Earthquake Hazards and Hazard Mapping

From Ground Shaking to Ground Failure

GROUND SHAKING

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Fundamental Questions

40 Years Ago

» Where are the sources of big earthquakes?
» How big?
» How strong will the ground shake?

Now

» How often?
» When was the last one?
» What is the slip distribution on the fault and rupture process?
Fundamental Questions

**Now (cont.)**

- How are the ground motions attenuating?
- What are the site effects due to soil, basins, and topography?
- What is the nature of the ground shaking in terms of response spectra and time histories?
- Etc.
Steps in Developing Ground Shaking Hazard Maps

- Characterize seismic sources – Active faults and background seismicity
- Characterize surficial geology and define site response units based on shear-wave velocities and material properties
- Develop amplification factors
- Characterize ground motion attenuation
- Perform seismic hazard analysis – Scenario (deterministic) and/or probabilistic
- Produce Maps
Commonly Used Ground Motion Parameters

- Peak ground acceleration (PGA)
- Peak ground velocity (PGV)
- Spectral acceleration (0.2 or 0.3 sec and 1.0 sec)
- Duration
- Time history
Acceleration Response Spectrum

SPECTRAL ACCELERATION (g/s)

PERIOD (Seconds)

PGA
0.01 sec (100 Hz)

0.2 sec (5 Hz)

0.3 sec (3.3 Hz)

1.0 sec (1 Hz)

\[ g = \text{gravitational acceleration at earth’s surface} = 980 \, \text{cm/sec}^2 \]
Factors Affecting Earthquake Ground Shaking

**EARTHQUAKE SOURCE**
Parameters: Magnitude, stress drop, rupture process, slip distribution

**PATH**
Parameters: Attenuation (Q)

**SITE**
Parameters: Shear-wave profile, dynamic material properties, kappa, basin geometry, topography

- Fault Plane
- Asperity
- Hypocenter
- Seismic Waves
Deterministic Seismic Hazard Analysis

- Objective is to estimate the ground shaking from a specified earthquake; sometimes called a scenario earthquake.

- In seismic design, characteristics of the maximum ground shaking are desired (Maximum Credible Earthquake).

- Scenario earthquakes, which may represent less severe but more probable events, are often used in loss estimation and response planning.

- Uncertainties are not comprehensively incorporated into a deterministic analysis. Frequency of earthquake occurrence also not considered other than it is a plausible event.
Probabilistic Seismic Hazard Analysis

- Objective is to estimate the probability that a specified level of ground motion will be exceeded or the level of ground motions that will occur in a specified exposure (return) period.
- Integrates hazard from all significant seismic sources – adds annual frequencies of ground motion occurrence.
- Incorporates the frequency of earthquakes for each seismic source.
- Allows for explicit treatment of uncertainty.
- Provides basis for making decisions based on risk.
Earthquake locations in space lead to distribution of locations $P[l]$:

Seismic Source $i$

$P[l]$ is the probability that the earthquake with any source properties occurs at location $l$

Size distribution and rates of occurrence on source $i$:

$P(s), v_i$

$P(s)$ is the probability of source properties $(s)$ (often just magnitude) and $v_i$ is the rate of occurrence of earthquakes on source $i$

Ground Motion Estimation:

$P[C > c | s \text{ at } l]$ is the probability that $c$ is exceeded at the site conditional on an earthquake on source $i$, with $M$ at location $l$

Probability analysis:

$\gamma_i[C > c] = \sum_i v_i \int \int P[C > c | s \text{ at } l]P(s)P[l]d sd l$

where $\gamma_i$ is the frequency with which $c$ is exceeded from earthquakes on source $i$

(McGuire, 2003)
Common Myths and Misconceptions

- How can probabilistic values exceed Maximum Credible Earthquake values?

- Doesn’t PSHA add up the ground motions from numerous sources and isn’t this unrealistic?

