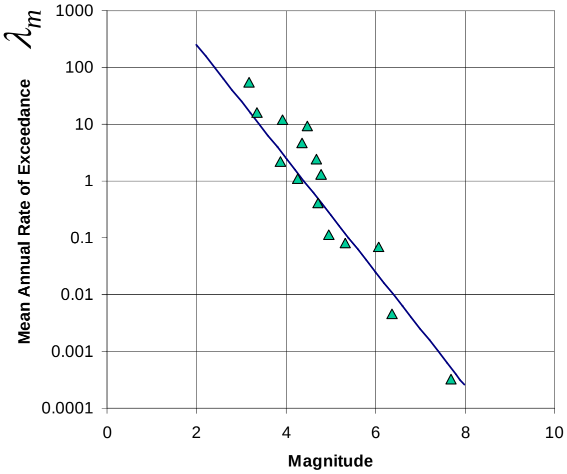
This is a very simple example of a deterministic SHA. Three sources were considered. In each case, the closest distance to the site was used. Note the different magnitudes for the different sources. These will be consistent with the selected "maximum earthquake." The PGA at the site was obtained from an appropriate attenuation relationship. The motion with the greatest resulting PGA is chosen as the controlling earthquake. Note that this is NOT ENOUGH to establish risk because the effect of the motion on the structure under consideration is not addressed. It could be that the more distant earthquake with its lower effective PGA produces waves at a frequency that is more in sync with the structure.




In a probabilistic analysis, the recurrence relationship (e.g., frequency of earthquakes above a certain magnitude) is introduced as is the uncertainty in each step of the process. Each of the uncertainties are included in a probabilistic analysis, and the result is a seismic hazard curve that relates the design motion parameter to the probability of exceedance. Hence, if a designer wished to design a dam for the ground motion that had only a 2% probability of being exceeded in a 50 year period, the ground motion parameter (e.g., PGA) would be taken from the seismic hazard curve.

## Empirical Gutenberg-Richter Recurrence Relationship




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

$\lambda_m$ = mean rate of recurrence (events/year)

$1/\lambda_m$ = return period

$a$ and $b$ to be determined from data

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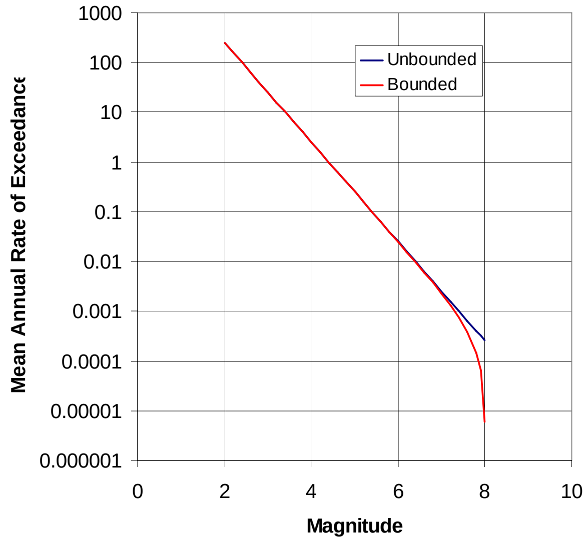
The relationship between magnitude and likelihood of occurrence is called a "recurrence relationship." The relationships are determined for regression analysis of historic ground motions.

In the original Gutenberg Richter relation, the vertical axis was the number of occurrences per unit of time per unit of area. The linear relation (log scale) works well for large areas but it does not necessarily work so well for small areas or single sources.

# Bounded vs Unbounded Recurrence Relationship

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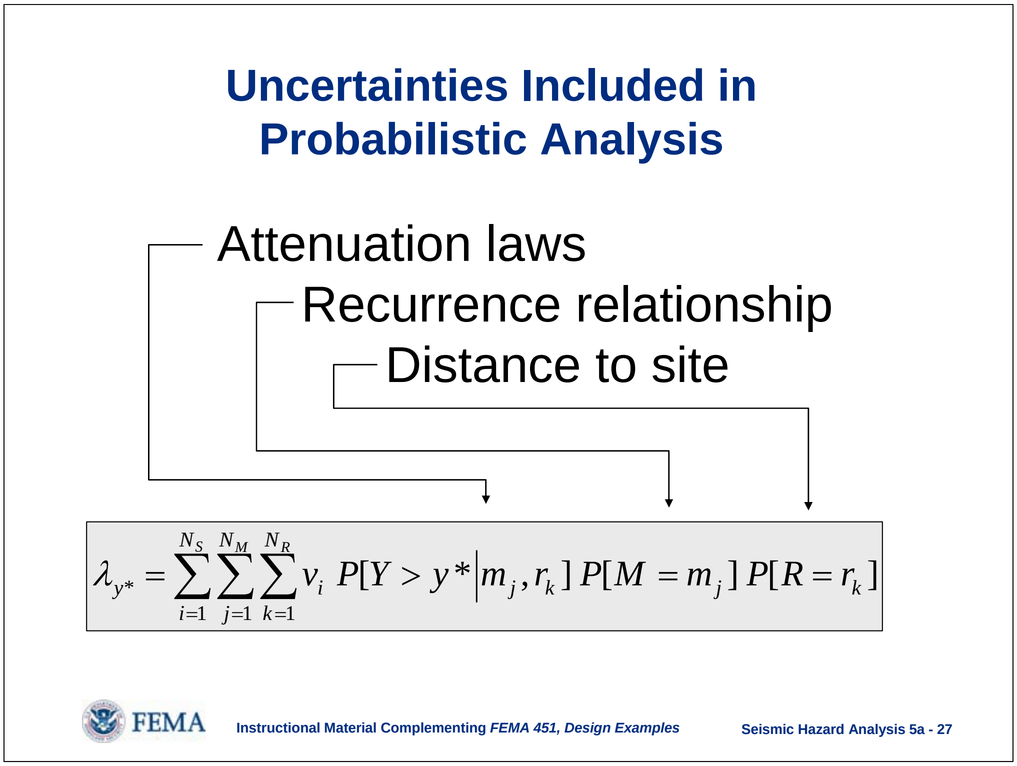
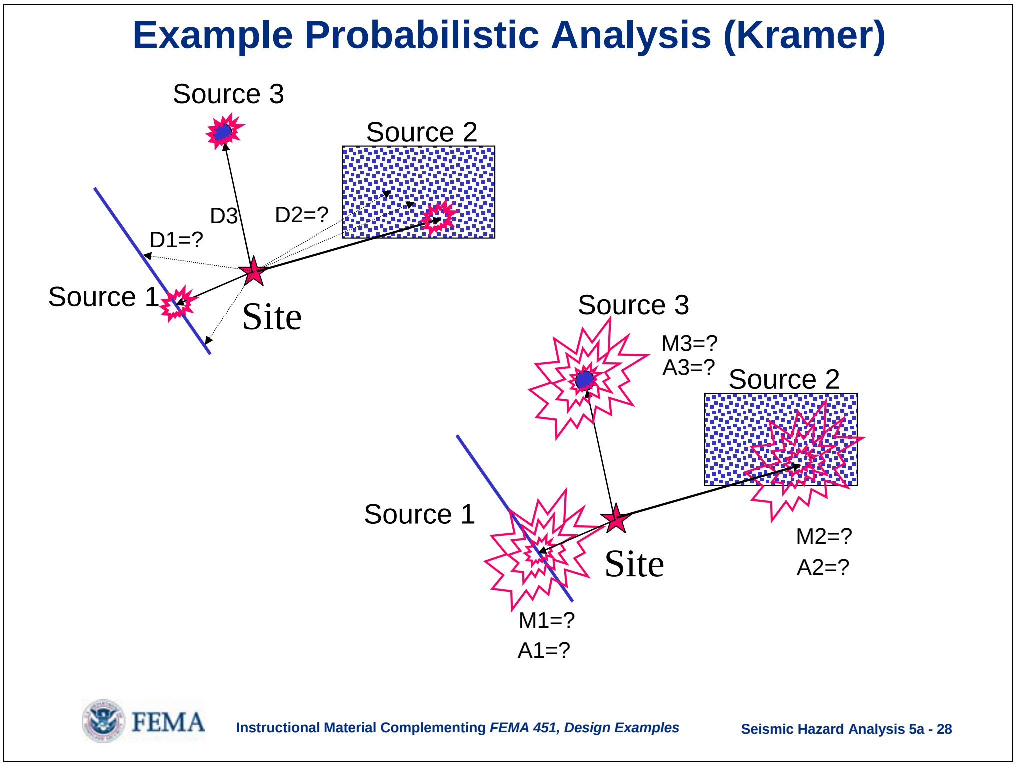
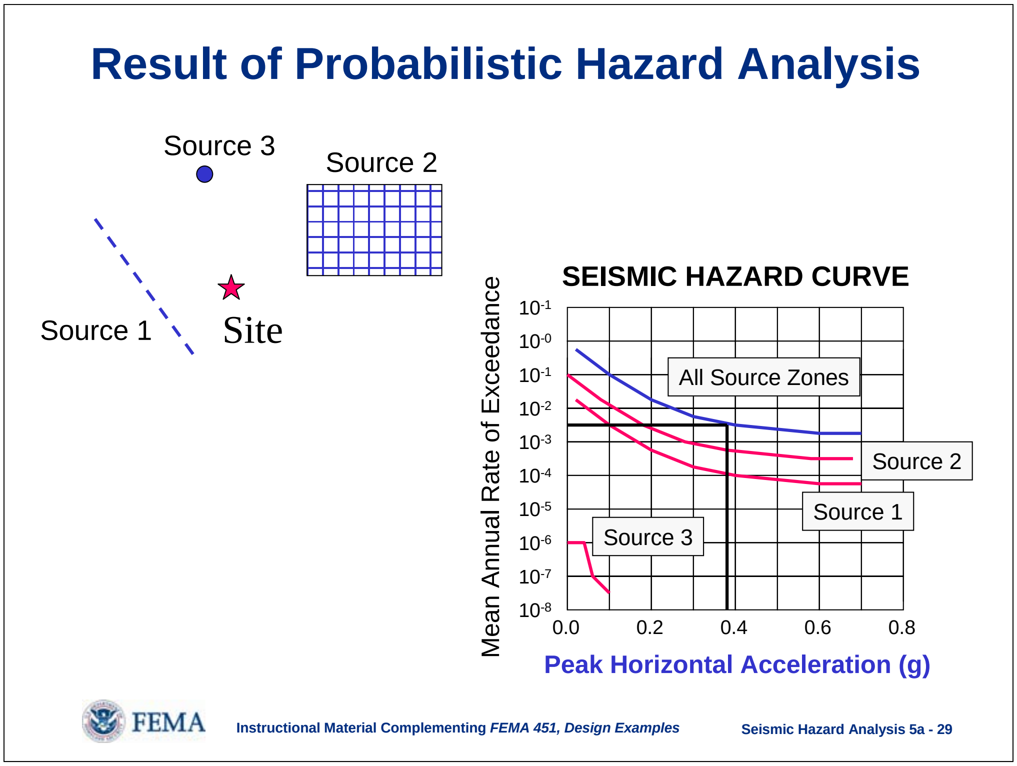
The bounded relationship corrects for the fact that faults are capable of generating earthquakes of a maximum magnitude.



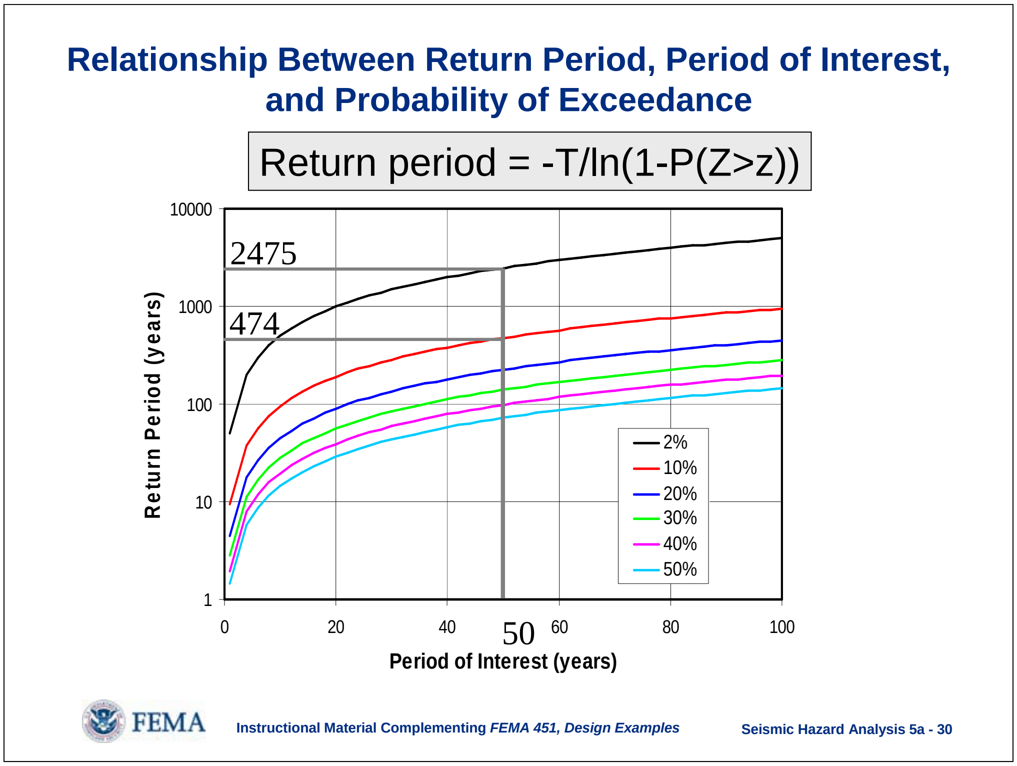

This is the basic probability equation.  Keep in mind the components and the particular uncertainties that are involved.




This slide emphasizes the uncertainties incorporated in probabilistic seismic hazard analysis. They include distance to site (all possible distances are included), magnitude, and attenuation. Deterministic SHA uses the closest distance, one particular definition of maximum earthquake (and its associated magnitude), and one set of attenuation relationships (tied to the given magnitude).

