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30 November - 4 December, 2009

Seismic Hazard and Risk Analyses: Issues and Alternatives

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Seismic Hazard and Risk Analyses: Issues and Alternatives

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Outline

- Seismic Hazard and Risk
  - Basic Concepts
  - Assessments
- Probabilistic Seismic Hazard Analysis (PSHA)
- Alternative Seismic Hazard Assessments
  - Seismic Hazard Analysis (SHA)
  - Deterministic Seismic Hazard Analysis (DSHA) or Neo-DSHA
- Observations from Wenchuan, China, Earthquake (M7.9)
- Summary

What is HAZARD? RISK?

What is Seismic Hazard? Seismic Risk?

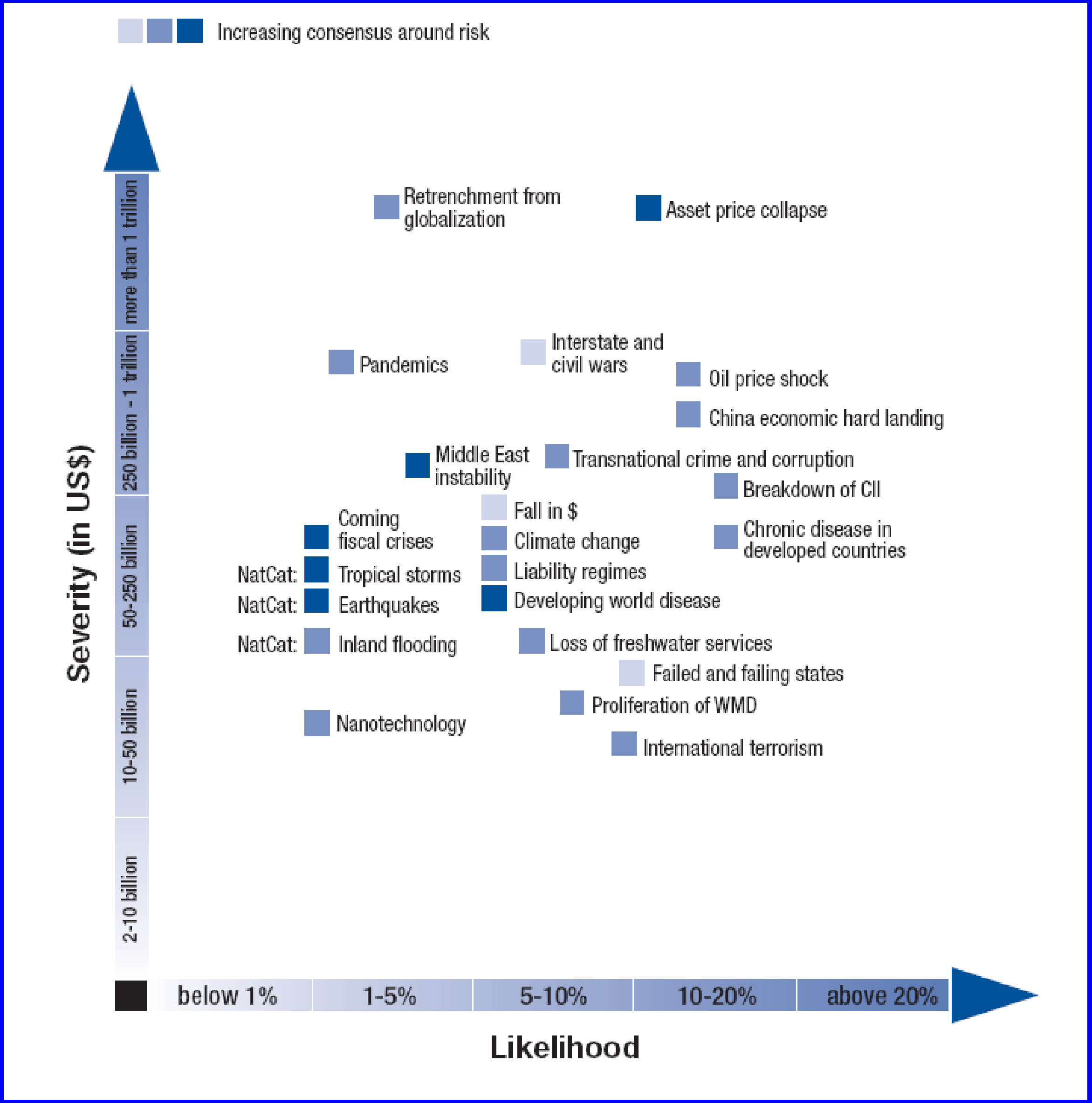
Hazard vs. Risk

- Hazard
  - Something (bad) that could cause harm
  - Quantification:
    - Physical measurement
    - Temporal measurement
    - Spatial measurement

- Risk
  - Probability of harm if something or someone (vulnerability) is exposed to a hazard
  - Quantification:
    - Probability
    - Physical/monetary measurement
    - Temporal measurement
    - Spatial measurement

<u>Risk= Hazard x Vulnerability (someone or something)</u>

Hazard vs. Risk



<u>Natural Hazard</u>:
Earthquakes
Tropical Storms
Floods

<u>Man-made Hazard</u>:
Wars
Terrorism
Crime and corruption

Any event:
1) What?
2) When?
3) Where?

<u>Risk:</u>
1) Probability
2) US$
3) 10 years
4) Global

The 23 core global risks over a 10-year time frame estimated by World Economic Forum (2007).

Hazard vs. Risk

USNRC Risk Definition (1998 White Paper):
“The risk definition takes the view that when one asks, "What is the risk?" one is really asking three questions:

1. "What can go wrong?" - Hazard (scenario)

2. "How likely is it?" - Probability

3. "What are the consequences?“ – Outcome from interaction between hazard and vulnerability

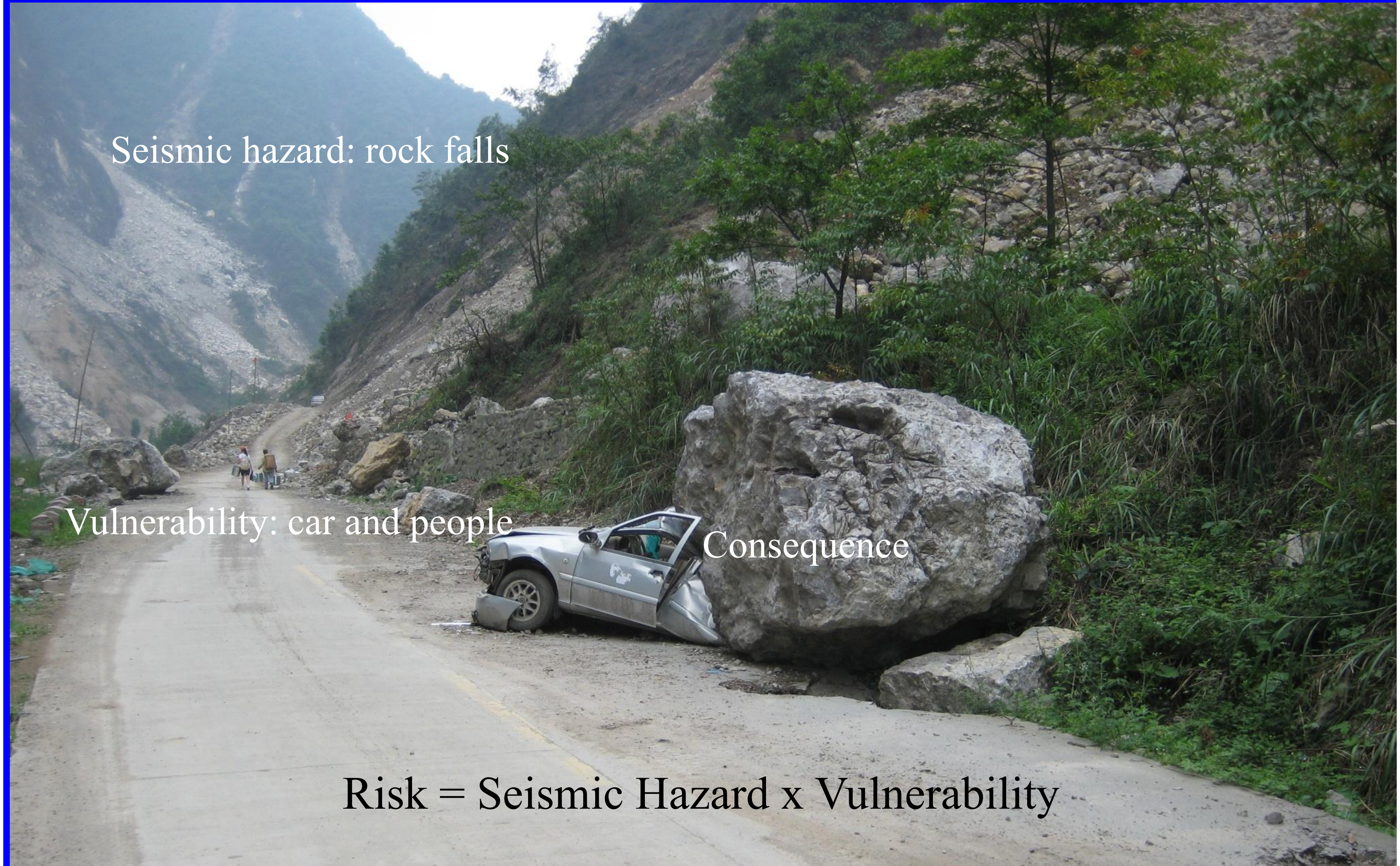
the "risk triplet”

Seismic Hazard vs. Seismic Risk

- Seismic Hazard
  - Natural phenomenon generated by an earthquake, such as fault rupture, ground shaking, liquefaction
  - Quantification:
    - Physical measurement (magnitude, PGA, MMI)
    - Temporal measurement
    - Spatial measurement
- Seismic Risk
  - Probability of harm if something or someone (vulnerability) is exposed to a Seismic hazard
  - Quantification:
    - Probability
    - Physical/monetary measurement
    - Temporal measurement
    - Spatial measurement

<u>Seismic Risk= Seismic Hazard x Vulnerability</u>

Seismic Hazard vs. Seismic Risk



Hazard may or may not be mitigated, but risk can always be reduced

Seismic Hazard and Risk Assessments

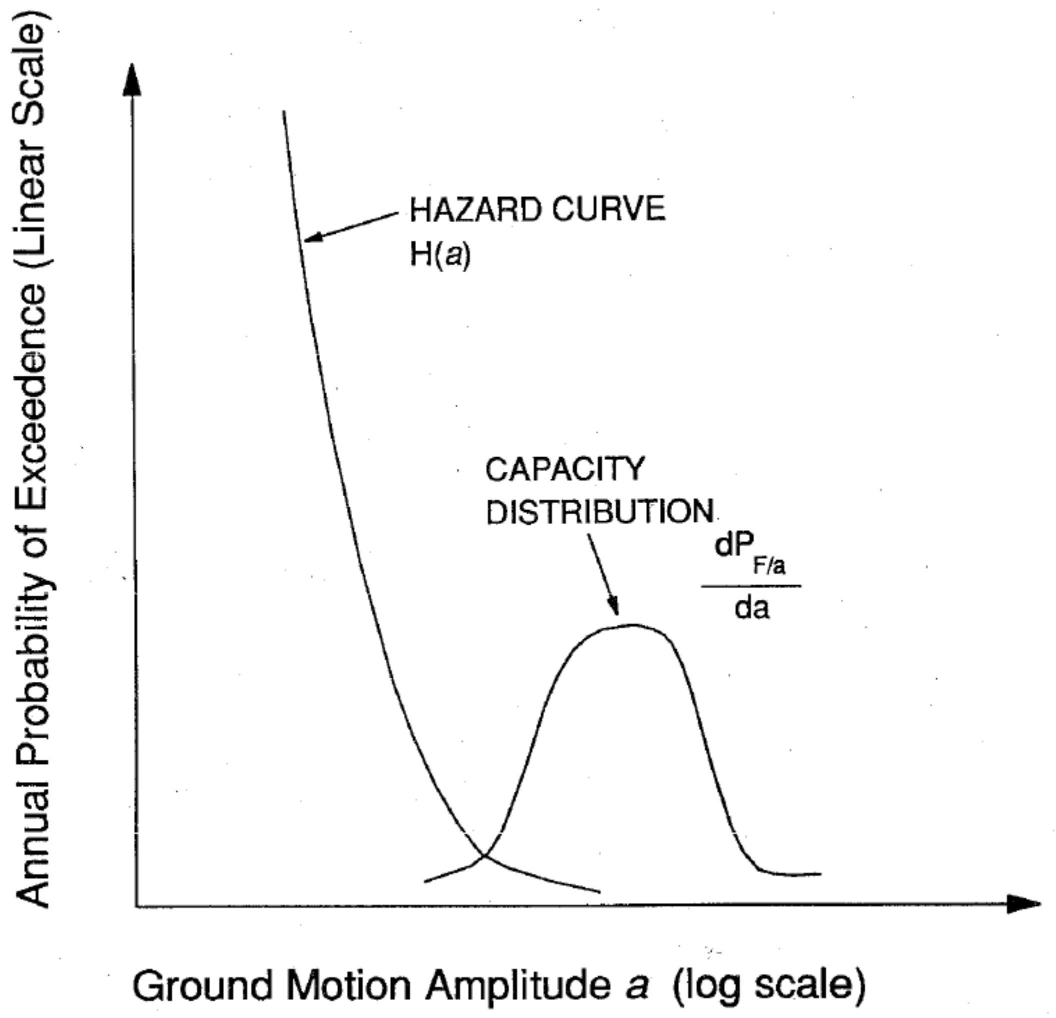
- Seismic Hazard
  - Quantification:
    - Physical measurement (magnitude, PGA, MMI)
    - Temporal measurement
    - Spatial measurement
- Seismic Risk
  - Quantification:
    - Probability
    - Physical/monetary measurement
    - Temporal measurement
    - Spatial measurement

<u>Seismic Risk= Seismic Hazard x Vulnerability</u>

1. Seismic hazard Assessment
2. Hazard and vulnerability interact:
   1) Spatially
   2) Physically
   3) Temporally
3. Risk estimation

Seismic Risk Assessment

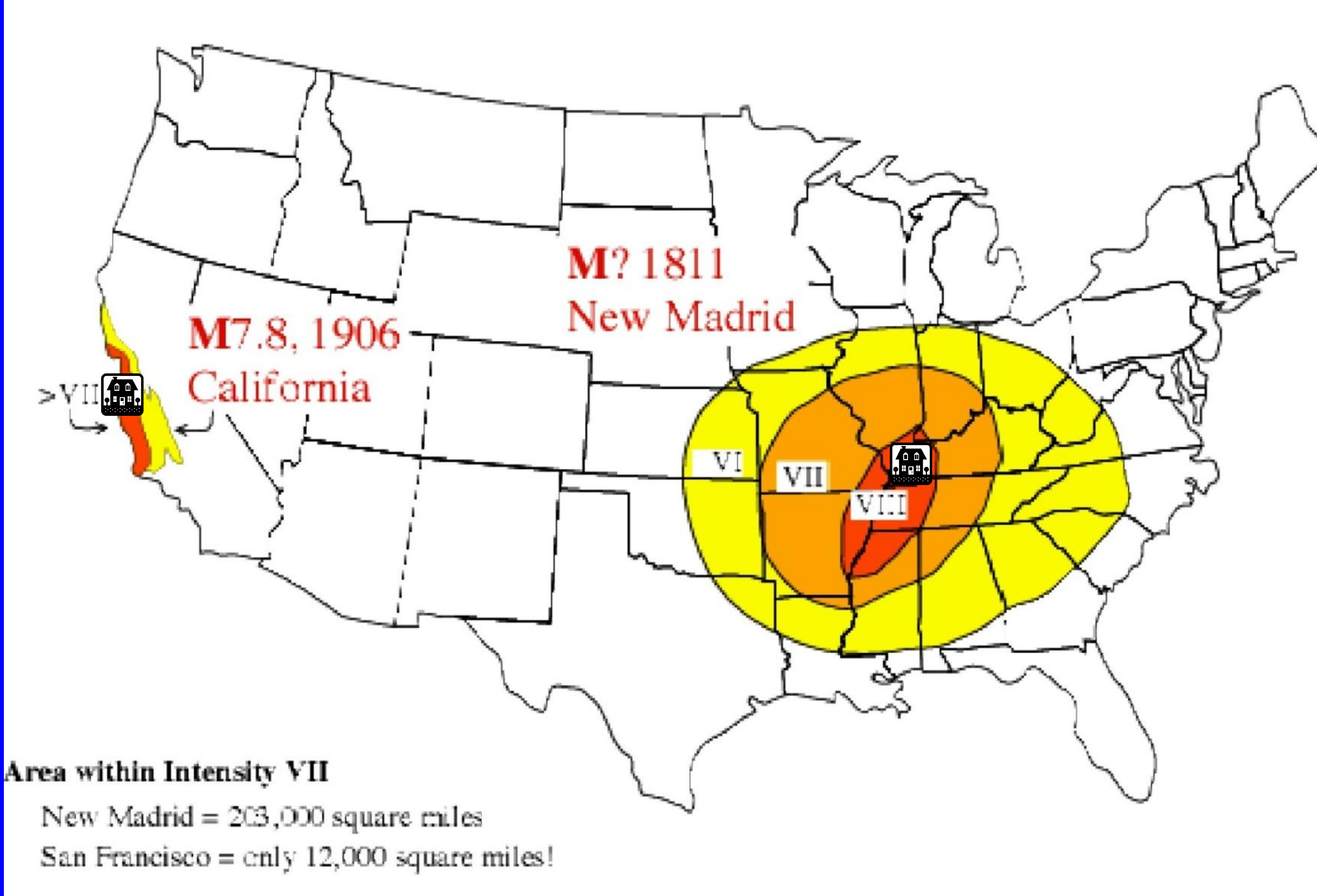
<u>Probabilistic Risk Analysis</u> (PRA) for nuclear facility



The two terms multiplied in the integrand of the "risk integral,"(NUREG/CR-6728)