- Return period, recurrence interval, and exposure period are often incorrectly intermixed.

- The mean hazard can be calculated using just mean values of the input parameters. No because the PSHA calculation is nonlinear.

- There isn’t enough data (earthquake frequency) to do a PSHA. Computing seismic hazard is a process of approximation.
Uncertainty

- Epistemic (or knowledge) – Uncertainty due to lack of knowledge about some model or parameter. This type of uncertainty can be reduced, at least conceptually, by additional data or improved information. Also called statistical or professional uncertainty, or simply uncertainty.

Examples:

- Geometry of seismogenic zones.
- Distributions describing source parameters (e.g., slip rate, maximum magnitude).
- Median value of ground motion given magnitude.

Approach: Logic trees
Uncertainty (cont.)

- **Aleatory (or random)** – Probabilistic uncertainty that is inherent to a random phenomenon that we cannot hope to reduce with additional data or information. Also been called randomness or inherent variability.

Examples:

- Future earthquake locations.
- Future earthquake source properties (e.g., magnitudes).
- Ground motion at a site given the median value of motion.
More Uncertainties Expressed

- “One person’s aleatory is another person’s epistemic.” (Personal communication with Norm Abrahamson – date unknown)
- The probabilities in the integrand of the PSHA equation are aleatory uncertainties
- Aleatory uncertainty is represented by a single hazard curve
- Epistemic uncertainty is represented by fractile hazard curves
Seismic Hazard Model Logic Tree

- **ATTENUATION RELATIONSHIPS**
- **SEISMIC SOURCES**
- **ACTIVITY**
- **SOURCE GEOMETRY** (Dip, Closest Distance, Depth)
- **MAXIMUM MAGNITUDE**
- **EARTHQUAKE RECURRENCE MODEL**
- **RECURRENCE METHOD**
- **SLIP RATES**

- Sadigh et al. (1997)
  - Abrahamson and Silva (1997)
  - Campbell (1997)
  - Spudich et al. (1999)/Boore et al. (1997)

- Foothill Fault System (North)
- Dog Valley Fault
- Genoa Fault
- Hayward-Rodgers Creek Fault Zone
  - San Andreas Fault Zone
  - Background Zones

- Yes (See Table 1 for weights)
- (See Table 1 and text)
- No

- M - 0.3
- M (See Table 1)
- M + 0.3

- Characteristic (0.6)
- Maximum Magnitude (0.2)
- Truncated Exponential (0.2)

- Slip Rate (1.0)
- Recurrence Intervals (0.0)

*Weighting of attenuation relationships varies for faults in coastal California, Sierran foothills, and Sierran Frontal fault system.*
**Earthquake Hazard Models**

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poisson Model</td>
<td>Earthquakes follow a Poisson process and are assumed to occur randomly in space and time along a fault or within a seismic source zone.</td>
</tr>
<tr>
<td>Time-Dependent (Renewal) Model</td>
<td>Earthquakes along a fault are dependent on the elapsed time since the last event. More realistic in physical basis.</td>
</tr>
</tbody>
</table>

“In any 50 years, not next 50 years.”
Types of Earthquake Sources Modeled in Hazard Analysis

- Active faults

- Areal source zones
  - Background (random) seismicity
  - All seismic sources including known faults and background seismicity
  - Zone of distributed faulting, e.g., intraslab regions of subducting plates
Seismic Source Characterization

- Seismogenic capability
- Source geometry
- Rupture characteristics
- Maximum magnitude
Source Geometry and Rupture Characteristics

**Faults**

- Orientation (strike and dip)
- Rupture dimensions
  - Length
  - Width – seismogenic crustal thickness
- Style of faulting and slip direction
- Rupture process

**Areal Source Zones**

Boundaries, seismogenic crustal thickness, and style of faulting
Seismogenic Capability

- Many definitions of active faults
- Capable of generating earthquakes – seismogenic
- Example criteria:
  - Displaced once in past 35,000 years and multiple times in 500,000 years
  - Holocene (past 11,000 years) displacement
  - Late Quaternary (past 500,000 years)
Fault Segmentation

- Earthquakes are the result of rupture on fault segments. Such segments have physical controls, which may define the extent of rupture over several seismic cycles.

