Advanced Conference on Seismic Risk Mitigation and Sustainable Development

10 - 14 May 2010

Seismic Hazard and Risk Assessment and Mitigation Policy in USA

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Seismic Hazard and Risk Assessment and Mitigation Policy in USA

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ICTP Advanced Conference on Seismic Risk Mitigation and Sustainable Development
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Outline

• Introduction
  – The NEHRP Provisions
  – NRC Regulatory Guide 1.208

• Probabilistic Seismic Hazard Analysis (PSHA)

• Alternative Seismic Hazard Assessments
  – Seismic Hazard Analysis (SHA)
  – Deterministic Seismic Hazard Analysis (DSHA)
  – Neo-DSHA or Scenario-Based Hazard Analysis

• Lesson from Wenchuan, China, earthquake

• Summary
Development of *Design Ground Motion (Policy)*

**Science**

Seismic Hazard Map (USGS)

BSSC – engineers, seismologists, and others

**Policy**

Seismic *Design Ground Motions* (FEMA)

Federal agencies  State Agencies  Other organizations
2009 NEHRP Provisions (Policy)

Figure 22-1 Uniform-hazard (2% in 50-Year) ground motions of 0.2-second spectral response Acceleration (5% of critical damping), Site Class B
0.2-second spectral response Acceleration (5% of critical damping), Site Class B

1980 Sharpsburg Earthquake (M5.2)
Development of *Seismic Ground Motion (policy)*

- **PSHA** → **Seismic Hazard Map** (USGS)
  - **BSSC** – engineers, seismologists, and others
  - **Seismic Design Ground Motions** (FEMA)
  - Impacts on society

- **Science - Basis** → **Stakeholders:** Scientists/Engineers/Economist, …
- **Policy**
Mon Apr 19 15:46:28 UTC 2010
1803 earthquakes on these maps

CONTERMINOUS 48 STATES
Figure 9. Composite DYFI? map of the U.S. (1988–2007) showing the maximum credible intensity reported by the public for each zip code for which there is reported felt information. To date, there are more than one million DYFI? entries for the U.S.
GPS results
Deformation rate: > 30 mm/y

Deformation rate: < 3 mm/y
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
HAZARD CURVES FOR SELECTED CITIES

(NRC RG: $10^{-4} - 10^{-5}$
(annual frequency of exceedance)

(Frankel and others, 1996)
Example:

$100,000,000$y RP,
$11g$ PGA?

Yucca Mountain, NV
(Stepp and others, 2001)

It was concluded in 2008 that “while many of the observations we present here are preliminary, they nevertheless suggest that the 1998 PSHA overstates the true seismic hazard at Yucca Mountain”
(Abrahamson and Hanks, 2008)
Development of mitigation policy in US

PSHA

Engineers, seismologists, and others

Seismic Design Ground Motions

Impact on society

Science - Basis

Stakeholders: Scientists/Engineers/Economist, …

Policy
Seismic Hazard versus Seismic Risk

Seismic Risk = Seismic Hazard $\Theta$ Vulnerability

- **Seismic Hazard**
  - Quantification:
    - Physical measurement (magnitude, PGA, MMI)
    - Temporal measurement
    - Spatial measurement

- **Seismic Risk**
  - Quantification:
    - Probability
    - Physical/monetary measurement
    - Temporal measurement
    - Spatial measurement

References
2. Panza and others (in press), Introduction, Pure and Applied Geophysics, Special Volume on Advanced Seismic Hazard Assessment
Seismic hazard: rock falls (rockfalls/minute)

Vulnerability: car and people

Risk = Seismic Hazard $\Theta$ Vulnerability

(the probability killed by a rockfall during passing through)

Hazard may or may not be mitigated, but risk can always be reduced
Seismic Hazard vs. Seismic Risk

\[ p = 1 - \exp\left(-\frac{t}{RI}\right) \]

Area within Intensity VII
New Madrid = 203,000 square miles
San Francisco = only 12,000 square miles!

