Assessment and mitigation or risk from competing low-probability, high-consequence hazards

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Uncertainty and risk

- Occurrence, intensity and system response to natural and man-made hazards are uncertain.
- Consequence of uncertainty is risk.
- Risk cannot be eliminated. It must be managed.
Traditional engineering approach to risk management

- Deterministic
  - Conservative demand, capacity
  - Factors of safety

- Problems
  - Margins of safety not commensurate with uncertainty or measurable
  - Failure rates cannot be benchmarked
  - Inconsistent measures of performance
  - Comparison of alternatives difficult
  - Wasted investments in risk mitigation
Motivation for quantitative risk assessment of civil infrastructure

- Rapidly evolving technologies leading to novel or critical infrastructure systems
- Demands for performance beyond code minimums
- Perception of increasing risk for certain facilities
- Public awareness of performance and demands for safety
- Low-probability, high-consequence events unsuited for suited to trial-and-error management of risk
Ingredients of risk

- Probability of occurrence
  - Hazard
  - System response

- Consequences
  - Deaths
  - Dollars
  - Downtime

- Context – who is the decision-maker?
Current probabilistic approaches to risk management

- Structural load requirements (*ASCE Standard 7-05*)
- Building design (AISC, AISI, ACI, AF&PA/ASCE)
- Bridges (AASHTO)
- Electrical transmission structures (EPRI)
- Offshore structures
- Seismic PRA/Margins analysis (NRC, EPRI)
- Natural phenomena hazards (DOE)
- Dam safety (USACE, FEMA, BuRec)
- Environmental hazards (GSA, EPA)
Low-probability, high-consequence hazards

- Aircraft impact
- Bomb explosion
- Design/construction error
- Earthquake
- Fire
- Gas explosion
- Hurricanes and tornadoes
- Transportation, storage of hazardous materials
- Vehicular collisions
Seismic hazard curves

Annual Frequency of Exceedence

City

- Memphis
- Seattle
- San Francisco
- Salt Lake City
- Denver
- St. Louis
- New Madrid
- Charleston
- New York City
- Crestline (CA)
- 500 Yr. MRI
- 2500 Yr. MRI
- Minneapolis

0.2 Sec Spectral Acceleration

0.00001 0.0001 0.001 0.01 0.1 1 10

Annual Frequency of Exceedence
Low-probability, high-consequence hazards
Order-of-magnitude annual frequencies

- Earthquake (MCE): $4 \times 10^{-4}$/yr
  
  Design at 2/3 MCE): $7 \times 10^{-4}$/yr (CEUS) to $2 \times 10^{-3}$/yr (WUS)
- Tornado strike probability (45m wide bldg): $1 \times 10^{-6}$/yr
- Gas explosion (per dwelling): $2 \times 10^{-5}$/yr
- Transportation of liquefied chlorine gas: $1 \times 10^{-6}$/yr
- Bomb explosion (per dwelling): $2 \times 10^{-6}$/yr
- Aircraft impact on building: $1 \times 10^{-8}$/yr
- Fully developed fires (per building): $1 \times 10^{-8}$/m$^2$/yr

(The National Building Code of Canada has a “trigger” of $10^{-4}$/yr)
Principles of risk-informed decision-making

- Performance consistent with social objectives, expectations and resources
- Investments in risk reduction targeted to achieve maximum benefits
- Balanced allocation of risk to competing hazards
- Transparency – understandable and acceptable decision process
- Formal methods for systematic treatment of uncertainty
  - Hazard
  - Facility response
  - Damage, loss assessment and social impact
Performance-based engineering

SEAOC Vision 2000 Performance Objectives

- Frequency: Frequent, Occasional, Rare, Very rare
- Performance: Operationally Safe, Basic Objective, Essential Objective, Safety Critical, Unacceptable Performance
- Near Collapse
<table>
<thead>
<tr>
<th>Cat.</th>
<th>Performance goal</th>
<th>Hazard (/yr)</th>
<th>Failure prob.(/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Occupant safety</td>
<td>$2 \times 10^{-3}$</td>
<td>$1 \times 10^{-3}$</td>
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<tr>
<td>2</td>
<td>Occupant safety, cont’d function</td>
<td>$1 \times 10^{-3}$</td>
<td>$5 \times 10^{-4}$</td>
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<td>3</td>
<td>Occupant safety, cont’d function; hazard confinement</td>
<td>$5 \times 10^{-4}$</td>
<td>$1 \times 10^{-4}$</td>
</tr>
<tr>
<td>4</td>
<td>Occupant safety; cont’d function; high confidence of hazard confinement</td>
<td>$1 \times 10^{-4}$</td>
<td>$1 \times 10^{-5}$</td>
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Acceptable risk (annual frequency)

- Risk-perception
- *De minimis* risk
- $P_{\text{loss}} < K \cdot 10^{-n}/N^m$

Large dams (Hoeg, 1996)
Sources of uncertainty in risk assessment

- Hazard – occurrence and intensity
- Demand on engineered systems
- Construction practices and in material and system properties for steel, concrete, masonry, timber construction -
- Structural and non-structural component modelling
- Quantitative definition of performance levels and limit states
- Damage and loss estimation for individual facilities
- Damage and loss aggregation for portfolios
- Economic loss and social impact
Framework for risk assessment