Seismic Risk Assessment

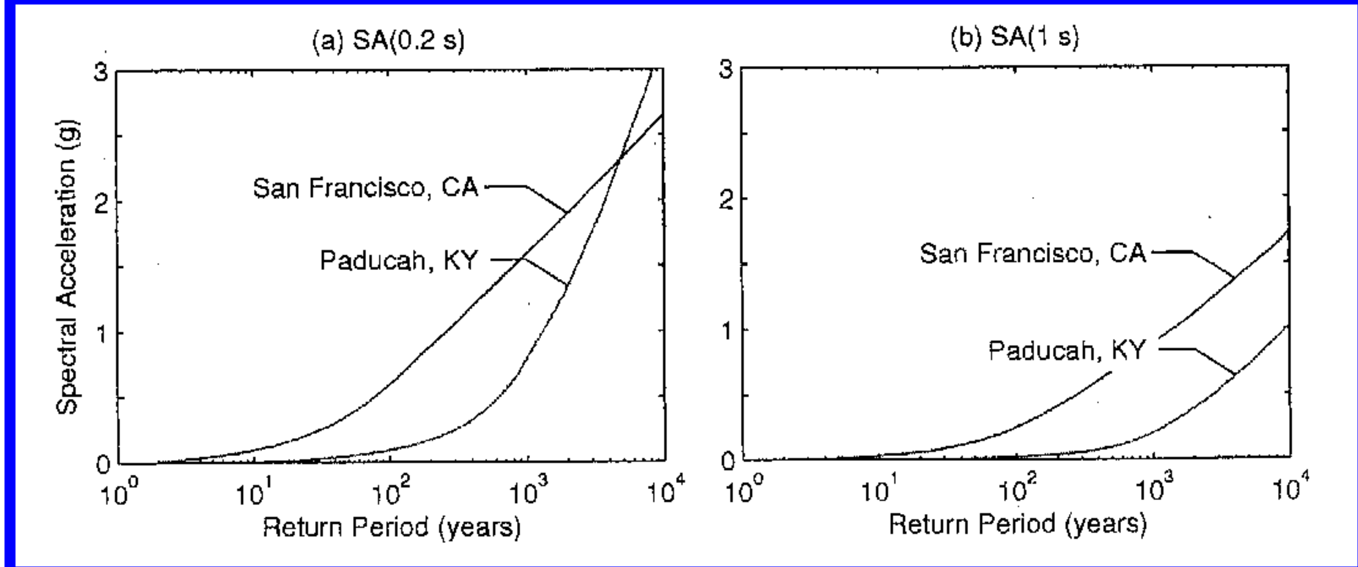
Step 1: Seismic hazard assessment



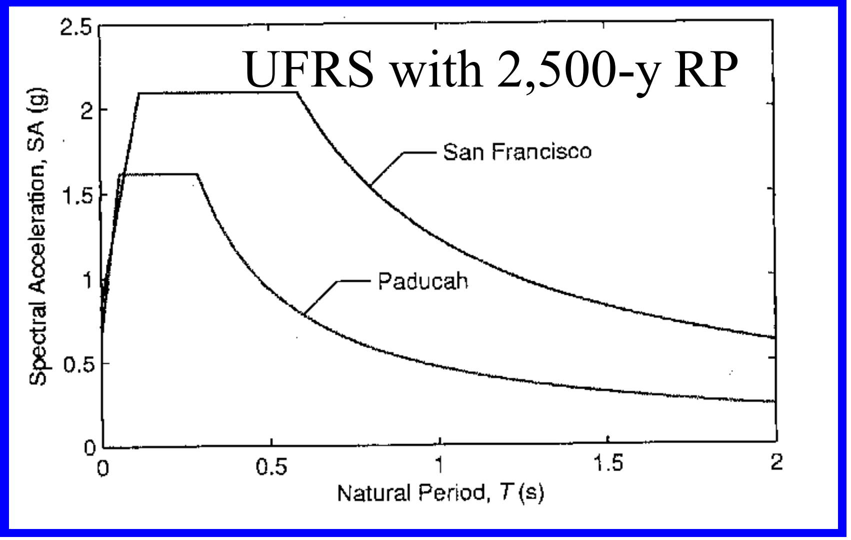
Three-story steel moment-frame building

Seismic Risk Assessment

Step 1: Seismic hazard assessment



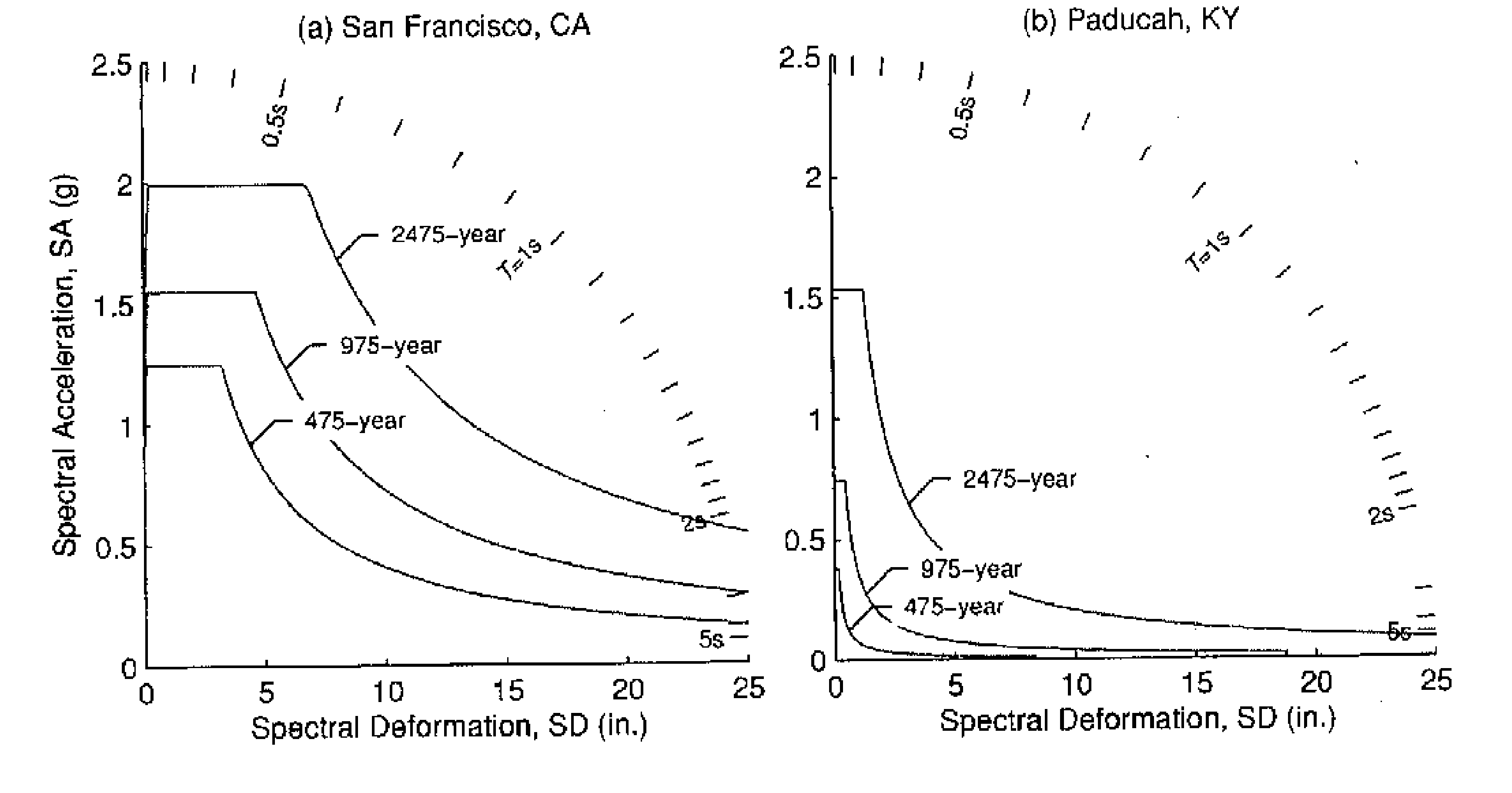
Seismic hazard curves from PSHA



For detail analyses see Malhotra (2006)

Seismic Risk Assessment

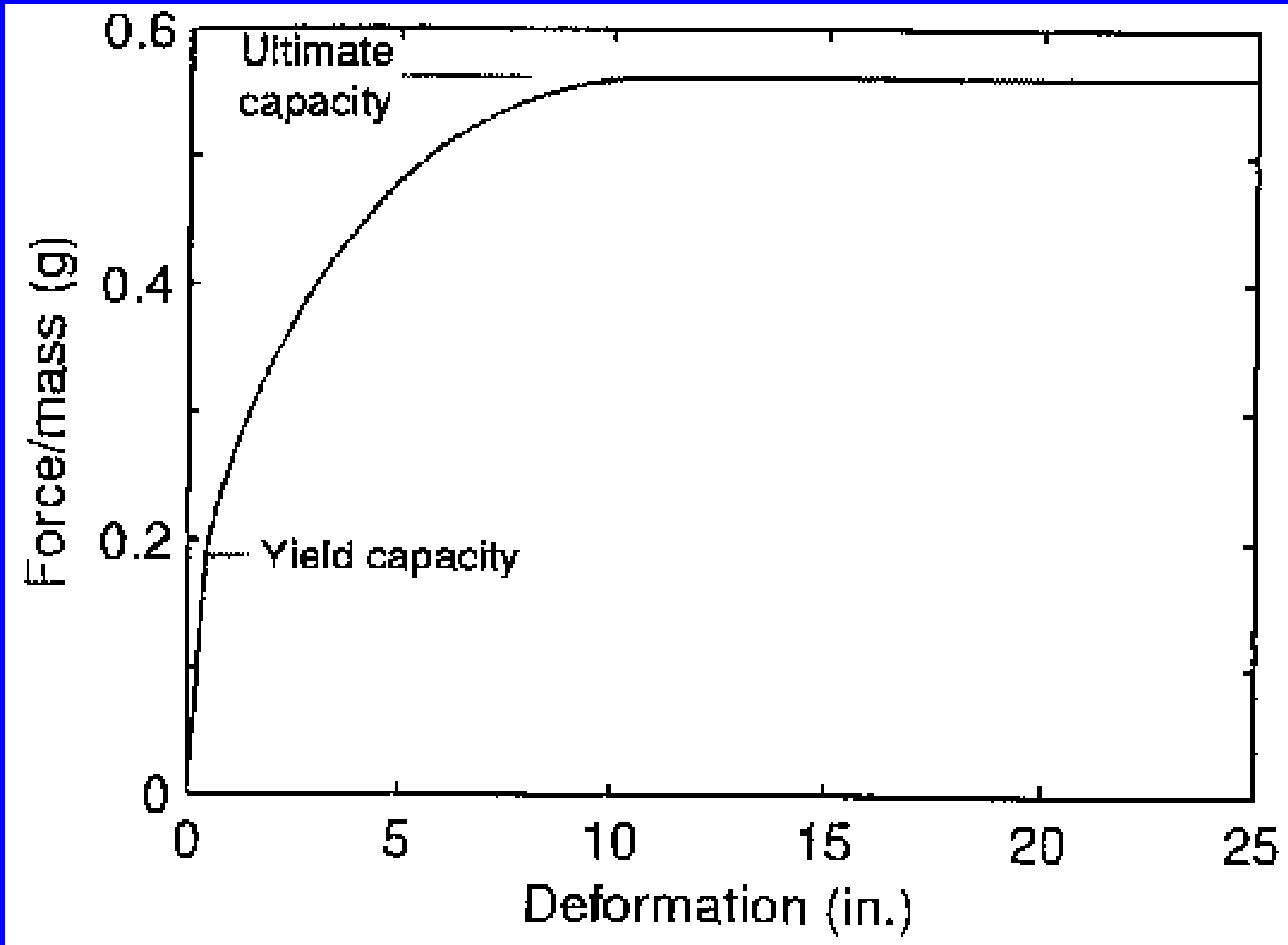
Step 1: Seismic hazard assessment



Demand curves for 5% damping

Seismic Risk Assessment

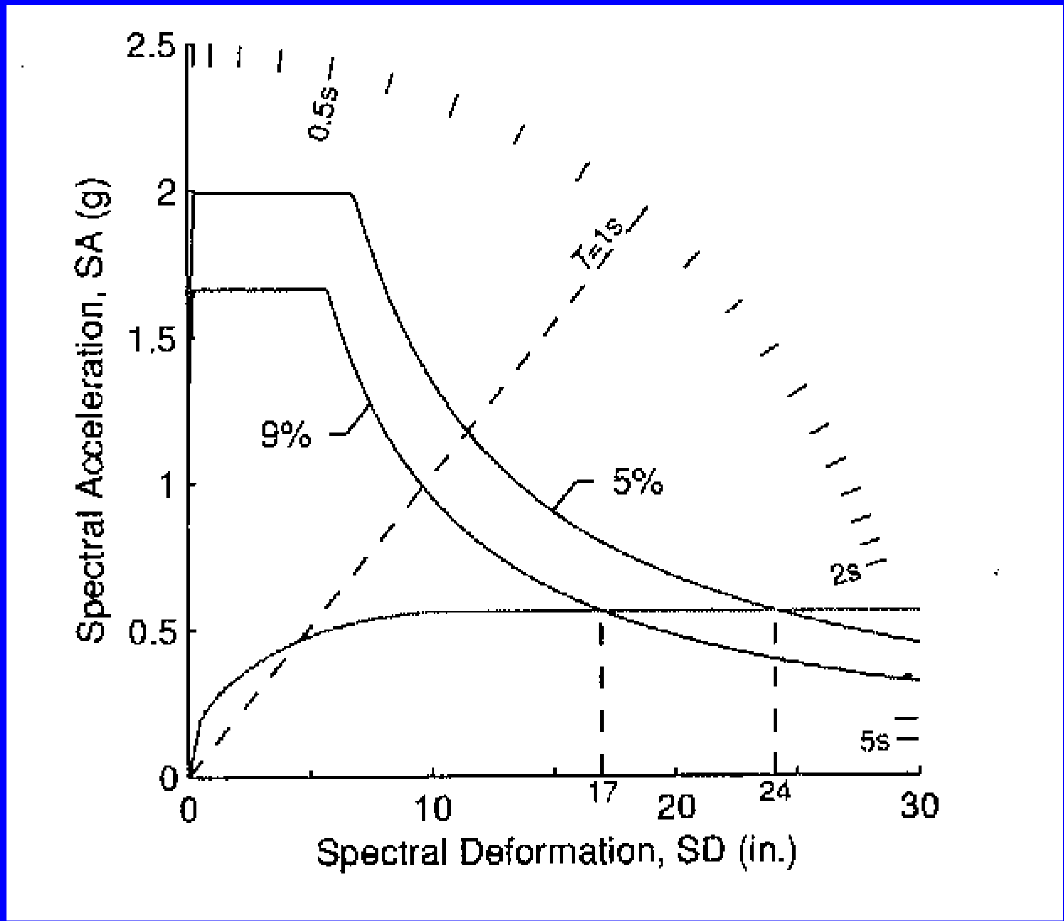
Step 2: Hazard and building interaction (physical)



Capacity curve (building response)

Seismic Risk Assessment

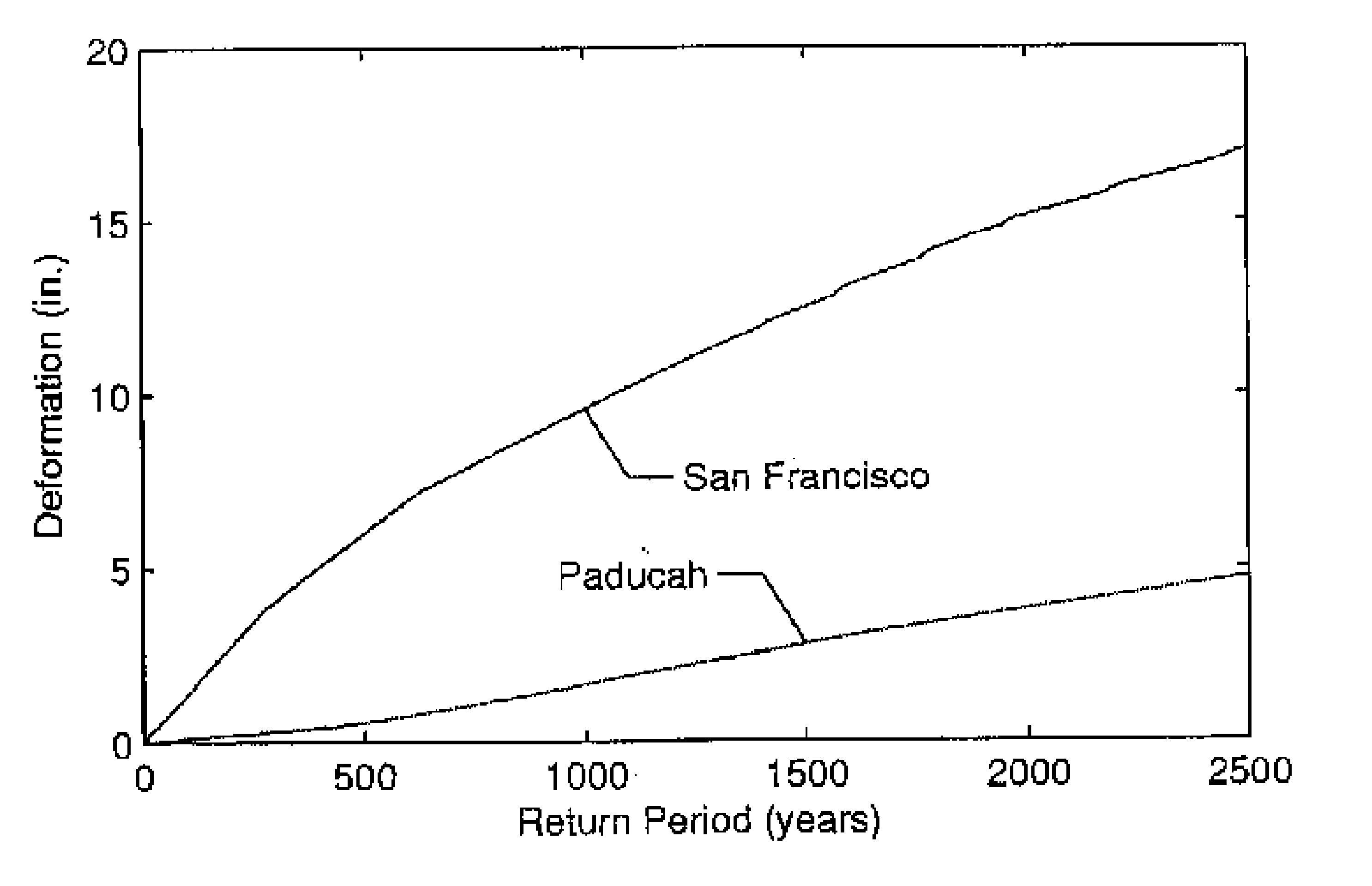
Step 2: Hazard and building interaction (physical)



Demand and capacity curves in SF for ground motion with 2,500y RP

Seismic Risk Assessment

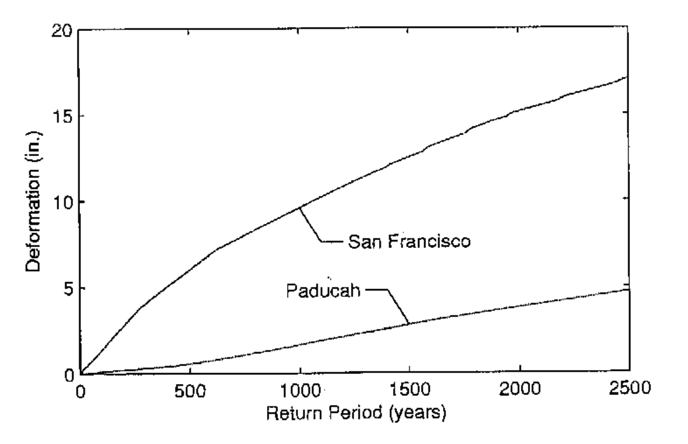
Step 2: Hazard and building interaction (physical)



Deformation curves in SF and Paducah

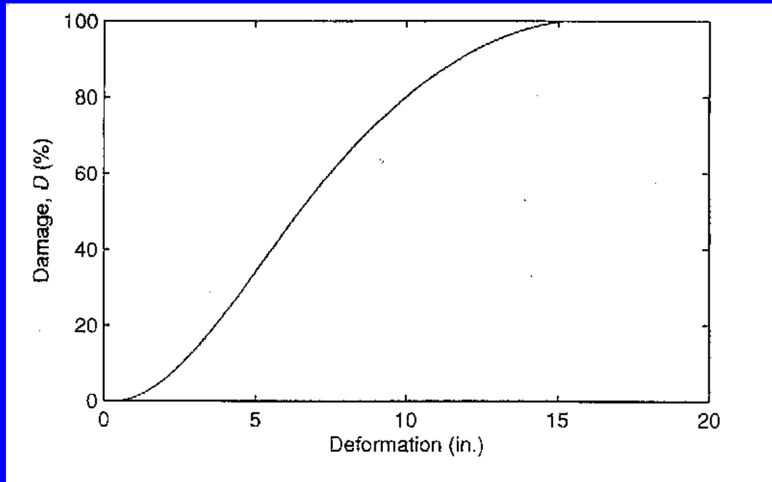
Seismic Risk Assessment

Step 2: Hazard and building interaction (physical)