<table>
<thead>
<tr>
<th></th>
<th>M7.8 or MMI VIII every 100 to 200 years</th>
<th>22 to 39% probability of M7.8 or MMI VIII being exceeded in 50 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Francisco</td>
<td>M7.8 or MMI VIII every 500 to 1,000 years</td>
<td>5 to 10% probability of M7.8 or MMI VIII being exceeded in 50 years</td>
</tr>
<tr>
<td>Memphis</td>
<td></td>
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</tr>
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</table>
Probabilistic Seismic Hazard Analysis – PSHA

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

\[ \gamma(y) = \sum v P(Y \geq y) = \sum v \int \int \frac{1}{\sqrt{2\pi} \sigma_{ln,y}} \exp \left[ -\frac{(\ln y - \ln y_{nr})^2}{2\sigma_{ln,y}^2} \right] d(ln y) f_M(m) f_R(r) dm dr \]

(McGuire, 2004)
PSHA end result: a hazard curve of ground motion vs. “frequency” at a site
Probabilistic Seismic Hazard Analysis – PSHA

Sensitivity Test

Input
A single EQ

PSHA
“Model”

Output
Infinite GM

Source
(M7.7 occurrence)

Site
(GM occurrence)

Dis. = 30 km

$T_{RI} = 500$ years

$T_{RP} = ?$

The return period: “the mean (average) time between occurrences of a seismic hazard, for example, a certain ground motion at a site” (McGuire, 2004, p.8).

$T_{RP}$: 500 years to infinity?

(Cornell, personal communication, 2004)
Probabilistic Seismic Hazard Analysis – PSHA

Kentucky Seismic and Strong-Motion Network

- Strong Motion and Seismic (weak rocks) Station
- Strong Motion Station (fsa)
- Seismic Station-government
- Seismic Station-temporary

New Madrid Seismic Zone

$T_RL = 500 \text{ years}$

$T_RP = 500 \text{ years}$
Probabilistic Seismic Hazard Analysis – PSHA

What is PSHA?

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

\( \gamma(y) \): the annual probability of ground motion \( y \) being exceeded

It was developed from mathematical statistics (Benjamin and Cornell, 1970; Mendenhall and others, 1986) under four fundamental assumptions (Cornell 1968, 1971):

(a) Constant-in-time average occurrence rate of earthquakes
(b) Equal likelihood of earthquake occurrence along a line or over an areal source (single point)
(c) Variability of ground motion at a site is independent
(d) Poisson (or "memory-less") behavior of earthquake occurrences.
Probabilistic Seismic Hazard Analysis – PSHA

**GMPE:**

\[ \ln(Y) = f(M, R) + \delta = f(M, R) + \varepsilon \sigma \]

1. \( \delta \) distribution depends on \( \sigma \), but not on \( \varepsilon \)
2. \( \varepsilon \) is a standardized normal distribution with a zero mean and standard deviation of 1
GMPE: \[\ln(Y) = f(M, R) + \delta = f(M, R) + \varepsilon \sigma\]

According to *mathematical statistics* (Benjamin and Cornell, 1970; Mendenhall and others, 1986), if and only if \(M, R,\) and \(\delta\) are independent random variables, then the exceedance probability \(P[Y \geq y]\) for seismic source \(j\) is

\[
P_j[Y \geq y] = \int \int \left\{1 - \int_0^y \frac{1}{\sqrt{2\pi}\sigma_j} \exp\left[-\frac{(\ln y - \ln y_{mr})^2}{2\sigma_j^2}\right] d(\ln y)\right\} f_{M,j}(m) f_{R,j}(r) dm dr
\]
Assumption (a): **Constant-in-time average occurrence rate of earthquakes.** For G-R relationship

\[
\lambda = \frac{1}{\tau} = e^{\alpha - \beta M}, \quad m_0 \leq M \leq m_{\max}
\]

