Developments in Probabilistic Performance-Based Optimum Seismic Design

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Outline

- Introduction and Overview
- Simple Illustration of Probabilistic Performance-Based Optimum Seismic Design (PPBOSD) Framework
- Application of PPBOSD Framework to Seismic Isolation for California High-Speed Rail (CHSR) Prototype Bridge
- Concluding Remarks & Future Research Needs
Introduction and Overview

Seismic Design

Simulation & Probabilistic Evaluation (e.g., FE Modeling/Analysis, PEER PBEE)

Performance-Based Design (PBD)

Philosophy

Tools

Technologies

Decision

Seismic Design

Earthquake Protection Systems (e.g., Seismic Isolation)

Structural Optimization (e.g., OpenSees, SNOPT)
Simple Illustration of Probabilistic Performance-Based Optimum Seismic Design

**Abbreviation:**
- Performance-Based Earthquake Engineering (PBEE) Methodology
Site, Structure and Structural Model

- Single-Degree-of-Freedom (SDOF) Bridge Model:

  \[ F = b \cdot k_0 \]

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

- Site-specific Seismic Hazard:
  - Site Location: Oakland
  - Soil Condition: \( V_{s30} = 360 \text{m/s (Soil C-D)} \)

- Earthquake Ground Motion Intensity Measure (IM):
  \[ IM = S_a \left( T_1, \xi = 5\% \right) \]
PBEE (Step 1): Probabilistic Seismic Hazard Analysis

- Seismic Hazard Curve:

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

De-aggregation for hazard (2% PE in 50 years)

Hayward Fault (East)
San Andreas Fault (West)

Hazard Level

0.015/yr \rightarrow T = 67 years
**PBEE (Step 2): Probabilistic Seismic Demand Hazard Analysis**

- **Engineering Demand Parameter(s):** EDPs

- **Demand Hazard Curve:**

  \[ \nu_{EDP}(edp) = \int_{IM} P[E^{DP} > edp \mid IM] \cdot d\nu_{IM}(im) \]

  [Seismic hazard curve]

- **Conditional Demand**

  [Graph showing EDP (Disp. Ductility) vs. IM (Sa, T, 5%)]

  - PDF (Lognormal)
  - E[ln(EDP)]
  - 50% in 50 Years
  - 10% in 50 Years
  - 2% in 50 Years

- **Demand Hazard Curve**

  [Graph showing Mean Annual Rate of Exceedance]

  - 50% in 50 Years (72 yrs return period)
  - 10% in 50 Years (475 yrs return period)
  - 2% in 50 Years (2,475 yrs return period)
**PBEE (Step 3): Probabilistic Damage Hazard Analysis**

- Limit-states (LS) or damage states (DS) are discrete measures of the stage of development of damage/failure mechanisms.

- Damage Hazard (Mean annual rate of limit-state exceedance):

  \[
  V_{DS_k} = \int_{EDP} P[DM > l_{S_k} | EDP = edp] \cdot |dV_{EDP}(edp)|
  \]

  - **Damage Measure**: \(k\)-th limit state
  - **Fragility Curve**
  - **Demand hazard curve**

<table>
<thead>
<tr>
<th>Associated EDP</th>
<th>Limit States</th>
<th>Return PE in 50 yrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement</td>
<td>I (A)</td>
<td>86%</td>
</tr>
<tr>
<td>Ductility</td>
<td>II (A)</td>
<td>76%</td>
</tr>
<tr>
<td></td>
<td>III (A)</td>
<td>68%</td>
</tr>
<tr>
<td>Normalized (E_H) Dissipated</td>
<td>I (A)</td>
<td>57%</td>
</tr>
<tr>
<td></td>
<td>II (A)</td>
<td>6%</td>
</tr>
<tr>
<td></td>
<td>III (A)</td>
<td>1.5%</td>
</tr>
<tr>
<td>Absolute Acceleration</td>
<td>I (A)</td>
<td>82%</td>
</tr>
<tr>
<td></td>
<td>II (A)</td>
<td>41%</td>
</tr>
<tr>
<td></td>
<td>III (A)</td>
<td>21%</td>
</tr>
</tbody>
</table>