Deconstruction of risk

\[ \lambda_{\text{Failure}} = \sum_H \sum_D P(\text{Failure}|D) P(D|H) \lambda_H \]

- \( \lambda_H \) = mean rate of hazard/yr
- \( P(D|H) \) = probability of damage, given hazard
- \( P(\text{Failure}|D) \) = probability of failure, given damage

*De minimis* level < 10^{-6}/yr
Framework for risk assessment
Scenario analysis

\[ P(\text{Failure}|\text{Scenario}) = \sum_D P(\text{Failure}|D) \ P(D|\text{Scenario}) \]

- \( P(D|\text{Scenario}) = \) probability of damage, given a postulated scenario
- \( P(\text{Failure}|D) = \) probability of failure, given damage
Structural vulnerability assessment
Six-story steel braced frame – Memphis, TN

Brace Members

13'
13'
13'
13'
13'
15'

53'-7" 20'-0" 53'-7"

1 in. = 25.4 mm; 1 ft. = 304.8 mm

Hinge Connection
Performance levels for steel frames
FEMA 356/ASCE 41-06

- Immediate occupancy (IO) – damage to nonstructural components occurs beyond elastic range (ISD 0.5% to 1.0% for steel frame buildings)

- Structural damage (SD) - damage occurs at an ISD 1% - 2%. (Drifts associated with “life safety” cannot be computed reliably)

- Collapse prevention (CP) – excessive P-\(\Delta\) effects develop even in well-designed frames at approximately 4% - 8% ISD. (ISDs beyond this level cannot be computed reliably with software currently being used for this purpose.)
Damage state probabilities

\[ F_R(x) = \Phi[\ln(x / m_C) / \beta_R] \]

\[ \beta_R = \sqrt{\beta_{\text{Demand}}^2 + \beta_{\text{Capacity}}^2 + \beta_{\text{Modeling}}^2} \]

Describes the probability of failure to meet certain performance states as a function of the seismic demand on the system.

Performance Levels:

- Continued Occupancy
- Impaired Occupancy
- Structural Damage
- Structural Collapse

\( S_a(T_1) (g) \)

Typical Fragility Curve
Point estimate of limit state probability

(Aleatoric uncertainty)

- \( P_f = \int H(x) \, dF_R(x) \)
  - \( H(x) = \) hazard
  - \( F_R(x) = \) fragility

- Structural fragility: \( F_R(x) = \Phi[\ln(x/m_R)/\beta_R] \)

- Demand (hazard): \( \ln H(x) \approx k_0 - k \ln x \)

- Limit state probability, \( P_f \)
Point estimate of probability of structural damage for braced frame

\[ P_{SD} \approx H_Q(m_{acc}) \exp\left[ \frac{1}{2}(k\beta_{acc})^2 \right] \text{ (acceleration)} \]

Drift = \( a(S_a)^b \varepsilon \) \quad \text{(Nonlinear FEA)}

- \( S_a \) = spectral acceleration at the fundamental period
- \( D \) = interstory drift
- \( a, b = \text{constants} \)
- \( \varepsilon = \text{uncertainty in seismic demand, modeled as a lognormal random variable (aleatoric uncertainty)} \)

At Memphis, TN, \( P_{SD} = 3.8 \times 10^{-4}/\text{yr} \)
Encoding epistemic uncertainty

Assume that

Median capacity can be estimated to within $\pm 30\%$ with “certainty” (90% confidence)

...implies $\beta_{UR} \approx 0.20$

Ratio of $85^{th}$ to $15^{th}$ percentiles of seismic hazard typically is about 3

...implies $\beta_{UH} \approx 0.50$
Frequency distribution of $P_{SD}$ for braced frame

Epistemic uncertainty
Confidence in risk assessment

If the structural damage limit of the frame is defined by interstory drift exceeding 0.015 from nonlinear FEA:

**Aleatoric uncertainty**
- A “best estimate” of $P_{SD}$ is:
  - $4.4 \times 10^{-4}$ (mean)
  - $3.8 \times 10^{-4}$ (median)

**Epistemic uncertainty**:
- $P_{SD}$ is *between* $1.3$ and $11.0 \times 10^{-4}$/yr *with 95% confidence*.
- $P_{SD}$ is *less than* $7.7 \times 10^{-4}$/yr *with 90% confidence*. 
Decisions involving low-probability, high-consequence events

- Understanding the hazard – precursor events
- Selection of performance goals
- Scenarios and uncertainties
- Assessment of competing hazards
- Relating damage states to losses or other decision variables
  - Losses to engineered systems
  - Damage to contents
  - Impact on social fabric
- Validation for low-probability, high-consequence hazards
- Risk communication
  - Metrics of acceptable risk
  - Risk perception differences among stakeholders
  - Value engineering; investment in risk reduction
- Contractual requirements and professional liability
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