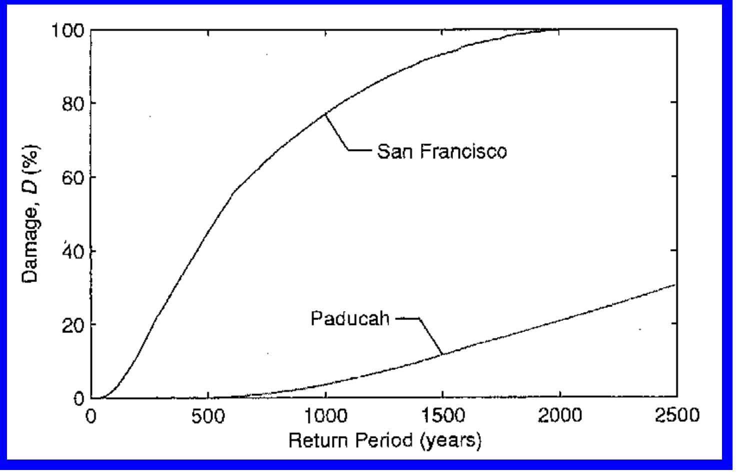


Deformation curves

Deformation vs. damage

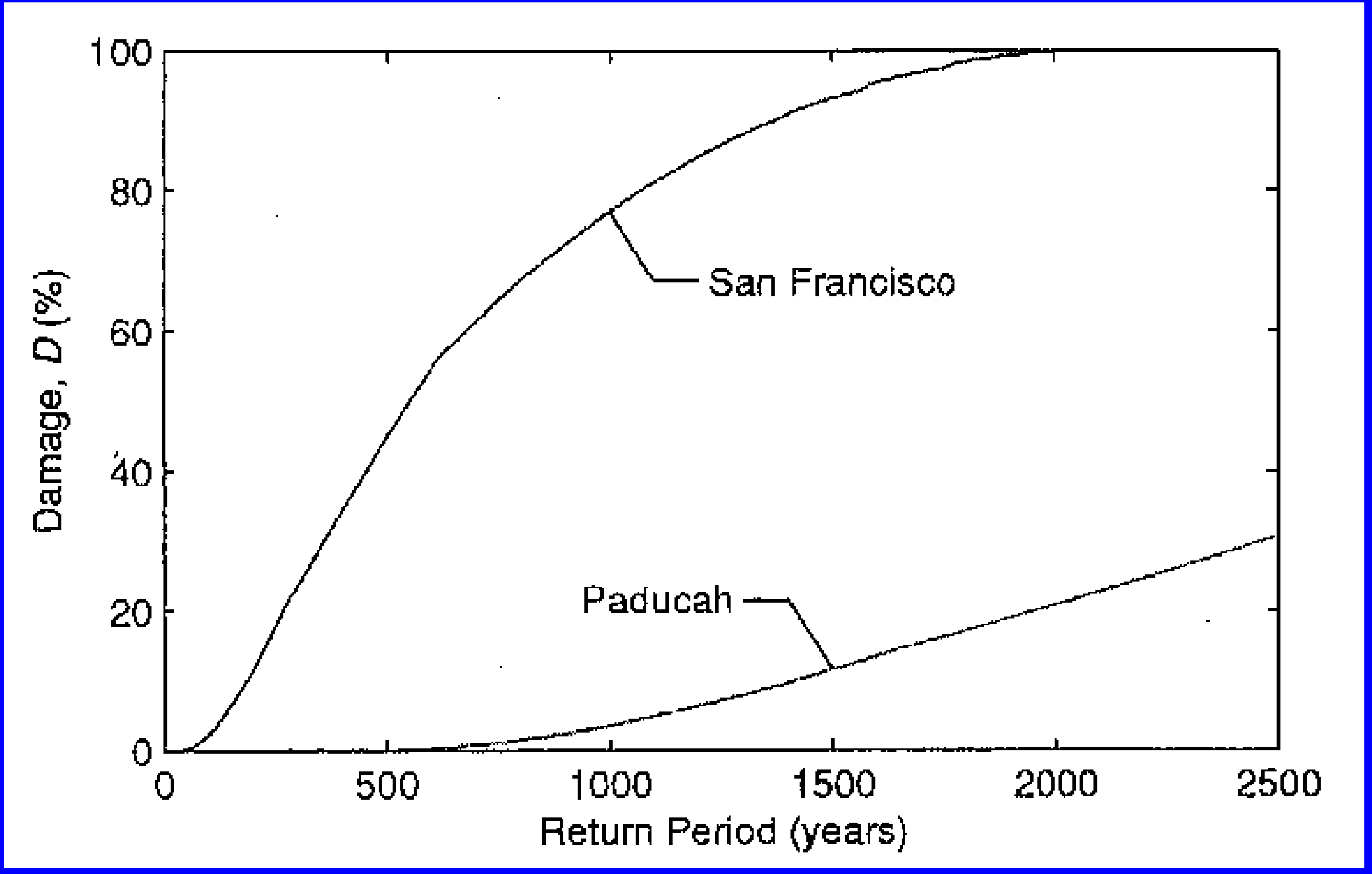


Damage curves



Seismic Risk Assessment

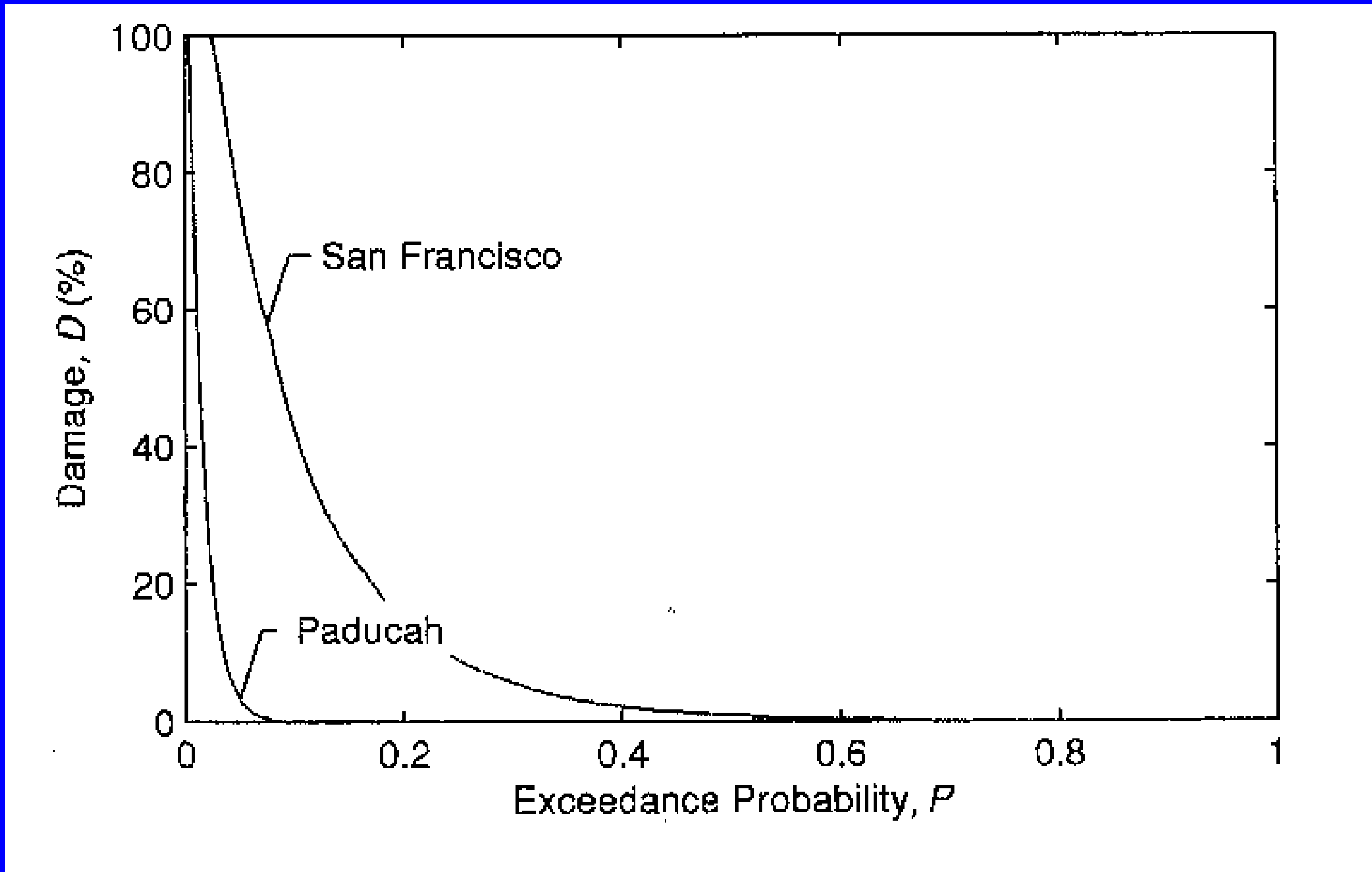
Step 3: Risk estimate



$p = 1 - \exp(-t / RP)$ (Poisson model)

Seismic Risk Assessment

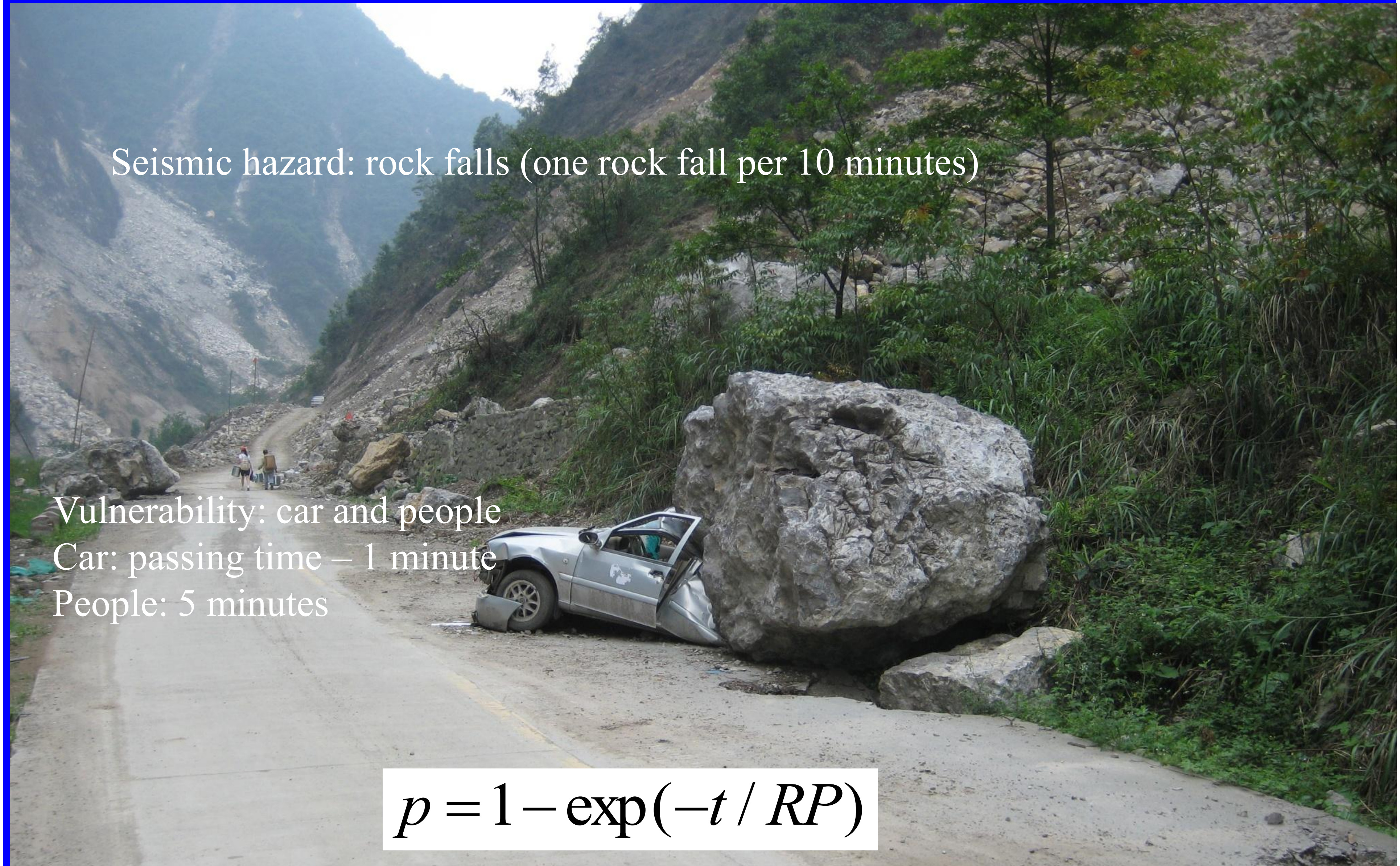
Step 3: Risk estimate



$$p = 1 - \exp(-t / RP)$$

t=100 years

Seismic Risk Assessment



Seismic hazard: rock falls (one rock fall per 10 minutes)

Vulnerability: car and people

Car: passing time – 1 minute

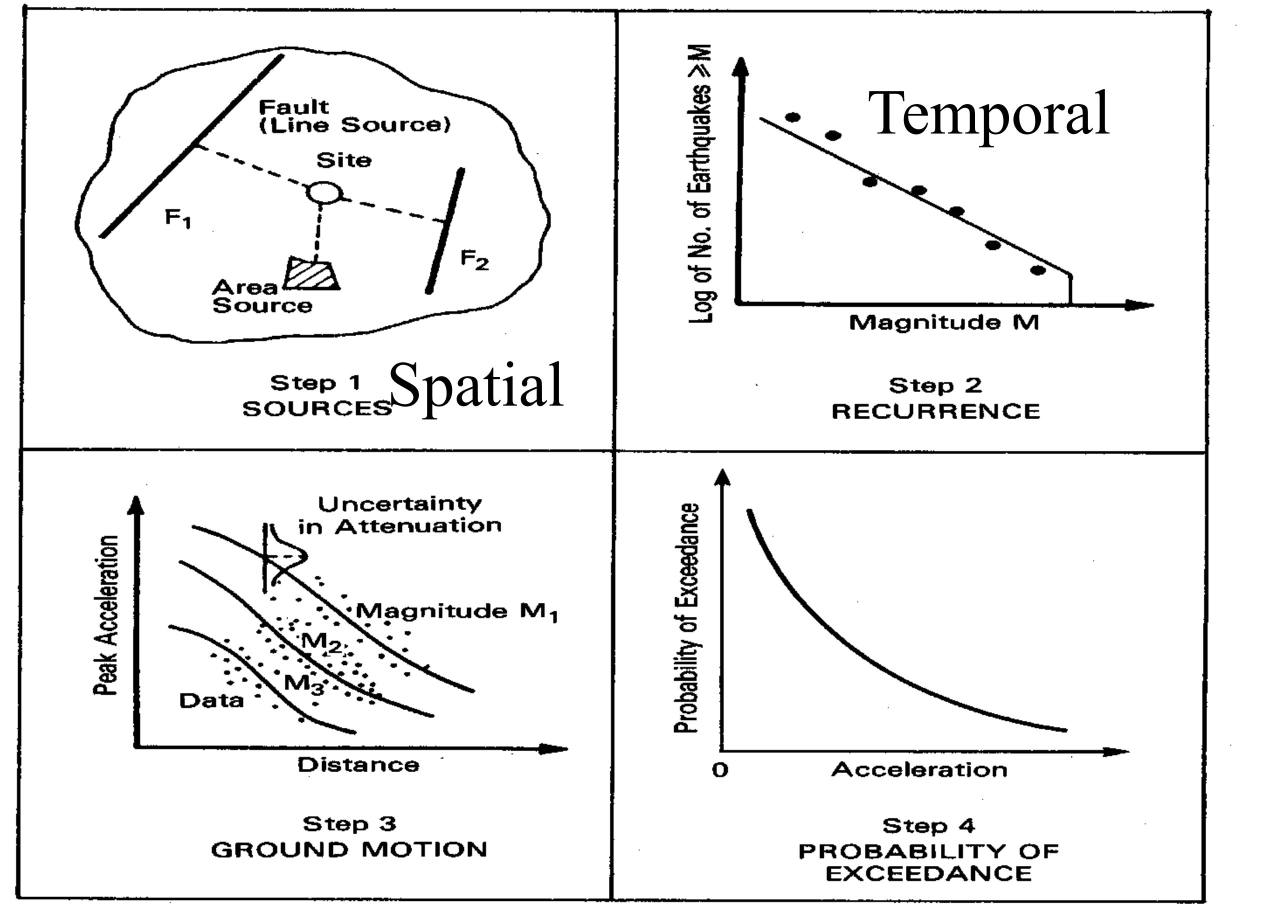
People: 5 minutes

$$p = 1 - \exp(-t / RP)$$

Car: 10% chance being hit; People: 39% chance being hit.

People has much higher chance being injured or killed because of more vulnerable

Probabilistic Seismic Hazard Analysis – PSHA

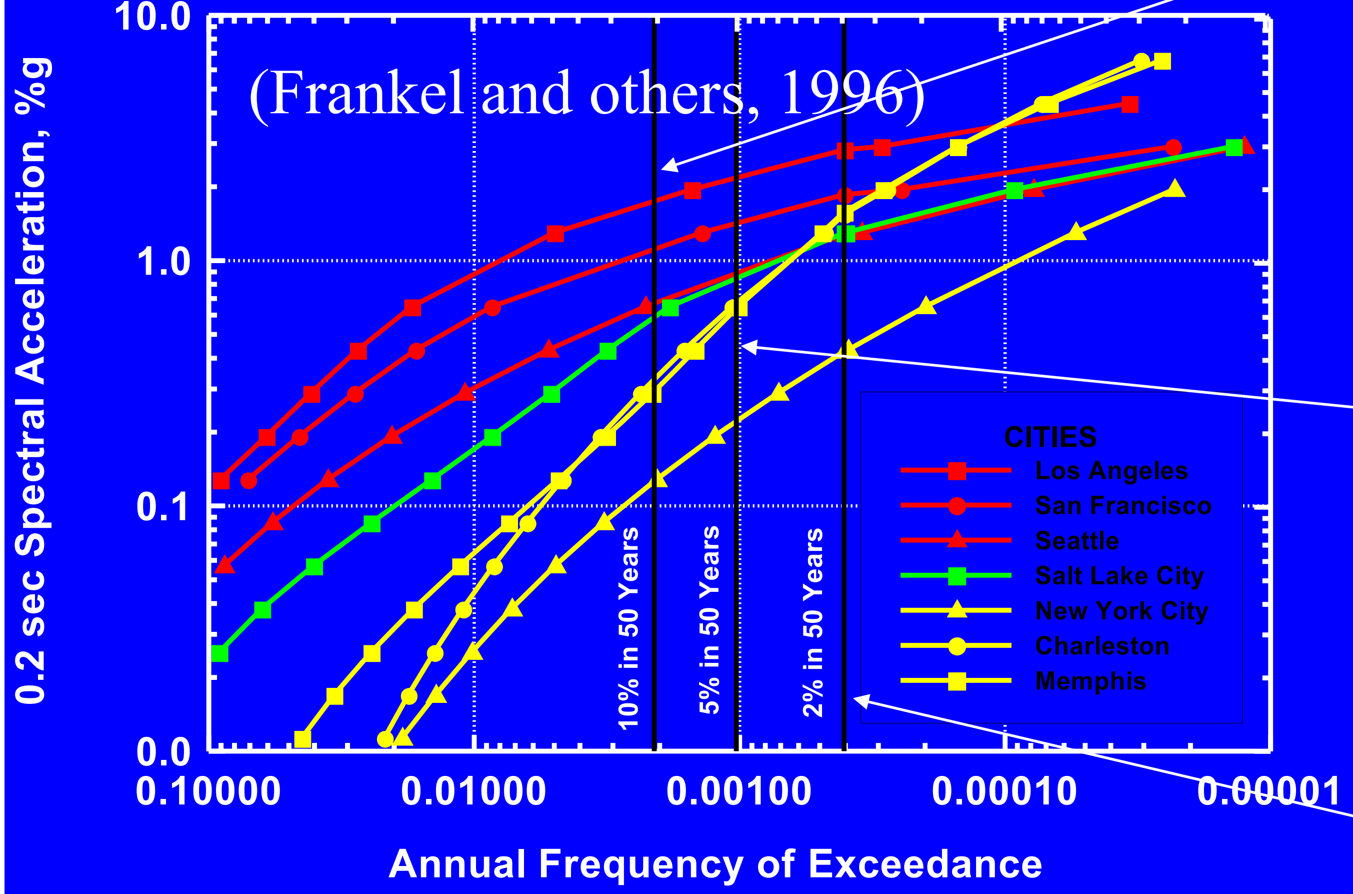


$$\gamma(y) = \sum \nu P(Y \geq y) = \sum \nu \iint \{1 - \int_0^y \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp[-\frac{(\ln y - \ln y_{mr})^2}{2\sigma_{\ln,y}^2}] d(\ln y)\} f_M(m) f_R(r) dm dr$$

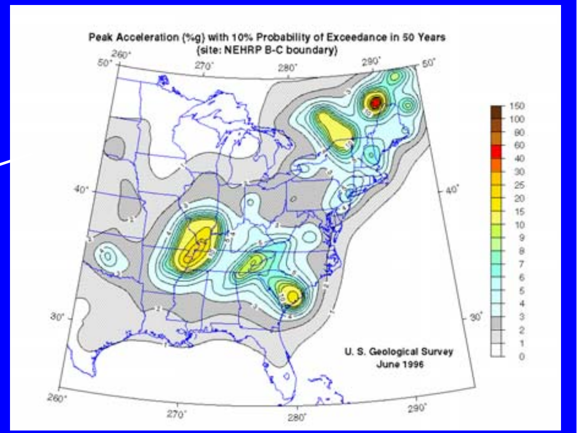
Developed by Cornell in 1970 (Cornell, 1968, 1971)

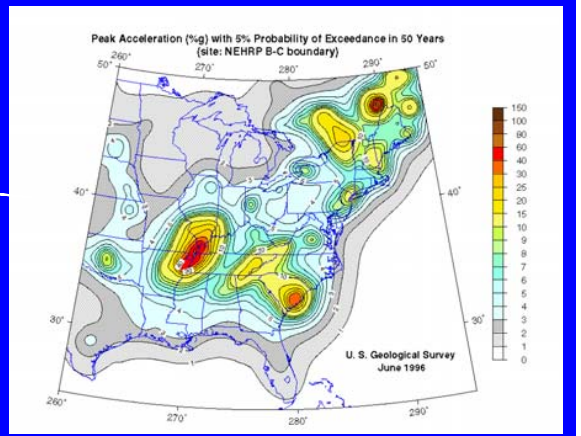
Probabilistic Seismic Hazard Analysis – PSHA

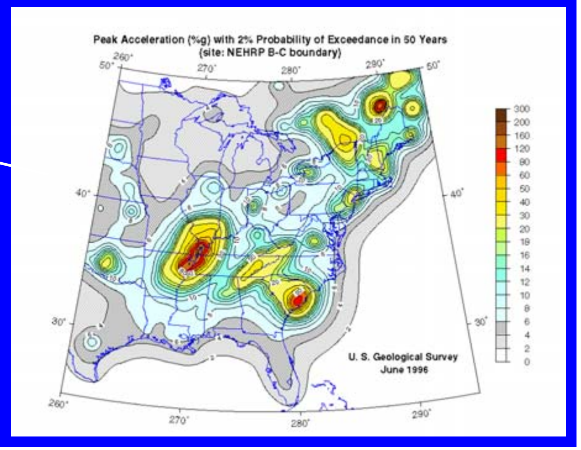
HAZARD CURVES FOR SELECTED CITIES



The US National Seismic Hazard Maps







Development of *Seismic Design Ground Motion*

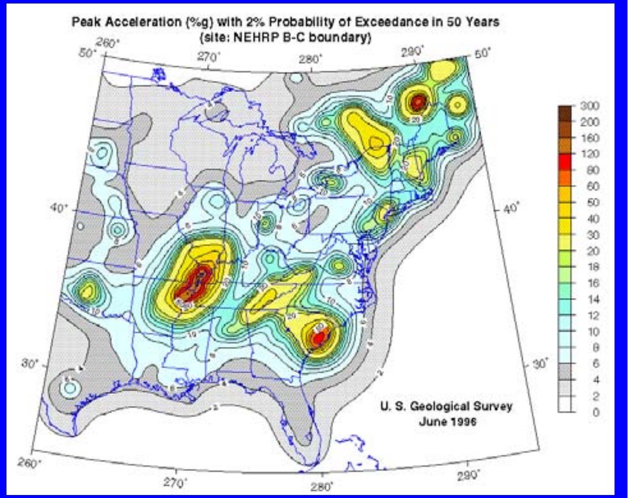
Seismic Hazard Map
(USGS)

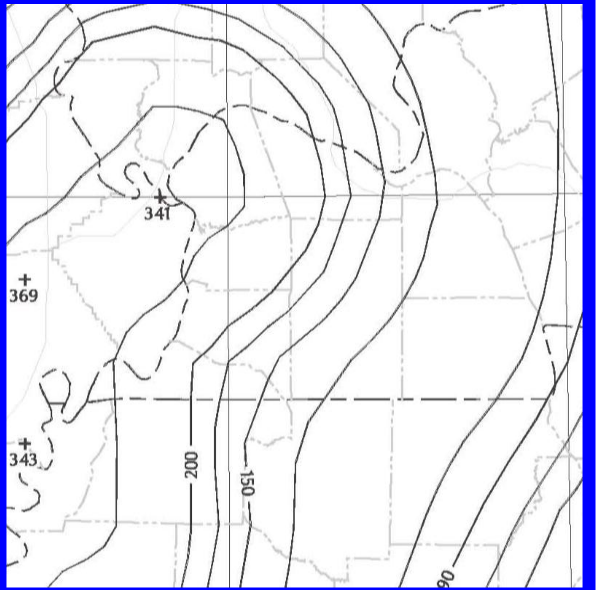
BSSC – engineers, seismologists, and others

Seismic *Design Ground Motions*
(FEMA)