- First excursion type failure mechanism
- Cumulative damage type failure mechanism
- Dynamic stability of vehicles
**PBEE (Step 4): Probabilistic Loss Hazard Analysis**

- **Loss Hazard Curve:**
  - Component-wise Loss Hazard Curve:
    \[
    \nu_{L_j}(l) = \int_{DM} P[L_j > l \mid DM] \cdot d\nu_{DM} = \sum_{k=1}^{nls_j} P\left[ L_j > l \mid DS = k \right] \cdot \nu_{DS_k} - \nu_{DS_{k+1}}
    \]

  - Total Loss Hazard Curve:
    \[
    L_T = \sum_{j=1}^{\text{#components}} L_j
    \]

  - Probability Distributions of Repair/Replacement Costs

- **Obtained in PBEE (3)**

- **Examples:**
  - Number of limit-states for component j
  - Repair/Replacement Cost Ratio
  - Annual Probability of Exceedance
  - Repair/Replacement Cost

- **Graphs:**
  - Loss Hazard Curve
  - Total Loss Hazard Curve
  - Probability Distributions

- **Equation:**
  - \( P[L_j \mid DS] \)
Probabilistic Performance-Based Optimum Seismic Design

A priori selected optimum design parameters

- **Optimization problem formulation:**

  \[
  \begin{align*}
  \text{Minimize } & f(k_0, F_y) = \sum_i |v_{LT}(k_0, F_y) - v_{LT}^{Obj}|^2 \\
  \text{subject to:} & \quad 80,000 \leq k_0 \leq 187,200 \text{ (kN/m)} \\
  & \quad 6,290 \leq F_y \leq 15,290 \text{ (kN)} \\
  \end{align*}
  \]

  \[k_0^{(0)} = 100,000 \text{ kN/m}, \quad F_y^{(0)} = 14,000 \text{ kN}\]
Probabilistic Performance-Based Optimum Seismic Design

- Optimization results:
  
  \[ \mathbf{X} = \begin{bmatrix} 137,200 \text{ kN/m} \\ 10,290 \text{ kN} \end{bmatrix} \]

\[ \mathbf{X}^* = \begin{bmatrix} 100,000 \text{ kN/m} \\ 14,000 \text{ kN} \end{bmatrix} \]

\[ \mathbf{X}_{\text{end}} = \begin{bmatrix} 135,774 \text{ kN/m} \\ 10,038 \text{ kN} \end{bmatrix} \]

\[ \mathbf{v}_{\text{EDP}} = \mu \left( k_0^*, F_y^* \right) \]
Probabilistic Performance-Based Optimum Seismic Design Framework

- **Site Location**
- **Structural System**
- **Seismic Hazards (IM)**
- **Design/Upgrade Alternatives (SP)**
- **Structural Parameters**

### Probabilistic Model Development
- **Hazard model**: P[IM]
- **Structural model**: P[EDP|IM]
- **Fragility model**: P[DM|EDP]
- **Loss model**: P[DV|DM]

### Probabilistic Performance Evaluation
- **Load Hazard Analysis**
- **Demand Hazard Analysis**
- **Damage Hazard Analysis**
- **Loss Hazard Analysis**

### Decision Analysis
- **Update Design (SP)**
- **Check Performance**
- **Optimization?**
- **Final design**

### Performance Objectives
- **Define Objectives**
  - Serviceability
  - Life Safety
  - Collapse Prevention
  - Resilience
  - Sustainability
  - Robustness

### Decision Making
- NO
- YES
Application of PPBOSD to Seismic Isolation for California High-Speed Rail Prototype Bridge
**Testbed Application: Seismic Isolation for CHSR Bridges**

California High-Speed Train Project (CHST)

Potential Seismic Risk in California

Aerial/Bridge Structure Supporting System

Promising Application of Seismic Isolation

CHST Alignment
CHSR Prototype Bridge
Comprehensive Bridge Model with SFSI and Rail-Structure Interaction

