Basic Principles of Earthquake Loss Estimation - PML and Beyond

- *Single-Site Seismic Risk*

Seismic Risk Terminology

- **Exposure**: the buildings, contents, people and processes at risk
- **Earthquake Hazards**: ground shaking, soil liquefaction, surface fault rupture, slope instabilities, tsunami, seiche, etc.
- **Seismic Vulnerability**: fragility or damageability, the relationship between hazard and damage, loss or disruption
- **Risk**: the relationship between loss severity and frequency
Risk occurs at the intersection of exposure, hazard and vulnerability

\[ R = E \times H \times V \]

Risk has at least two dimensions:
- severity and frequency, or
- mean and variance
Return Period vs. Exposure Period and Probability of Exceedance

\[ P = 1 - e^{-\frac{t}{T}} \]

- \( t \) = exposure period (years)
- \( P \) = probability of exceedance in exposure period, \( t \)
- \( T \) = average return period

Seismic Risk Standards

Damage Relationships:
- ATC-13, ATC 13-1
- NIBS – HAZUS
- K.V. Steinbrugge, J.H. Wiggins, Thiel & Zsutty

Seismic Risk Terminology:
- ASTM E 2026-99

Rapid Visual Screening:
- FEMA 154

Vulnerability of Buildings:
- ASCE 31-03 (FEMA 310)

Vulnerability of Contents:
- FEMA 74

Rehabilitation of Buildings:
- FEMA 356
Qualifications for Seismic Risk

*Needed: Engineering Judgment*

**Minimum: C.E. or S.E. + lots of experience**

**Seismic Risk Assessment, Individual Buildings**
Expertise in Seismology + Geology + Structural Engineering and Statistics

**Seismic Risk Assessment, Building Portfolios**
Expertise in Seismology + Geology + Structural Engineering + Actuarial Science + Systems Analysis

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**Seismic Risk Tools**

ATC 13-1

HAZUS-MH MR1

FEMA Benefit/Cost Tools

Proprietary Tools
- Multi-Site tools for insurance – RMS, AIR, ABS, URS
- For Engineers
  - ST-Risk (Risk Engineering and Degenkolb)
  - SiteRisk (URS)
**Probable Loss** - a direct relationship between probability and earthquake damage, considering both the hazard and damage function uncertainties.

**Scenario Loss** - estimates damage for a defined quake scenario:
- Scenario Expected Loss (mean estimate)
- Scenario Upper Loss (90% estimate)

‘PML’ is redefined in ATC 13-1 for “...probable maximum loss studies”
PML50 and PML90 are equivalent to SEL and SUL for earthquake hazards with a 475-year return period

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### Levels of Investigation

Higher levels of investigation are required where higher hazards exist, and/or where higher confidence is required in the result.

<table>
<thead>
<tr>
<th>Assessment</th>
<th>Level 0 (Screening)</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building Stability</td>
<td>Visual observation or drawing review or age and code-based</td>
<td>Detailed visual inspection</td>
<td>Engineering Review (limited/manual calculations)</td>
<td>Engineering review (computer modeling)</td>
</tr>
<tr>
<td>Site Stability</td>
<td>Assess site area, using general data from maps or geotechnical report</td>
<td>Assess site-specific hazards using maps or geotechnical report</td>
<td>Assess site-specific hazards and building impacts using maps or geotechnical report</td>
<td>Detailed (new) studies of site hazards and building impacts</td>
</tr>
<tr>
<td>Damageability</td>
<td>Use BS 0 investigation results and tables for basic building type. Excludes site failures.</td>
<td>Use BS 1 investigation results and tables or software for basic building type. Excludes site failures.</td>
<td>Use BS 2 investigation results and estimate damage specific to each building. Consider site failures.</td>
<td>Use BS 3 investigation results and estimate damage specific to each building. Consider site failures, SS, etc.</td>
</tr>
</tbody>
</table>
Seismic Hazards –

- Ground shaking
- Surface fault rupture
- Soil liquefaction and soil failures
- Slope instability
- Tsunami

