Probabilistic Performance-Based Optimum Seismic Design of (Bridge) Structures

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I) PEER PBEE Methodology
(Forward PBEE Analysis)
**SDOF Model and Site**

- **SDOF Model and Site**

  - Single-Degree-of-Freedom Bridge Model:
    - SDOF bridge model with the same initial period as an MDOF model of the **Middle Channel Humboldt Bay Bridge** developed in OpenSees.

  - **Site:**
    - Site Location: Oakland (37.803N, 122.287W)
    - Site Condition: Vs30 = 360 m/s (NHERP Class C-D)
      - Uniform Hazard Spectra are obtained for **30 hazard levels** from the USGS 2008 Interactive Deaggregation software/website (beta version)

  \[ F = k_0 U \]

  \[ F_y = 10,290 \text{ kN} \]

  \[ m = 6,150 \text{ tons} \]

  \[ k_0 = 137,200 \text{ kN/m} \]

  \[ T_1 = 1.33 \text{ sec} \]

  \[ \xi = 0.02 \]

  \[ b = 0.10 \]

  \[ U_y = 0.075 \text{ m} \]
Prob. Seismic Hazard Analysis and EQ Selection

- Seismic Hazard Curve (for single/scalar Intensity Measure $IM$):

$$
\nu_{IM}(im) = \sum_{i=1}^{N_{fl}} \nu_i \cdot \int_{R_i} \int_{M_i} P[IM > im | m, r] \cdot f_{M_i}(m) \cdot f_{R_i}(r) \cdot dm \cdot dr
$$

- Least Square Fitting of 30 Data Points ($IM_i$, $MARE_i$) from USGS:

Deaggregation ($T_1 = 1$ sec, 2% in 50 years)

- Earthquake Record Selection:
  - 146 Records were selected from NGA database based on fault mechanism, M-R deaggregation, and local site condition (e.g., Vs30)
Probabilistic Seismic Demand Hazard Analysis

• Demand Hazard Curve:

\[ \nu_{EDP}(edp) = \int_{IM} P[EDP > edp|IM] \, d\nu_{IM}(im) \]

• Probabilistic Seismic Demand Analysis conditional on IM:

  “Cloud Method”

  “Convolution”

  “Deaggregation”

• Deaggregation of \( \nu_{EDP}(edp) \) with respect to IM:

\[ \nu_{EDP}(edp) = \sum_{i} P[EDP > edp|IM = im_i] \cdot \frac{d\nu_{IM}(im_i)}{\Delta(im_i)} \cdot \Delta(im_i) \]

Contribution of bin \( IM = im_i \) to \( \nu_{EDP}(edp) \)
Probabilistic Seismic Demand Hazard Analysis

PDF (Lognormal)

EDP: Normalized $E_H$

“Cloud Method”

PDF (Lognormal)

EDP: Peak Abs. Accel.

“Convolution”

“Deaggregation”
Probabilistic Capacity (Fragility) Analysis

- Fragility Curves (postulated & parameterized):
  - Defined as the probability of the structure/component exceeding $k^{\text{th}}$ limit-state given the demand.

\[
P\left[ DM > l_s \mid EDP = edp \right]
\]

- Developed based on analytical and/or empirical capacity models and experimental data.

Displacement Ductility

Normalized $E_H$ Dissipated

Absolute Acceleration
Probabilistic Damage Hazard Analysis

• Damage Hazard (MAR of limit-state exceedance):

\[ \nu_{DS_k} = \int_{EDP} P[DM > l_{Sk} | EDP = edp] \, d\nu_{EDP}(edp) \]

Fragility Analysis

• Damage Hazard Results:

<table>
<thead>
<tr>
<th>Associated EDP</th>
<th>Limit States</th>
<th>MARE</th>
<th>Return Period</th>
<th>PE in 50 yrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement Ductility</td>
<td>I ((\mu_d = 2))</td>
<td>0.0394</td>
<td>26 Years</td>
<td>86%</td>
</tr>
<tr>
<td></td>
<td>II ((\mu_d = 6))</td>
<td>0.0288</td>
<td>35 Years</td>
<td>76%</td>
</tr>
<tr>
<td></td>
<td>III ((\mu_d = 8))</td>
<td>0.0231</td>
<td>44 Years</td>
<td>68%</td>
</tr>
<tr>
<td>Normalized E_H Dissipated</td>
<td>I (E_H = 5)</td>
<td>0.0171</td>
<td>58 Years</td>
<td>57%</td>
</tr>
<tr>
<td></td>
<td>II (E_H = 20)</td>
<td>0.0012</td>
<td>833 Years</td>
<td>6%</td>
</tr>
<tr>
<td></td>
<td>III (E_H = 30)</td>
<td>0.0003</td>
<td>3330 Years</td>
<td>1.5%</td>
</tr>
<tr>
<td>Absolute Acceleration</td>
<td>I (A_Abs = 0.1g)</td>
<td>0.0349</td>
<td>29 Years</td>
<td>82%</td>
</tr>
<tr>
<td></td>
<td>II (A_Abs = 0.2g)</td>
<td>0.0104</td>
<td>96 Years</td>
<td>41%</td>
</tr>
<tr>
<td></td>
<td>III (A_Abs = 0.25g)</td>
<td>0.0048</td>
<td>208 Years</td>
<td>21%</td>
</tr>
</tbody>
</table>
Probabilistic Loss Hazard Analysis

- Loss Hazard Curve:
  - Component-wise Loss Hazard Curve:
    \[
    \nu_{L_j}(l) = \int P[L_j > l \mid DM] \, d\nu_{DM} = \sum_{k=1}^{nls_j} P[L_j > l \mid DS = k] \nu_{DS_k} - \nu_{DS_{k+1}}
    \]
  - Total Loss Hazard Curve:
    \[
    L_T = \prod_{j=1}^{\text{#components}} L_j
    \]

Ensemble of FE seismic response simulations

Multilayer Monte Carlo Simulation

Number of eqkes in one year
\( N = n \)

Conditional probability of collapse given IM

Seismic hazard

Poisson model

Marginal PDFs and correlation coefficients of EDPs given IM

NATAF joint PDF model of EDPs

Fragility curves for all damage states of each failure mechanism

Probability distribution of repair cost

For each eqke

IM = im

For each eqke

Collapse?

