Application of Performance Based Earthquake Engineering (PBEE) to Caltrans Ordinary Standard Bridge Design

California Dep. of Transportation
Structures Policy and Innovation
Office of Earthquake Engineering

Background

1. External

Seismic Advisory Board

2. Internal

PDCA

Approach, Theoretical Background And Research Needs

PBEE Application

Components of Performance Based Earthquake Engineering

1. **Hazard Analysis**:

    Hazard Identification: Location, Intensity, Risk Loading: Seismic Intensity -> Acceleration Record/Input Motion

2. **Structural Analysis:**

    Structural Analysis: Modeling Guidelines & Software

3. **Damage Analysis:**

    Displacement, Ductility, & Strain

4. **Loss Analysis**

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1. Hazard Analysis

- Linear Spectral Analysis: Acceleration Response Spectra: ARS Online
- NLTHA: Uniform Excitation → Acceleration Time History
  - Basis of Design: Site-Specific Design (Target) ARS obtained from ARS online
  - Synthetic Records (captures important site characteristics)
  - Record Selection (subset of all generated records)
  - Spectral Matching (Modify record to have its ARS match a target ARS)
  - Average of 7 Records

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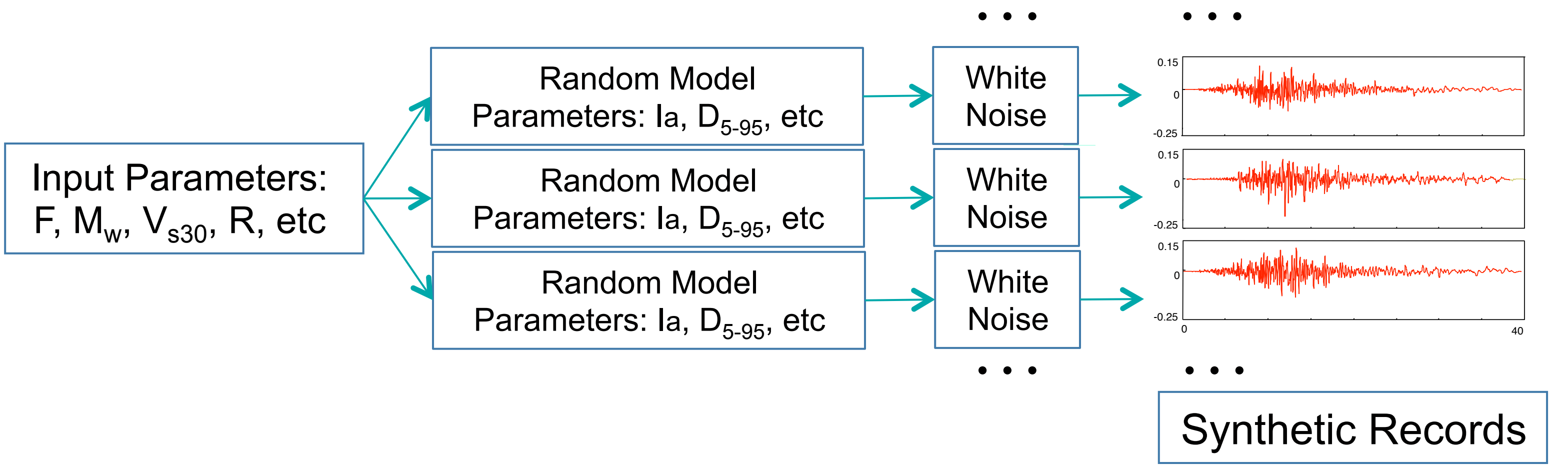
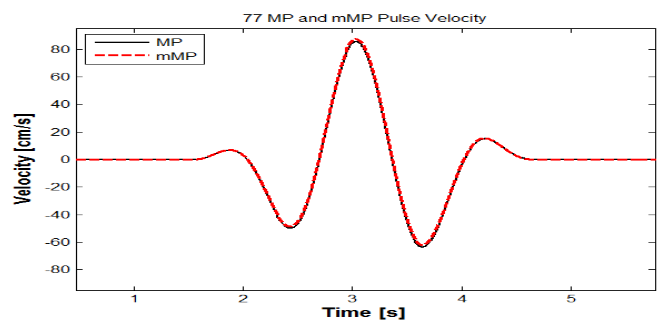
1. Hazard Analysis