Seismic Hazards – Ground shaking

Hazard-recurrence: Use this where loss is related to a single ground motion parameter, with no magnitude dependence

Good Source: USGS National Seismic Hazard Mapping Project [2002]
Seismic Hazards – Ground shaking
USGS National Seismic Hazard Mapping Project 2002

Hazard-recurrence (single-site, single ground motion parameter)

Where losses are magnitude dependent, multi-site, or multi-period, use an event set

Seismic Hazards – Ground shaking
Damage from ground motions: which parameter works best?
- Peak ground acceleration (PGA)
- Peak ground velocity (PGV)
- Spectral acceleration (SA) @ fundamental structural period
- Modified Mercalli Intensity (MMI)
- Arias Intensity

Base - Ch 4 (90°)  1901 Avenue of the Stars, 1/17/94

[Graph showing seismic data]
**Seismic Hazards – Local Hazards**
Liquefaction, surface faulting, landslide, Site Class
Adjustment for Site Conditions

\( F_a, F_v \) factors in SEI/ASCE 31-03 and FEMA 356

Soil Factors are amplitude-dependent
Uncertainty in Seismic Hazards

Large uncertainty

Local Hazards per HAZUS

Table 10.2 PESH Module Outputs - Ground Deformation

<table>
<thead>
<tr>
<th>Component</th>
<th>Description of Output</th>
<th>Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquefaction</td>
<td>HAZUS determines the probability of and expected level of permanent ground deformations for liquefaction susceptible sites during the deterministic, probabilistic, or user-defined event.</td>
<td>a) PGD Contour Maps</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b) Location-Specific PGD</td>
</tr>
<tr>
<td>Landsliding</td>
<td>HAZUS determines the probability of and expected level of permanent ground deformations for landsliding susceptible sites during the deterministic, probabilistic, or user-defined event.</td>
<td>a) PGD Contour Maps</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b) Location-Specific PGD</td>
</tr>
<tr>
<td>Surface Fault Rupture</td>
<td>HAZUS determines the probability of and expected level of permanent ground deformations for surface fault rupture susceptible sites during the deterministic, probabilistic, or user-defined event.</td>
<td>a) PGD Contour Maps</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b) Location-Specific PGD</td>
</tr>
</tbody>
</table>
Structural Vulnerability Assessment

Resources -- see Bibliography

Structural Evaluation
ASCE 31-03 (previously FEMA 310, or FEMA 178)
Building Codes (IBC, UBC, etc.)

Relationship? \(\rightarrow\) Engineering Judgment!

Damage Relationships
ATC 13 "Earthquake Damage Evaluation Data for California"
Steinbrugge, K.V. *various publications*
Thiel & Zsutty, EERI Spectra, 1987
Wesson et al., EERI Spectra, 2004
Porter et al, CUREE
HAZUS MH
Structural Evaluation

“Wish List” for Documents for Seismic Studies

Structural drawings (originals, mods, retrofits)
Architectural drawings
Geotechnical report (‘soils report’)
Construction photos
Earthquake damage reports
Accelerometer recordings
Computer models (ETABS, SAP, …)

Also, access to Engineer-of-Record, Constructor

Damage Relationships

Courtesy USGS
Damage Relationships

Two parts to the damage relationship:
1) Damage versus ground motion
2) Variability of damage

Damage to wood frame dwellings in Northridge [Wesson, Spectra, August 2004]

Damage Relationships

Two parts to the damage relationship:
1) Damage versus ground motion
2) Variability of damage

Damage to wood frame dwellings [Porter, CUREE-CalTech, 2002]
ATC 13 Damage Probability Matrices

<table>
<thead>
<tr>
<th>Damage State</th>
<th>Damage Factor Range (%)</th>
<th>Central Damage Factor (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – None</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2 – Slight</td>
<td>0 – 1</td>
<td>0.5</td>
</tr>
<tr>
<td>3 – Light</td>
<td>1 – 10</td>
<td>5</td>
</tr>
<tr>
<td>4 – Moderate</td>
<td>10 – 30</td>
<td>20</td>
</tr>
<tr>
<td>5 – Heavy</td>
<td>30 – 60</td>
<td>45</td>
</tr>
<tr>
<td>6 – Major</td>
<td>60 – 100</td>
<td>80</td>
</tr>
<tr>
<td>7 – Destroyed</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Facility Class 6: Low-rise concrete shear wall

ATC 13 Facility Class 6 California Construction (Zone 4?)