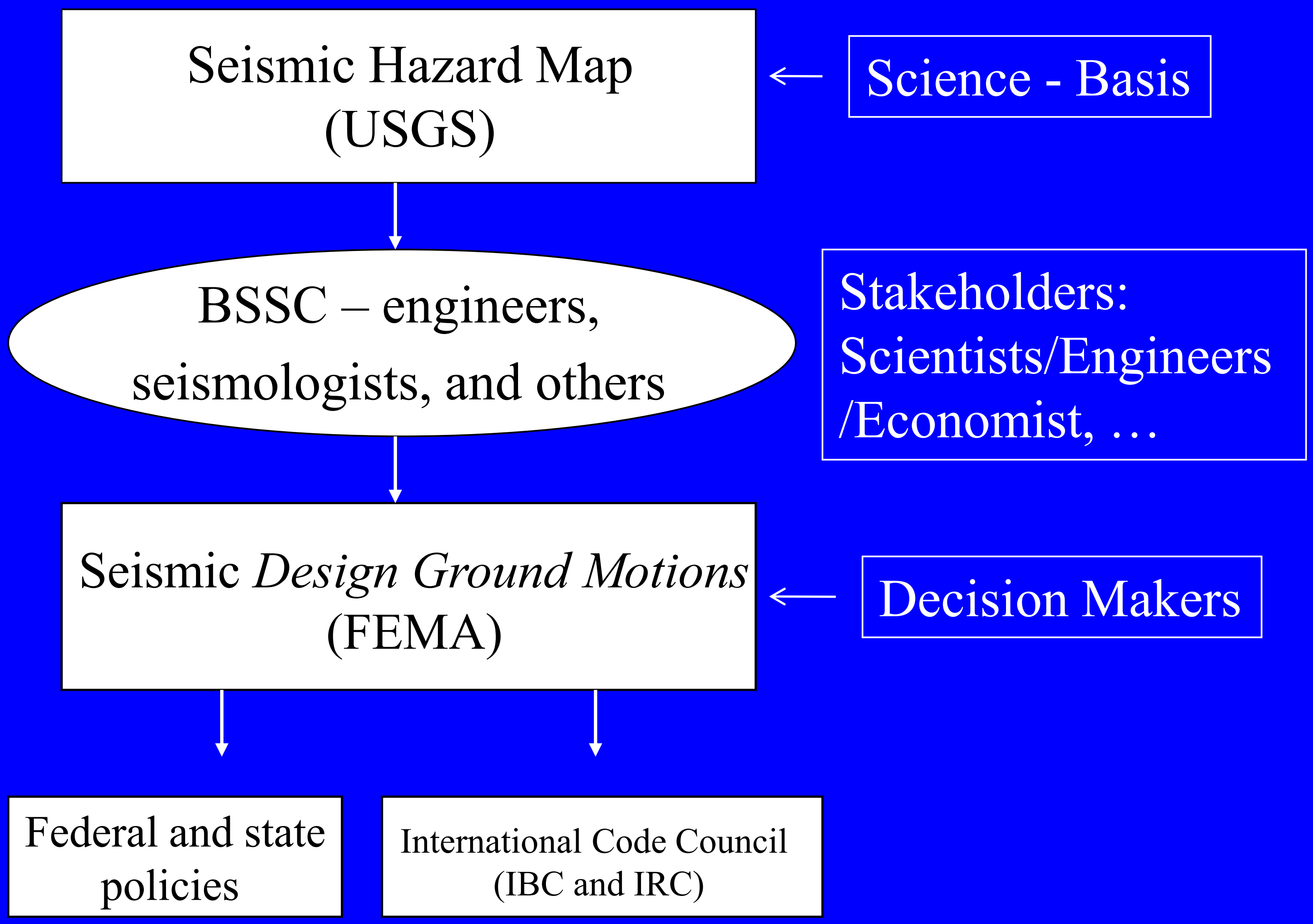
Federal and state policies

International Code Council
(IBC and IRC)

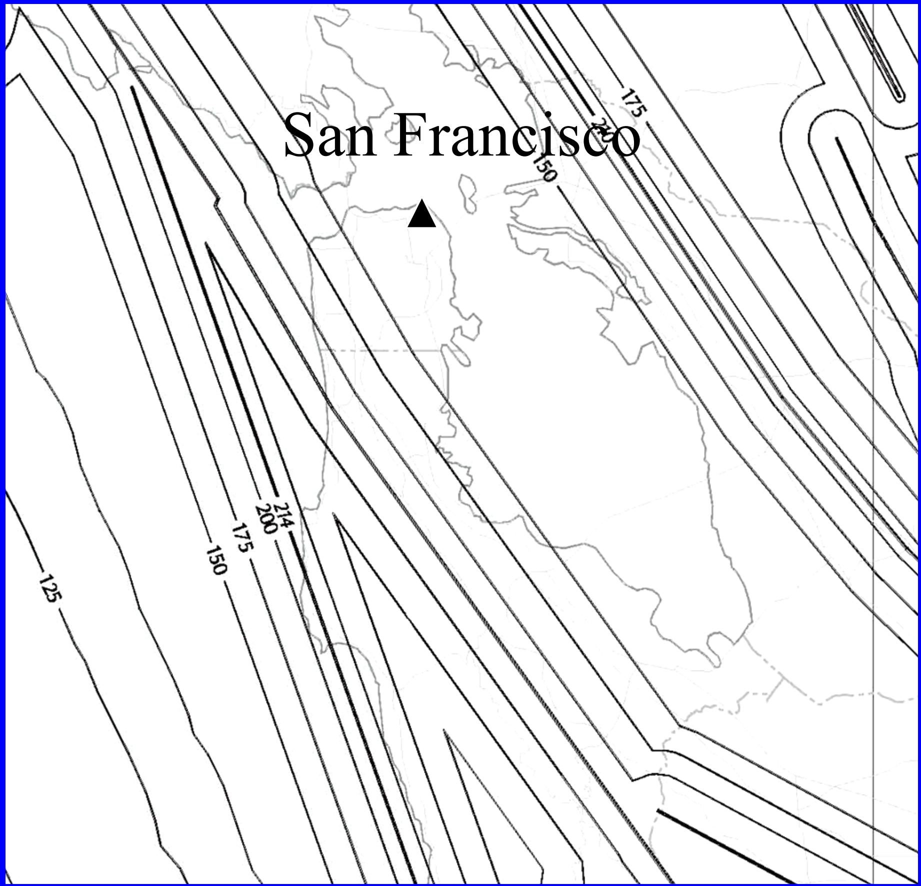


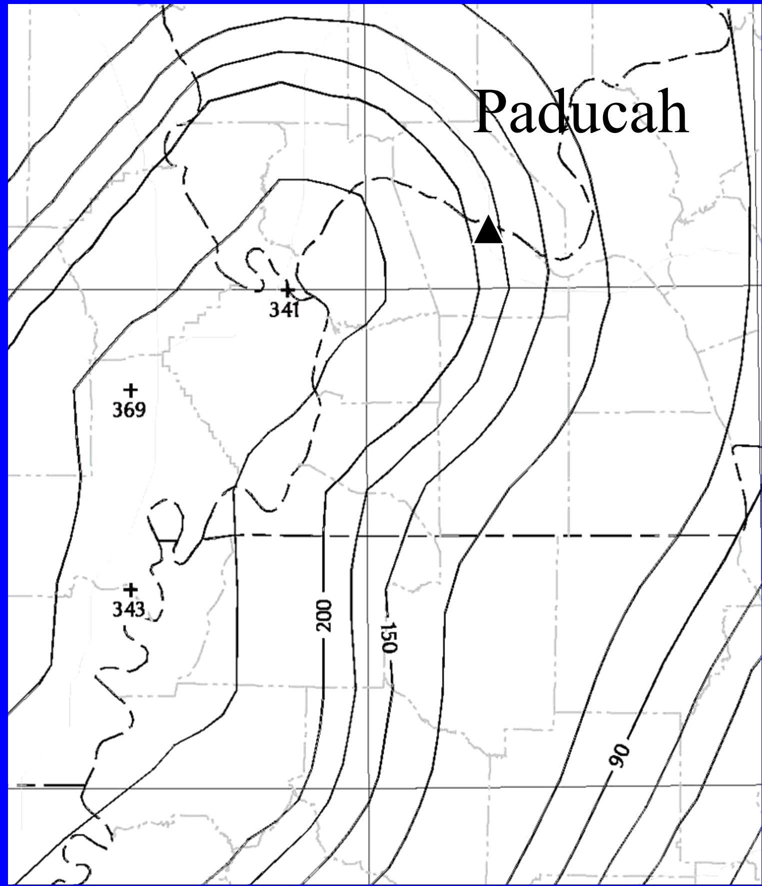


Development of *Seismic Design Ground Motion*



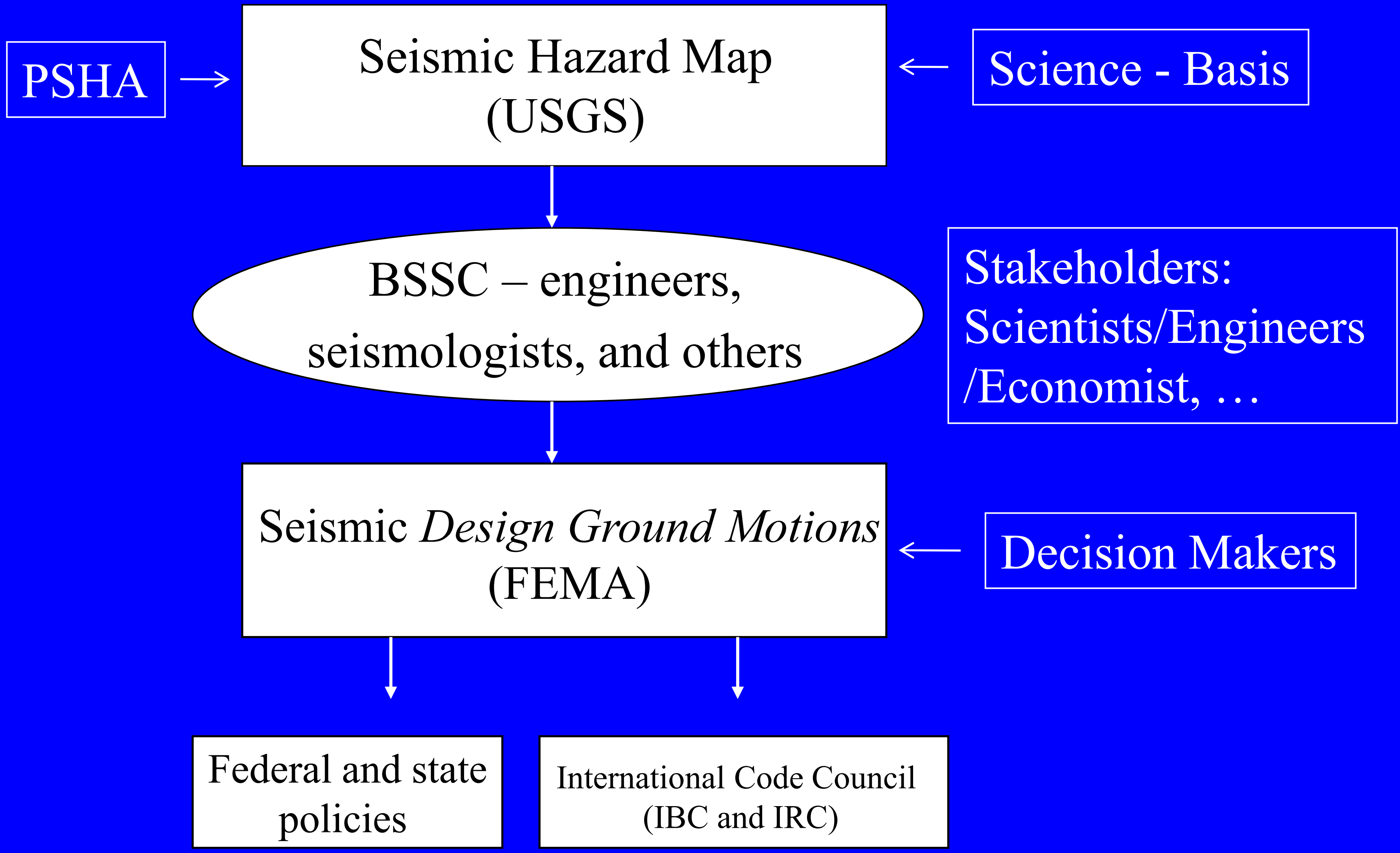
0.2s Response Acc. in Western Kentucky and SF Bay





1) Mr. David Mast (a staff member from KY congressman Ed Whitfield office): Why can I not build a regular two-story house in Paducah?
2) DOE will not get permit from Ky-EPA to build a landfill at PGDP for clean-up.
3) Design ground motion for bridges will be much higher than those in CA
4) One of the main reasons that Kentucky lost the centrifuge facility ($2B) to Ohio.

Development of *Seismic Design Ground Motion*



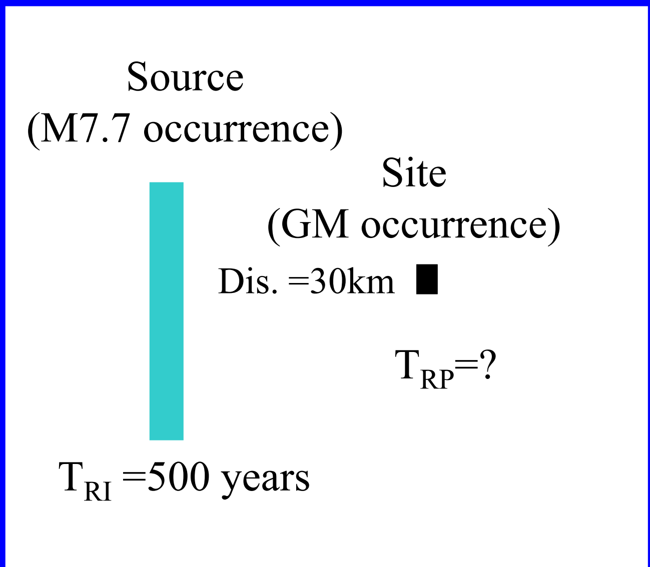
Probabilistic Seismic Hazard Analysis – PSHA

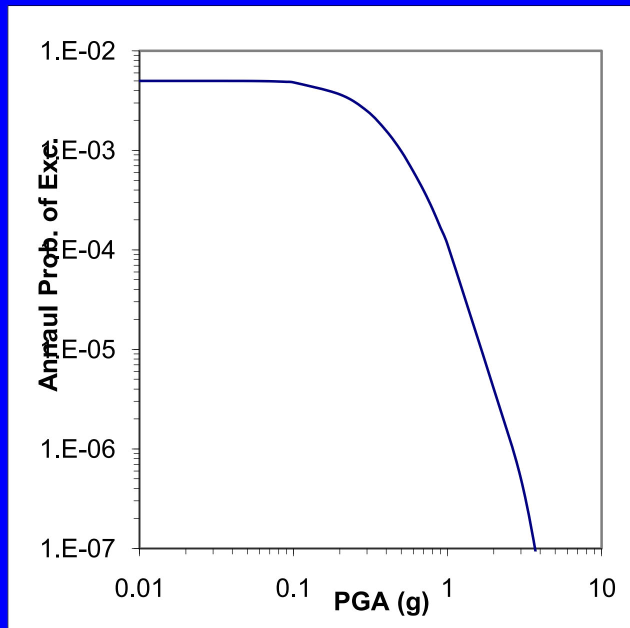
Sensitivity Test

PSHA

Input → "Black box" → Output

A single EQ → Infinite GM

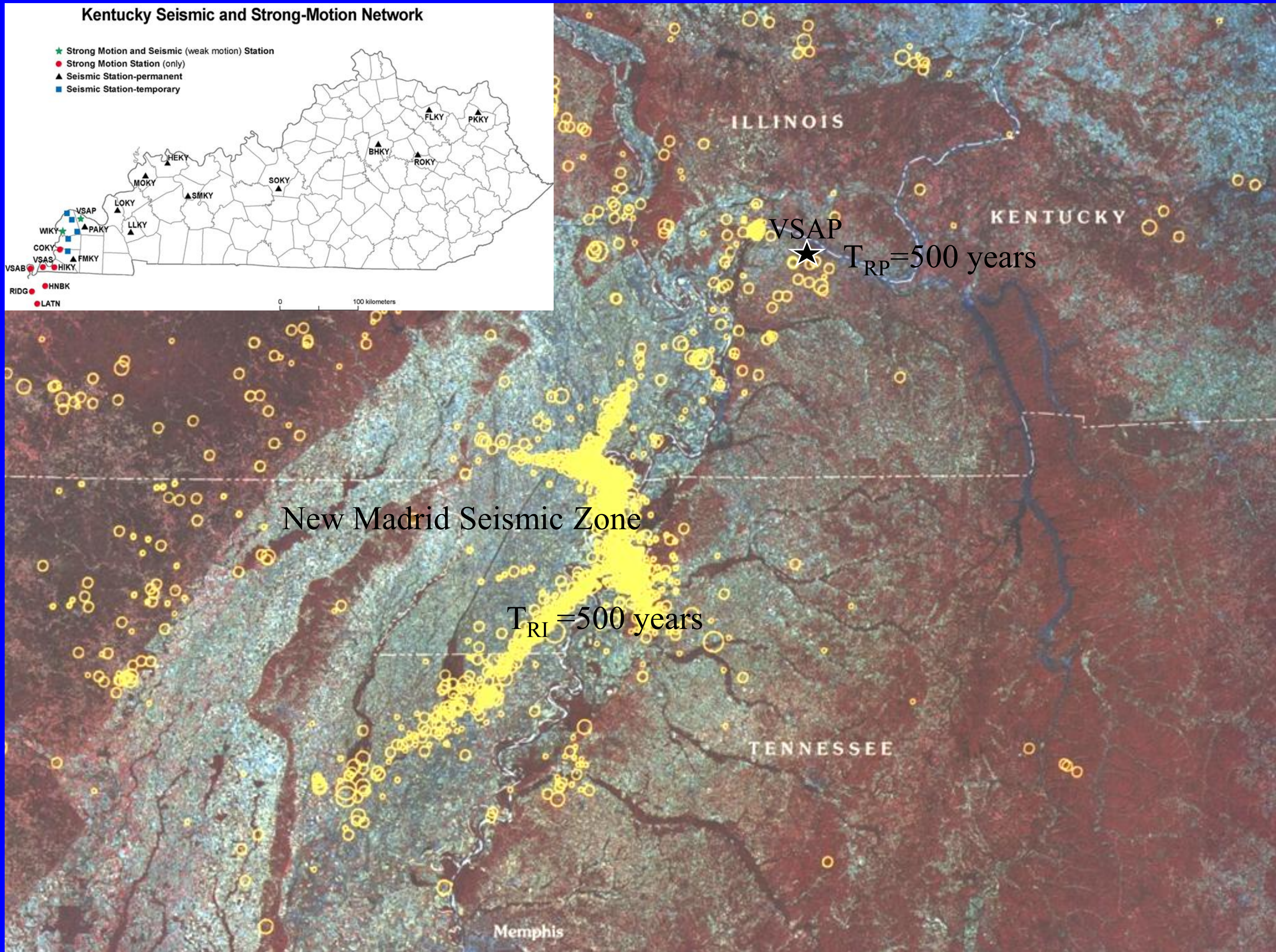




T_{RP}: 500y to infinity?

(Cornell, personal communication, 2004)

Probabilistic Seismic Hazard Analysis – PSHA



Probabilistic Seismic Hazard Analysis – PSHA

1. What is it? seismic hazard or seismic risk?

$$\gamma(y) = \sum v \iint \{1 - \int_0^y \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp[-\frac{(\ln y - \ln y_{mr})^2}{2\sigma_{\ln,y}^2}] d(\ln y)\} f_M(m) f_R(r) dm dr$$

$\gamma(y)$: the annual probability of ground motion y being exceeded (Cornell, 1968)

Probabilistic Seismic Hazard Analysis – PSHA

1. What is it? seismic hazard or seismic risk?

Of particular interest is the probability distribution of $I_{\max}^{(t)}$ the maximum intensity over an interval of time t (often one year). Observe that

$P[I_{\max}^{(t)} \leqq i] = P$[exactly zero special events in excess of i occur in the time interval 0 to t]

which from equation (20) is

$$P[I_{\max}^{(t)} \leqq i] = P[N = 0] = e^{-p_i \nu t}. \qquad (21)$$

If we let $I_{\max}$ equal $I_{\max}^{(1)}$, the *annual* maximum intensity, $t = 1$, and

$$F_{I_{\max}^{(i)}} = e^{-p_i \nu} = \exp\left[-\nu CG \exp\left(-\frac{\beta}{c_2} i\right)\right] \qquad i \geqq i' \qquad (22)$$

The annual probability of exceedance: probability of exceedance in ONE year
t ≡ 1 year

If the annual probabilities of exceedance are small enough (say ≦0.05), the distribution of $I_{\max}$ can be approximated by

$$1 - F_{I_{\max}^{(i)}} = 1 - e^{-p_i \nu} \cong 1 - (1 - p_i \nu)$$

$$\cong p_i \nu$$

$$\cong \nu CG \exp\left(-\frac{\beta}{c_2} i\right) \qquad i \geqq i'. \qquad (23)$$

Left side: *1-F* (dimensionless)
Right side: 1/Time (t=1 year)

(page 1590-91 of Cornell, 1968)

Probabilistic Seismic Hazard Analysis – PSHA

1. What is it? seismic hazard or seismic risk?

$$\gamma(y) = \sum v \iint \{1 - \int_0^y \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp[-\frac{(\ln y - \ln y_{mr})^2}{2\sigma_{\ln,y}^2}] d(\ln y)\} f_M(m) f_R(r) dm dr$$

$\gamma(y)$: the annual probability of ground motion y being exceeded (Cornell, 1968)

form. For large design values associated with small risks the results to an approximate risk of exceeding y of

$$P[Y_{\max} > y] = 1 - F_{Y_{\max}}(y) \simeq \nu t p_y$$

(page 478 of Cornell, 1971)

$$1 - F_{Y_{\max}^{(i)}} = 1 - e^{-p_i \nu} \cong 1 - (1 - p_i \nu) \cong p_i \nu$$

$t \equiv 1$ year

By definition: seismic risk (probability of exceedance in ONE year), not seismic hazard

Probabilistic Seismic Hazard Analysis – PSHA

1. What is it? seismic hazard or seismic risk?

form. For large design values associated with small risks the results : to an approximate risk of exceeding y of

$$P[Y_{\max} > y] = 1 - F_{Y_{\max}}(y) \simeq \nu t p_y$$

The average return period, T_i, of an intensity equal to or greater than i is defined as the reciprocal of $1 - F_{I_{\max}^{(i)}}$ or

$$T_i = 1/(1-F) = 1/(p_i \nu t)$$

Return period has NO unit

$$1 - F_{I_{\max}^{(i)}} = 1 - e^{-p_i \nu} \cong 1 - (1 - p_i \nu)$$

$$\cong p_i \nu$$

$t \equiv 1$ year

$$T_i = 1/(p_i \nu)$$

Return period has unit of time (WRONG)

Probabilistic Seismic Hazard Analysis – PSHA

1. What is it? seismic hazard or seismic risk?

$$T_i = 1/(p_i v)$$

Return period has unit of time (WRONG)