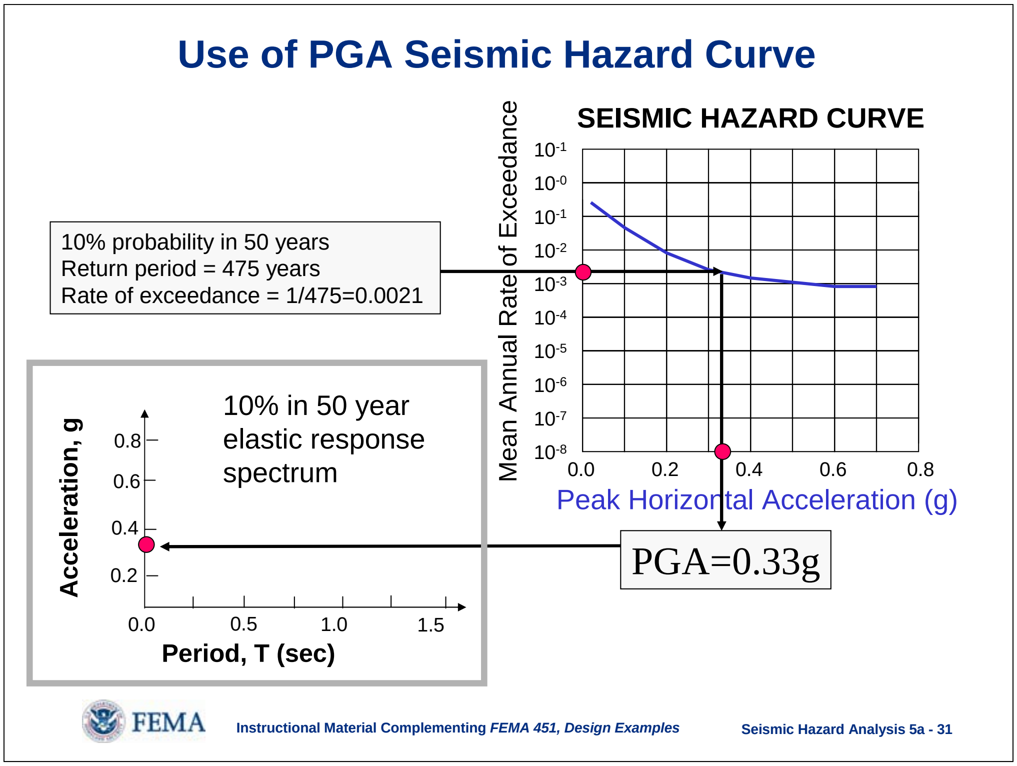



The result of the probabilistic seismic hazard analysis is the seismic hazard curve. One of these curves (red line) is produced for each source, and the sum (blue line) is the seismic hazard curve for the site. Note that the vertical axis gives the (desired) level of probability, and the horizontal axis is some ground motion parameter such as peak ground acceleration. The desired parameter could also be a 5% damped spectral acceleration at $T$ = 1 second.



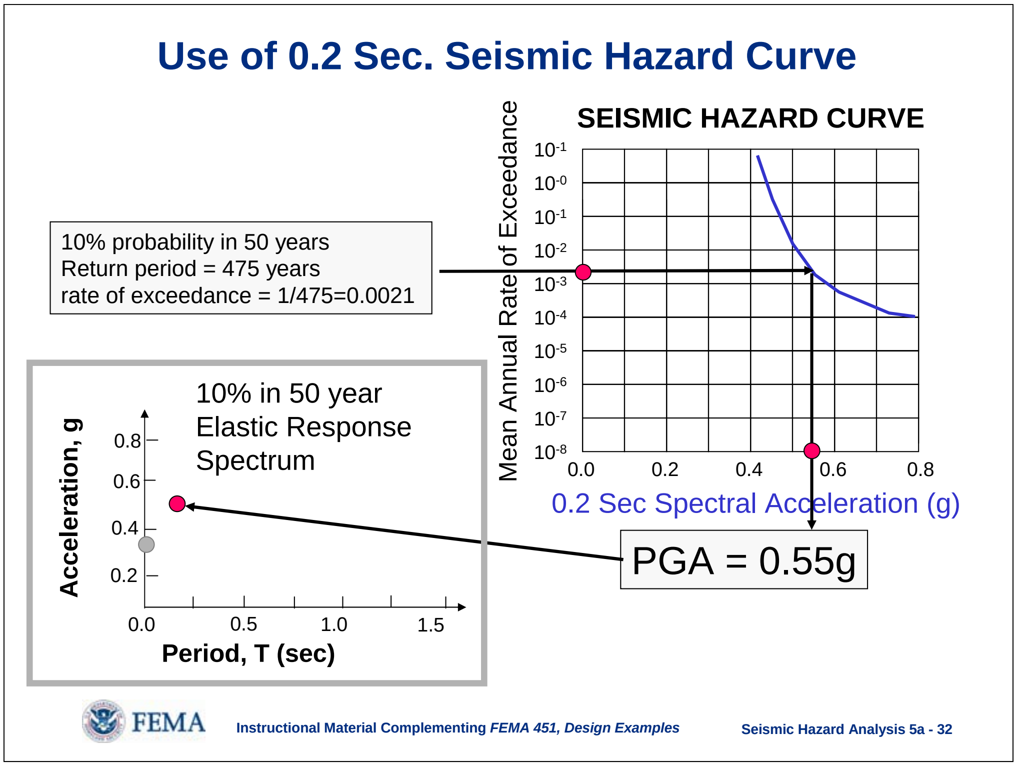

This slide illustrates the relationship between return period, period of interest, and probability of exceedance. A 2% probability of being exceeded in 50 years has a return period of 2475 years. A 10 percent probability of exceedance in 50 years has a 474-year return period. For building design, a 50-year base line is used as this is estimated as the service life of a typical building. For structures such as dams, a longer return period may be more appropriate as the required service life might be much longer. While return period stands alone, the probability of exceedance must be tied to a period of interest. For example, an earthquake with a 2% probability of being exceeded in 100 years has a return period of –100/ln(1-.02) = 4950 years.]

Note that the precision of knowledge of the phenomenon is such that the return periods should be rounded so that the number of significant digits is not out of whack with the initial criteria – thus, the computation of 2475 years should be rounded to 2500 years for most purposes.



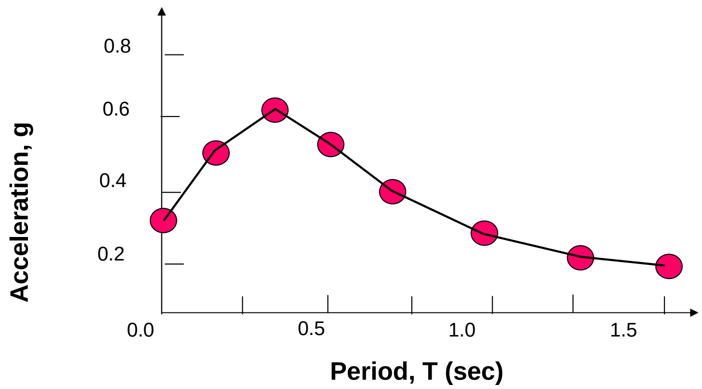

If a series of seismic hazard curves is developed for a range of different parameters (e.g., PGA, 1 sec spectral acceleration, 0.2 sec spectral acceleration) and values are extracted for a certain constant probability (say a 10% in 50 year probability of exceedance), then a design response spectrum may be created by plotting the parameter magnitudes vs period.

The plot at the lower left shows the first point on such a spectrum -- in this case, the PGA with a 10% probability of being exceeded.




A point representing the 0.2 second (5% damped) spectral ordinate with a 10% probability of being exceeded in 50 years is plotted on the response spectrum.

## 10% in 50 Year Elastic Response Spectrum

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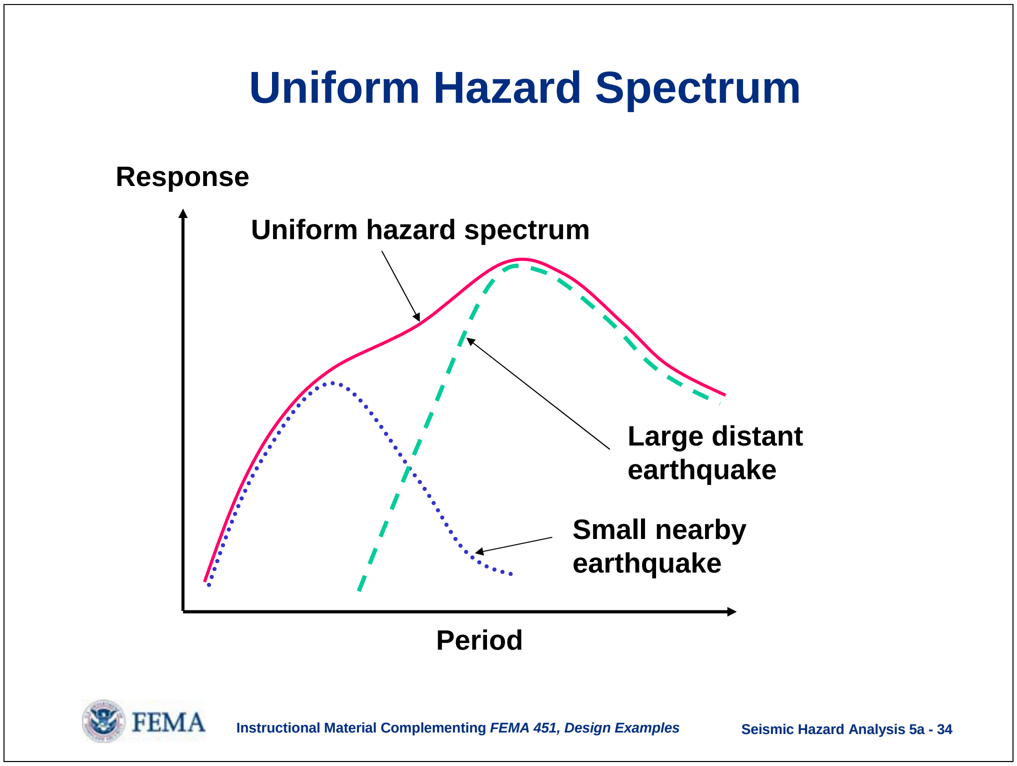
If the process is continued, the result is a complete response spectrum. It is called a uniform hazard spectrum (UHS) because each point on the spectrum has the same probability of being exceeded in the given period. These spectra could then be used in a response spectrum analysis of the structure.

Note that the information from the analysis may instead be used to assist in the development of ground motion time histories. To do this, the ground motion amplitudes (and possibly frequency content) is scaled such that the spectrum of the scaled ground motion closely matches the UHS. There is some danger in doing this, however, because the UHS is a composite of hundreds if not thousands of earthquakes, any two of which are highly unlikely to occur simultaneously.




This slide illustrates the previous point. It should be possible to generate a realistic earthquake ground motion that matches the small or large earthquake. However, a generated earthquake that matches the UHS would be unrealistic (and possibly too demanding).

## Uniform Hazard Spectrum

Developed from *probabilistic* analysis

All ordinates have equal probability of exceedance

Represents contributions from small local, large distant earthquakes

May be overly conservative for modal response spectrum analysis

May not be appropriate for artificial ground motion generation

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This is a summary of the previous points. Note that in certain regions of the western United States, the *NEHRP Recommended Provisions* spectrum is not a true UHS because of the deterministic cap (discussed later). The spectrum generated from the USGS maps is a true UHS.

## Probabilistic vs Deterministic Seismic Hazard Analysis

"The *deterministic* approach provides a clear and trackable method of computing seismic hazard whose assumptions are easily discerned. It provides understandable scenarios that can be related to the problem at hand."

"However, it has no way for accounting for uncertainty. Conclusions based on deterministic analysis can easily be upset by the occurrence of new earthquakes."

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Self explanatory. The quote is from Reiter.

## Probabilistic vs Deterministic Seismic Hazard Analysis

"The *probabilistic* approach is capable of integrating a wide range of information and uncertainties into a flexible framework."

"Unfortunately, its highly integrated framework can obscure those elements which drive the results, and its highly quantitative nature can lead to false impressions of accuracy."

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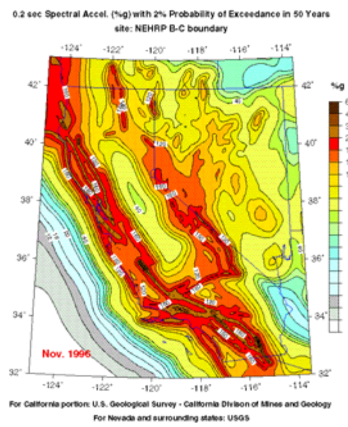
Self explanatory. The quote is from Reiter.

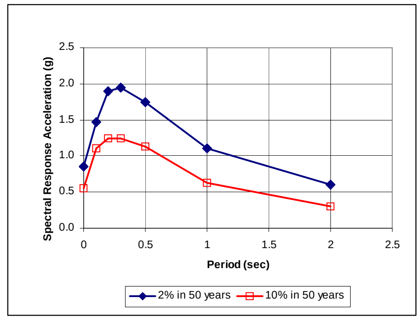
The best solution is often a mix of DSHA and PSHA. The DSHA may be used for the "maximum expected earthquake" and a PSHA used for the more frequent operational basis earthquake.

The important thing to recognize is that the two methods are simply tools to be used to assist in decision making. One method is not better than the other; rather, the methods are complimentary.

# USGS Probabilistic Hazard Maps (Project 97)




**HAZARD MAP**




**RESPONSE SPECTRA**

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The maps in the 1997, 2000, and 2003 *NEHRP Recommended Provisions* are based on a set of probabilistic maps developed by Frankel, et al., of the USGS. See the references for more details. Note that it is these maps that are reflected in the IBC and ASCE 7.

By using the maps it is possible to develop 5% damped response spectra for a variety of exceedance probabilities (e.g., 2/50, 10/50, and so on.)

The maps are developed for sites with firm rock. Modification factors for softer/harder rock will be discussed later.

For the eastern United States, the *NEHRP Recommended Provisions*, 2000 IBC, and USGS maps are identical. In the western United States, the *NEHRP Provisions* and IBC maps have a deterministic cap in certain areas as explained later. There is also a deterministic cap in the New Madrid area in the updated maps used in the *2003 NEHRP Recommended Provisions*.

## USGS Probabilistic Hazard Maps (and *NEHRP Provisions* Maps)

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



Some detail on the development of the maps can be found several articles in the *Earthquake Spectra* volume cited.

# Maximum Considered Earthquake (MCE)

The MCE ground motions are defined as the maximum level of earthquake shaking that is considered as reasonable to design normal structures to resist.

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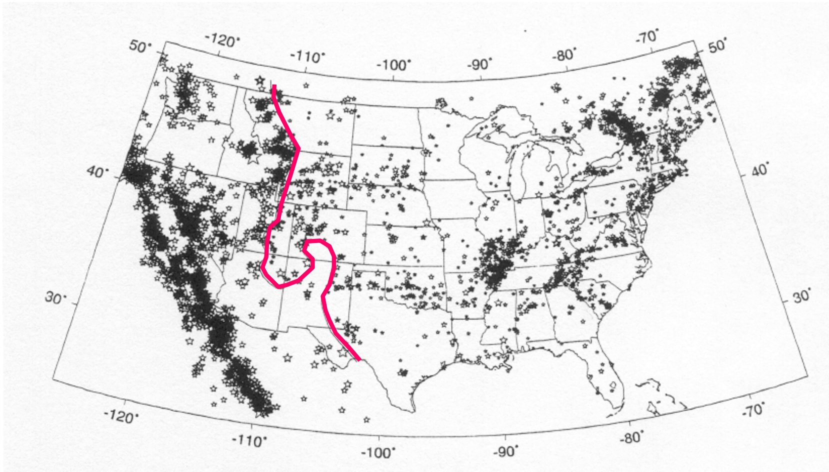
This slide is a bit out of sequence. It describes the intent of the application of the USGS maps to the *NEHRP Recommended Provisions.* In certain areas of the western United States, the USGS probabilistic values have been deemed "too high" for design, and a deterministic approach has been used to cap the probabilistic values. Also, the USGS maps are based on a 2% in 50 year probability, which is also thought to be excessive for design. Hence, the transformation of the USGS values (2% in 50 year purely probabilistic) to a *NEHRP Recommended Provisions* design response spectrum (somewhat less than 2% in 50 years, probabilistic-deterministic) is consistent with the notion of a maximum considered earthquake.

## USGS Seismic Hazard Regions




Note: Different attenuation relationships used for different regions.