- Structural versus rupture segments.

- Was the 1992 Landers earthquake a multi-segment rupture?
San Francisco Bay Region Fault Model

[Map showing fault lines and geographic features of the San Francisco Bay Region.]
Hayward-Rodgers Creek Fault System

scenario 1
scenario 2
scenario 3
scenario 4
scenario 5

Windsor Creek
Santa Rosa
San Pablo Bay
Mira Vista
Rocky Mound
Montclair
Mills College
San Leandro
Agua Caliente Creek
Alum Rock

150km
98km
63km
63km
35km
87km
52km
52km

[RC]
[NH]
[SH]

floating 1868
150km
Maximum Magnitude

- Historical and characteristic earthquake
- Empirical relationships based on rupture dimensions (e.g., Wells and Coppersmith, 1994; Hanks and Bakun, 2002)
- Seismic moment $M_o = \mu \ AD$
Individual faults or fault segments will tend to generate essentially the same size or “characteristic” earthquake through time as long as changes in the geometry, mechanical properties or state of stress of the fault do not change.
Earthquake Recurrence

- Recurrence interval – time between events of similar size
- Slip rate

\[ s \equiv \text{Total Displacement} \]
\[ \text{Time} \]

- Historical seismicity

Gutenberg-Richter Relationship

\[ \log N = a - bM \]
Frequency Density Function Characteristic Model

Cumulative Frequency Function Characteristic Model
Frequency Density Function Maximum Magnitude Model

Cumulative Frequency Function Maximum Magnitude Model
Frequency Density Function Truncated Exponential Model

Cumulative Frequency Function Truncated Exponential Model
Background Earthquakes

- “Background” earthquakes show no apparent association with known geologic structures.
- Example – “blind” or buried faults.
- Use of areal source zones excluding faults incorporates hazard from such random earthquakes.
- Assumes randomly distributed in time and space—Poissonian.
- Maximum magnitude based on threshold for surface faulting.
Gaussian Smoothing

- Smoothing of historical seismicity
- Allows selectable degree of stationarity by choosing size of spatial window
- Used in USGS National Hazard Maps
- Preferred approach is to use areal source zones for random seismicity and smoothing for stationarity
Attenuation Relationships

Median & Median ± c Using Attenuation Relationship for Rock and Stiff Soil Sites by Idriss (1991)

Motions recorded during the 1994 Northridge Earthquake
Average of the two horizontal components
- Rock Sites
- Soil Sites

Peak Acceleration (Average of the two horizontal components) - g

Closest Distance to the Rupture Surface - km
1997 Western U.S. Attenuation Relationships

(a) Vertical SS, Rock

(b) Vertical SS, Soil
Thoughts on Attenuation Relationships

- Big uncertainties – until recently no strong motion data for CA design earthquakes.

- What will impact of Taiwan strong motion data be on current models? Is the data appropriate for CA?

- Need to continue to evaluate differences between tectonic regimes, e.g., compressional versus extensional relationships.

- Need to extend relationships out to 5 sec and more. Watch out for long-period effects, e.g., rupture directivity and basin effects.
Thoughts on Attenuation Relationships (cont.)

- PEER NGA (Next Generation of Attenuation Model) Project scheduled for completion April 2006?