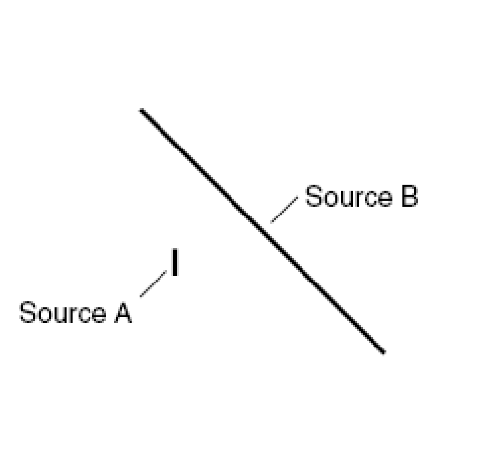


Figure 1a shows a 400 × 400-km region with only two seismic sources (faults). Source *A* produces only M_w 6 earthquakes with a recurrence interval (RI) of $RI_A = 50$ yr or an occurrence rate of $1/50 = 0.02$/yr. Source *B* produces only M_w 7.5 earthquakes with an RI of $RI_B = 450$ yr or an occurrence rate of $1/450 = 0.0022$/yr. The lengths of these

(1994) relationship. It is assumed that the occurrence of an earthquake on source *A* or source *B* has no effect on the future occurrence of earthquakes on these two sources (time-independent assumption). For the sake of simplicity,

(Malhotra, 2008)

For y=0, pi=1 and Ti=1/v

where the RI of earthquakes (on any of the two sources) in the region is given by

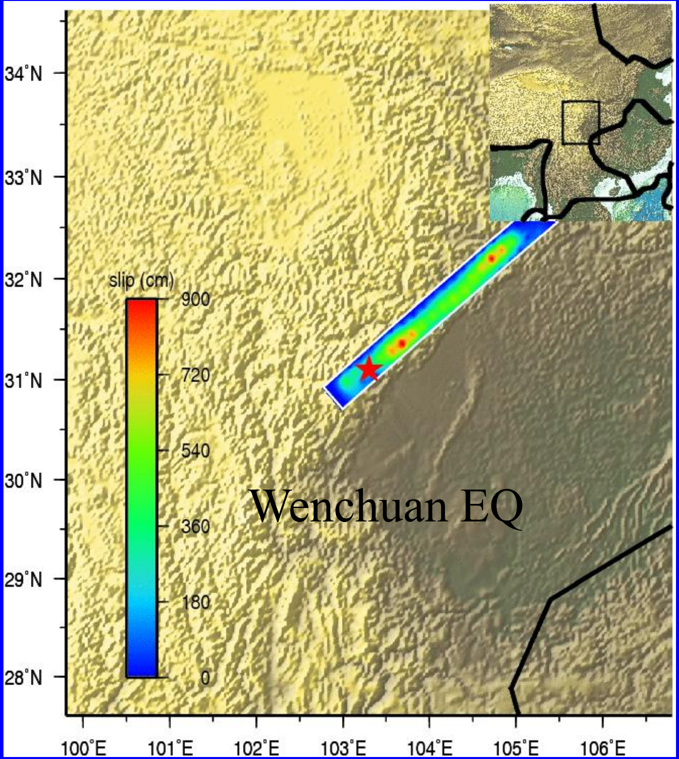
$$\frac{1}{RI} = \frac{1}{RI_A} + \frac{1}{RI_B}. \qquad (7)$$

Equation (7) is derived by simply adding the occurrence rates (reciprocal of RIs) of earthquakes on source *A* and source *B* to obtain the overall occurrence rate of earthquakes in the region. Substituting $RI_A = 50$ yr and $RI_B = 450$ yr in equation (7) gives RI = 45 yr. Equation (6) is rewritten to express

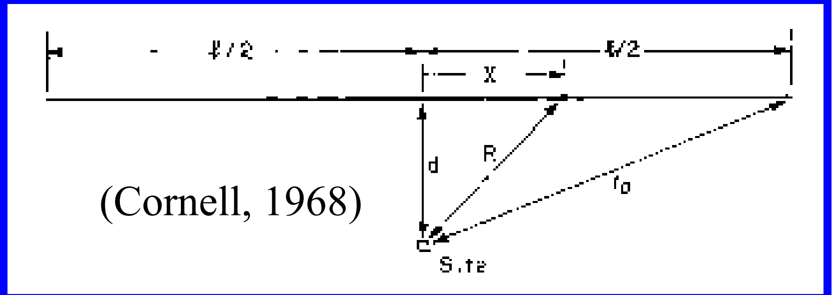
PSHA creates an EARTHQUAKE of RI=45y

Probabilistic Seismic Hazard Analysis – PSHA

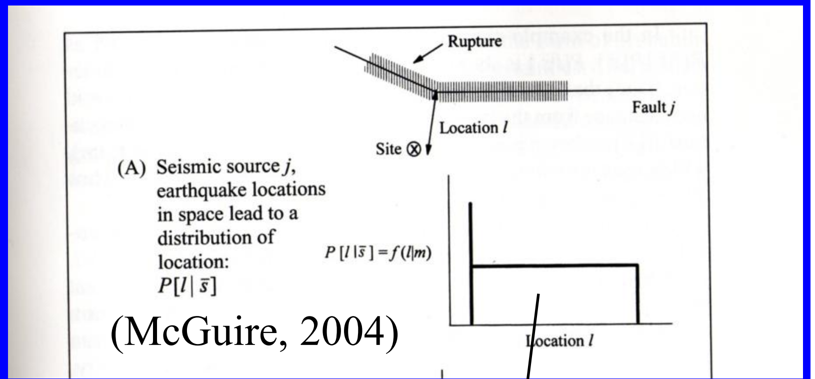
2. Physical source model (point vs. finite)



Rupture length: 300 km



(Cornell, 1968)



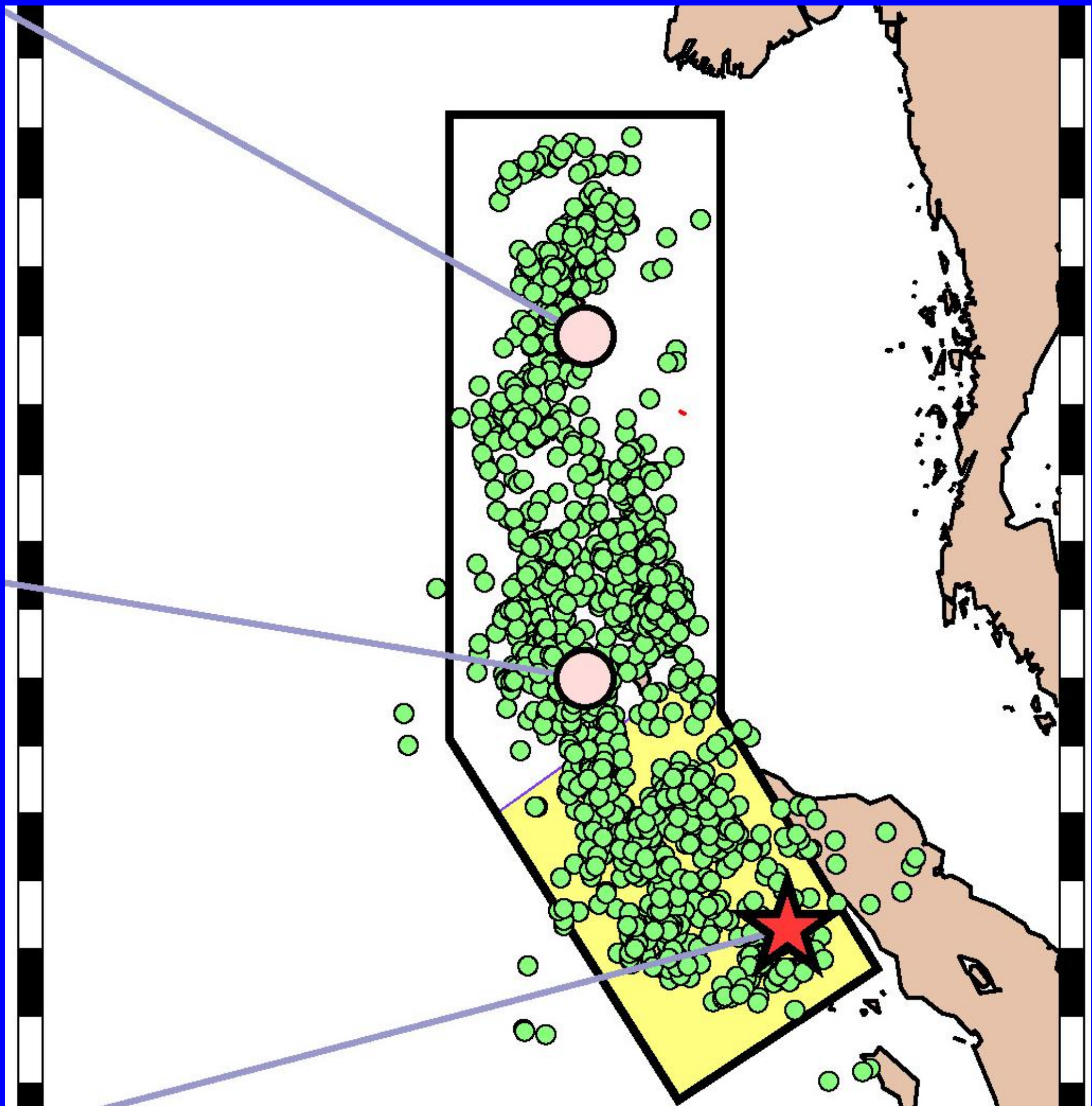
(McGuire, 2004)

$$\gamma(y) = \sum \nu P(Y \geq y) = \sum \nu \iint \{1 - \int_0^y \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp[-\frac{(\ln y - \ln y_{mr})^2}{2\sigma_{\ln,y}^2}] d(\ln y)\} f_M(m) f_R(r) dm dr$$

Physical and Mathematical problems (Wang and Zhou, 2007; Wang, 2009)

Probabilistic Seismic Hazard Analysis – PSHA

2. Physical source model (point vs. finite)

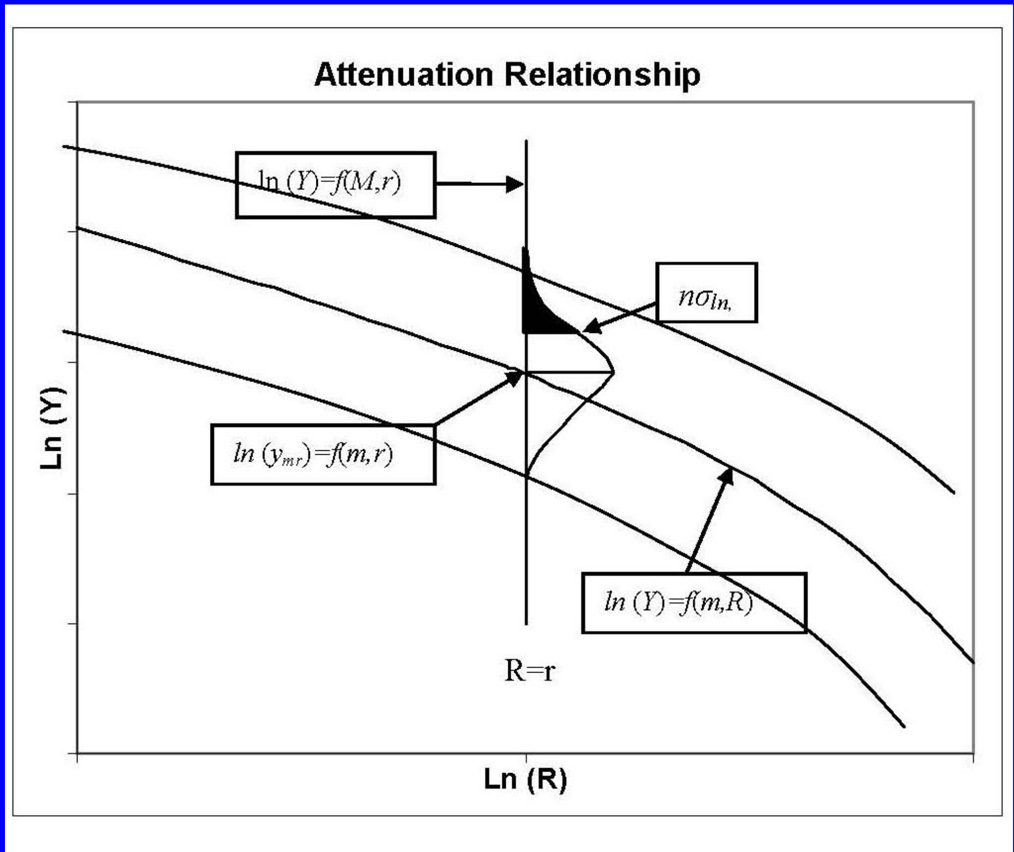


The December 26, 2004 Indian Ocean earthquake (M9.3)

Rupture: ~1,200 km

Probabilistic Seismic Hazard Analysis – PSHA

3. Mathematical problem (dependency)



$$\ln(Y) = f(M,R) + n\sigma_{\ln,Y}$$

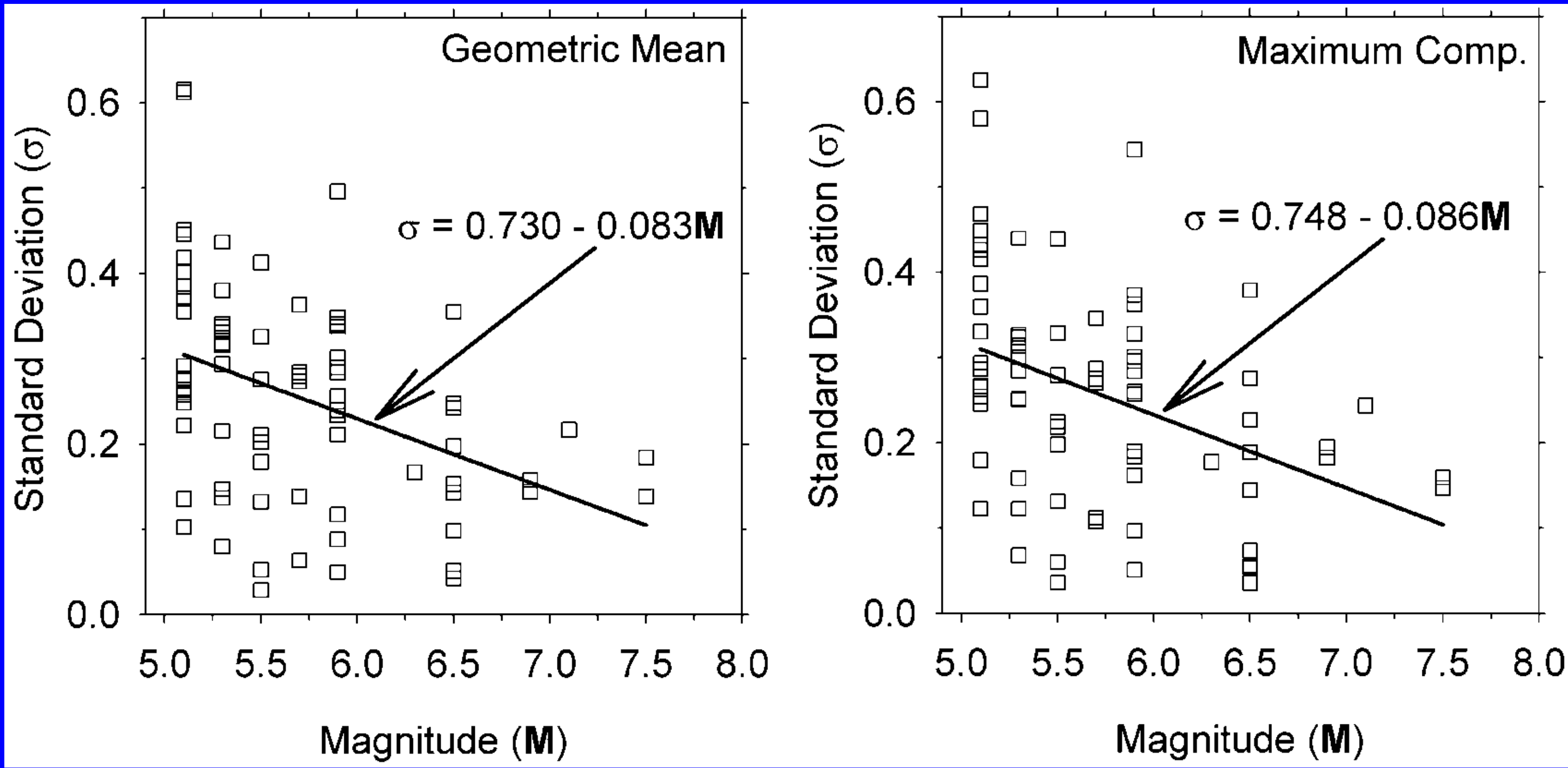
Median

Uncertainty

$$\sigma_{\ln,Y} = g(M,R,site\ and\ others)$$

Probabilistic Seismic Hazard Analysis – PSHA

3. Mathematical problem (dependency)



(Akkar and Bommer, 2007)

Probabilistic Seismic Hazard Analysis – PSHA

3. Mathematical problem (dependency)

$$\gamma(y) = \sum v \iint \{1 - \int_0^y \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp[-\frac{(\ln y - \ln y_{mr})^2}{2\sigma_{\ln,y}^2}] d(\ln y)\} f_M(m) f_R(r) dm dr$$

↑

If and only if *M*, *R*, and $\sigma_{ln,Y}$ are independent random variable (Benjamin and Cornell, 1970; Mendenhall and others, 1986)

↑

$$\ln(Y) = f(M,R) + n\sigma_{\ln,Y}$$

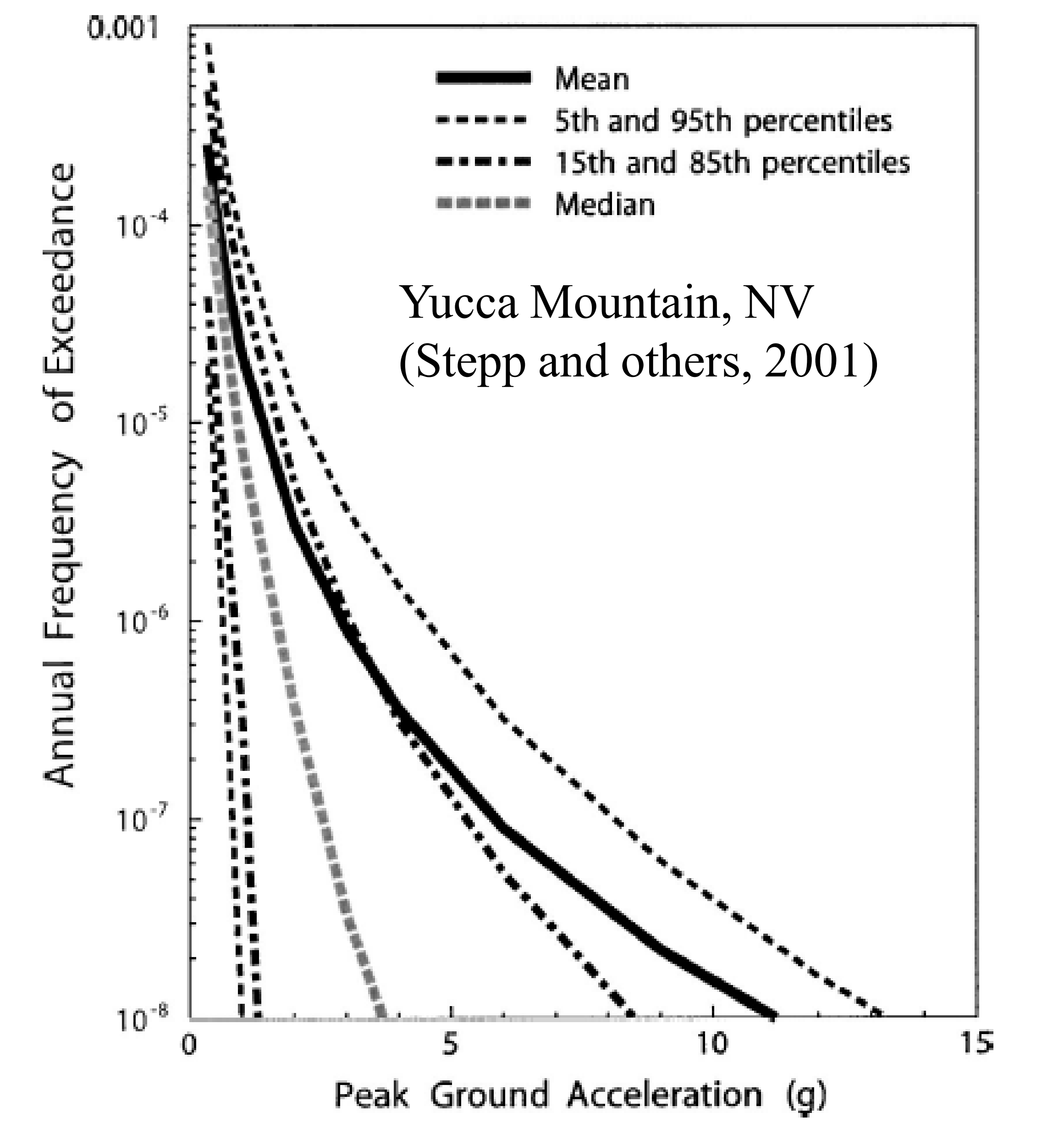
↓

$\sigma_{ln,Y}$ is not an independent random variable, but an explicit or implicit dependence of *M, R, and others*.