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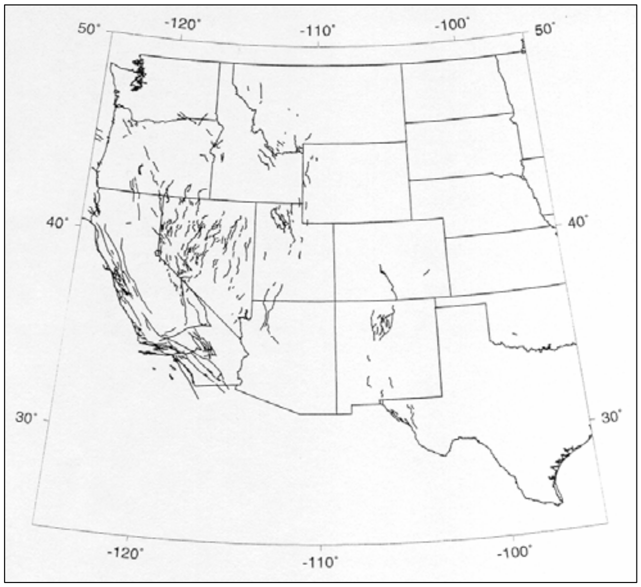
In the development of the USGS maps, the coterminous United States was divided into two principal regions. Different sets of attenuation relationships were used as applicable.

## USGS Seismic Hazard WUS Faults

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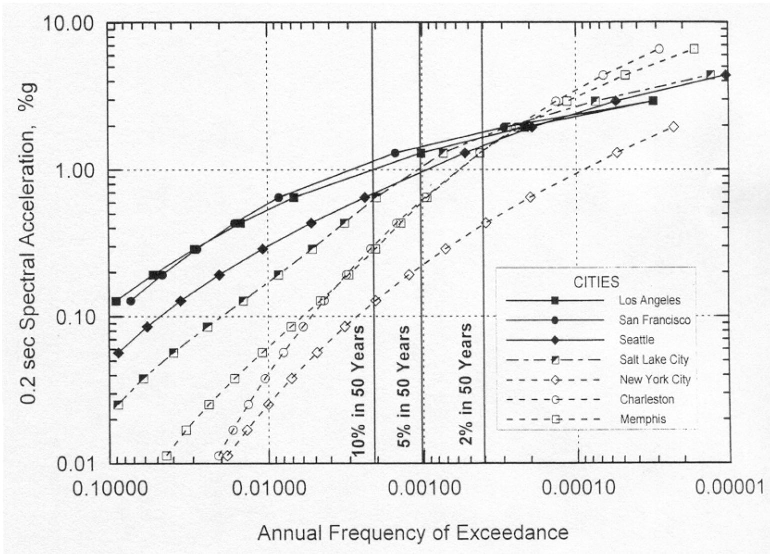
These are the faults considered in the probabilistic analysis for the western United States. In the eastern states, it is much more difficult to identify active faults and, therefore, localizing structures and seismotectonic provinces were used.

## USGS Seismic Hazard Curves for Various Cities

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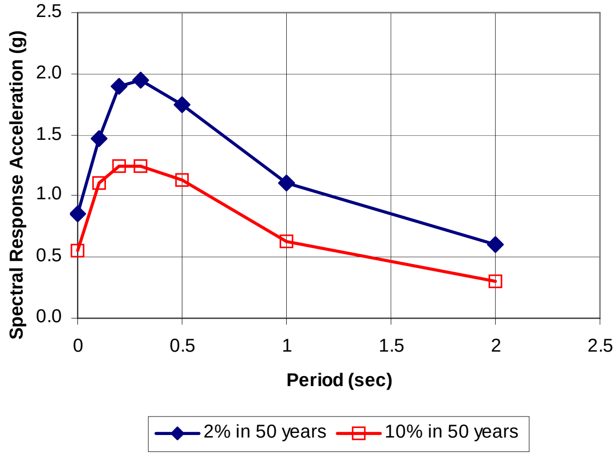
This slide shows some of the seismic hazard curves for major cities in the coterminous United States. Note that the axes are switched from some of the earlier hazard curves. The main difference to note is the slope of the curves for the western states compared to the central and eastern states. For the western United States, there is not nearly as dramatic an increase in the ground motion parameter when going from a 10/50 to a 2/50 probability as there is in the eastern states.

## Uniform Hazard Spectra for San Francisco

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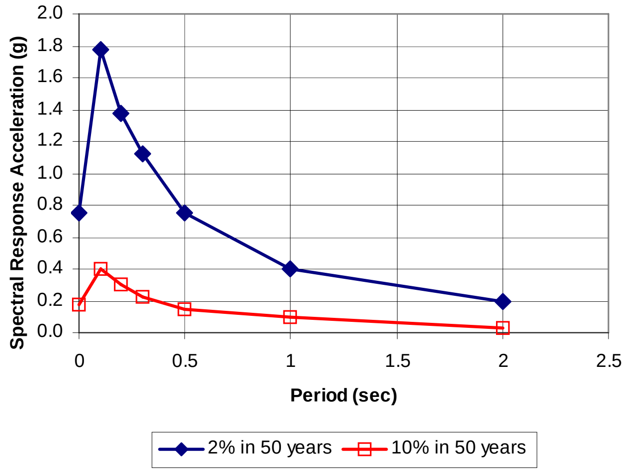
This is a plot of the uniform seismic hazard response spectrum for San Francisco. The 2/50 and 10/50 curves are shown. Note that, in general, the 10% in 50 year curve gives about 2/3 the 2% in 50 year acceleration for a particular period. The next slide shows similar curves for the eastern United States. The difference is significant.

## Uniform Hazard Spectra for Charleston, SC

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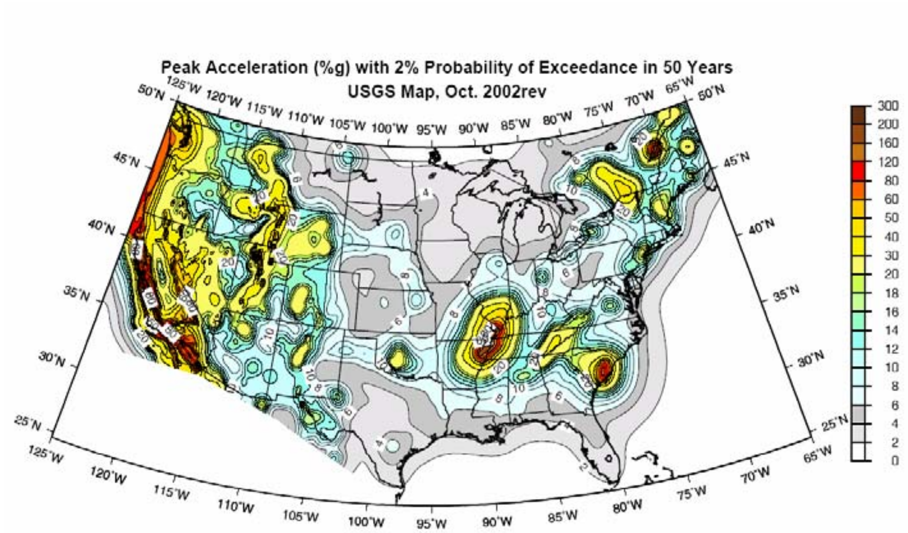
This is the uniform seismic hazard curve for Charleston, South Carolina. Note here that the 10% in 50 year curve gives about 1/4 of the corresponding values for 2% in 50 year curve.

Note also that the shape of the spectrum is different (in comparison to previous slide) with the peak at a shorter period.

## USGS Seismic Hazard Map of Coterminous United States

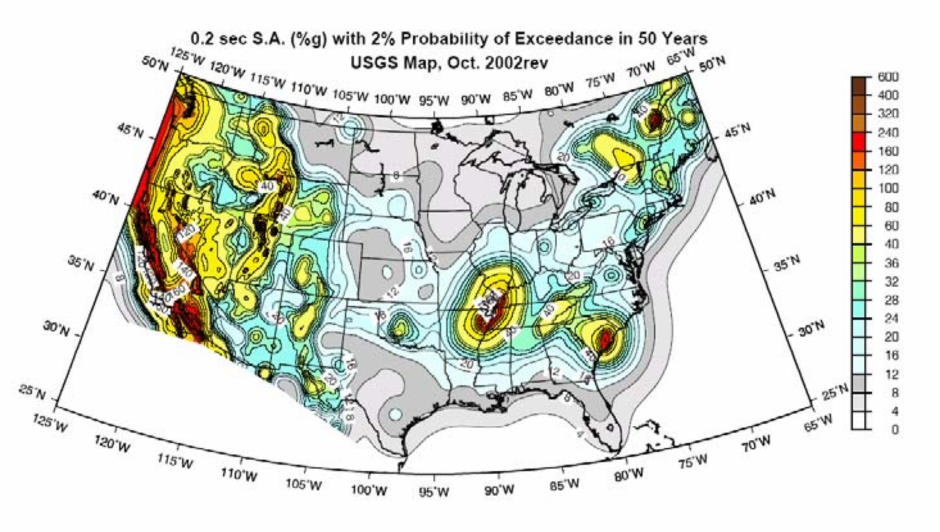



http://earthquake.usgs.gov/hazmaps/

FEMA Instructional Material Complementing *FEMA 451, Design Examples* Seismic Hazard Analysis 5a - 46

This map shows the 2 percent in 50 year peak ground acceleration ordinates for the coterminous United States. Note that in the western states, peak ground accelerations can be as high as 3g. It was not too long ago that engineers believed than the maximum ground accelerations from real earthquakes could not exceed approximately 0.4g!

## USGS Seismic Hazard Map of Coterminous United States

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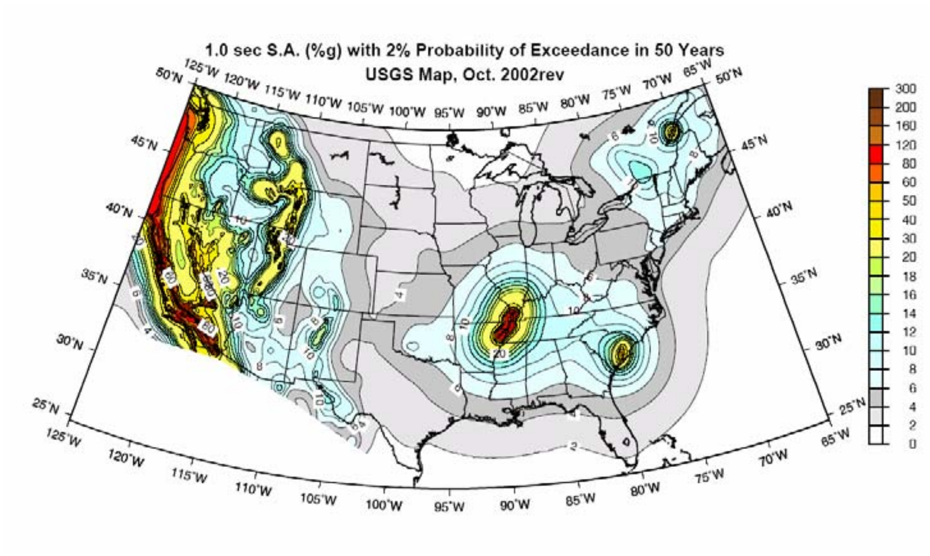
This is the similar map for the 5% damped 0.2 second spectral acceleration. Here, due to dynamic amplification, the peak total structural acceleration may be as high as 6g in the western states.

## USGS Seismic Hazard Map for Coterminous United States

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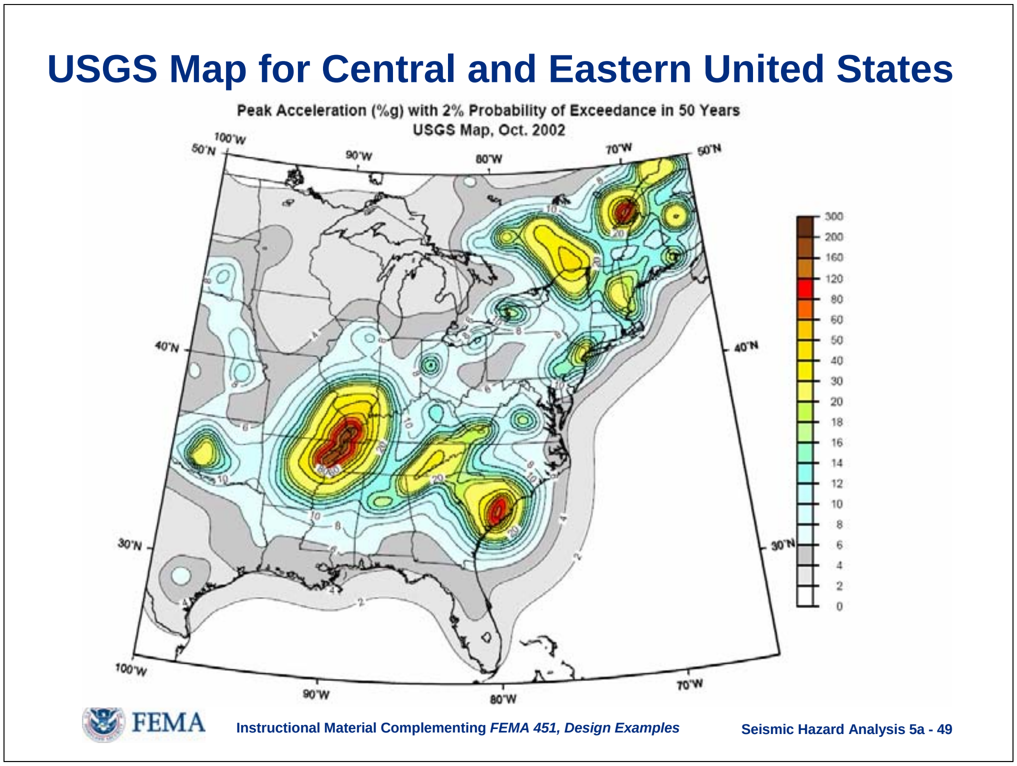
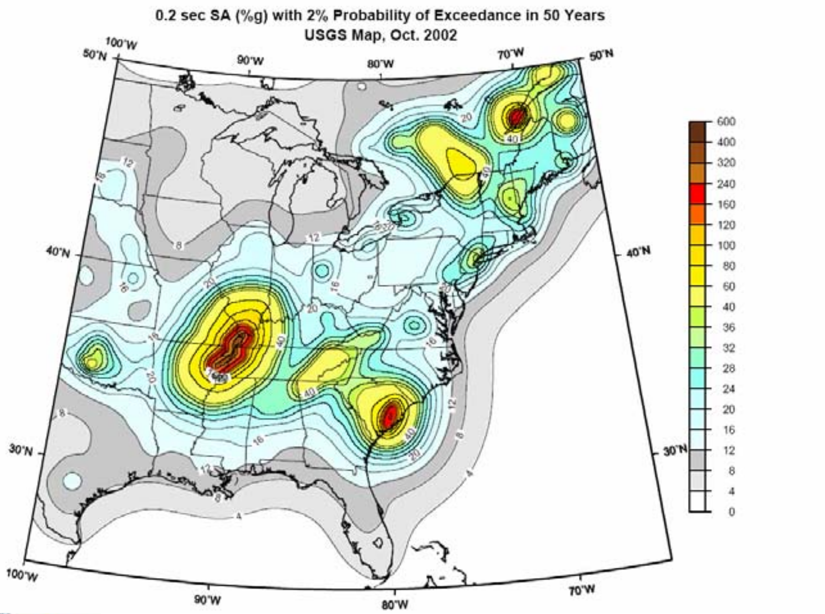
This is the 1.0 second map for 2% in 50 probability.