- Subduction zone relationships need more strong motion data for large $M > 8$ megathrust earthquakes at short (< 50 km) distances.
Peak Acceleration Hazard (%g) with 2% Probability of Exceedance in 50 Years
Seismic Hazard Curves for Peak Horizontal Acceleration
Seismic Source Contributions to Mean Peak Horizontal Acceleration Hazard
Magnitude and Distance Contributions to Mean Peak Horizontal Acceleration Hazard at 10,000-Year Return Period
Peak Acceleration Hazard (%g) with 2% Probability of Exceedance in 50 Years
Maximum Considered Earthquake Map
Amplification Factors

- Amplification factors are used to modify the rock motions and hence incorporate site response into the hazard maps.

- Amplification factors are best derived from region-specific strong motion data.

- However, because of the lack of such data particularly at higher ground motions, amplification factors have been developed (e.g., equivalent-linear) using numerical site response approaches.

- Amplification factors are a function of site response unit (lithology), strain, frequency, and thickness of site response unit.
Soil/Rock Strong Motion Records of the 1989 M 6.9 Loma Prieta, CA Earthquake
1997 NEHRP Site Categories

A  Hard rock  (> 1500 m/sec)
B  Rock  (760 – 1500 m/sec)
C  Very dense soil and soft rock  (360 – 760 m/sec)
D  Stiff soils  (180 – 360 m/sec)
E  Soft soils  (< 180 m/sec)
F  Soils requiring site specific evaluations
Soil Amplification Factors

<table>
<thead>
<tr>
<th>Site Class B</th>
<th>Site Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Acceleration</td>
<td>A</td>
</tr>
<tr>
<td>Short-Period, S_{AS} (g)</td>
<td>Short-Period Amplification Factors, F_A</td>
</tr>
<tr>
<td>≤ 0.25</td>
<td>0.8</td>
</tr>
<tr>
<td>0.50</td>
<td>0.8</td>
</tr>
<tr>
<td>0.75</td>
<td>0.8</td>
</tr>
<tr>
<td>1.0</td>
<td>0.8</td>
</tr>
<tr>
<td>≥ 1.25</td>
<td>0.8</td>
</tr>
</tbody>
</table>
$V_s$ Profiles for the Site-Response Units

a) Lacustrine-alluvial silt and clay

b) Lacustrine sand

c) Lacustrine-alluvial gravel

d) Parley’s Canyon - City Creek Canyon

Lacustrine-Alluvial Gravel

e) Older Alluvial Fan/Glacial Gravel

Model, EFRI (1993) stiff cohesionless soil
Example of Strain-Dependent Amplification Factors
Peak Horizontal Acceleration at the Ground Surface for Central Wasatch Front
Challenges in Seismic Hazard Analysis

➢ Seismic Source Characterization

➢ Assessing seismogenic capability
  ▪ Absence of dateable deposits and limitations in age-dating
  ▪ Low activity faults (e.g., Pitaycachi fault)

➢ Earthquake Recurrence
  ▪ Complete seismic cycle
  ▪ Uniform stress loading? Oops, Parkfield.
  ▪ Stress triggering and stress shadows
  ▪ Recurrence models
  ▪ Time-dependent models

➢ Rupture Process
Challenges in Seismic Hazard Analysis (cont.)

Ground Motion Estimation

- Big uncertainties – Until recently no strong motion data for CA design earthquakes and no data outside of CA.

- Need to continue to evaluate differences between tectonic regimes, e.g., compressional versus extensional relationships.

- How will the new NGA relationships be accepted by the engineering community and regulatory agencies?
Challenges in Seismic Hazard Analysis (conc.)

- Near-field effects, e.g., directivity and fling
- Site response due to soil / unconsolidated sediments
- Kappa – rock attenuates too!
- Quantifying basin effects – major urban areas in basins
“The more you know, the more you know you don’t know”

Anonymous Seismologist
Circa 1994
Future Developments

As we obtain more data, our understanding of earthquake processes and effects will improve so the uncertainties in hazard analyses can be reduced and our hazard estimates improved.

- Improvements in Site-Specific Seismic Hazard Analysis
- Urban Hazard Microzonation Maps
- Region-Specific Building Code Parameters