\(M\) is independent

PDF for \(M\)

\[
f_M(m) = \frac{\beta e^{-\beta(m-m_0)}}{1 - e^{-\beta(m_{\max}-m_0)}}, \quad m_0 \leq m \leq m_{\max}.
\]
Assumption (b): Equal likelihood of earthquake occurrence along a line or over an areal source (single point)

PDF for $R$

$$f_R(r) = \frac{dF_R(r)}{dr} = \frac{d}{dr} \left( \frac{2\sqrt{r^2 - d^2}}{l} \right)$$

$$= \frac{2r}{l\sqrt{r^2 - d^2}}, \quad d \leq r \leq r_0.$$
\[ \ln(Y) = f(M, R) + \delta = \ln(Y_{MR}) + \varepsilon \sigma \]

**PDF for \( \delta \)**

\[ f_\delta(\delta) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(\delta - \ln y_{mr})^2}{2\sigma^2}\right] \]

**PDF for \( \varepsilon \)**

\[ f(\varepsilon) = \frac{1}{\sqrt{2\pi}\cdot1} \exp\left[-\frac{(\varepsilon - \ln y_{mr})^2}{2\cdot1^2}\right] \]

**Assumption (c): Variability of ground motion at a site is independent**
Assumption (d) Poisson (or "memory-less") behavior of earthquake occurrences

fault. Next we must consider the question of the random number of occurrences in any time period. For illustration, it is assumed that the occurrences of these major events follow a Poisson arrival process (Parzen, 1962; Cornell, 1964) with average occurrence rate (along the entire fault) of \( \nu \) per year. Then, \( \hat{N} \), the number of events of interest along the fault in a time interval of length \( t \) years is known to be Poisson distributed

\[
p_{\hat{N}}(n) = P[\hat{N} = n] = \frac{e^{-\nu t}(\nu t)^n}{n!} \quad n = 0, 1, 2, \ldots.
\]  

(18)

It is easily established that, if certain events are Poisson arrivals with average arrival rate \( \nu \) and if each of these events is independently, with probability \( p \), a "special event," then these special events are Poisson arrivals with average rate \( \nu p \). (This is said to be a Poisson process with ("random selection.") In our case the special events are those which cause an intensity at the site in excess of some value \( \dot{i} \). The probability, \( p_{\ddot{i}} \), that any event of interest \( (M \geq M_0) \) will be a special event is given by equation 12.

\[
p_{\ddot{i}} = P[I \geq \dot{i}] = \frac{1}{\dot{i}} CG \exp \left[-\frac{\beta_0}{c_2} \dot{i} \right].
\]

Thus the number of times \( N \) that the intensity at the site will exceed \( \dot{i} \) in an interval of length \( t \) is

\[
p_{\hat{N}}(n) = P[N = n] = \frac{e^{-\nu \dot{i} t}(p_{\ddot{i}} \nu t)^n}{n!} \quad n = 0, 1, 2, \ldots.
\]  

(20)

(page 1590 of Cornell, 1968)
Pre-condition (1), \( t = 1 \) (year)

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

\[
P[I^{(t)}_{\text{max}} \leq i] = P[\text{exactly zero special events in excess of } i \text{ occur in the time interval } 0 \text{ to } t]\]

which from equation (20) is

\[
P[I^{(t)}_{\text{max}} \leq i] = P[N = 0] = e^{-\rho_{t} i}. \tag{21}
\]

If we let \( I_{\text{max}} \equiv I^{(1)}_{\text{max}} \), the annual maximum intensity, \( t = 1 \), and

\[
F_{I_{\text{max}}} = e^{-\rho_{t} i} = \exp\left[-\rho_{t} \exp\left(-\frac{\beta}{c_{2}} i\right)\right] \quad i \geq i'. \tag{22}
\]

Pre-condition (2) Small annual prob. of exc. \( \leq 0.05 \)

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

\[
1 - F_{I_{\text{max}}}^{(t)} = 1 - e^{-\rho_{t} i} \approx 1 - (1 - p_{i})
\]

\[
\approx p_{i}
\]

\[
\approx \rho_{t} \exp\left(-\frac{\beta}{c_{2}} i\right) \quad i \geq i'. \tag{23}
\]