Elevation View of the FE Element Model

- De-convolution analysis for depth-variation of ground displacement
- Response simulation for Multiple-support-excitation
Definition of Risk Features/Metrics

• Risk features defined based on conditional demand hazard

- Conditional median: $\eta_{EDP|IM=im}$
- Conditional mean: $\mu_{EDP|IM=im} = E[EDP|IM=im]$
- Conditional c.o.v: $\delta_{EDP|IM=im} = c.o.v. [EDP|IM=im]$
- Conditional percentiles: $Pctl.95^{th}[EDP|IM=im]$

• Risk features defined based on unconditional demand hazard

- Single point demand hazard
- Area to the left side of the demand hazard curve or area under the demand hazard curve
- Unconditional statistics (mean, median, etc.) based on:

$$f_{EDP}(x) = \frac{dF_{EDP}(x)}{dx} = -\frac{d(PE_{100\text{yrs}})}{dx}$$
Risk Features for Different EDPs Conditional on OBE

**SI Detrimental**
- Max. bending moment in piles under Pier #5
  - NIB: 1.07

**Mean Demand Conditional on OBE**
- Deck rel. disp. in transv. dir.
- Rail axial stress at interior exp. joint #2

**SI Beneficial**
- Total base shear in transv. dir.
- NIB: 8,599

**SI Beneficial**
- Max. bending moment in piles under Pier #5
- NIB: 4,066

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**NIB:**
- NIB: 1.07
- NIB: 0.5
- NIB: 8,599
- NIB: 4,066
Optimization Problems for Seismic Isolation of CHSR Prototype Bridge
Optimization Problem Formulations for Probabilistic PBD

Optimum Seismic Design Problems using PPBOSD Framework

- The risk features/metrics defined earlier are used to define the objective/constraint functions in the optimization formulation
  - Formulation considering different risk features
  - Formulation considering different EDPs
  - Formulation across different (seismic or other) hazard levels
  - Formulation across different stages of the PBEE assessment methodology

Optimum Seismic Design Problems using PPBOSD Framework

- Optimization using grid-based “brute force” approach taking advantage of cloud-based computing for high-throughput.
Optimum Probabilistic PBD

- Optimization problem formulated for PBD conditional on OBE

Minimize conditional median demand: \( \eta \left[ F_{\text{transv.}}^{\text{TBS, all columns}} \mid OBE \right] \)

Subject to constraints:

1. \( E \left[ A_{\text{transv.}}^{\text{deck}} \mid OBE \right] \leq 0.35 \text{g} \)
2. \( \text{Pctl.}^{95\text{th}} \left[ A_{\text{transv.}}^{\text{deck}} \mid OBE \right] \leq 0.5 \text{g} \)
3. \( \text{Pctl.}^{95\text{th}} \left[ M_{\text{transv.}}^{\text{Pier #5}} \mid OBE \right] \leq M_{\text{cr}}^{\text{pier}} \left(1.5 \times 10^4 \text{kips-ft}\right) \)
4. \( \text{Pctl.}^{95\text{th}} \left[ M_{\text{transv.}}^{\text{Piles, Pier #5}} \mid OBE \right] \leq M_{\text{cr}}^{\text{pile}} \left(5.3 \times 10^3 \text{kips-ft}\right) \)
5. \( \text{Pctl.}^{95\text{th}} \left[ \sigma_{\text{rail, left abut.}}^{\text{P}} \mid OBE \right] \leq 12.5 \text{ksi} \)
6. \( \eta \left[ \sigma_{\text{P+M, abut.}}^{\text{rail}} \mid OBE \right] \leq 42.5 \text{ksi} \)
**Optimum Probabilistic PBD**

- Optimization problem formulated for PBD with constraints conditional on two hazard levels (OBE & MCE)