This is the 2% in 50 year map PGA for the central and eastern states. It is highly influenced by the New Madrid and the Charleston earthquakes. Peak accelerations are 3g, just like California!

# USGS Map for Central and Eastern United States

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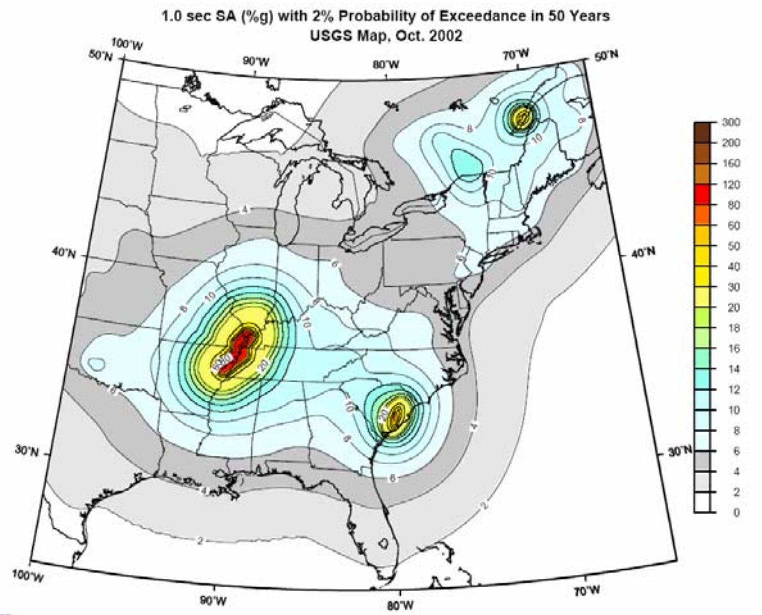
As with California, the peak 0.2 second acceleration is 6g.

## USGS Map for Central and Eastern United States

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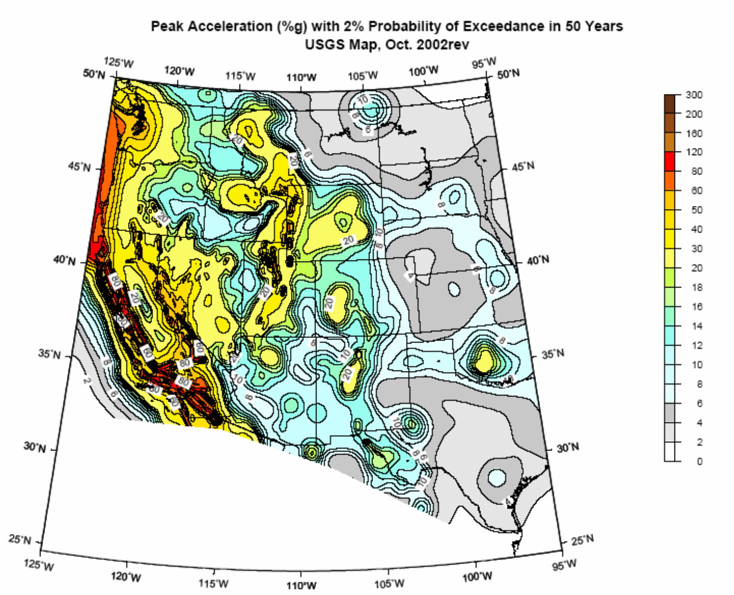
Self explanatory.

# USGS Map for Western United States

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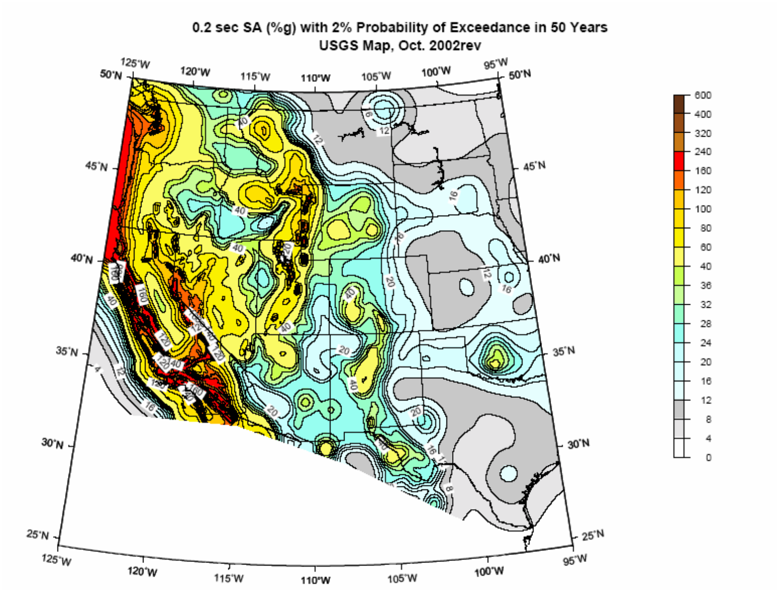
Seismic Hazard Analysis 5a - 52

Self explanatory.

## USGS Map for Western United States

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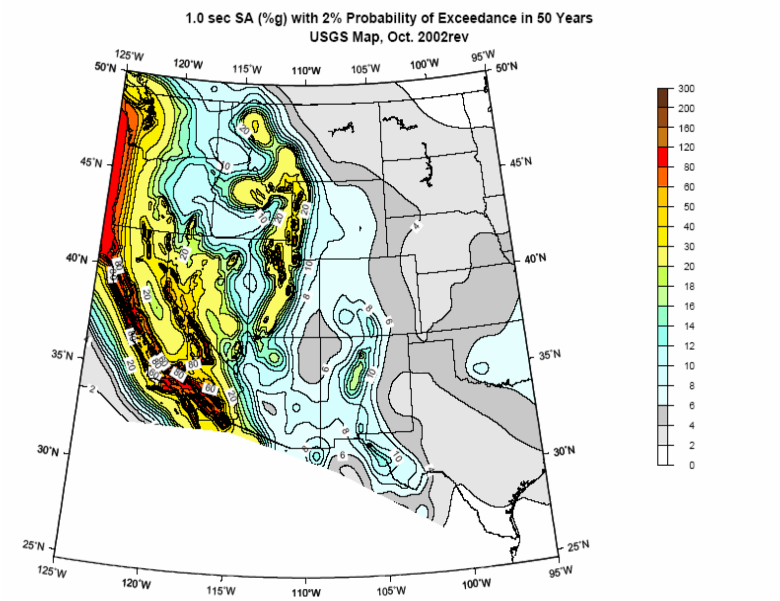
Self explanatory.

# USGS Map for Western United States

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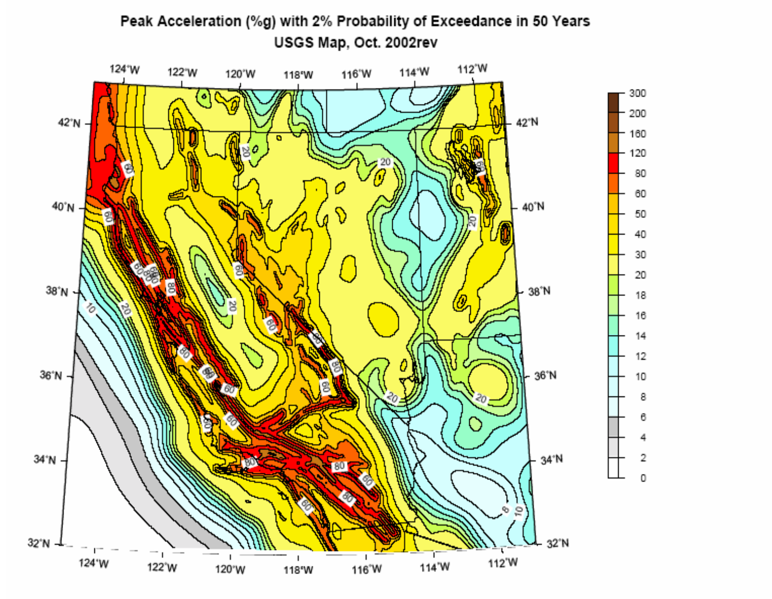
Self explanatory.

# USGS Map for California

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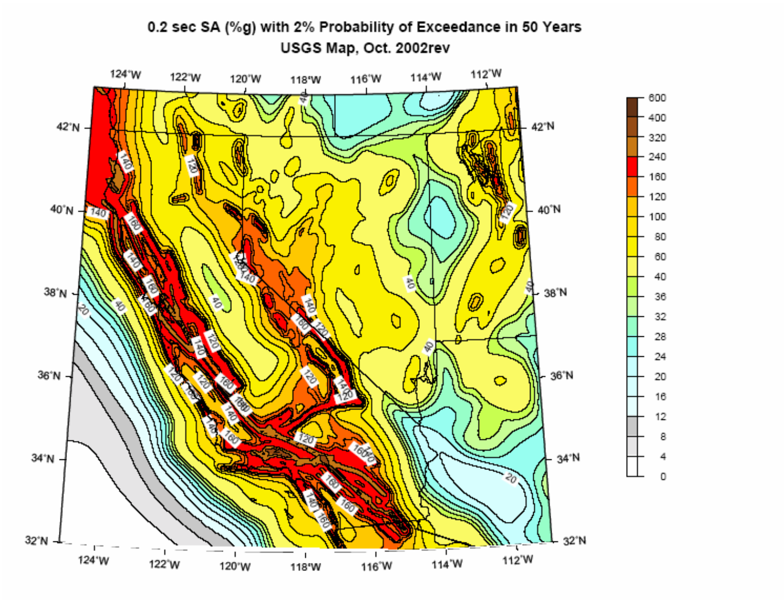
Self explanatory.

# USGS Map for California

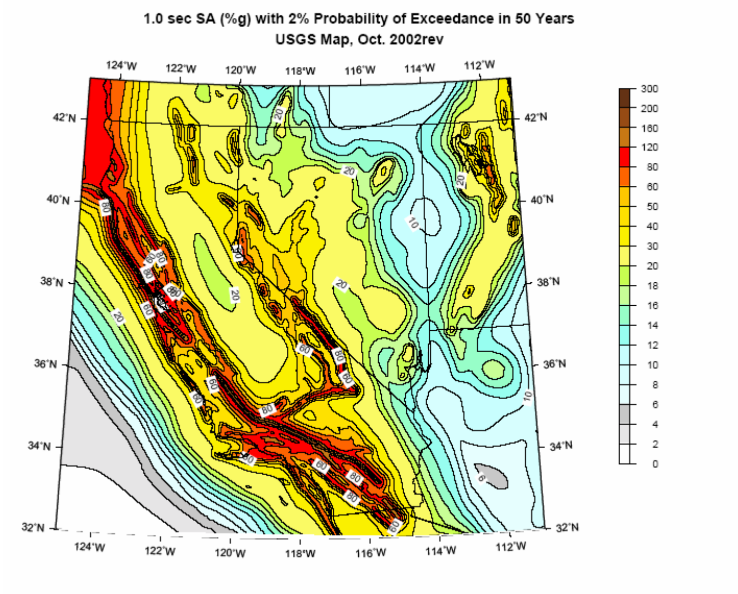



Instructional Material Complementing *FEMA 451, Design Examples*

Seismic Hazard Analysis 5a - 56

Self explanatory.

# USGS Map for California

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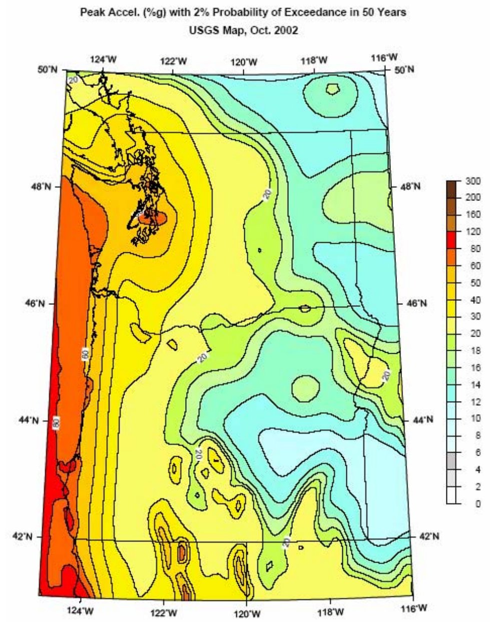
Self explanatory.

# USGS Map for Pacific Northwest

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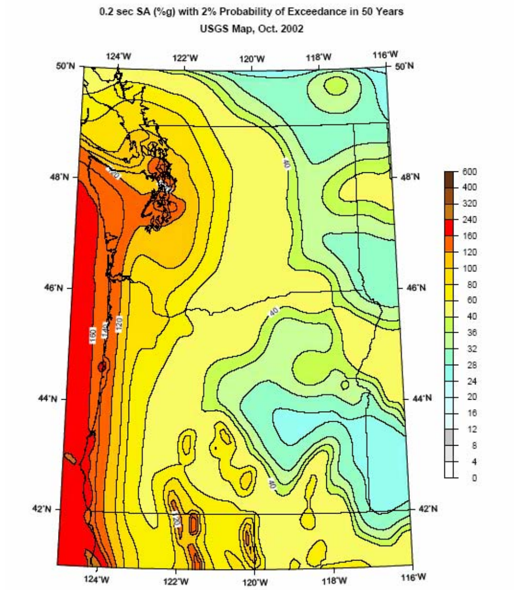
Self explanatory.

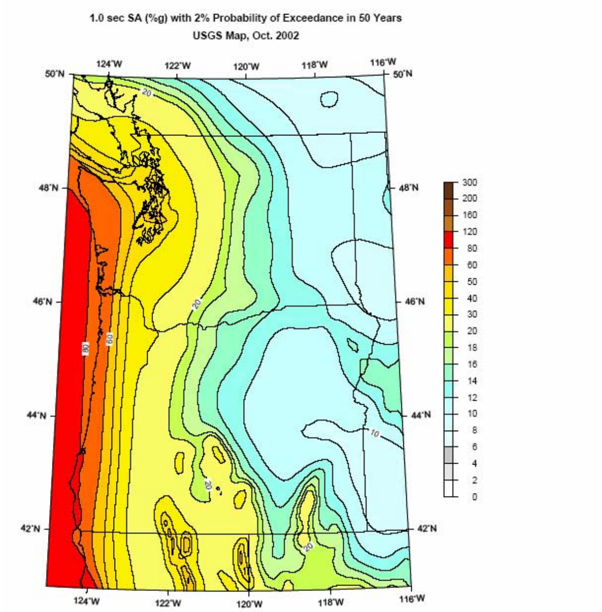
# USGS Map for Pacific Northwest




FEMA Instructional Material Complementing *FEMA 451, Design Examples* Seismic Hazard Analysis 5a - 59

Self explanatory.