↓

Hazard calculation is mathematically incorrect

Probabilistic Seismic Hazard Analysis – PSHA

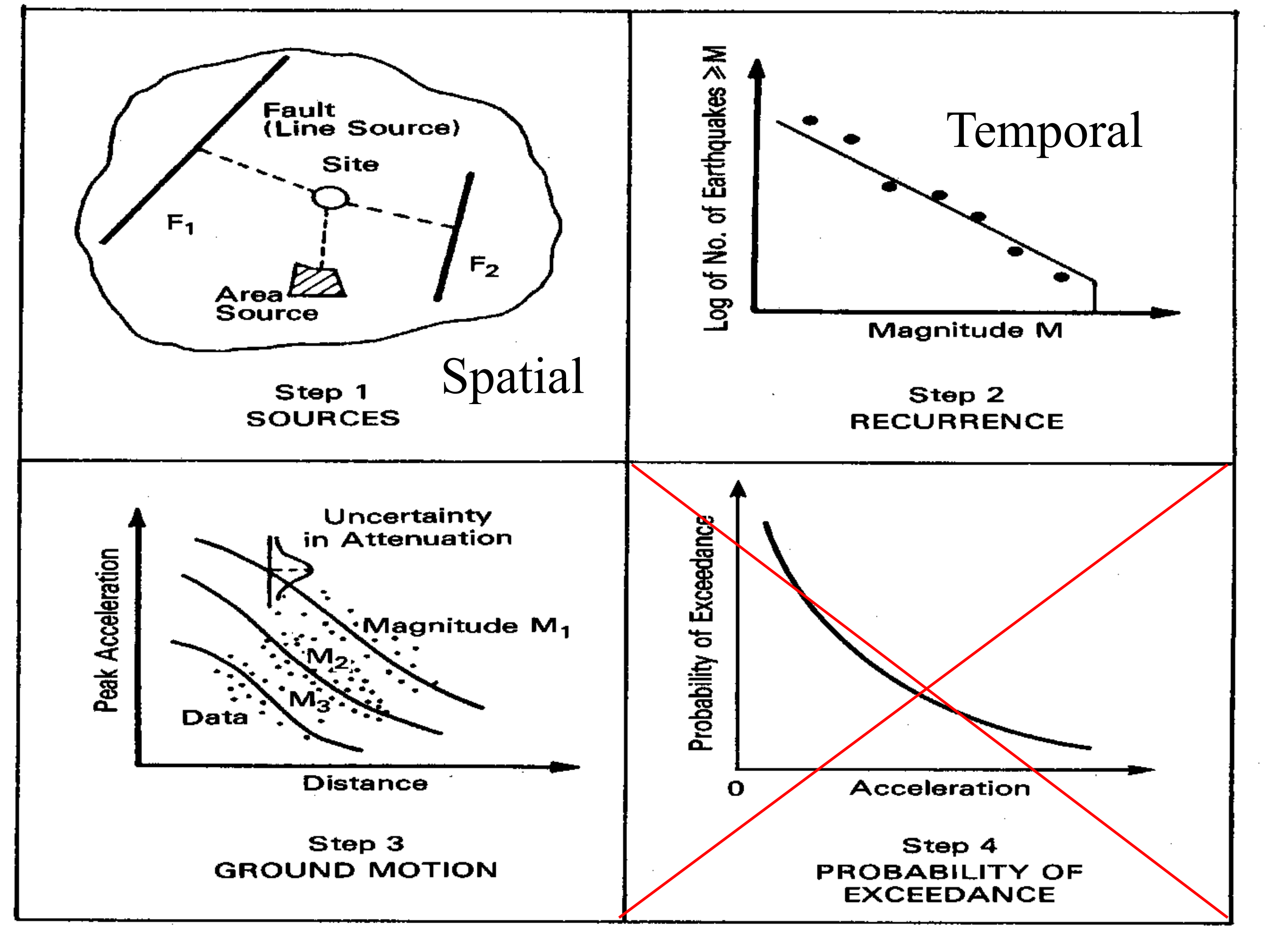


Example:
100,000,000y RP,
11g PGA?

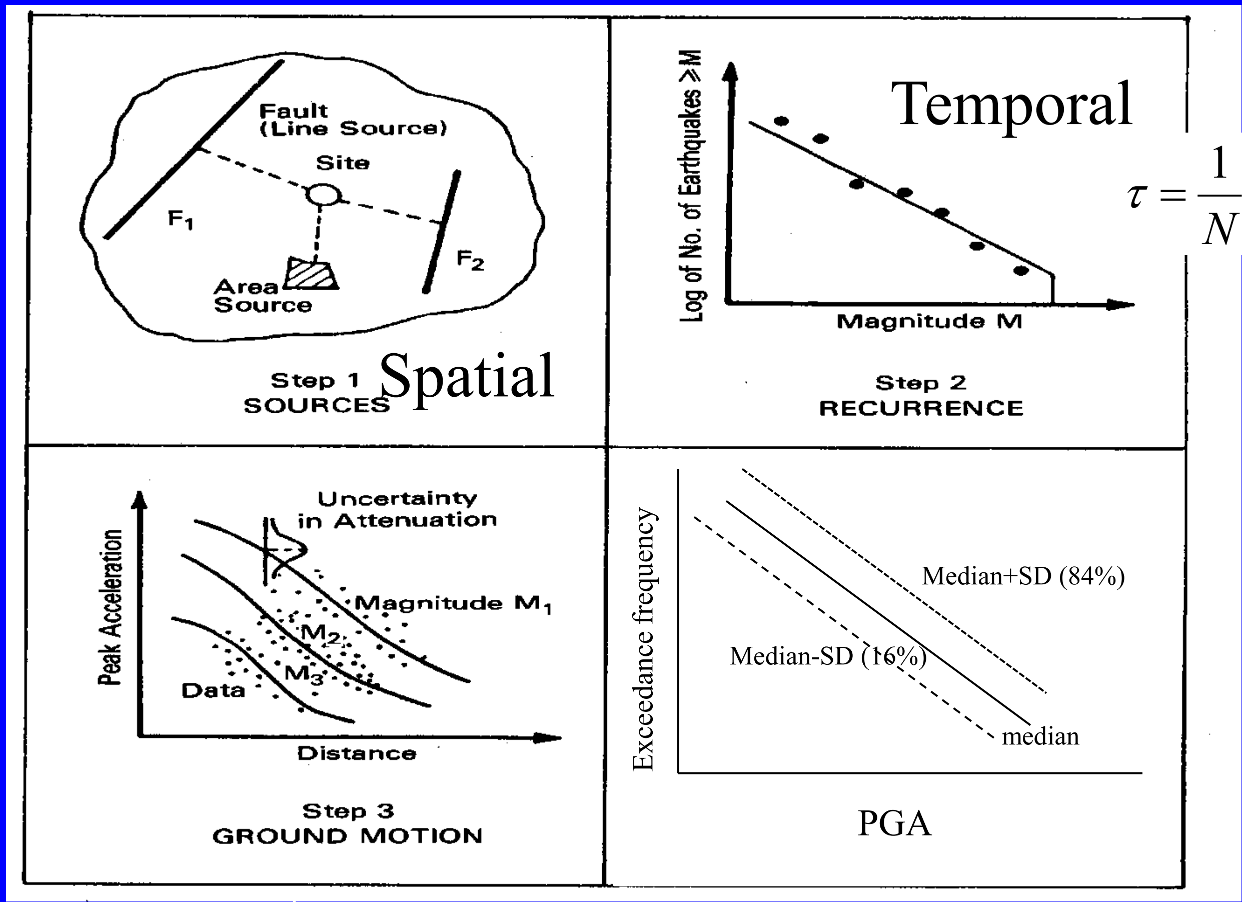
Probabilistic Seismic Hazard Analysis – PSHA

- Confusion on seismic hazard and risk:
  - mis-interpretation of the annual probability of exceedance or return period
- Physical source model (point) – not appropriate
- Mathematical problem (dependency)
  - Ergodic assumption (Anderson and Brune, 1999)
- Results: pure numerical creation with NO SCIENTIFIC BASE

Alternative Seismic Hazard Assessment



1. Seismic Hazard Assessment - Theoretical



$$\tau = \frac{1}{N} = e^{-2.303a+2.303bM}$$

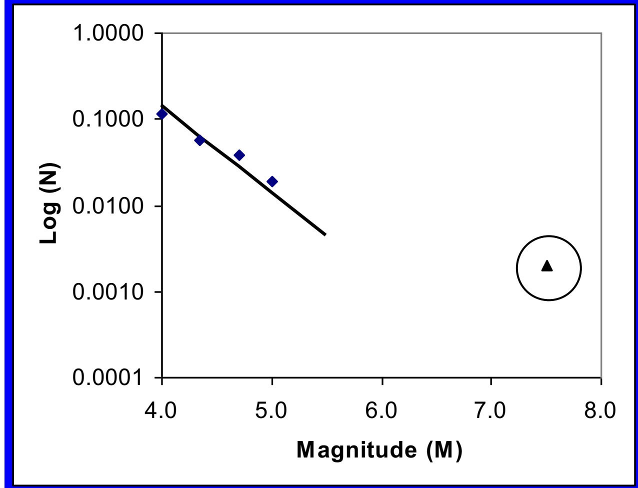
$$\ln(Y) = f(M,R) + n\sigma$$

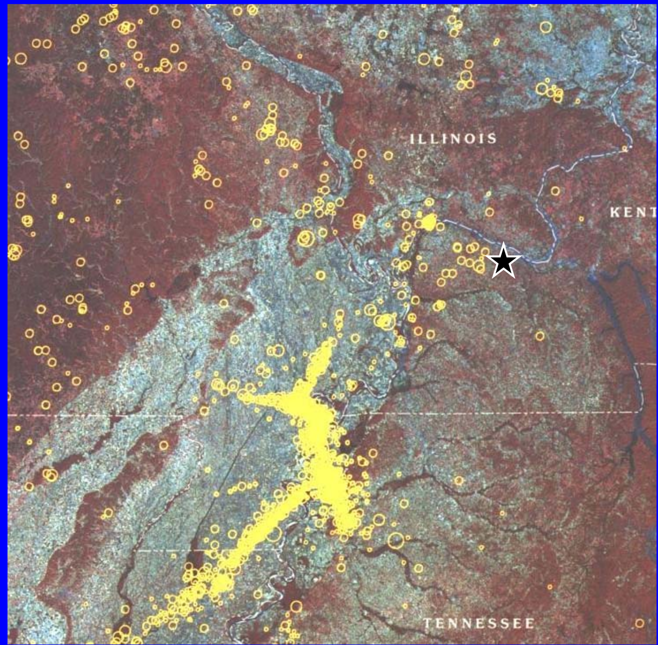
$$M = g(R, \ln Y, n\sigma_{\ln Y})$$

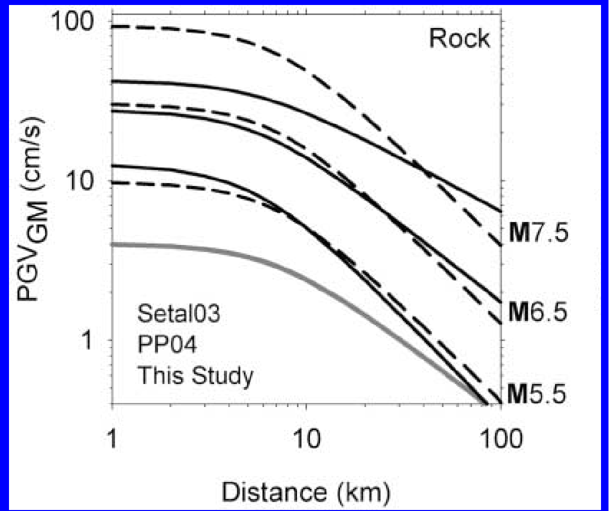
$$\tau = \frac{1}{N} = e^{-2.303a+2.303bg(R,\ln Y, n\sigma_{\ln Y})}$$

(Wang, 2006, 2007)

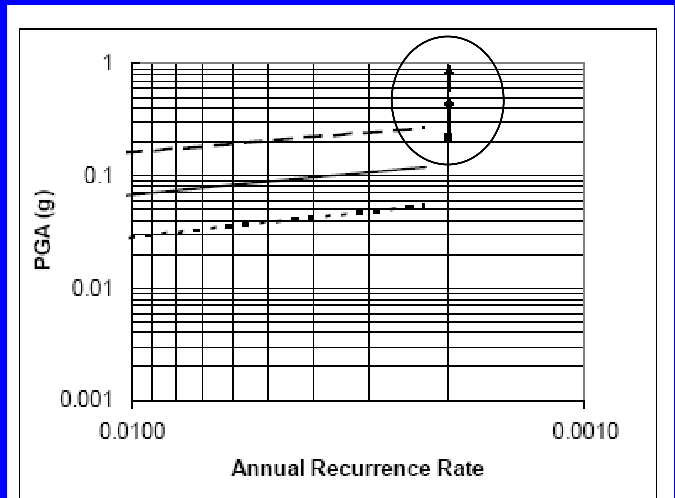
SHA to DSHA







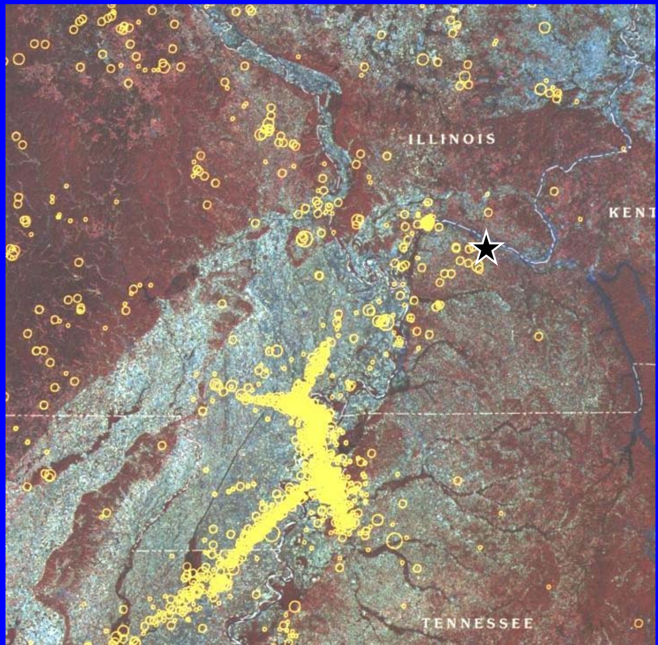
Characteristic earthquake:
M7.5/RI=500y

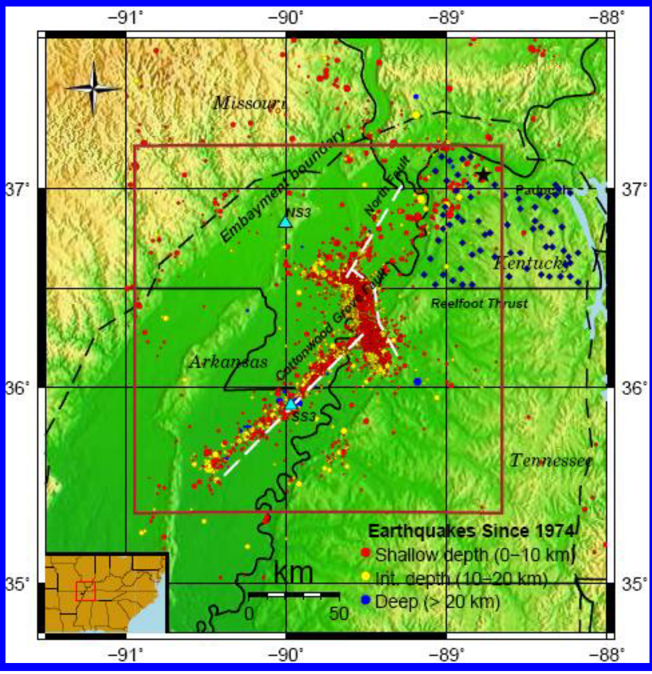


<u>For one characteristic Earthquake:</u>
<u>SHA becomes DSHA</u>

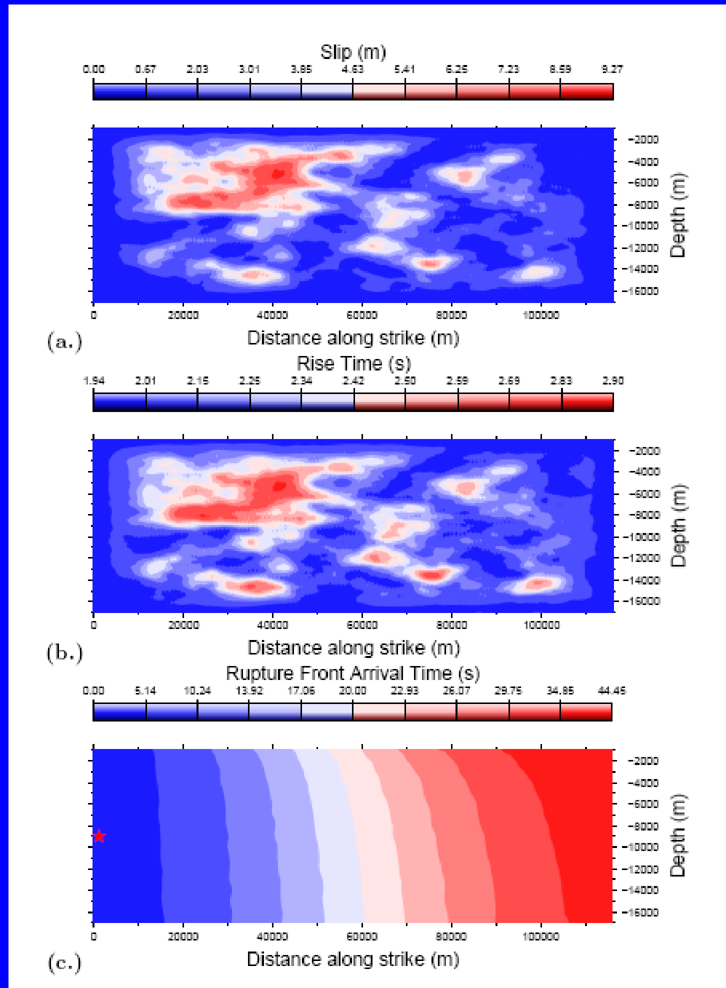
Ground motion at 30km:
0.44g PGA (median)
0.22g PGA (median–SD)
0.88g PGA (median+SD)
/RP≡500y

SHA to DSHA to Neo-DSHA



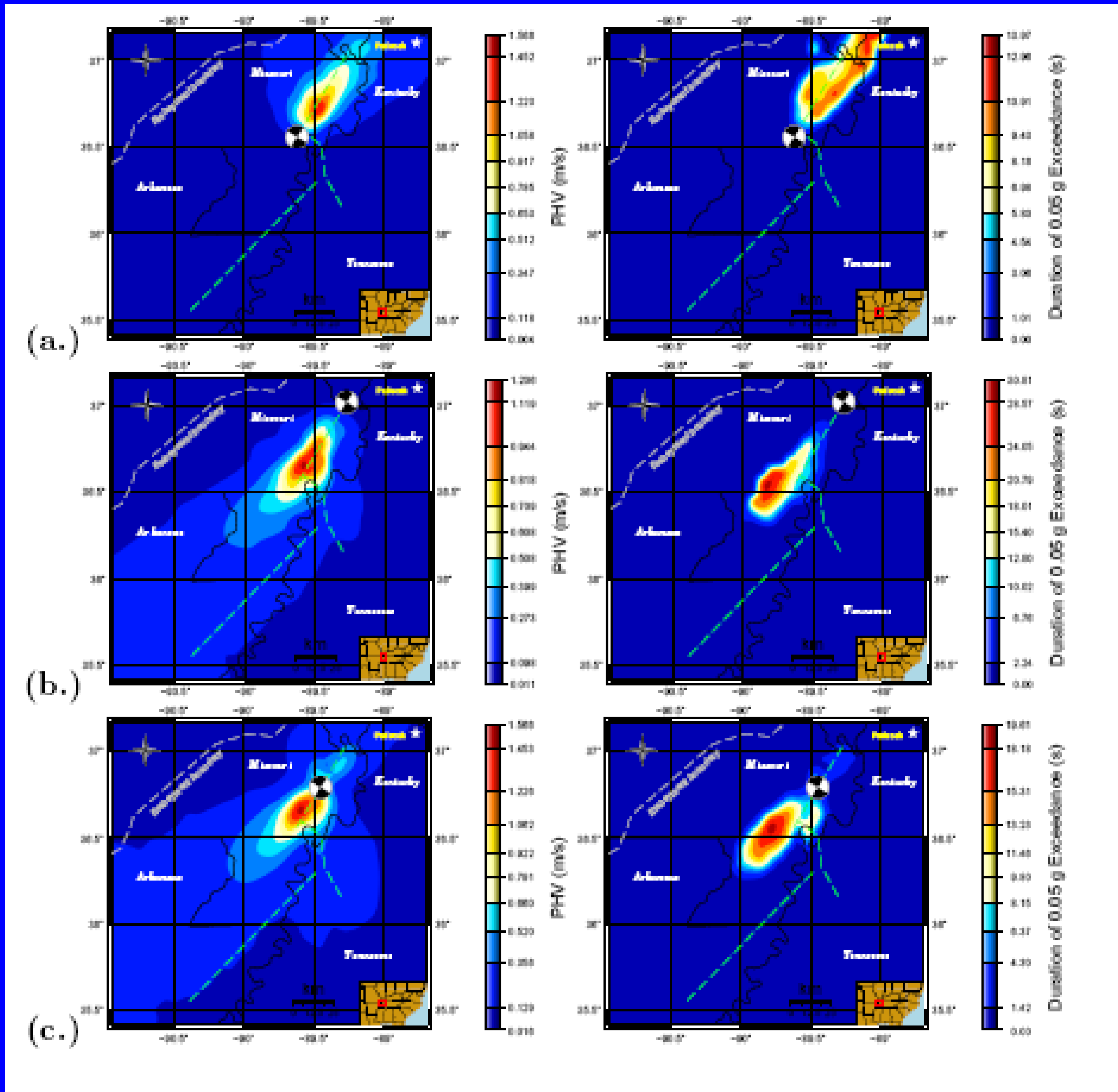


Neo-DSHA (Panza and others, 2001)