Low-rise bearing reinforced concrete shear wall

Facility Class 6: Low-rise concrete shear wall

Probability

Damage Factor (DF)
ATC 13 Damage Probability Matrices

Variability of Building Damage

Damage Histograms from Wesson, 2004, Northridge Damage to Dwellings And Gamma function fits

These are “fat” distributions -- high uncertainty.
Variability of Building Damage

Fit DF, CV to: Beta, Lognormal or Gamma distribution

Levels of Investigation

Typical Levels of Investigation

Level 0 – Desktop

Level 1 – Site Visit (visual survey, exteriors + interiors, nondestructive examination of readily available areas)

Level 2 – Site Visit + review of design documents

Level 3 – Detailed Engineering Review (with computer models, material testing)

Compare: ASTM levels; ASCE 31-03 Tiers
**Levels of Investigation**

Level 0 – Desktop
Level 1 – Site Visit
Level 2 – Site Visit + review of design documents
Level 3 – Detailed Engineering Review

How do we relate ‘Level of Investigation’ and uncertainty in the risk model?

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**Major Challenges**

Modifying seismic vulnerability to reflect seismic retrofit.

How do changes in strength, ductility, period, and damping, and increased regularity and redundancy, affect damage?
Major Challenges
Seismic vulnerability relationships for new systems.

Buckling-restrained brace

Major Challenges
Relating Damage to ‘Code’ Factors

<table>
<thead>
<tr>
<th>Wood Frame</th>
<th>Moment Frame</th>
<th>Shear Wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frame</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mean Damage Factor vs. Demand Capacity

1.0
The Future? Damage vs. Demand-to-Capacity

Casualties

Relationships for injuries and fatalities

Note high variance!

Table 1. ATC-13 injury and death rates.

<table>
<thead>
<tr>
<th>Damage State</th>
<th>Range</th>
<th>Minor Injuries</th>
<th>Serious Injuries</th>
<th>Dead</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 None</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2 Slight</td>
<td>0-1</td>
<td>3/100,000</td>
<td>1/250,000</td>
<td>1/1,000,000</td>
</tr>
<tr>
<td>3 Light</td>
<td>1-10</td>
<td>3/10,000</td>
<td>1/25,000</td>
<td>1/100,000</td>
</tr>
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<td>4 Moderate</td>
<td>10-30</td>
<td>3/1,000</td>
<td>1/2,500</td>
<td>1/10,000</td>
</tr>
<tr>
<td>5 Heavy</td>
<td>30-60</td>
<td>3/100</td>
<td>1/250</td>
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<td>6 Major</td>
<td>60-100</td>
<td>3/10</td>
<td>1/25</td>
<td>1/100</td>
</tr>
<tr>
<td>7 Destroyed</td>
<td>100</td>
<td>2/5</td>
<td>2/5</td>
<td>1/5</td>
</tr>
</tbody>
</table>

*For light steel and wood frame construction, multiply all numerators by 0.1.
Contents Damage
ATC 13 damage relationships for equipment and contents

Downtime Relationships
Dependent upon building damage state + Social Function Class (occupancy)
Risk Assessment

HAZUS-MH   MR1
Advanced Engineering Building Module

- Scenario-based
- Building- and site-specific
HAZUS-MH MR1
Advanced Engineering Building Module

Capacity Spectrum

HAZUS Fragility Curves

National Institute of BUILDING SCIENCES

Light Shaking

Moderate Shaking

Severe Shaking

None

Slight

Moderate

Extensive

Complete
HAZUS-MH MR1
Advanced Engineering Building Module

- HAZUS is scenario-based (deterministic or semi-probabilistic) and it can provide expected loss (SEL).
- Uncertainty in damage state is listed, but HAZUS does not provide upper-bound loss (SUL) or Probable Loss (PL)
- High degree of user knowledge and expertise required.