## USGS Map for Pacific Northwest

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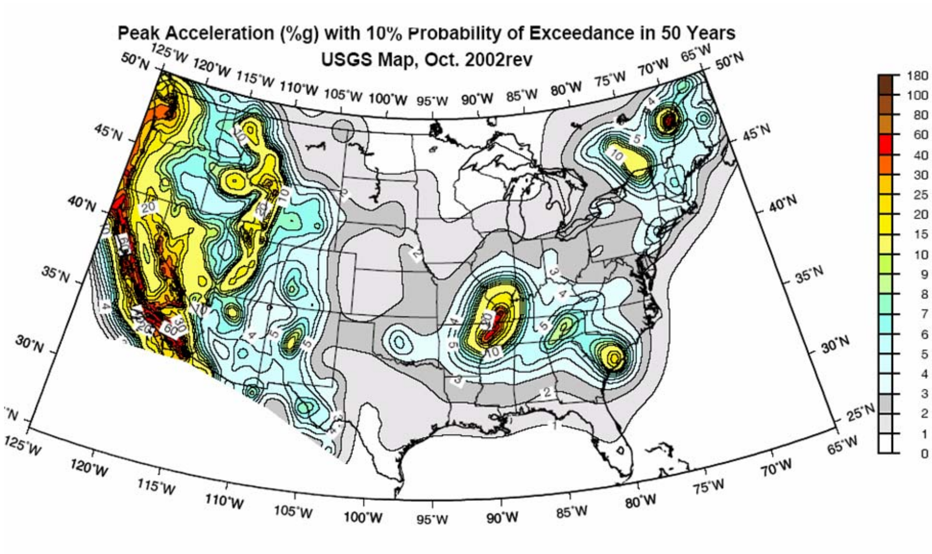
Seismic Hazard Analysis 5a - 60

Self explanatory.

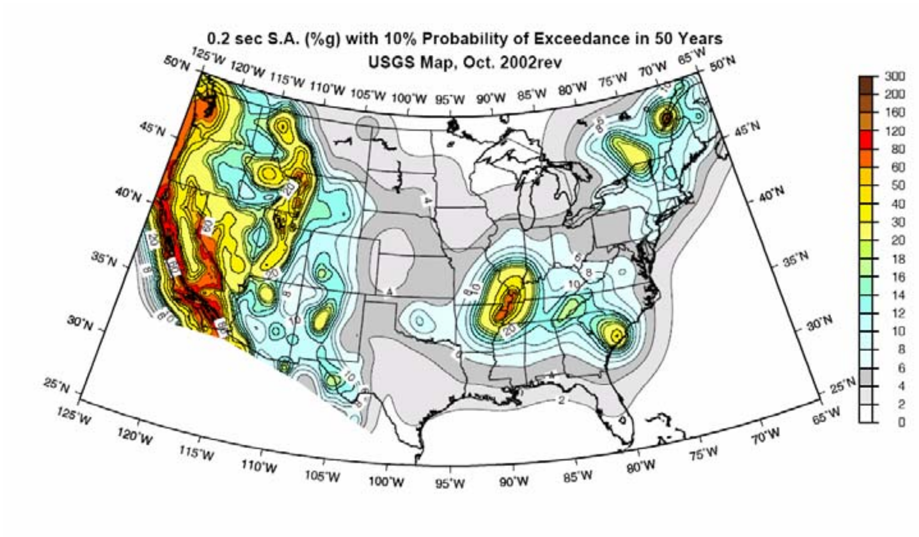
## USGS Seismic Hazard Map of Coterminous United States




FEMA Instructional Material Complementing *FEMA 451, Design Examples* Seismic Hazard Analysis 5a - 61

This map shows the 10% in 50 year peak ground acceleration ordinates for the coterminous United States. Note that in the western states, peak ground accelerations can be as high as 1.8g.

## USGS Seismic Hazard Map of Coterminous United States

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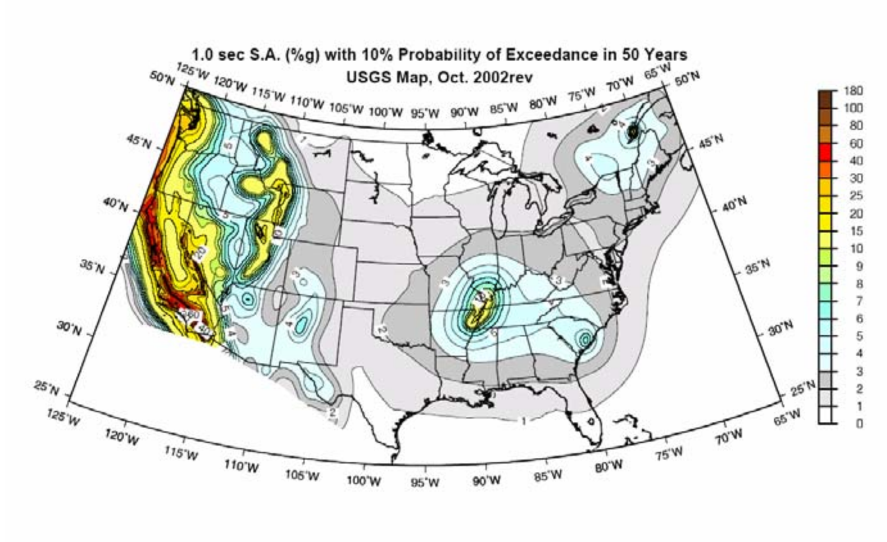
This is the similar map for the 5% damped 0.2 second spectral acceleration. Here, due to dynamic amplification, the peak total structural acceleration may be as high as 3g in the western states.

## USGS Seismic Hazard Map of Coterminous United States

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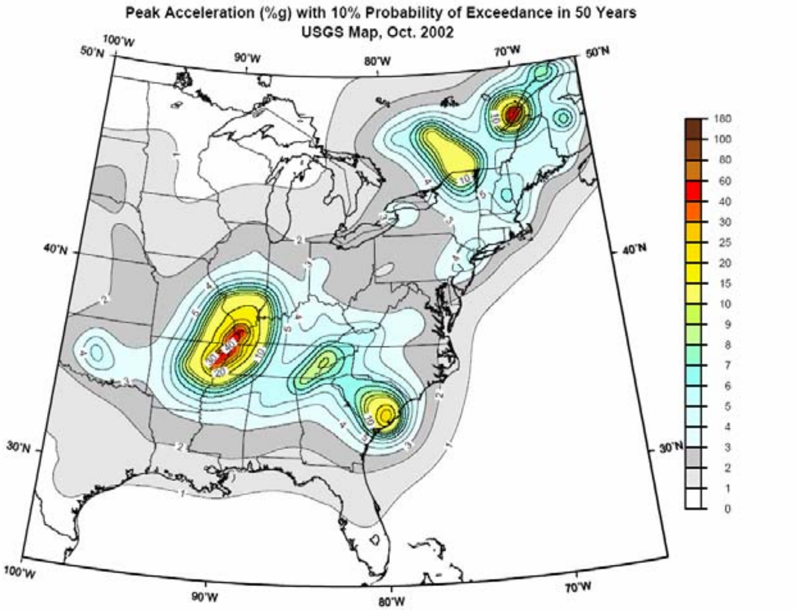
This is the 1.0 second map for 10% in 50 year probability.

# USGS Map for Central and Eastern United States

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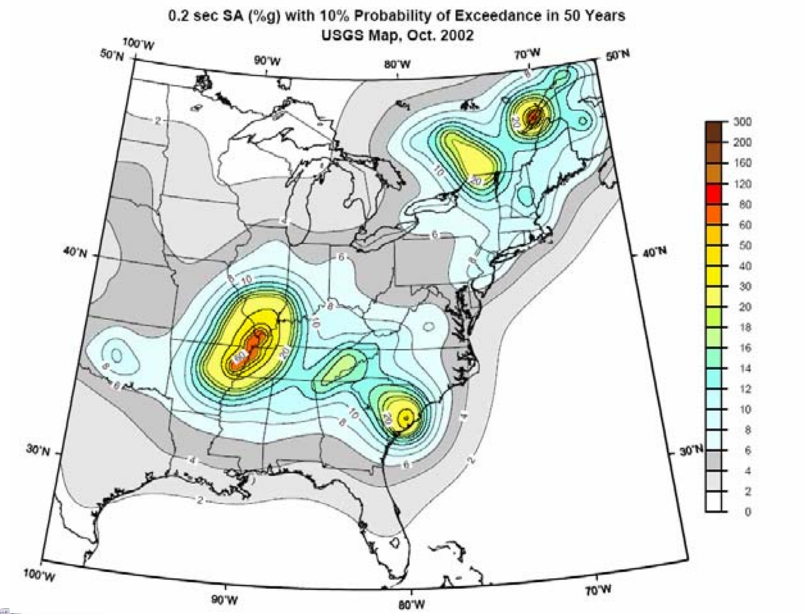
Self explanatory.

# USGS Map for Central and Eastern United States

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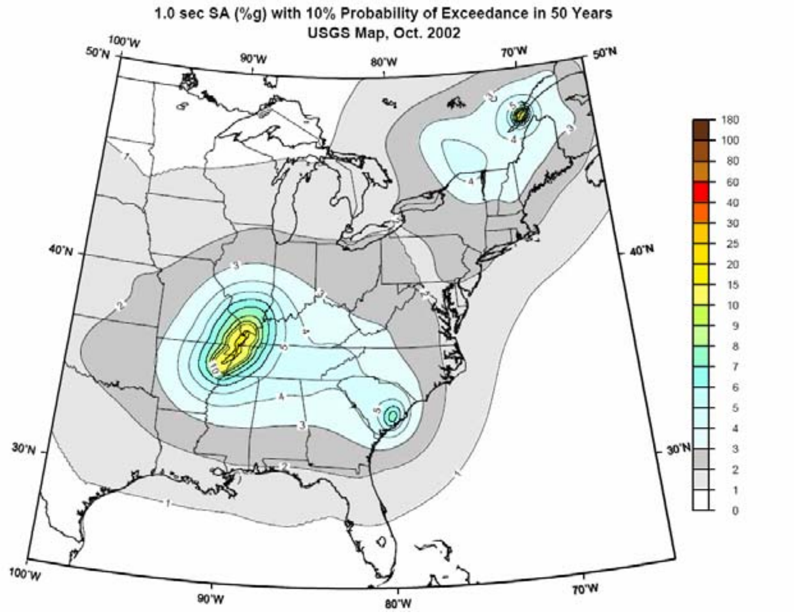
Self explanatory.

## USGS Map for Central and Eastern United States

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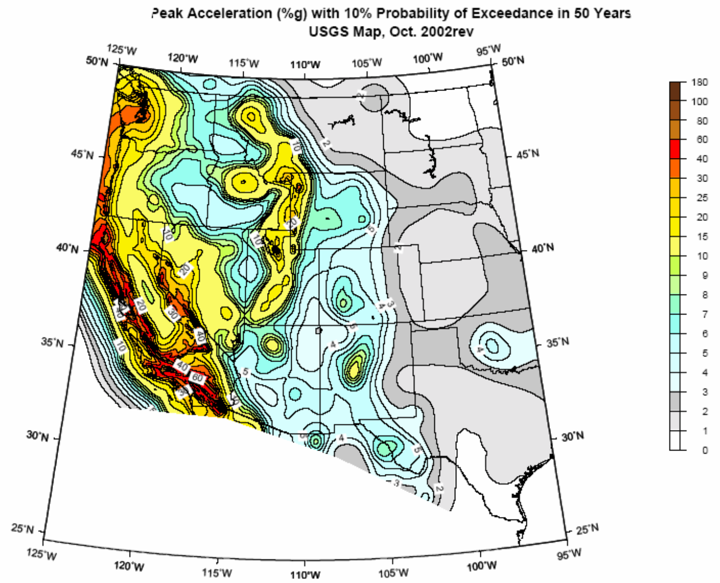
Self explanatory.

# USGS Map for Western United States

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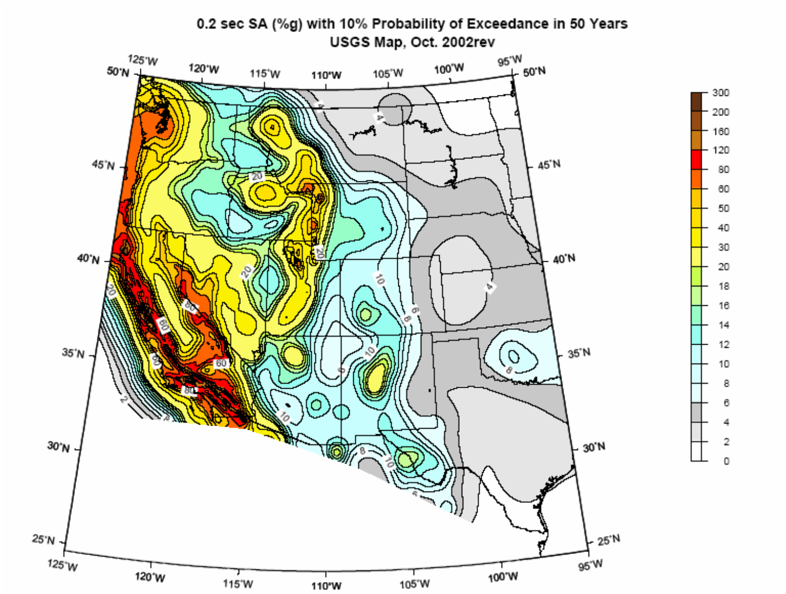
Self explanatory.

# USGS Map for Western United States

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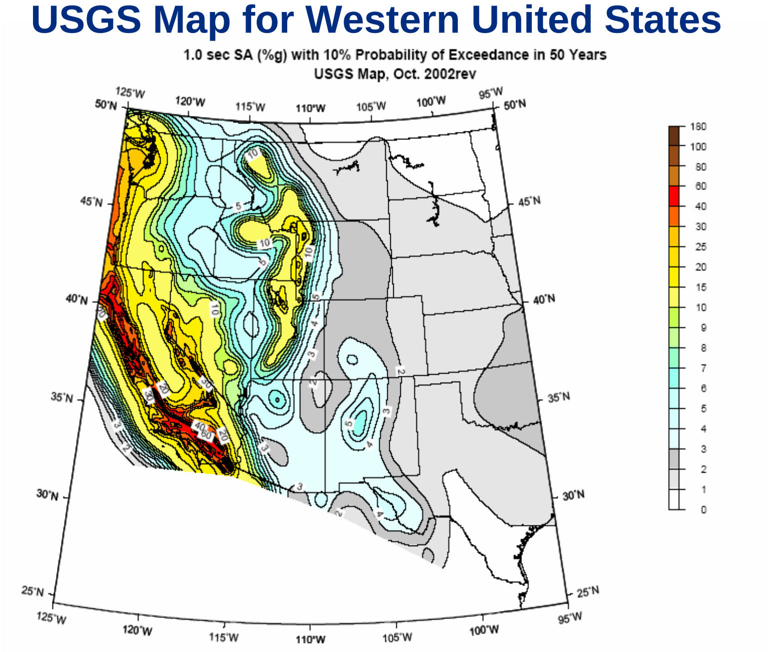
Seismic Hazard Analysis 5a - 68

Self explanatory.