(page 1590-91 of Cornell, 1968)
Probabilistic Seismic Hazard Analysis – PSHA

The annual probability of exceedance – probability of exceedance in ONE year

\[ 1 - F_{t_{\text{max}}}^{(i)} = 1 - e^{-p_i \nu} \cong 1 - (1 - p_i \nu) \cong p_i \nu \]

Pre-condition (1): \( t \equiv 1 \) (year)
Pre-condition (2): \( \leq 0.05 \)

The return period

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

Basic Equation of PSHA (total annual probability of exceedance)

\[ \gamma(y) = \sum v \int \int \left\{ 1 - \int_{0}^{y} \frac{1}{\sqrt{2\pi\sigma_{\ln,y}}} \exp\left[ -\frac{(\ln y - \ln y_{mr})^2}{2\sigma_{\ln,y}^2} \right] d(\ln y) \right\} f_M(m) f_R(r) dm dr \]
**Probabilistic Seismic Hazard Analysis – PSHA**

| Assumption (a): | Constant-in-time average occurrence rate of earthquakes |
| Assumption (b): | Single point source |
| Assumption (c): | Variability of ground motion at a site is independent |
| Assumption (d): | Poisson (or "memory-less") model |

1. Pre-condition (1) \( t = 1 \) (year)

2. Pre-condition (2) small annual prob. of exc. \( \leq 0.05 \)

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

1. If any of the assumptions is not valid, PSHA calculation is NOT valid.
2. If any of the pre-conditions is violated, PSHA calculation is NOT valid.
3. The annual probability of exceedance is a **PROBABILITY** of exceedance in ONE year and **dimensionless**.
Fig. 4. Numerical example: Intensity versus return period.

The average return period, $T_i$, of an intensity equal to or greater than $i$ is defined as the reciprocal of $1 - F_{I_{imax}}^{(i)}$ or
Source model: finite fault, not point source

Haiti earthquake
\( \delta (\sigma) \) is not independent
Probabilistic Seismic Hazard Analysis – PSHA

Assumption (a): Constant-in-time average occurrence rate of earthquakes?

Assumption (b): Single point source – Not valid

Assumption (c): Variability of ground motion at a site is independent - No

Assumption (d): Poisson (or "memory-less") model - ?

1) Pre-condition (1) \( t = 1 \) (year)

2) Pre-condition (2) small annual prob. of exc. \( \leq 0.05 \)

\[
\gamma(y) = \sum v \int \int \{1 - \int_0^y \frac{1}{\sqrt{2\pi}\sigma_{ln,y}} \exp\left[-\frac{(\ln y - \ln y_{mr})^2}{2\sigma_{ln,y}^2}\right]d(\ln y)\} f_M(m)f_R(r)dmdr
\]

1. PSHA (model) is NOT valid.
2. The annual probability of exceedance is a PROBABILITY of exceedance in ONE year and dimensionless - Not “frequency”.
Probabilistic Seismic Hazard Analysis – PSHA

PSHA could “create” 11g PG with a return period of 100,000,000 years.

Yucca Mountain, NV
(Stepp and others, 2001)
Assumption (d) Poisson (or "memory-less") behavior of earthquake occurrences

\[
1 - F_{I_{\text{max}}} = 1 - e^{-p_i \nu} \approx 1 - (1 - p_i \nu) \\
\approx p_i \nu
\]

Example: tossing a coin

\[p_h = 0.5\]
\[p_t = 0.5\]
\[\nu = 10 \text{ (tosses/min.)}\]

The probability of having at least one head in 1 minute 5.0
Alternative Seismic Hazard Assessment

(Reiter, 1990)
1. Seismic Hazard Assessment - Theoretical

\[ \ln(Y) = f(M, R) + \alpha \sigma \]

\[ M = g(R, \ln Y, \alpha \sigma ) \]

\[ \tau = \frac{1}{N} = e^{-2.303\alpha + 2.303b_g(R, \ln Y, \varepsilon \sigma)} \]