Single-Site Seismic Risks: SEL, SUL
A more complete answer is a loss curve or a distribution

@ 475 year return period
Single-Site Seismic Risks: Probable Loss

- Loss Limit
- 475 Years

Typical Seismic Risk Analysis
Comparing Scenario Losses and Probable Loss
Single-Site Seismic Risks

Average Annual Loss (AAL) or Expected Annual Loss (EAL) – The long-term annual loss rate

AAL is found by summing the product of each discrete loss state (Li) x its annual frequency of occurrence (fi), over all loss states:

$$AAL = \sum L_i \times f_i$$

...mean and variance

Benefit/Cost Analysis

The reduction in Average Annual Loss afforded by retrofit is an annual benefit. The present value of the loss reduction benefit can be compared with (present) cost of retrofit, to estimate a benefit-to-cost ratio.

Benefit/cost ratios are long-term, time-averaged “expected values.” But retrofit for any single structure has a high uncertainty: what is the probability that it will experience earthquake hazards high enough to pay back the retrofit?
**Benefit/Cost Analysis Example**

5-Story nonductile concrete frame in San Bernardino, CA

$25/s.f retrofit to increase the effective “R” from 4 to 6 and the design strength (USD) from $V=0.1W$ to $V = 0.25W$
Benefit/Cost Analysis Example

Excludes Life-safety Benefits
Benefit/Cost Analysis Example

Other benefits of seismic retrofit -- not included in a simple benefit-to-cost calculation:

- **enhanced life-safety** (fewer deaths and injuries)
- **increased resale value** and **marketability** (i.e., salvage value and rentability)
- **extended useful life** for the building
- **fewer customers lost** due to interruption or delay of service
- possible **lower insurance rates**
- **reduced need for insurance**
- **reduced demand on emergency resources**
**Single-Site Seismic Risks**

Geographic correlation of risks

![Graphs showing risk correlation](image)

**Geographic diversification!**
Use multi-site analysis...

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**Uncertainties in Seismic Risks**

*Ground Motion uncertainty* in the selected ground motion parameter for damage, and uncertainty in annual frequency of occurrence

*Building Performance variability* (damage or loss, given the ground motion parameter)

*Risks from "Special" hazards* (fault rupture, liquefaction, landslide, ...) are difficult to model
Glossaries, Websites

GLOSSARIES
Hazard:
http://www.seis.utah.edu/qfacts/glossary.shtml

Structural Engineering:
http://www.seaonc.org/public/what/glossary.html

WEBSITES:
United States Geological Survey
http://earthquake.usgs.gov/

California Geology
http://www.consrv.ca.gov/CGS/
http://www.consrv.ca.gov/CGS/geologic_hazards/regulatory_hazard_zones/index.htm

Utah Geology
http://geology.utah.gov/utahgeo/hazards/index.htm
http://www.seis.utah.edu/guide/guide.shtml

Oregon Geology
http://www.oregongeology.com/sub/default.htm

Washington Geology
http://www.dnr.wa.gov/geoology/
http://www.dnr.wa.gov/geoology/hazardshmg.htm

Seismic Hazards In Canada
http://earthquakescanada.nrcan.gc.ca/index_e.php

Global Seismic Hazard Assessment Program
http://www.seismo.ethz.ch/GSHAP/index.html

Single-Site Seismic Risk Bibliography

- K. V. Steinbrugge and S. T. Algernier (1990) “Earthquake Losses to Single-Family Dwellings: California Experience,” United States Geological Survey Bulletin 1899A. This study was made in cooperation with the California Insurance Department.
- FEMA 134, 155: “Rapid Visual Screening of Buildings for Potential Seismic Hazards”
- FEMA 74: “Reducing the Risk of Nonstructural Earthquake Damage”
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