# USGS Map for Western United States

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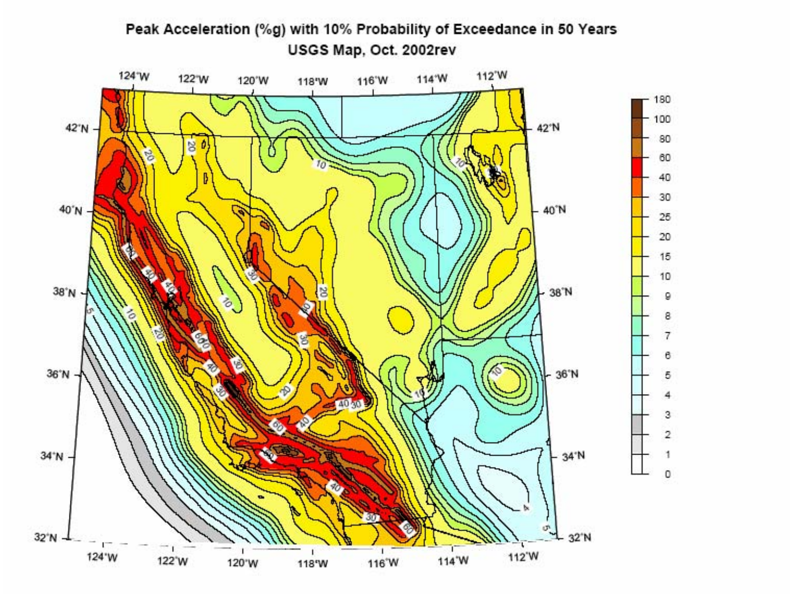
Self explanatory.

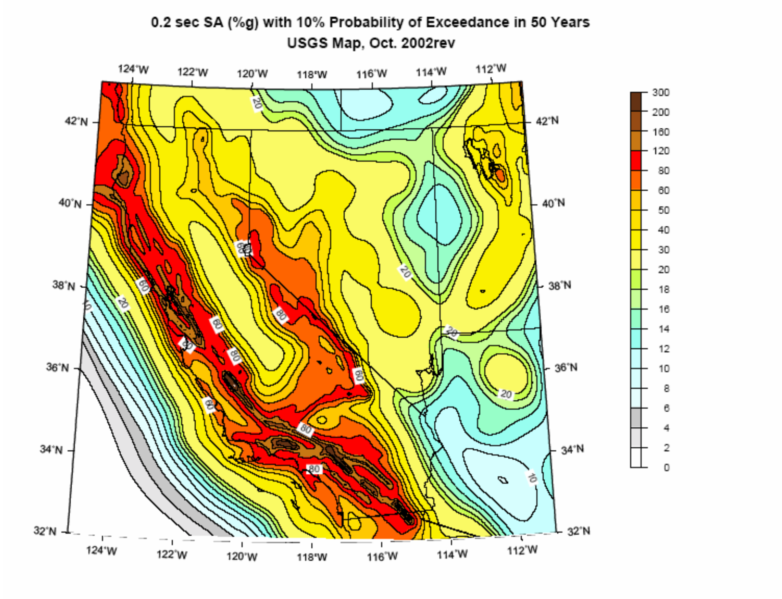
# USGS Map for California






Self explanatory.

# USGS Map for California

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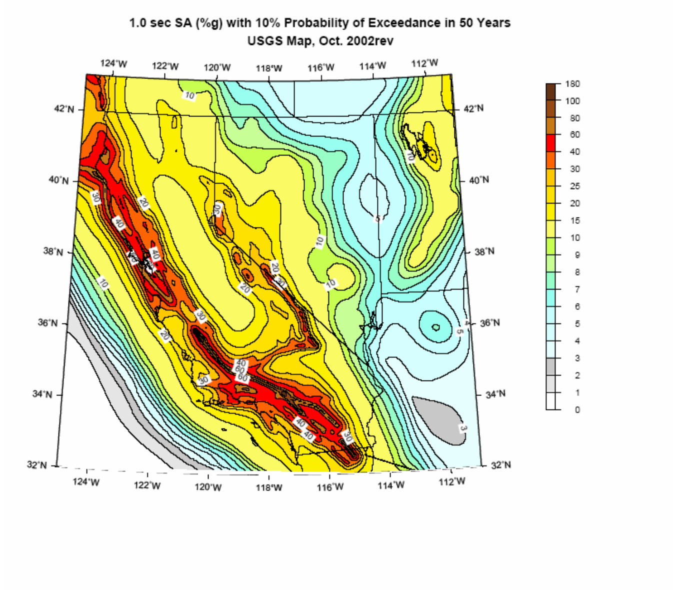
Self explanatory.

# USGS Map for California

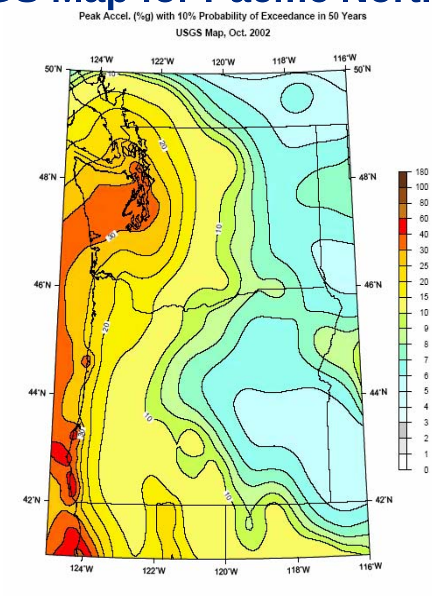



Instructional Material Complementing *FEMA 451, Design Examples*

Seismic Hazard Analysis 5a - 72

Self explanatory.

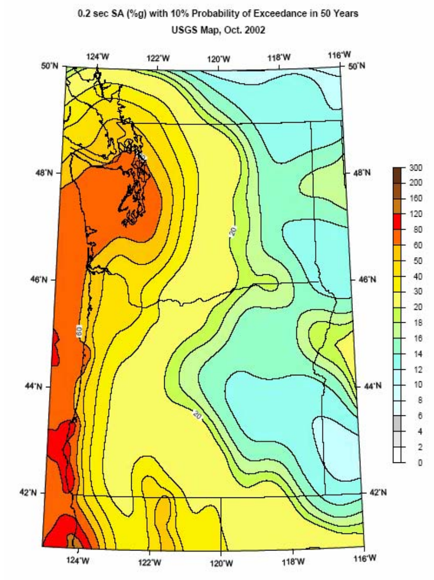
# USGS Map for Pacific Northwest




FEMA Instructional Material Complementing *FEMA 451, Design Examples* Seismic Hazard Analysis 5a - 73

Self explanatory.

# USGS Map for Pacific Northwest

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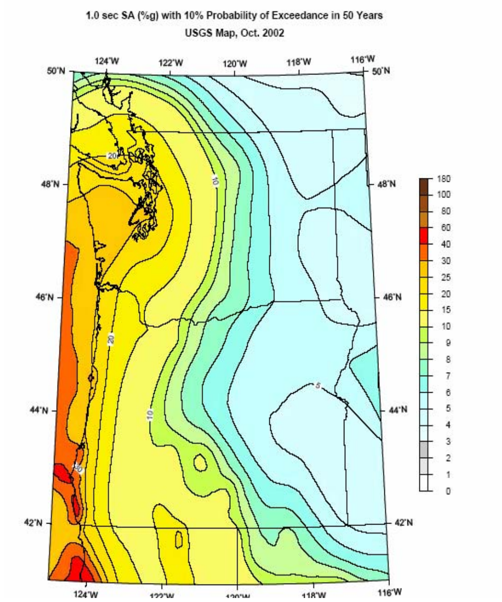
Instructional Material Complementing *FEMA 451, Design Examples*

Seismic Hazard Analysis 5a - 74

Self explanatory.

# USGS Map for Pacific Northwest




FEMA Instructional Material Complementing *FEMA 451, Design Examples* Seismic Hazard Analysis 5a - 75

Self explanatory.

## USGS Website for Map Values

**http://earthquake.usgs.gov/research/hazmaps/design/**

```
   The input zipcode 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
```

**CAUTION: USE OF ZIPCODES IS DISCOURAGED; LAT-LONG VALUES WILL GIVE ACCURATE RESULTS.**

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Spectral acceleration values may be obtained by latitude-longitude or zipcode using the indicated web site. Four spectral ordinates are provided for three different return intervals. Note that these are from the USGS maps, and have not been modified with a deterministic cap in the western United States.

Also note that use of zipcodes for a specific project is strongly discouraged since zipcodes are arbitrary units and can be changed often by the U.S. Post Office. For a specific project, use the latitude-longitude.

The USGS tends to change the web address often. To find the latest version, Google “USGS Seismic Hazard Maps” or use the CD distributed with the IBC and IRC.

## Relative PGAs for the United States


FEMA Instructional Material Complementing *FEMA 451, Design Examples* Seismic Hazard Analysis 5a - 77

This is a visual of PGAs for the United States. All data were taken from the USGS web site for the 2003 version of the *Provisions* source maps and are for firm rock. Note that the accelerations in the Pacific Northwest (Seattle) rival those for coastal California. Memphis is also prominent due to the New Madrid earthquake.

The new version of the USGS maps being reviewed in 2007 reflect new attenuation relationships based on study over the past 10 year and they may change these relationships.

## 2000 *NEHRP Recommended Provisions* Maps

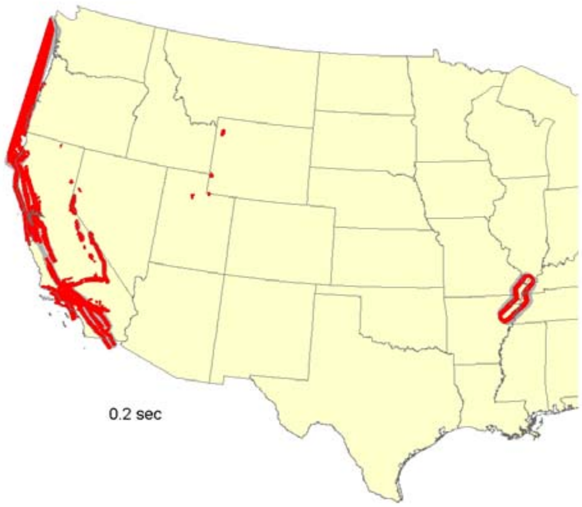
- 5% damped, 2% in 50 years, Site Class B (firm rock)
- 0.2 second and 1.0 second spectral ordinates provided
- On certain faults in California, Alaska, Hawaii, and CUS *Provisions* values are deterministic cap times 1.5. Outside deterministic areas, *Provisions* maps are the same as the USGS maps.
- USGS longitude/latitude and zipcode values are probabilistic MCE. To avoid confusion, ALWAYS use *Provisions* (adopted by ASCE and IBC) maps for design purposes.

FEMA Instructional Material Complementing *FEMA 451, Design Examples* Seismic Hazard Analysis 5a - 78

This slide summarizes the key points in the development of the *NEHRP Provisions* maps. Much of this has already been introduced in previous slides.

It is worth pointing out that the 2003 *NEHRP Recommended Provisions*, ASCE 7-05, and the 2006 *International Building Code* use maps updated in the 2002 USGS effort.

# Location of Deterministic Areas



## Deterministic Cap

Applies only where probabilistic values exceed highest design values from old (Algermissen and Perkins) maps.

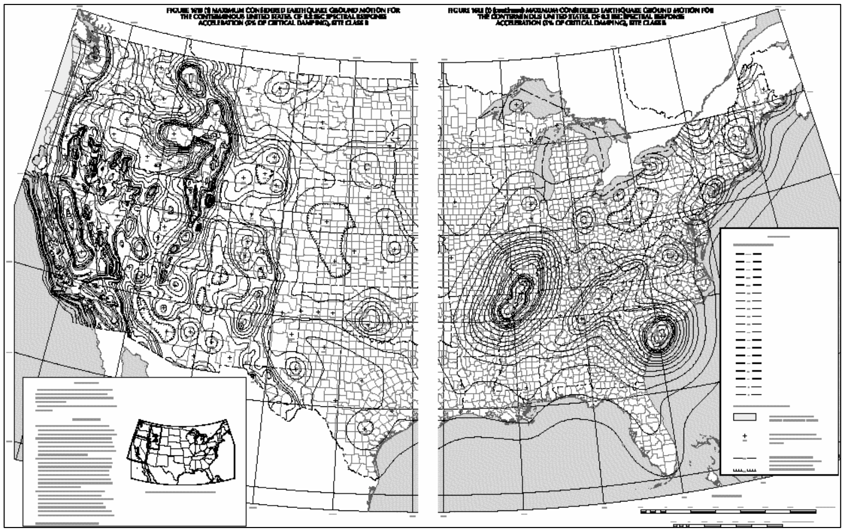
The deterministic procedure for mapping applies:
- For known “active” faults
- Uses characteristic largest earthquake on fault
- Uses 150% of value from median attenuation

Use deterministic value if lower than 2% in 50 year value



Details of the deterministic cap.

## *NEHRP Provisions* Maps
## 0.2 Second Spectral Response ($S_S$)



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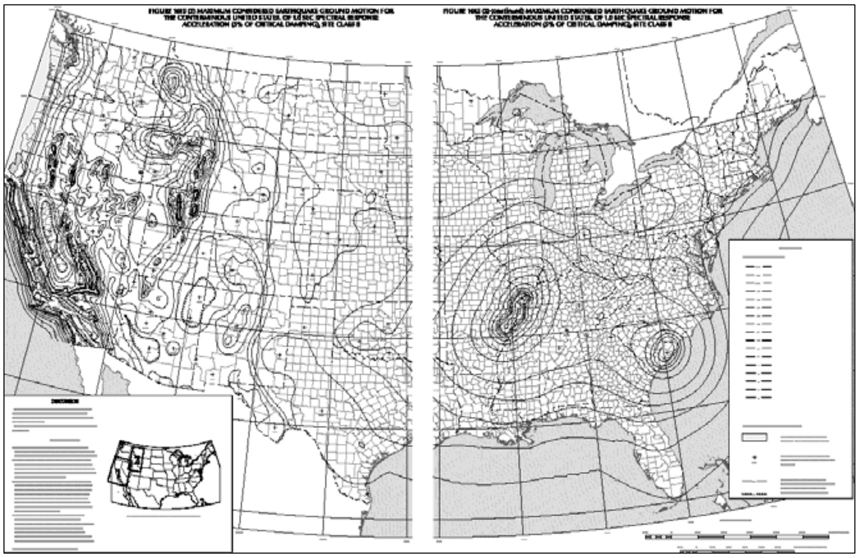
These are the 2% in 50 year 5% damped "short period" spectral accelerations from the *NEHRP Recommended Provisions* maps. East of California, they are the same as the USGS maps. In close proximity to active faults in western California, Hawaii, Alaska and the New Madrid region, the *Provisions* maps have been capped at 1.5 times the deterministic value.

The 2003 IBC and ASCE 7-05 use the same maps as the 2003 *NEHRP Recommended Provisions*.