(Wang, 2006, 2007)
SHA to DSHA

Characteristic earthquake:
M7.5/RI=500y

For one characteristic Earthquake:
SHA becomes DSHA

Ground motion at 30km:
0.44g PGA (median)
0.22g PGA (median–SD)
0.88g PGA (median+SD)
/RP≡500y
Maximum Credible Earthquake
PGA for Maximum Credible Earthquake
SHA to DSHA to Neo-DSHA

Neo-DSHA (Panza and others, 2001)

Earthquakes Since 1974
- Shallow depth (0–10 km)
- Mid depth (10–20 km)
- Deep (>20 km)

(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

Seismic hazard curve: $A$ vs. $\tau$ at a site

Step 2

<table>
<thead>
<tr>
<th>Modified Mercalli</th>
<th>Rossi-Forel</th>
<th>JMA</th>
<th>Mercalli Caucaud-Sieberg</th>
<th>Medvedev Spolletti-Kanitk</th>
<th>PGA (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I III IV V VI VII VIII IX X XI XII</td>
<td>I II III IV V VI VII VIII IX X XI XII</td>
<td>I II III IV V VI VII VIII IX X XI XII</td>
<td>I II III IV V VI VII VIII IX X XI XII</td>
<td>I II III IV V VI VII VIII IX X XI XII</td>
<td>0.01-0.025 0.025-0.05 0.05-0.1 0.1-0.2 0.2-0.4 0.4-0.8 0.8-1.6 &gt;1.6</td>
</tr>
</tbody>
</table>

Step 3

Intensity table (Panza)

(Historical records)

(Milne and Davenport, 1969)

<table>
<thead>
<tr>
<th>Year</th>
<th>A (PGA,g)</th>
<th>Rank (m)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>1895</td>
<td>0.001</td>
<td>96</td>
<td>0.888889</td>
</tr>
<tr>
<td>1896</td>
<td>0.01</td>
<td>84</td>
<td>0.777778</td>
</tr>
<tr>
<td>1897</td>
<td>0.1</td>
<td>29</td>
<td>0.268519</td>
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</table>
2. Seismic Hazard Assessment - Empirical

Step 3

<table>
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<td>0.268519</td>
</tr>
</tbody>
</table>

(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

Seismic hazard curves

Fig. 13. Extreme value distribution plot for Quebec City.
2. Seismic Hazard Assessment - Empirical

Tokyo, Japan
(400-year data)

(Bozkurt and others, 2007)
2. Seismic Hazard Assessment - Empirical

Beijing area, China (500 years data)
(Xie and others, in press)
Lesson 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
Lesson from Wenchuan Earthquake

汶川8.0级地震烈度分布图
Lesson 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)
Lesson from Wenchuan Earthquake

Rupture and asperity effects

Wolong (A) Acceleration records

Qingping (A) Acceleration records

Zengjia (A) Acceleration records
Lesson from Wenchuan Earthquake

Design PGA (10% PE in 50 yrs)
Summary

• Probabilistic seismic hazard analysis: PSHA (model) is flawed
  • Is not based on earthquake science
    • Invalid physical models
    • Point source
    • Poisson distribution
  • Invalid mathematics
  • Mis-interpretation of annual probability of exceedance or return period
  • Become a pure numerical “creation”
Summary

• Alternative seismic hazard assessment
  • The goal of any seismic hazard assessment is to quantify
    • Physical measurement (ground motion)
    • Temporal measurement (when/how often)
    • Spatial measurement (where)

• Approaches
  • Theoretical
    • SHA
    • DSHA
    • Neo-DSHA
  • Empirical
Summary

• Seismic hazard and risk are different concepts, and play different roles in policy making

• Earth-scientists, seismologists in particular, must
  • provide seismic hazard information that is consistent with modern sciences
  • also communicate the information in an understandable way
  • work with engineers and others to assess seismic risk
Thank you very much!