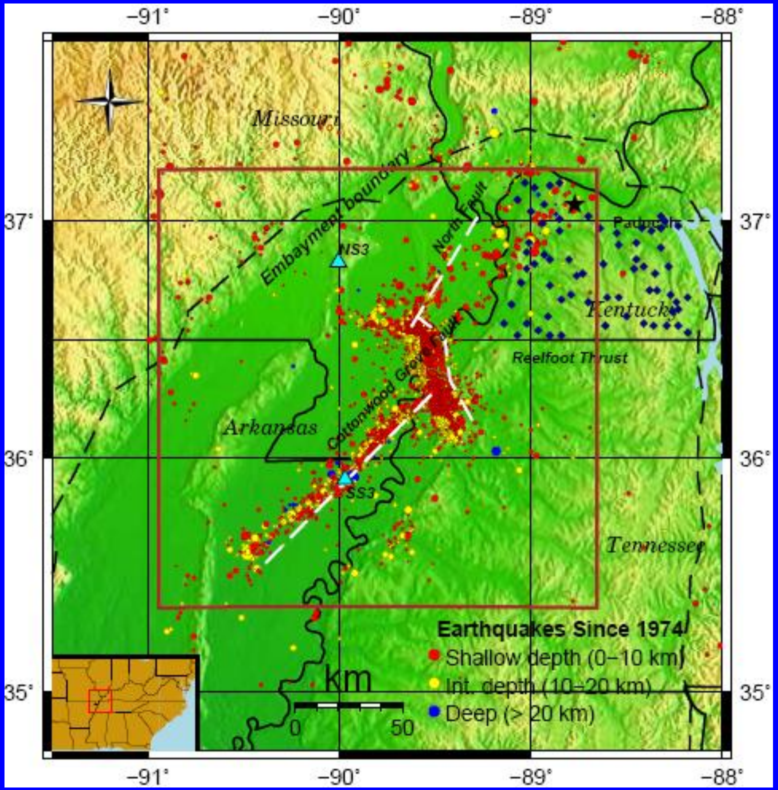
(Macpherson and others, 2009)

SHA to DSHA to Neo-DSHA

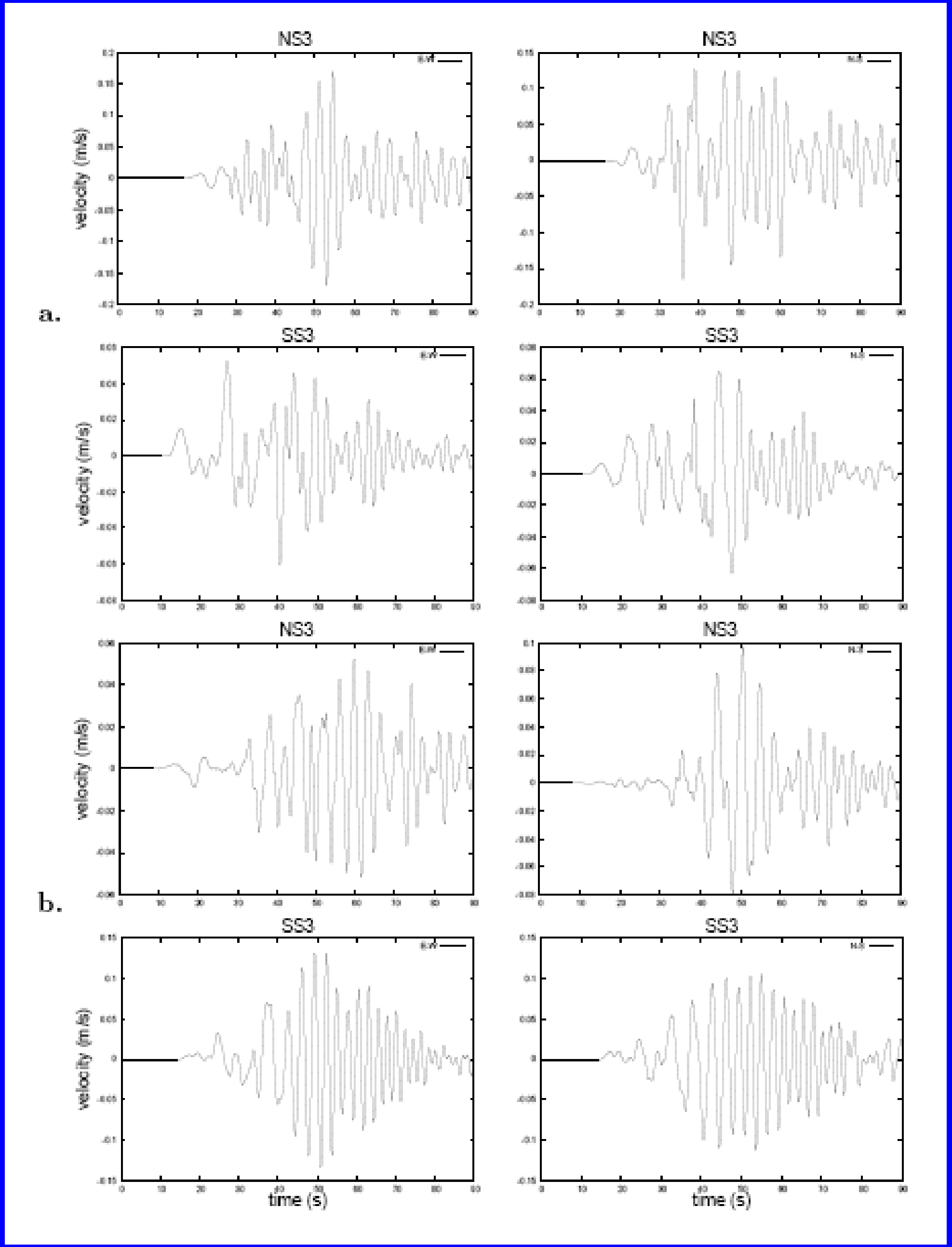


Limitation:
<0.5 Hz

SHA to DSHA to Neo-DSHA

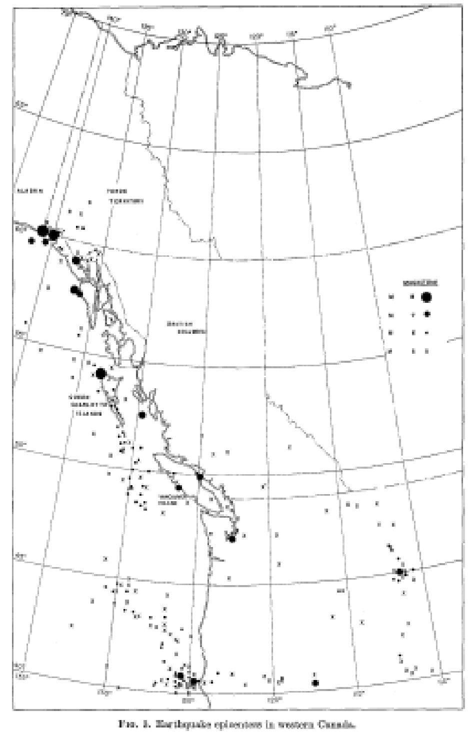


Reelfoot (central) fault rupture



2. Seismic Hazard Assessment - Empirical

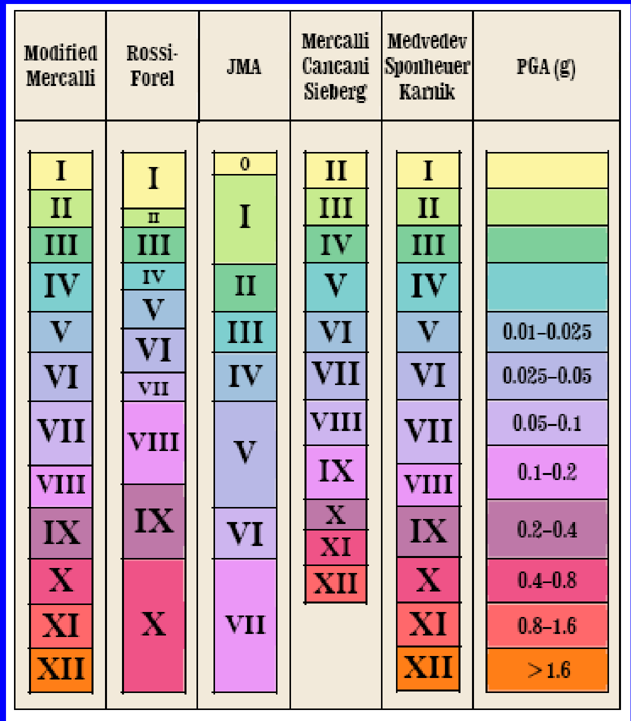
Step 1



(Historical records)

Seismic hazard curve: *A* vs. *τ* at a site

Step 2



Intensity table (Panza)

Step 3

Year	A (PGA,g)	Rank (m)	P
1895	0.001	96	0.888889
1896	0.01	84	0.777778
1897	0.1	29	0.268519

(ground motion at a site)

(Milne and Davenport, 1969)

2. Seismic Hazard Analysis - Empirical

Step 3

Year	A (PGA,g)	Rank (m)	P
1895	0.001	96	0.888889
1896	0.01	84	0.777778
1897	0.1	29	0.268519

(ground motion at a site)

$$P = \frac{m}{N+1}$$

(*N* is total number of years of records)

$$\tau = \frac{1}{P} = \frac{N+1}{m}$$

Step 4

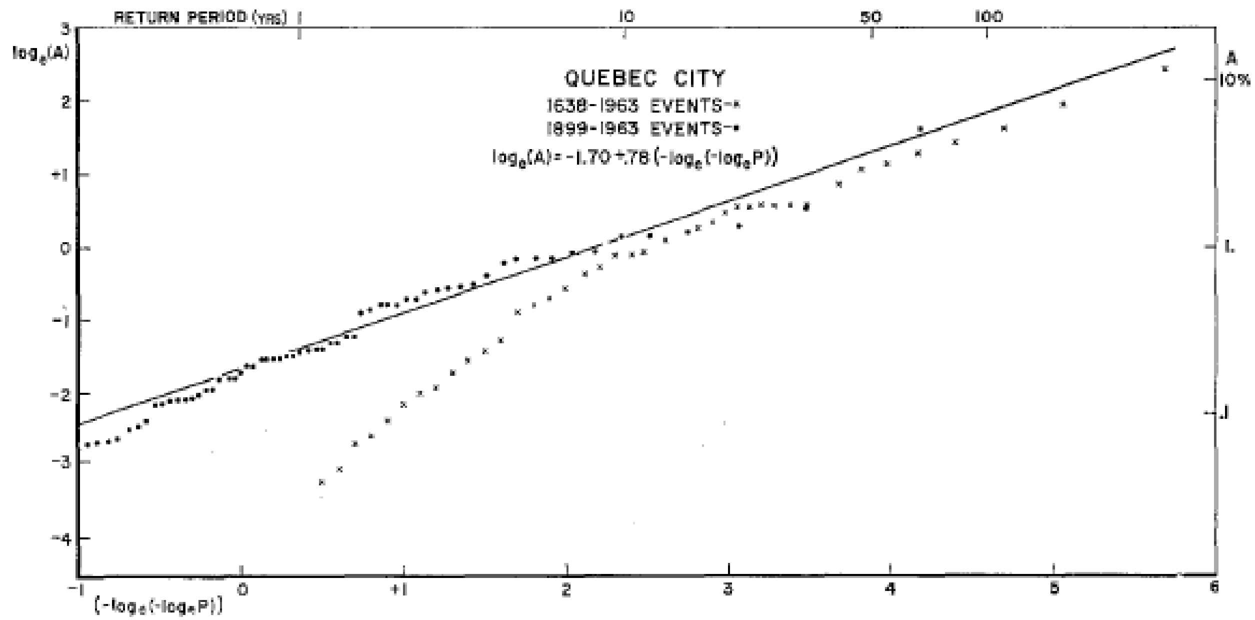
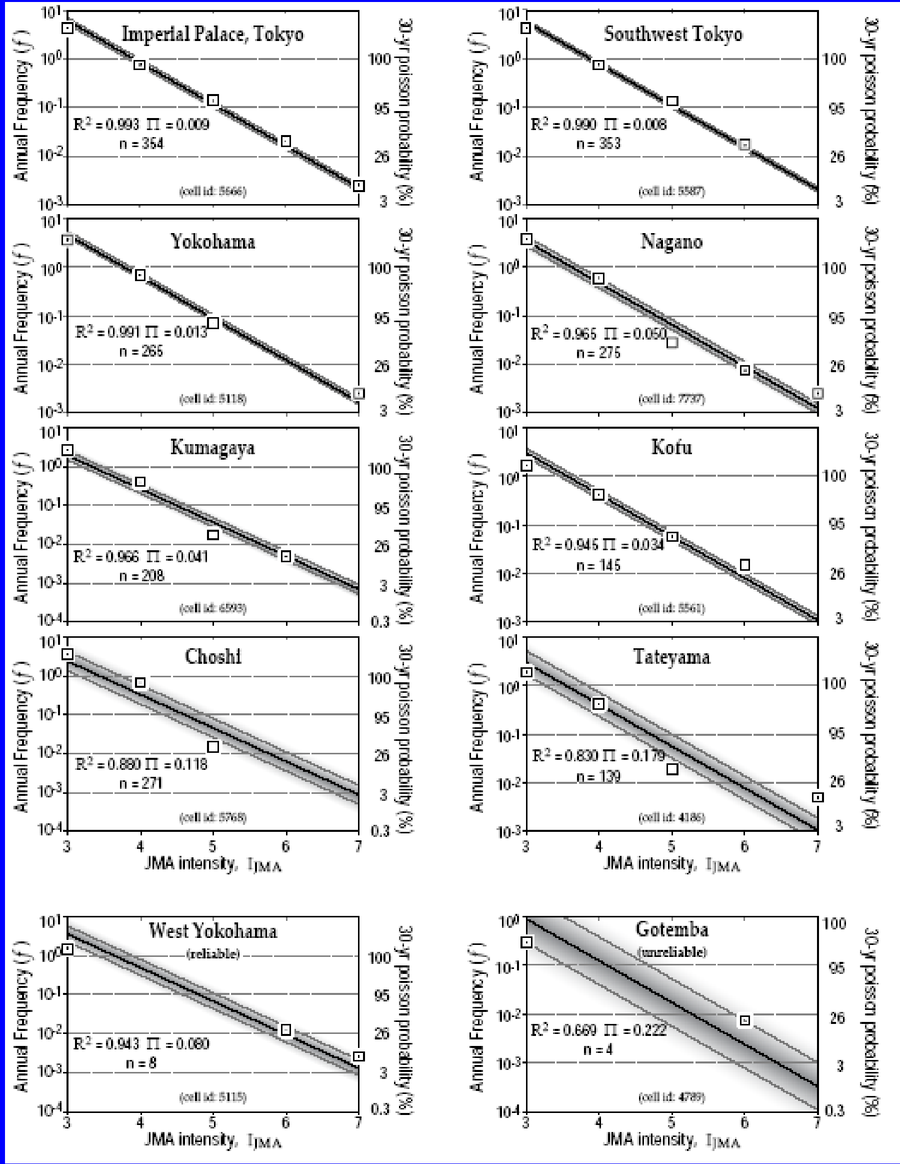


FIG. 13. Extreme value distribution plot for Quebec City.

Seismic hazard curves

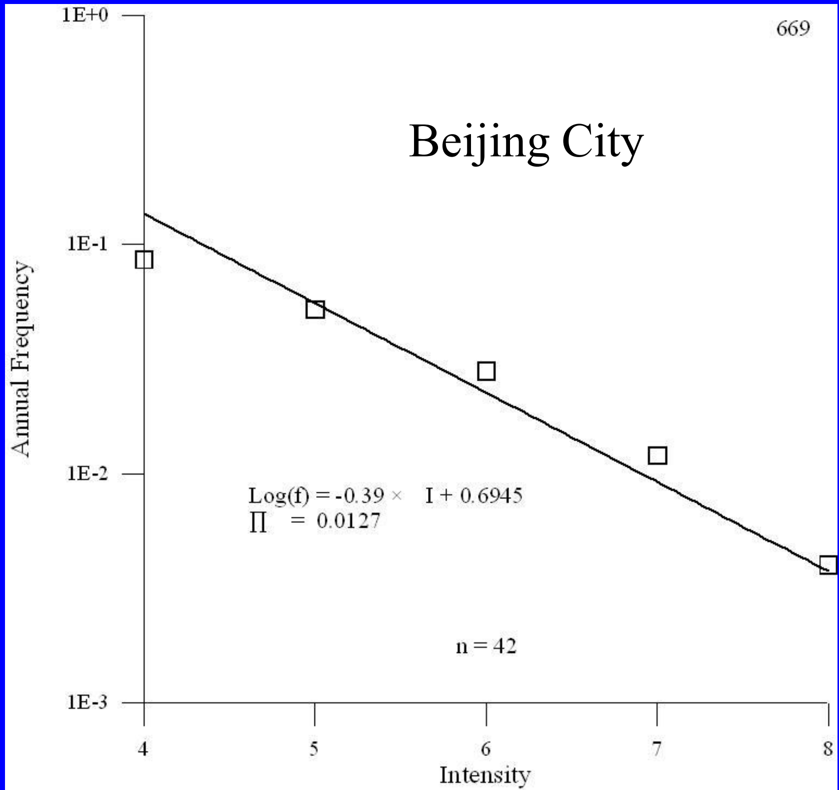
2. Seismic Hazard Analysis - Empirical

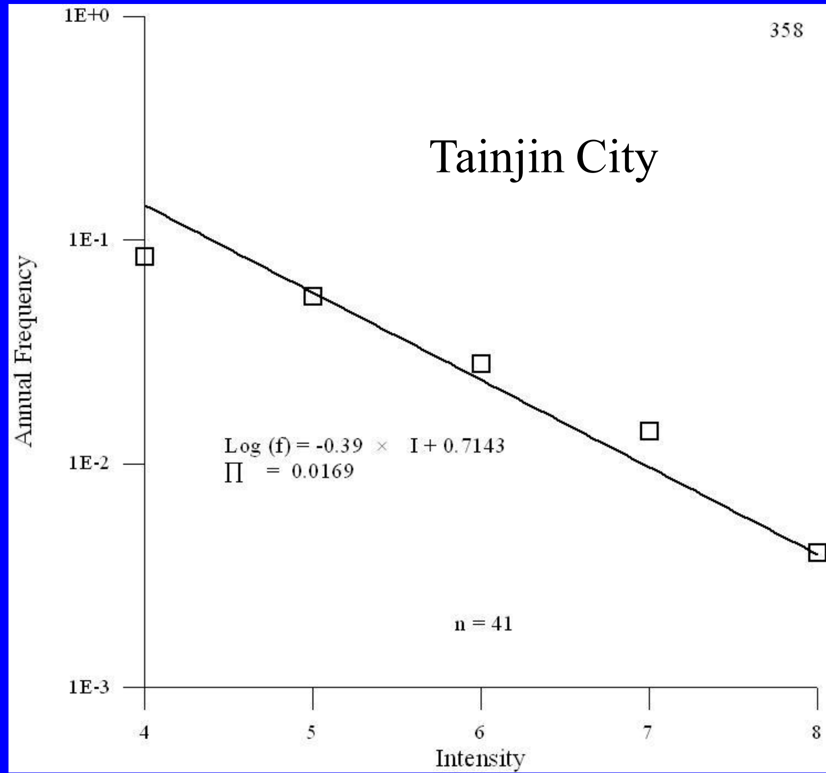


Tokyo, Japan
(400-year data)

(Bozkurt and others, 2007)