Synthetic Record Generation:

- UCB Synthetic Record Generation Algorithm (By Prof. ADK)



- Modeling of Velocity Pulse



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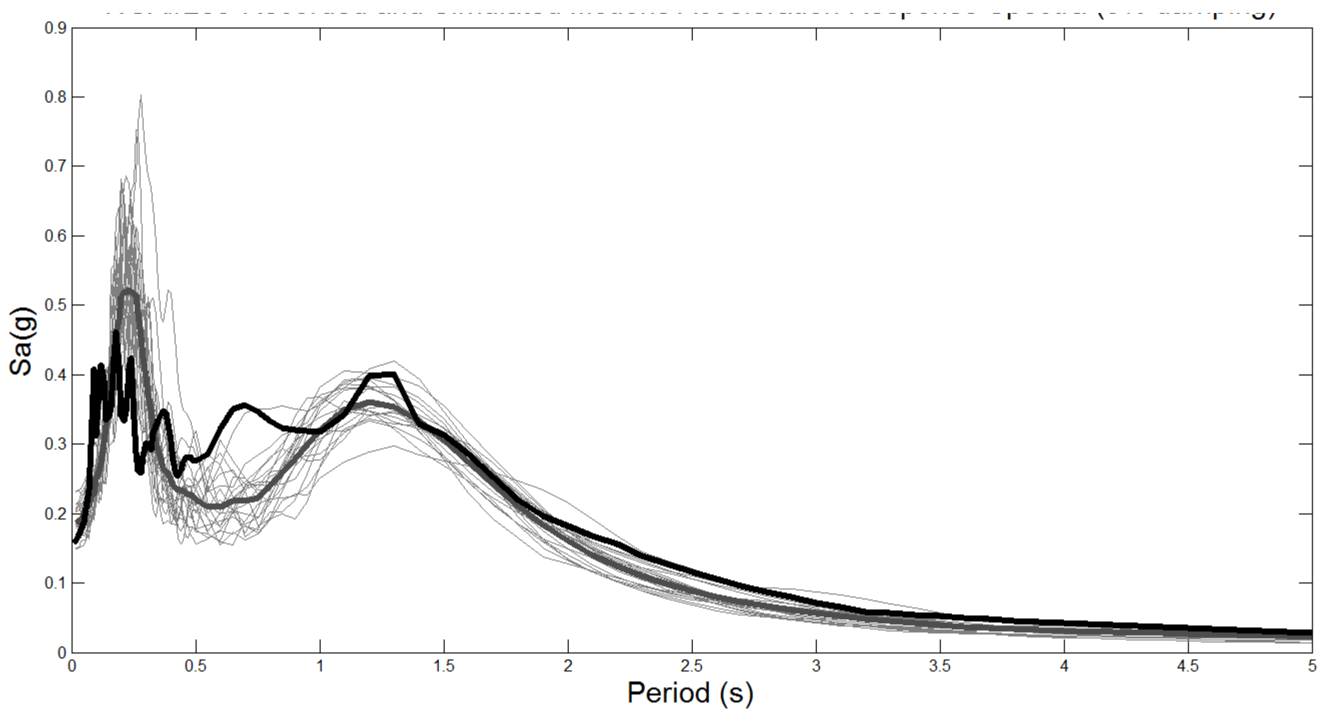
1. Hazard Analysis

Synthetic Record Generation - Example



Pseudo-acceleration response spectra at 5% damping of the NGA record #285 (black thick line), of 20 simulated ground motions using the fitted parameters (grey lines), and their geometric mean (thick grey line)