## *NEHRP Provisions* Maps
## 1.0 Second Spectral Response ($S_1$)



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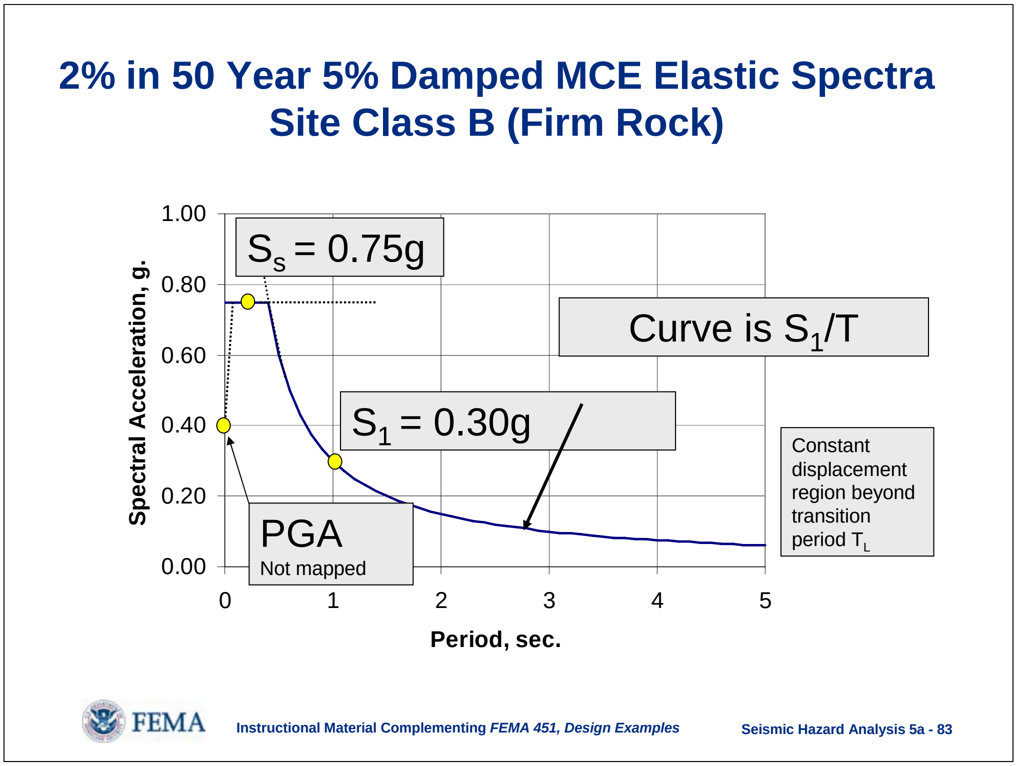
These are the long (1 second) *NEHRP Recommended Provisions* spectral ordinates for 2% in 50 years.




In the *NEHRP Recommended Provisions*, the basic design spectrum consists of four lines.

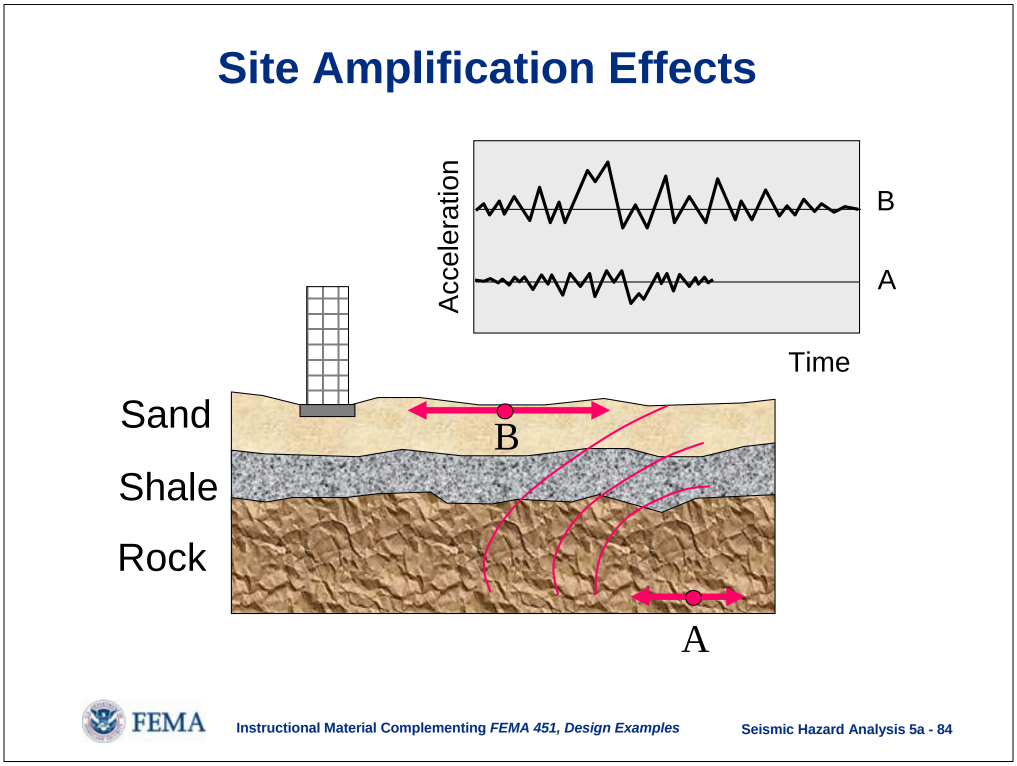
In the constant acceleration region, the spectrum is tied to the 0.2 second mapped ordinate ($S_s$). (In the equivalent lateral force procedure, the constant acceleration region extends all the way to $T$ = 0 seconds.)

In the constant velocity region, the 1 second ordinate, S1, is used to locate the position of the descending (proportional to 1/$T$) curve.

Beyond the constant velocity region is a constant displacement region that initiates at a transition period $T_L$. $T_L$ is provided in a separate map, is a minimum of 4 seconds, and is 6 seconds or greater in most of the United States.

The *NEHRP Recommended Provisions* does not give mapped values for peak ground acceleration. However, the PGA is estimated as 1/2.4 times the 0.2 second acceleration.

Note that this spectrum will be modified systematically to produce a “design spectrum.”




All of the previous developments (e.g., seismic hazard maps) were for sites on very firm soil. For sites on softer soil, the ground motions will be amplified. This slide shows ground motion occurring in rock (lower time history) and in a softer material such as a clay. At point B, the ground motions are significantly amplified over those at A. Also, the duration of the motion may be increased and the frequency content may change. The principal effect is that high frequency components are filtered out and longer period motions are enhanced.

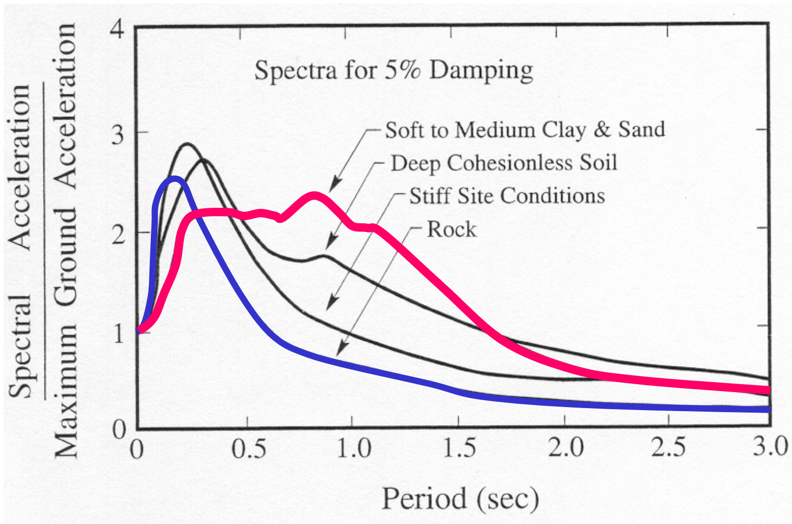
## Site Amplification Effects

- Amplification of ground motion
- Longer duration of motion
- Change in frequency content of motion
- Not the same as soil-structure interaction



This is a continuation from the previous slide. Soil-structure interaction occurs for all sites and may be more pronounced at softer sites because of the increased flexibility of the supporting medium. However, soil-structure interaction is a separate issue.

## Site Amplification (Seed et al.)

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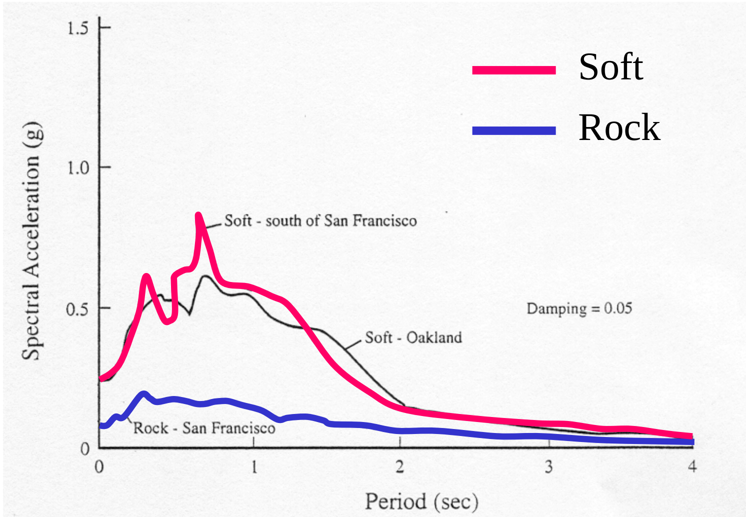
This is from Seed and shows how the shape of the response spectrum is amplified at higher periods. (Note that the curves on this slide are normalized to the PGA whereas the curves on the next slide are not. This is discussed in the note to the next slide).

The USGS maps are developed essentially for the blue line, but motions on very soft soil may be better represented by the red line. The effects of site amplification were devastating in Mexico City during the 1985 earthquake. The earthquake occurred in a subduction slab in the Pacific Ocean with a focus 350 km from Mexico City. Most of the destruction in the city ($4 billon damage, 9000 deaths) occurred as a result of the site amplification. Buildings with a period of about 2.0 seconds were most affected as this was the period of the surface waves preferentially amplified by the underlying clays. The duration of strong shaking was also increased in the city.

# Site Amplification: Loma Prieta Earthquake

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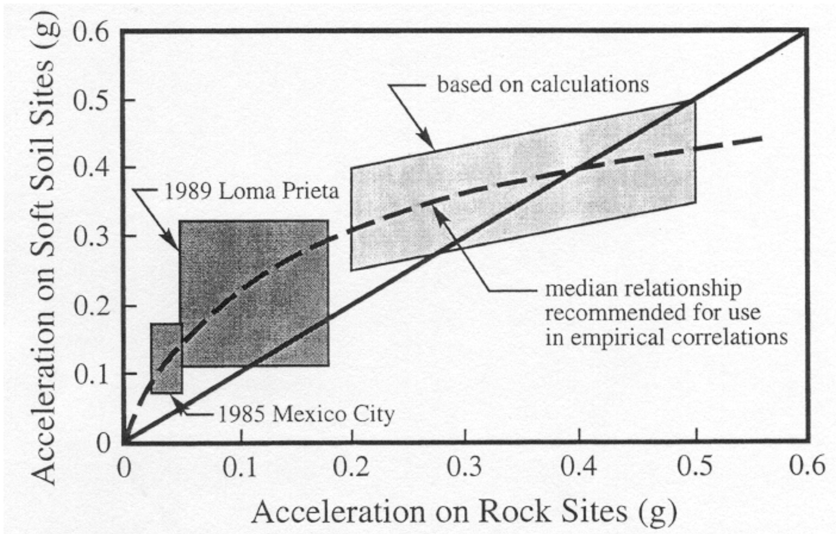
This is a similar slide for the Loma Prieta earthquake. Note the vast difference in response on firm rock in San Francisco vs softer soils south of San Francisco and in Oakland.

Because of site amplification, an isoseismal map of the Loma Prieta earthquake would show that the largest intensity is not coincident with the epicenter.

It is interesting to note that the Seed approach (see the previous slide) for site effects was used for a quarter of a century before anyone realized what this slide shows so clearly -- that the PGA is influenced very strongly by site conditions. Seed (see the previous slide) normalized to PGA and, therefore, completely lost this effect.

## Site Amplification: Loma Prieta and Mexico City Earthquakes

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This slide shows the ratio of soft soil to rock (PGA) for a variety of peak ground accelerations.

## *NEHRP Provisions* Site Classes

**A** Hard rock $v_s$ > 5000 ft/sec

**B** Rock: 2500 < $v_s$ < 5000 ft/sec

**C** Very dense soil or soft rock: 1200 < $v_s$ < 2500 ft/sec

**D** Stiff soil : 600 < $v_s$ < 1200 ft/sec

**E** $V_s$ < 600 ft/sec

**F** Site-specific requirements

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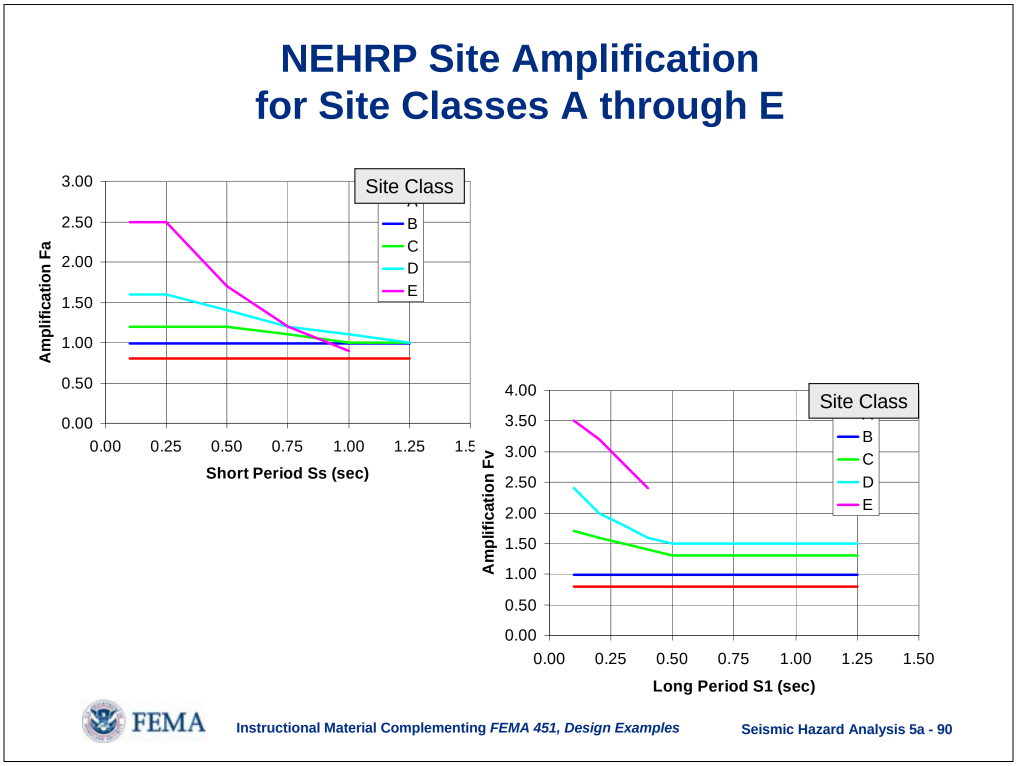
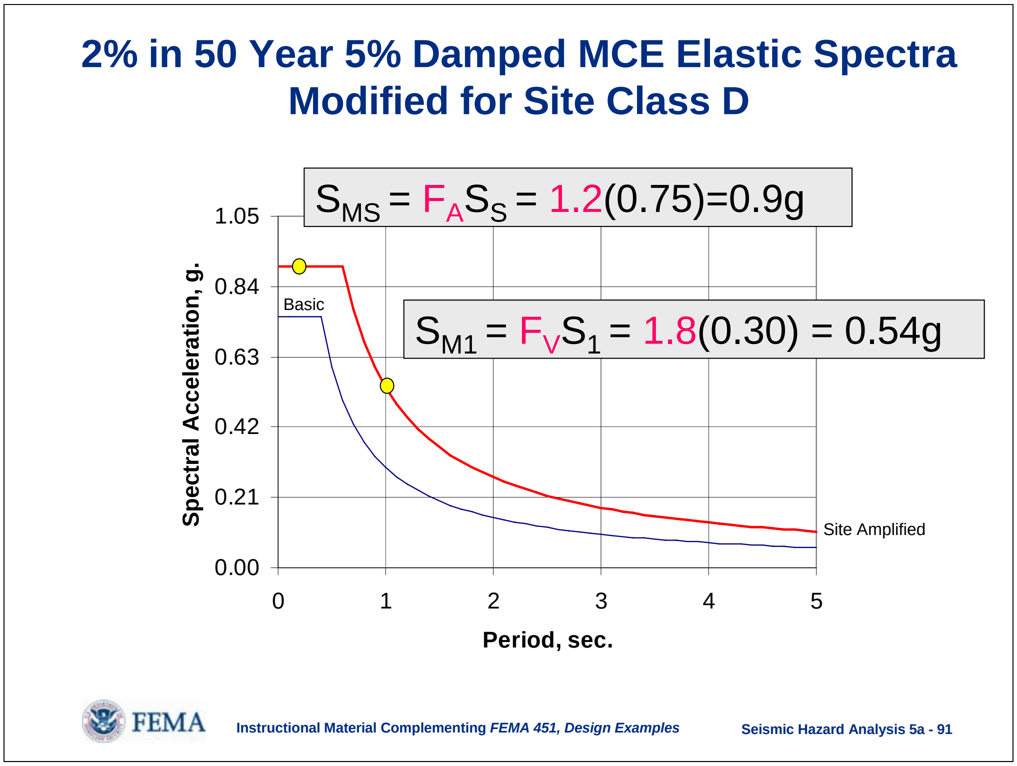
The *NEHRP Recommended Provisions* use the firm soil USGS maps (modified for deterministic cap in the western US) and then apply a series of amplification factors to the mapped values with the amplification factor depending on the characteristics of the soil at the site. For most soils, the shear wave velocity can be used to determine the Site Class.