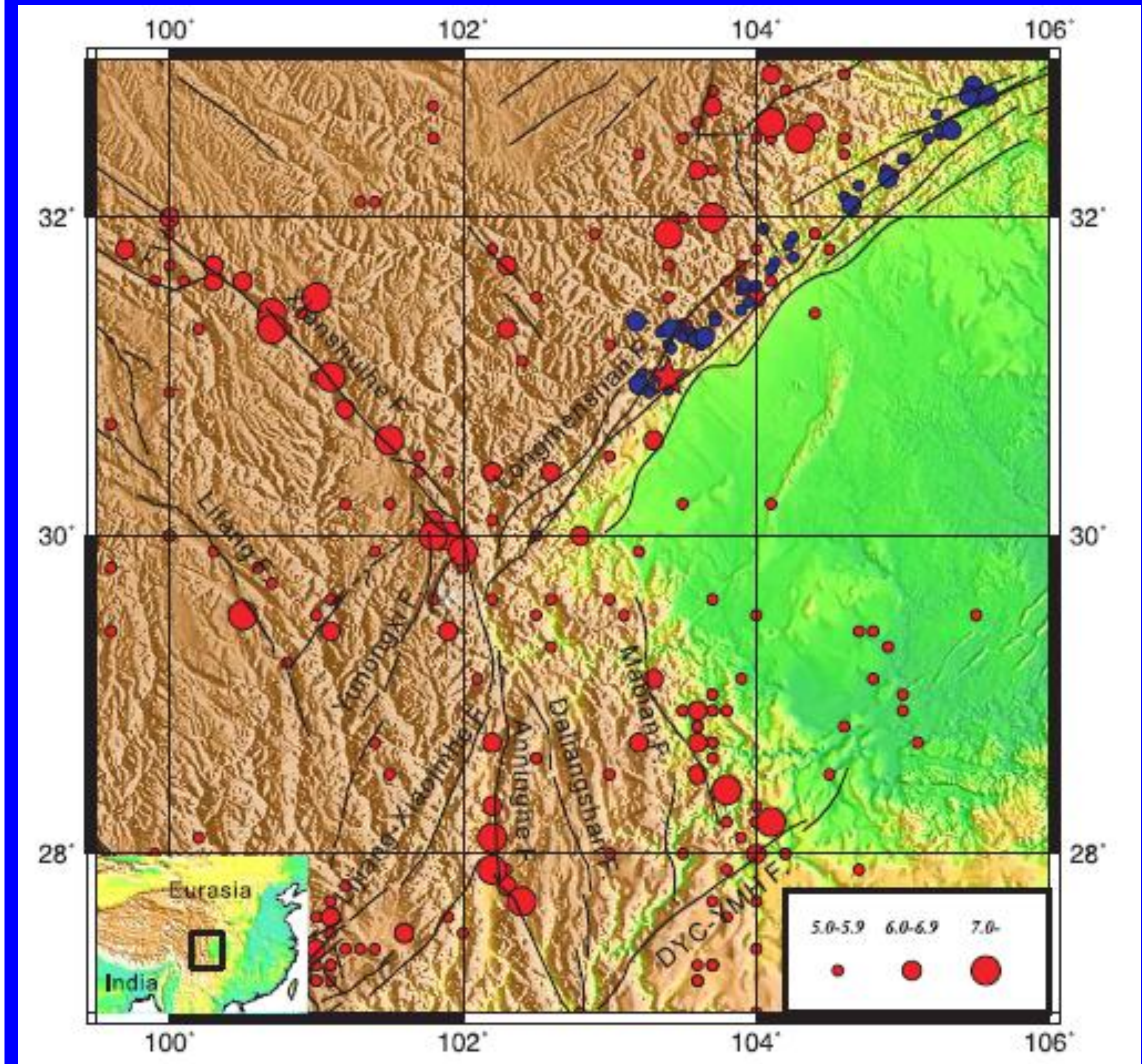
2. Seismic Hazard Analysis - Empirical





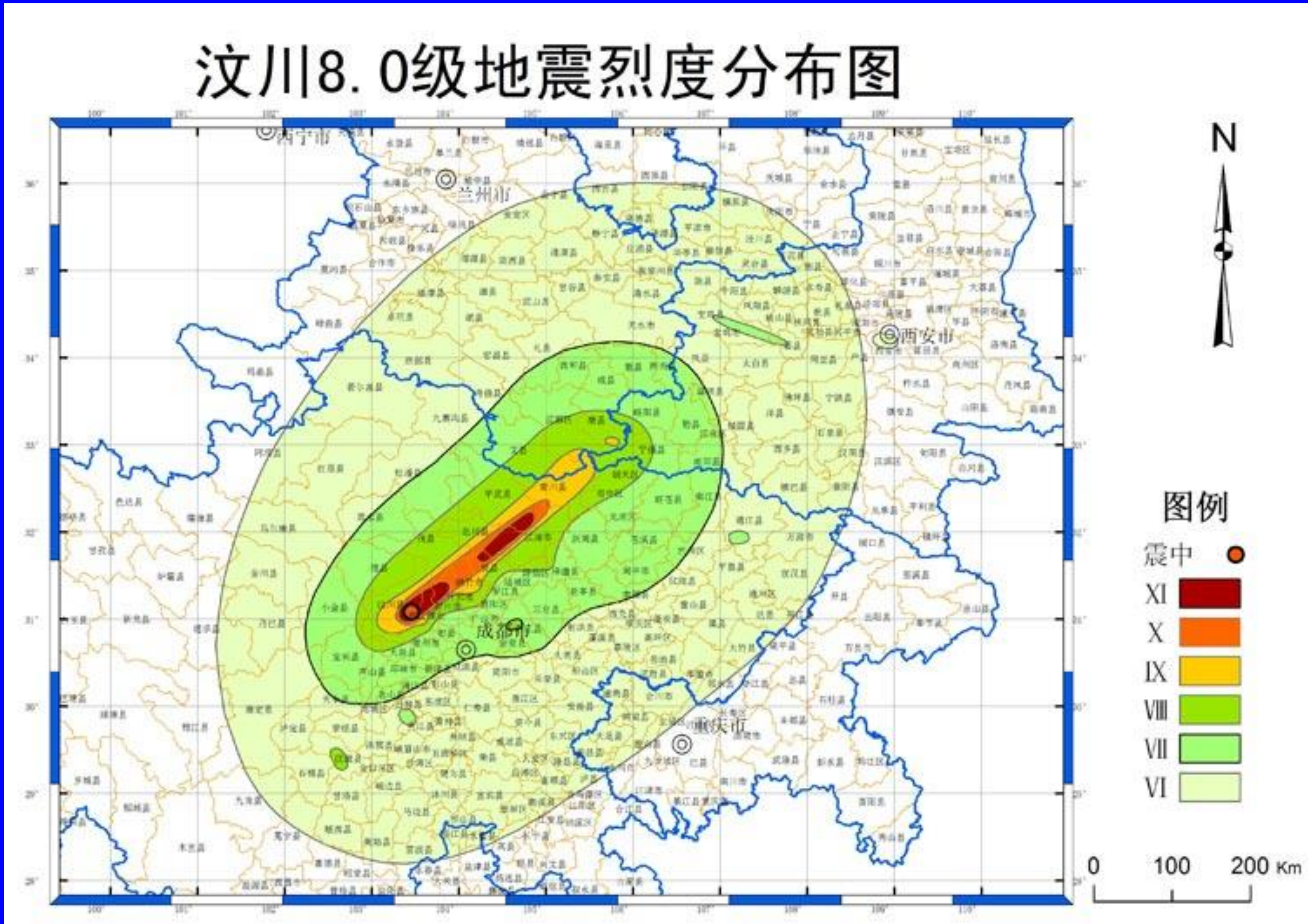
Beijing area, China
(500-year data)

Observations from Wenchuan Earthquake

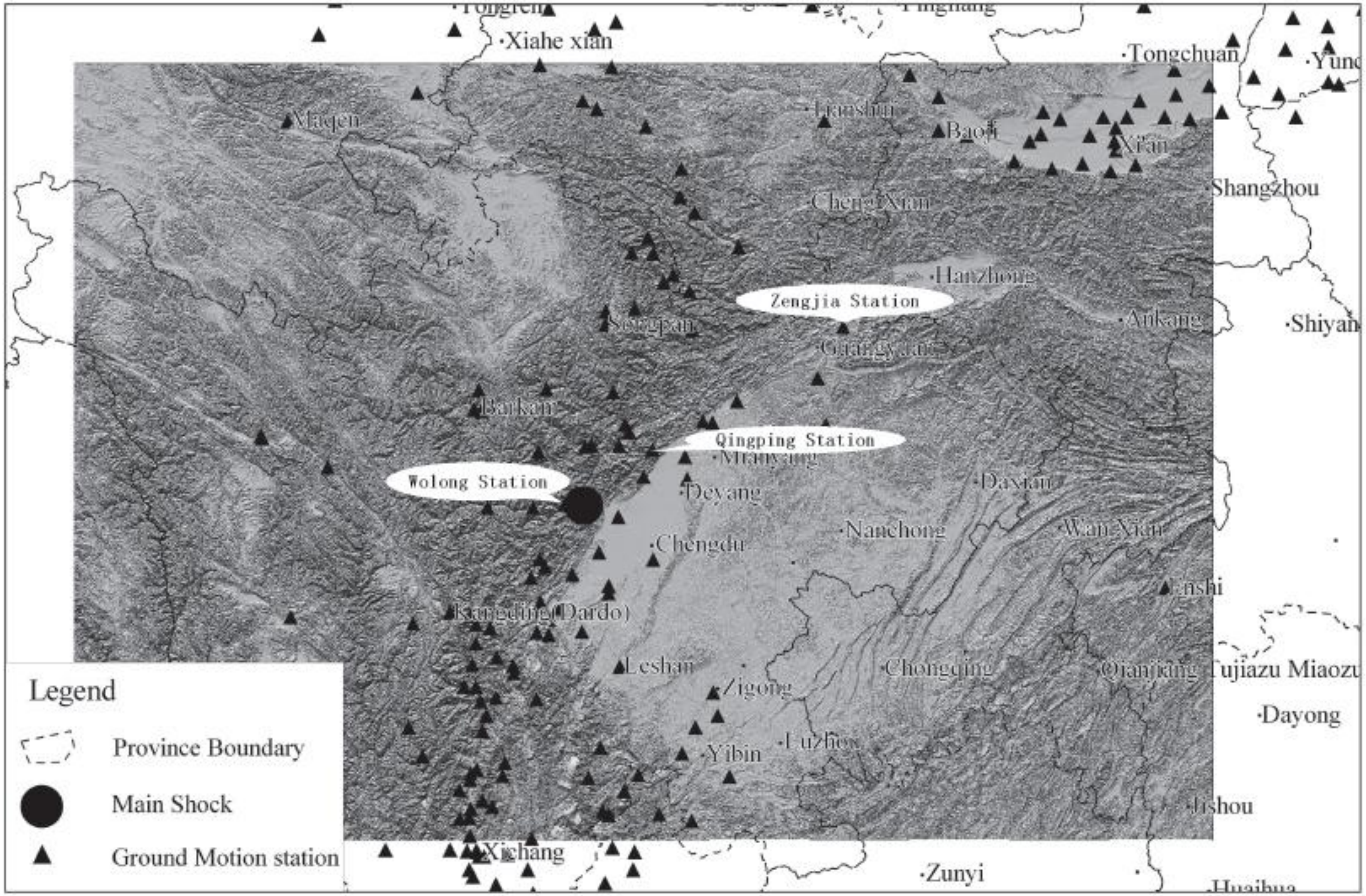


Magnitude: 8.0 (7.9 USGS)
Fault Rupture: ~300 km x 30 km
Surface Displacement: 5m (v), 4.8m (h)
Largest Recorded PGA: 0.65g
Death: ~70,000
Missing: ~20,000
Injured: ~380,000
Economic loss: >US$120B

Observations from Wenchuan Earthquake



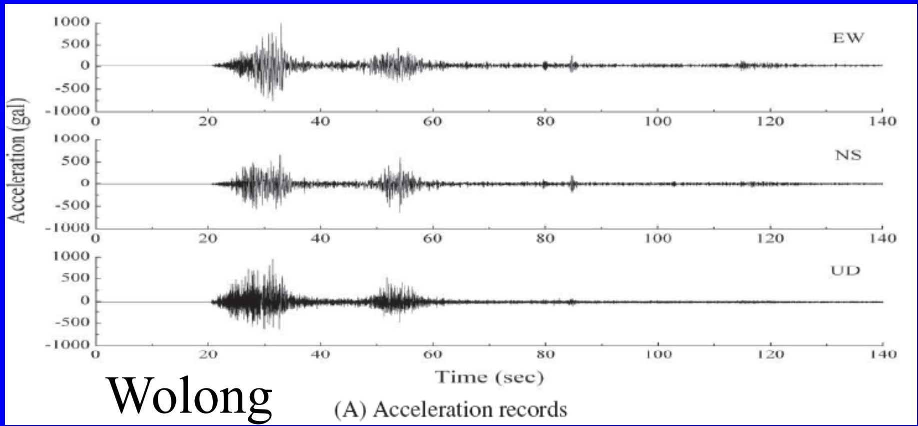
Observations from Wenchuan Earthquake



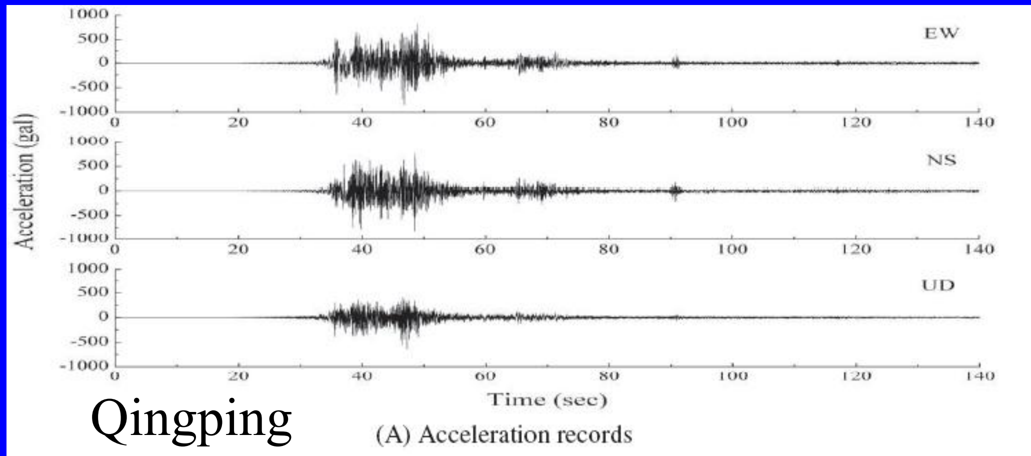
▲ **Figure 4.** Locations of strong-motion observation stations in the vicinity of the epicenter of the Wenchuan, China, earthquake of 12 May 2008 that recorded the mainshock. Locations of the three stations from which records are presented herein are indicated.

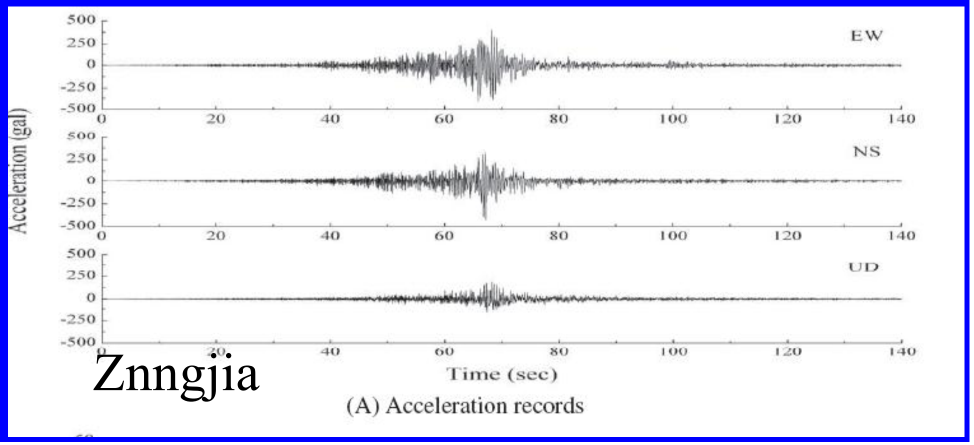
(Li and others, 2008)

Observations from Wenchuan Earthquake

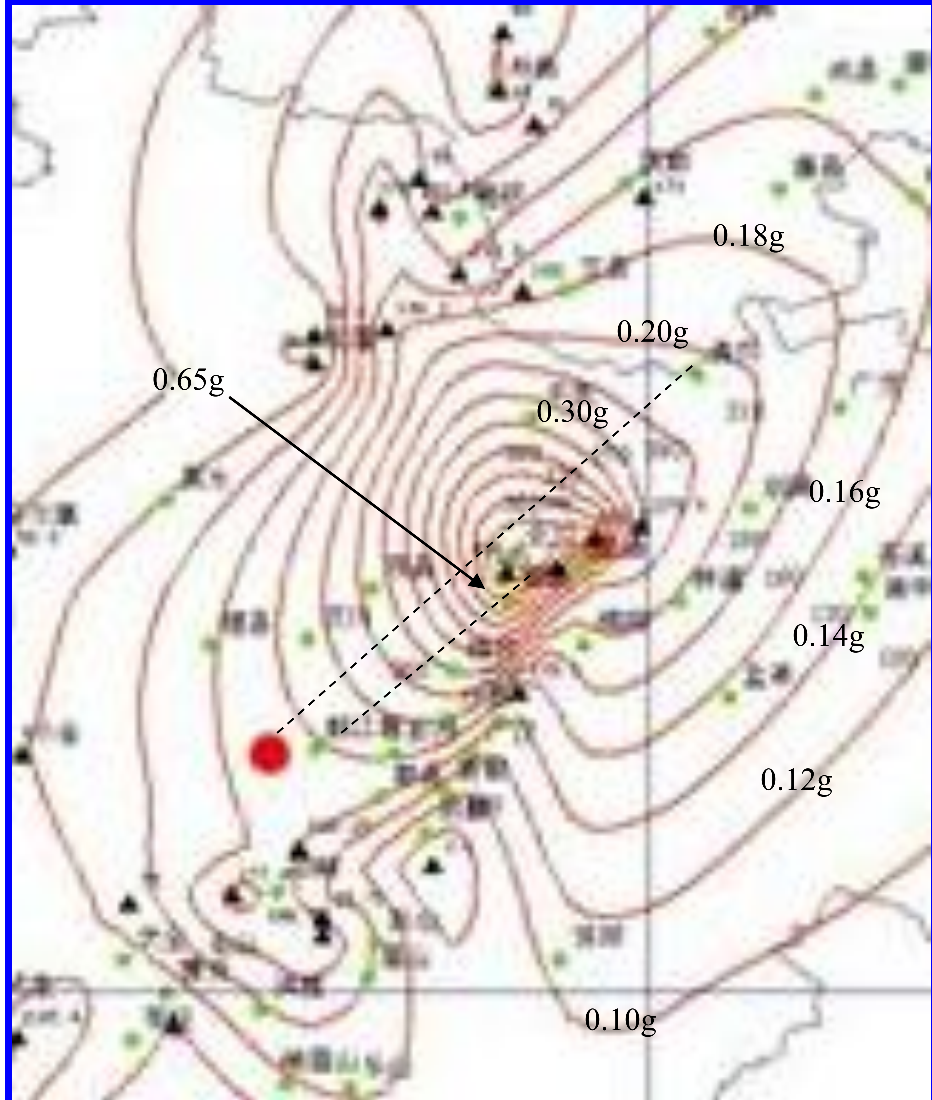


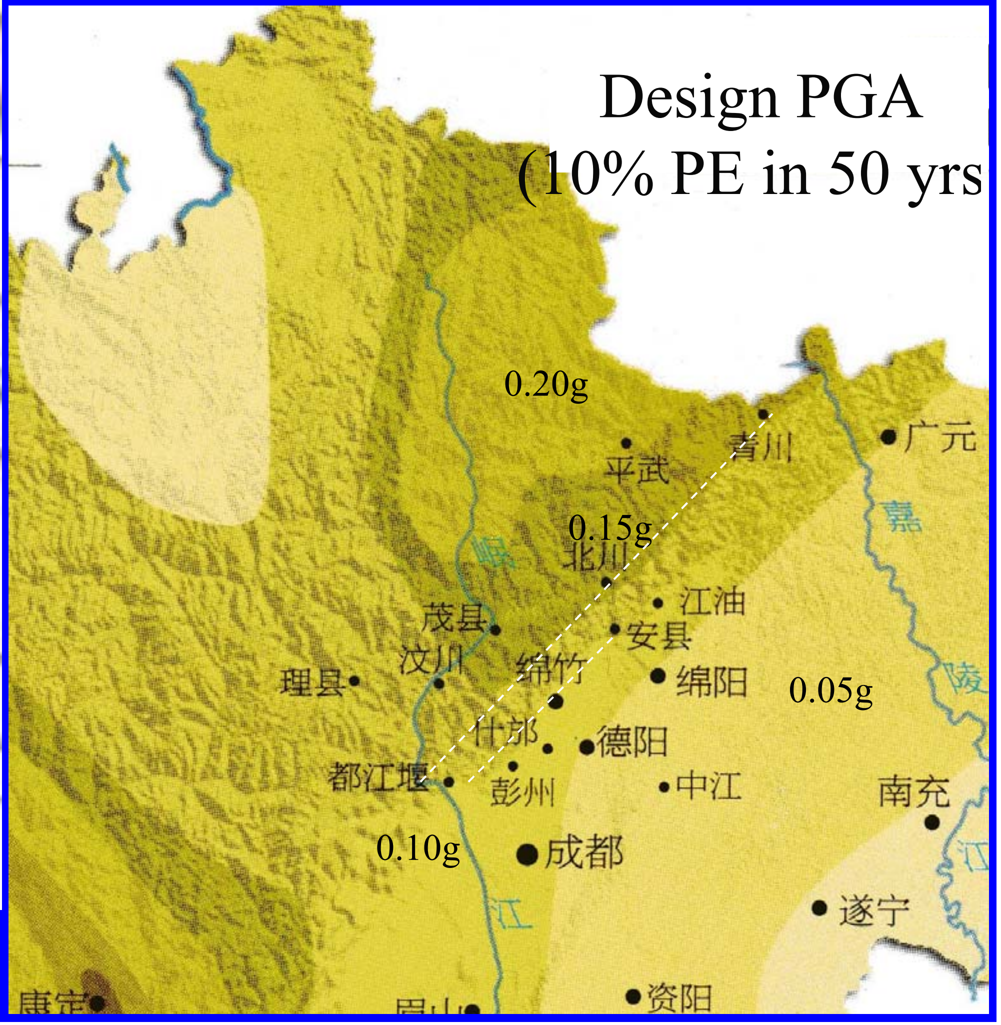
Rupture and asperity effects





Observations from Wenchuan Earthquake





Observations from Wenchuan Earthquake

Observations from Wenchuan Earthquake

Wudu, Jiangyou

Dong Qi MS (Hanwang)

Shan Zhao MS

Wenxian, Gansu

Summary

- Seismic hazard and risk are two fundamentally different concepts
  - Seismic hazard: a natural phenomenon generated by an earthquake, quantified by three parameters
    - Physical measurement (magnitude, PGA, PGV, MMI, etc.)
    - Temporal measurement
    - Spatial measurement
  - Seismic risk: a probable outcome from interaction between a seismic hazard and vulnerability, quantified by four parameters
    - Probability
    - Physical/monetary measurement
    - Temporal measurement
    - Spatial measurement

Summary

- Probabilistic seismic hazard analysis: PSHA (model) is flaw
  - Is not based on earthquake science
    - Invalid physical model (point source)
    - Invalid mathematics
    - Mis-interpretation of annual probability of exceedance or return period
  - Should not be used for seismic hazard and risk assessments

Summary

- Alternative seismic hazard assessment
  - The goal of any seismic hazard assessment is to quantify
    - Physical measurement
    - Temporal measurement
    - Spatial measurement
  - Should reflects earthquake science
  - Approaches
    - Theoretical (model)
      - SHA
      - DSHA
      - Neo-DSHA
    - Empirical (model)

Summary

- Again, Wenchuan earthquake shows that mitigation works
- Earthquake science is the bases for engineering design and mitigation policy consideration.

A Quote from Alan Greenspan

-the former U.S. Federal Reserve Chairman
(1987-2006)

"I found a flaw in my model"

said a very distressed Greenspan
at the U.S. House Oversight Committee
on October 23, 2008, in Washington, DC

(www.youtube.com/watch?v=3ggPHNuEEH8&NR=1&feature=fvwp)

A Questions for Everyone

U.S. NUCLEAR REGULATORY COMMISSION **March 2007**

REGULATORY GUIDE

OFFICE OF NUCLEAR REGULATORY RESEARCH

REGULATORY GUIDE 1.208

The general process to determine a site-specific, performance-based GMRS includes the following:

(1) site- and region-specific geological, seismological, geophysical, and geotechnical investigations
(2) a probabilistic seismic hazard analysis (PSHA)
(3) a site response analysis to incorporate the effects of local geology and topography
(4) the selection of appropriate performance goals and methodology

What are these analyses? Are we really safe? Or are we too conservative?

Three Mile Island NPP

The partial meltdown at Three Mile Island NPP, March 28, 1979
A minor radiation leak at the plant on November 21, 2009

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Any Question?