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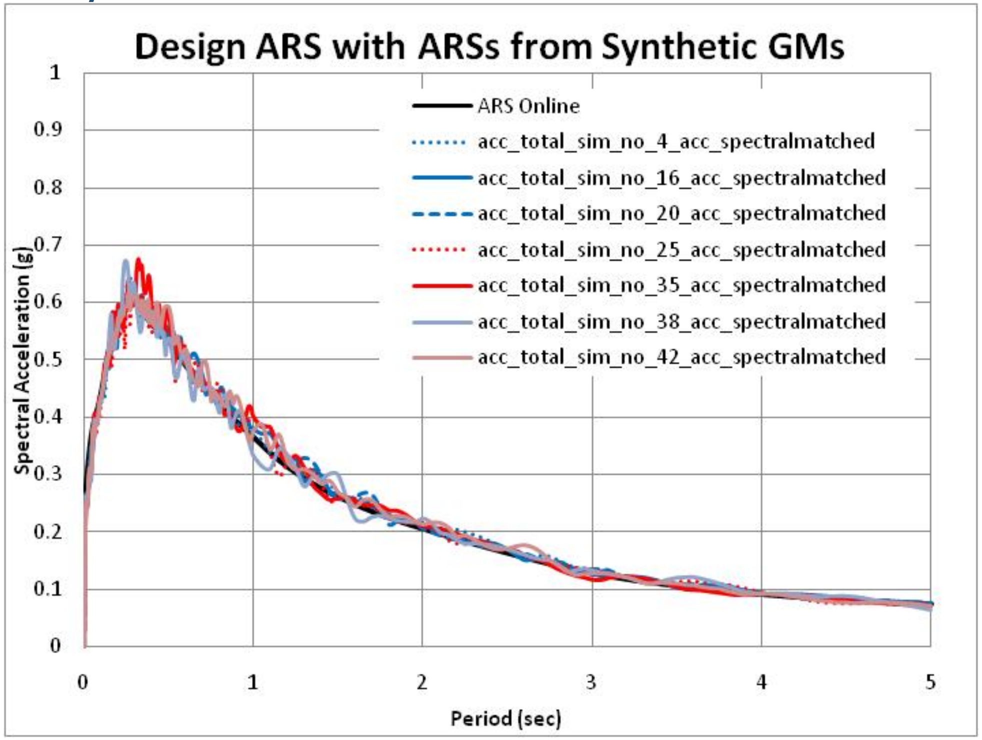
1. Hazard Analysis

Record Selection:

- Spectral Matching using TDSMatch based on Time Domain algorithm by Norm Abrahamson used in RSPMatch



TDSMatch

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1. Hazard Analysis – Where we are:

Input Motion Generation/Selection:

- Generate Design ARS from ARS Online (Target ARS), based on 1000-year return period
- Generate Synthetic Records: 50 Records (with near field velocity pulse if near field effect is needed)
- Select 7 records (from set of 50) with closest match to target ARS within $0.5 \le T \le 3.0$ seconds
- Scale Records: Use TDSMatch to adjust the 7 selected records to the target ARS
- Use the adjusted records for analysis

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1. Hazard Analysis – Where we are headed (Our Needs)

Input Motion Generation/Selection:

- Generating Synthetic motions in two directions
- Generating motions with hazard intensities and variations to warrant use in design without considering ARS
- Near-field and pulse consideration
- Fault Crossing
- Directionality

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2. Structural Analysis

Nonlinear Time History Analysis (NLTHA):

- Bridge Behavior in Seismic event is NONLINEAR
- NLTHA is the most accurate method available
- Current tools are efficient enough for NLTHA
- Response Spectrum Analysis does not capture some key nonlinear responses (e.g., column plastic hinge, span hinge, shear key, abutment response, & isolation bearing)
- Equal displacement principal is an approximation

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2. Structural Analysis

What is needed for Nonlinear Time History Analysis:

- Loading Guidelines (i.e., Acceleration Time History Records):
  - ➢ Intensity, peak acceleration, #of peaks
  - ➢ Duration
  - ➢ Frequency content
  - ➢ Near-Field Effect
- Modeling Guidelines: PEER 2008-03
- Reliable Software: CSI-Bridge, OpenSees, & Midas-Civil
- Acceptance Criteria: $\Delta_{capacity}/\Delta_{demand}$, Ductility, etc.