The maps are based on Site Class B.




This slide shows the *NEHRP Recommended Provisions* site amplification factors. Note that there are two sets of factors: one for the short period (0.2 sec) acceleration and one for the long period acceleration.

Note that all factors for Site B are 1.0 because this is what the maps are based on. Site Class A gets a reduction because it is stiffer that Site B.




This is the first slide in a series that goes through the development of the *NEHRP Recommended Provisions* design spectrum starting with the mapped values, amplifying for site conditions (this slide), modifying for "maximum considered earthquake," and modifying for ductility.

The blue line shows the initial spectrum and the red line shows the amplified spectrum for this Site Class D structure. Note that the 2% in 50 year mapped values have been used.

## Scaling of *NEHRP Provisions* Spectra by 2/3 for "Margin of Performance"

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

Design with current maps (2% in 50 year) but scale motions by 2/3

Results in 2/3 x 1.5 = 1.0 deterministic earthquake (where applicable)

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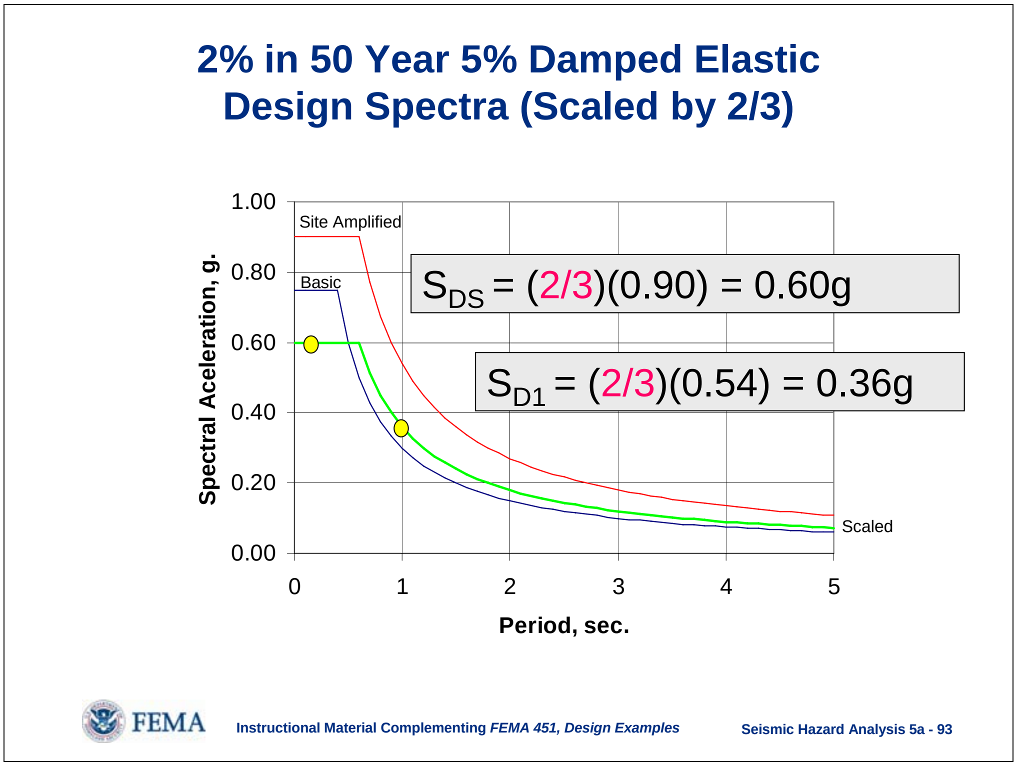
As mentioned previously, the USGS maps are based on 2% in 50 year probability as are the *NEHRP Recommended Provisions* maps. However, the ground motions so obtained (subjectively) exceed the notion of maximum considered ground motion.

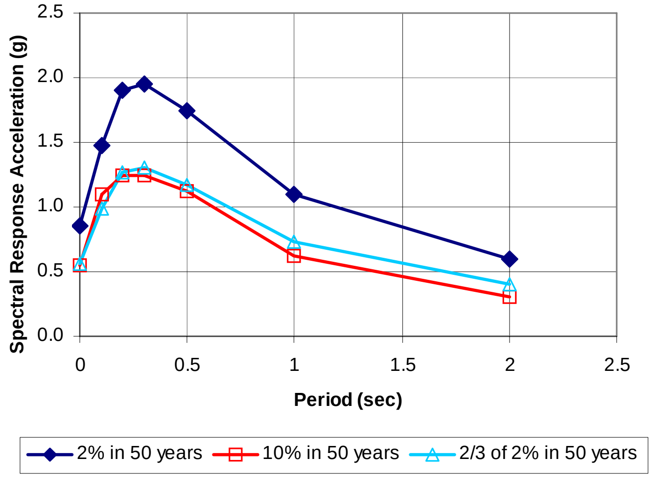
Going to a 10% in 50 year probability would work well for the western states but would go too far in the eastern states (producing motions too low for design). Recall Slide 44.

The solution was to use for design 2/3 of the mapped 2% in 50 year values.




The green line shows the site amplified spectrum (red line) multiplied by 2/3. This could be considered a design elastic response spectrum.

# Effect of Scaling in Western United States

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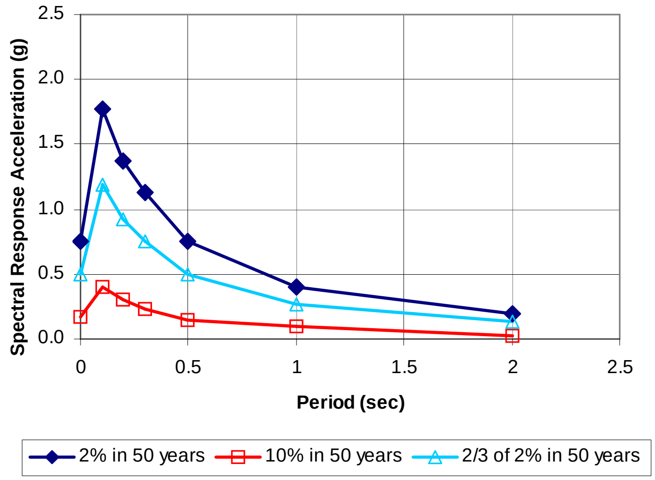
This slide shows three response spectra for the western states. The dark blue line is the 2% in 50 year spectrum and the red line is the 10% in 50 year spectrum. The light blue line is the 2% in 50 year line multiplied by 2/3. As can be seen, the resulting spectrum is almost identical to the 10% in 50 year spectrum. Hence, it could be said that in the western states, one is essentially designing with a 10% in 50 year spectrum.

## Effect of Scaling in Eastern United States

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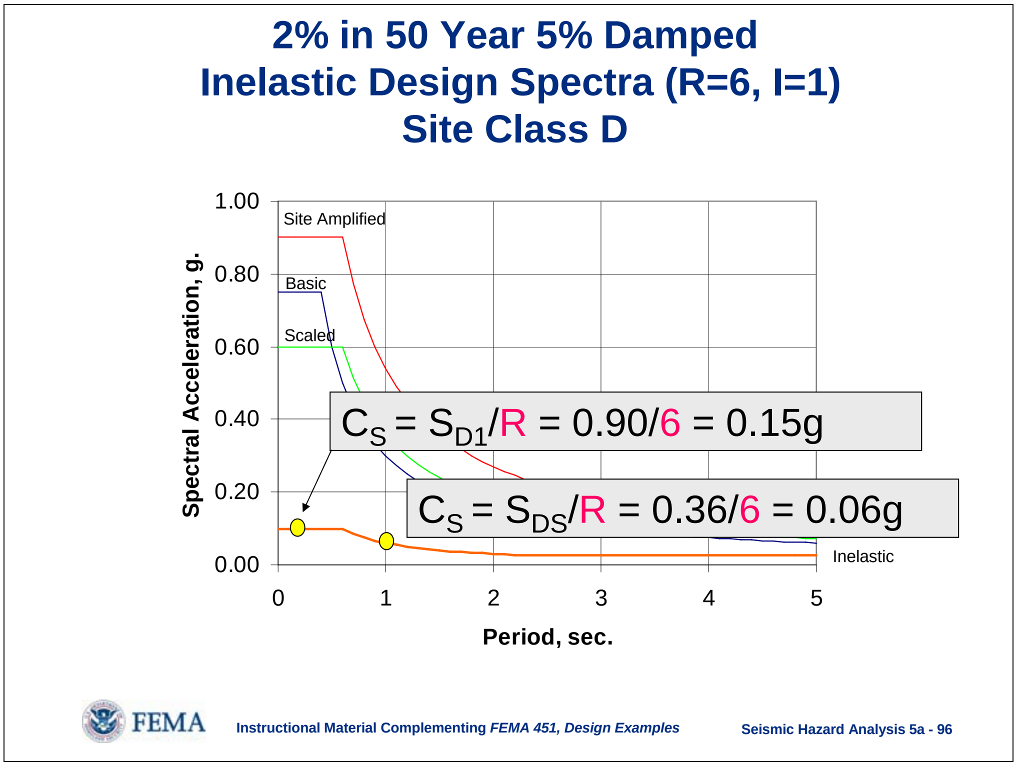
In the eastern states, the effect of scaling is quite different. Note how the scaled (light blue line) gives greatly increased accelerations compared to the 10% in 50 year spectrum.

Versions of the *NEHRP Recommended Provisions* issued before 1997 were based on 10% in 50 year maps (not the recent USGS maps) and were used without the 2/3 factor. Hence, the use of the new 2% in 50 year maps with the 2/3 factor applied has the effect of increasing the design ground motions in the eastern states compared to the previous maps, whereas the accelerations in the western states were essentially unchanged.




Here, the expected ductility supply is used to convert the elastic design spectrum to the inelastic design spectrum. The bottom curve would be used to estimate the base shear demand for the structure.

## Basis for Reduction of Elastic Spectra by *R*

Inelastic behavior of structures

Methods for obtaining acceptable inelastic response are presented in later topics

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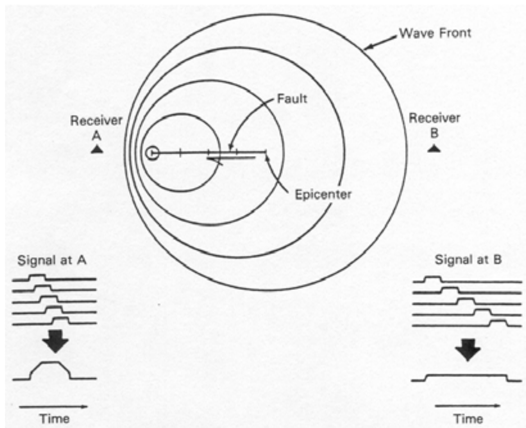
Inelastic behavior has already been discussed in a previous topic.  This slide emphasizes that information on how to obtain “good” inelastic behavior will be addresses in the individual topics on steel, concrete, masonry, and timber structures.

## Directionality and “Killer Pulse” Earthquakes

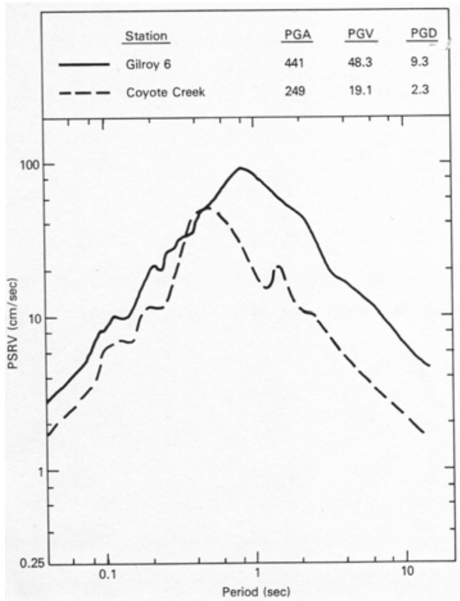
For sites relatively close to the fault, the direction of fault rupture can have an amplifying effect on ground motion amplitude.






Another important effect not considered in the seismic hazard maps is directionality of ground motions. When the fault rupture front is moving towards a site, the seismic waves “pile up,” causing relatively stronger shaking. This is a near-field effect that can be responsible for generation of “killer pulses” -- acceleration histories that have one or two unusually high incremental velocity pulses. This effect can be important for all structures.

## Effect of Directionality on Response Spectra

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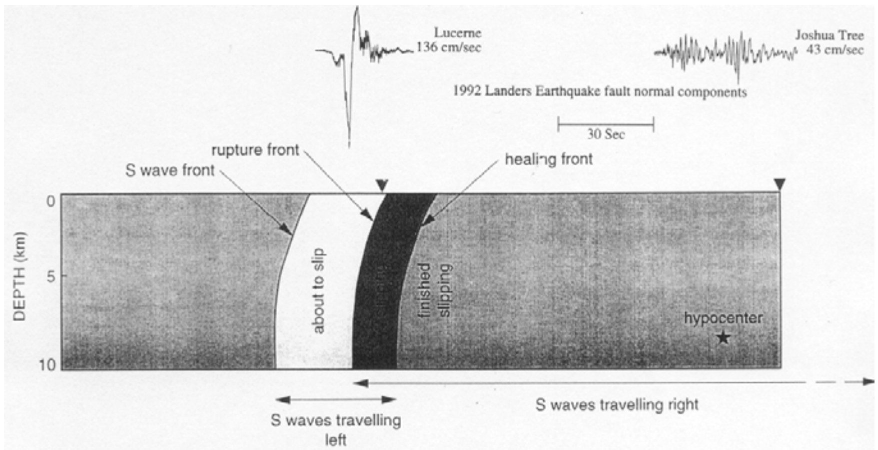
This is a plot of two response spectra generated from the same earthquake. Note how the spectrum for the ground moving towards the site has increased (the pseudovelocity) at almost all periods but most particularly at the higher periods.

## Effect of Directionality on Ground Motion

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Another illustration of directionality.  Note the differences in the ground motion.