**Minimize** conditional mean:  \( E\left[F_{\text{transv.}}^{\text{TBS, all columns}} \mid OBE\right] \)

**Subject to:**

**Constraints for OBE hazard level**

1. \( E\left[ AA_{\text{transv.}}^{\text{deck}} \mid OBE\right] \leq 0.35g \)
2. \( \text{Pctl.}^{95\text{th}}\left[ AA_{\text{transv.}}^{\text{deck}} \mid OBE\right] \leq 0.5g \)
3. \( \text{Pctl.}^{95\text{th}}\left[ M_{\text{Pier #5 transv.}}^{\text{Pile}} \mid OBE\right] \leq M_{cr}^{\text{Pile}} (1.5 \times 10^4 \text{kips-ft}) \)
4. \( \text{Pctl.}^{95\text{th}}\left[ M_{\text{Pile}}^{\text{Pile}} \mid OBE\right] \leq M_{cr}^{\text{Pile}} (5.3 \times 10^3 \text{kips-ft}) \)
5. \( \text{Pctl.}^{95\text{th}}\left[ \sigma_{\text{P + M transv. left abut.}}^{\text{Stress}} \mid OBE\right] \leq 12.5ksi \)
6. \( \eta\left[ \sigma_{\text{P + M transv. left abut.}}^{\text{Stress}} \mid OBE\right] \leq 42.5ksi \)

**Constraints for MCE hazard level**

7. \( \text{Pctl.}^{95\text{th}}\left[ \theta^{\text{Rot. Pile #5 transv.}} \mid MCE\right] \leq 1.3\% \)
8. \( \text{Pctl.}^{95\text{th}}\left[ \text{Defl. Isolator #13 transv.} \mid MCE\right] \leq 20 in \)
9. \( \text{Pctl.}^{95\text{th}}\left[ M_{\text{Pile}}^{\text{Pile}} \mid MCE\right] \leq M_{cr}^{\text{Pile}} (4.15 \times 10^4 \text{kips-ft}) \)
10. \( \text{Pctl.}^{95\text{th}}\left[ M_{\text{Pile}}^{\text{Pile}} \mid MCE\right] \leq M_{cr}^{\text{Pile}} (1.2 \times 10^4 \text{kips-ft}) \)
Concluding Remarks

• Probabilistic Performance-based Optimum Seismic Design (PPBOSD) framework

✓ Incorporates the PEER PBEE analysis methodology for probabilistic seismic performance evaluation/assessment.

✓ Wraps the PBEE methodology in an optimization layer to tune the design/retrofit/upgrade of a structural/geotechnical system for target probabilistic performance objectives and constraints so as to achieve Probabilistic Performance-based design (PBD).

✓ Provides an integrated and scientific approach for optimum seismic design of civil infrastructure systems in the face of uncertainty, with objective and constraint functions defined in terms of risk features/metrics defined at different stages of the PBEE assessment methodology (i.e., demand, damage, loss exceedance).

✓ Can be readily extended to other natural and man-made hazards (e.g., tsunami, wind/hurricane/tornadoes, blast, fire), as well as multi-hazard design problems.

✓ The PPBOSD framework provides high flexibility in the formulation of risk-based design criteria in support of Probabilistic PBD.
**Future Research Needs**

- **Finite Element Modeling & Simulation**
  - Component and system-level validation of FE modeling techniques used for civil infrastructure systems, using field data and experimental data (e.g., shake table tests, hybrid dynamic testing, centrifuge tests).

- **PBEE Assessment/Evaluation Methodology**
  - Uncertainties associated with FE modeling, FE model parameters and predicted capacity (damage/failure criteria) of the structure need to be accounted for.
  - Use of vector intensity measure for probabilistic characterization of the seismic hazard.
  - Accommodate the treatment of multiple failure/damage mechanisms and corresponding limit-states involving multiple EDPS (vector EDP), accounting for statistical dependence.
  - Incorporation of physics-based earthquake ground motion simulations with uncertain seismological variables and source parameters.
Future Research Needs

• Probabilistic Performance-based Optimum Seismic Design (PPBOSD) Framework

  ✓ Develop fully integrated, distributed, software system in support of the PPBOSD framework, making use of cloud computing resources (for high throughput and/or high performance computing).

  ✓ Using the PPBOSD framework, simplified probabilistic PBD methods need to be developed, calibrated and validated for the use of practicing engineers (i.e., development of PBD codes).