Y

For each EDP

EDP = δ

For each damaged component

DM = k

For each damaged component

\( L_j = l_j \)

For all eqkes in one year and all damaged components

\( L_T = \sum_{j=1}^{\text{#components}} L_j \)
Parametric PBEE Analysis

- Varying Parameter: Yield Strength $F_y$

**Demand Hazard for EDP = $\mu_d$**

**Demand Hazard for EDP = $A_{Abs.}$**

**Demand Hazard for EDP = $E_H$**

**Cost Hazard**
Parametric PBEE Analysis

- Varying Parameter: Initial Stiffness $k_0$
Optimization Formulation of PBEE

• Optimization Problem Formulation:

  ➢ **Objective (Target/Desired)** Loss Hazard Curve: \( v_{LT}^{Obj} (l) \)

  ➢ Objective function: 

  \[
  f(k_0, F_y, b, \ldots) = \sum_i |v_{LT} (l_i, k_0, F_y, b, \ldots) - v_{LT}^{Obj} (l_i)|^2
  \]

  ➢ Optimization Problem:

  \[
  \begin{align*}
  \text{Minimize } & f(k_0, F_y, b, \ldots) \\
  \text{subject to: } & h(k_0, F_y, b, \ldots) = 0 \\
  & g(k_0, F_y, b, \ldots) \leq 0
  \end{align*}
  \]

• Optimization Performed using **OpenSees-SNOPT** extended Framework

(II) Optimization Tool of OpenSees-SNOPT
OpenSees and SNOPT

• OpenSees:

Open source objected-oriented FE analysis software framework, used to model structural, geotechnical and SSI systems to simulate their responses to static and dynamic loads, especially for earthquakes (PEER)

- Supports distributed computing capabilities & cloud computing
- Includes modules for FE response sensitivity and reliability analysis
- Flexibility to incorporate with other software packages

• SNOPT:

General purpose nonlinear optimization code using Sequential Quadratic Programming (SQP) algorithm (Professor Phillip Gill @UCSD)

- Advantages of SNOPT as an optimization toolbox for solving structural/geotechnical problems requiring optimization (e.g., structural optimization, FE model updating, design point search problems):
  - Applies to large scale problems
  - Tolerates gradient discontinuities
  - Requires relatively few evaluations of the limit-state (objective) function
  - Offers a number of options to increase performance for special problems
- Open source in Fortran language available for academic use
OpenSees-SNOPT Extended Framework

• OpenSees & SNOPT Link:
  ➢ After abstract class of Optimization, subclass SNOPTClass is used to encapsulate the SNOPT software package as an interface
  ➢ Subclass SNOPTReliability for the design point search problem in reliability analysis; while the SNOPTOptimization structural optimization & model updating

Flowchart for OpenSees-SNOPT FE-based Optimization
(III) Illustration of Performance-Based Optimum Seismic Design

(Inverse PBEE Analysis)
Illustrative Example

Objective function: \( f(k_0, F_y) = \sum_i \left| \nu_{LT}(k_0, F_y) - \nu_{LT}^{Obj} \right|^2 \)

**SDOF Model (Menegotto-Pinto)**

- \( k_0 = 100,000 \text{ kN/m} \)
- \( F_y = 14,000 \text{ kN} \)
- \( m = 6,150 \text{ tons} \)
- \( b = 0.10 \)
- \( \xi = 0.02 \)
- \( U_y = 0.075 \text{ m} \)

**PBEE Analysis**

**A priori selected optimum design parameters**

- \( k_0^* = 137,200 \text{ kN/m} \)
- \( F_y^* = 10,290 \text{ kN} \)

**Expected Optimizer**

**OpenSees-SNOPT**
Objective Function

- Optimization Problem:

\[
\text{Minimize } f \left( k_0, F_y \right) \\
\text{subject to:}
\]

\[
80,000 \leq k_0 \leq 187,200 \text{ (kN/m)} \\
6,290 \leq F_y \leq 15,290 \text{ (kN)}
\]

- Starting Point:

\[
k_0^{(0)} = 100,000 \text{ kN/m}, F_y^{(0)} = 14,000 \text{kN}
\]

- Objective Function Plot:
Optimization Results

• Optimization Route:

$X^* = [137,200 \text{kN/m}, 10,290 \text{kN}]$

$X_{\text{start}} = [100,000 \text{kN/m}, 14,000 \text{kN}]$

$X_{\text{end}} = [135,774 \text{kN/m}, 10,038 \text{kN}]$
Current and Future Work

• Application to base isolated bridge structure:
  - Using nonlinear MDOF models of increasing complexity.
  - With increasing number of optimization parameters, e.g., base isolation parameters.
  - Considering multiple objectives and practical constraints, such as constraints on demand hazard.

Marga-Marga Bridge, Vina del Mar in Chile

Isolator
Thank you!
Questions?