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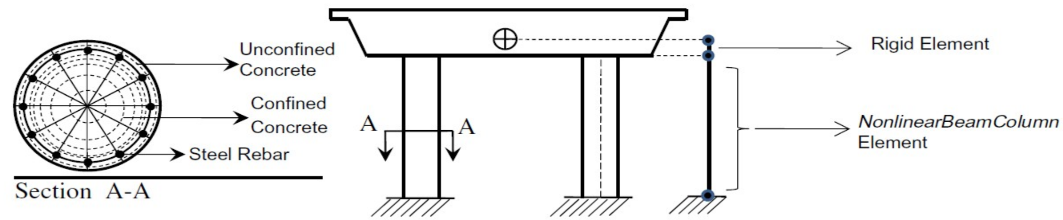
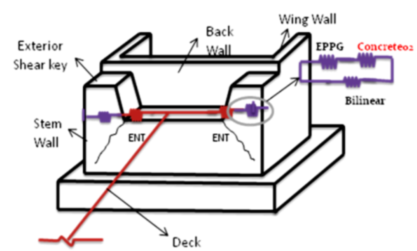
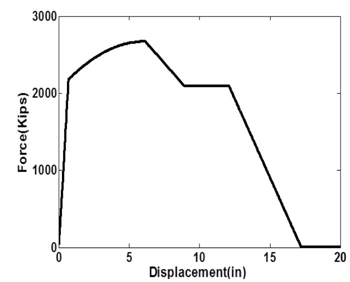
2. Structural Analysis
Modeling Nonlinear Behavior:

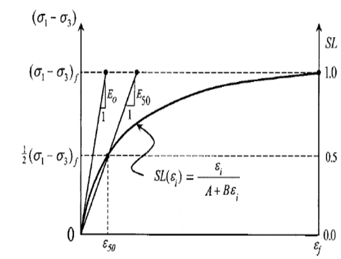
- Column Hinge



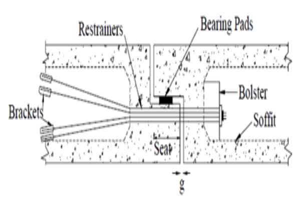
- Abutment Springs

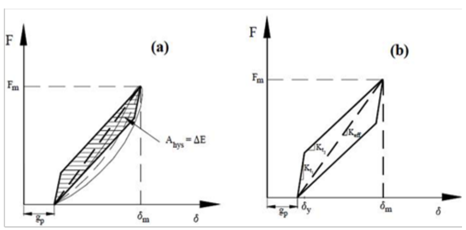


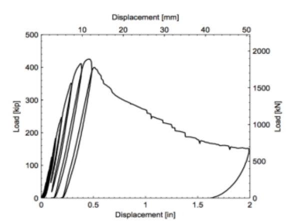


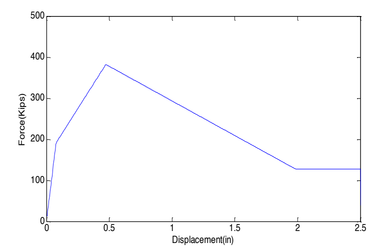


- Hinge impact & Shear key

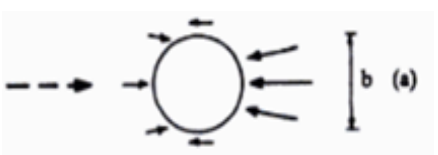


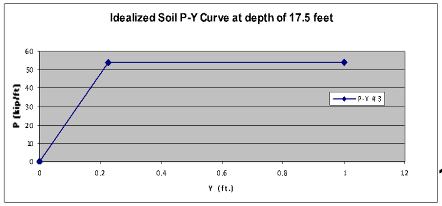






- Soil Structure Interaction
  (p-y, t-z, & q-z)





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2. Structural Analysis – Where we are:

Response Calculation:

- Apply each input motion in longitudinal and transverse directions (and more directions if curved or highly skewed)
- Record maximum displacements in longitudinal and transverse directions
- Calculate average of the maximum displacements (in each direction) as displacement demand

Capacity Calculation:

- Perform push-over analysis in longitudinal and transverse directions
- Calculate displacement capacity based on strain limits given in SDC

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2. Structural Analysis – Where we are headed (Our Needs):

Response Calculation:

- Formal guidance for THA
- Better quantification of damping
- Better modeling of various nonlinear elements
- Improved tools for analysis

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3. Damage Analysis: Where we are:

Capacity Calculation:

- Perform push-over analysis in longitudinal and transverse directions
- Calculate displacement capacity based on strain limits given in SDC

Acceptance Criteria / Damage Assessment:

- Displacement-based, Current SDC Limits:
  - Δ_{demand} = average $\Delta_{max.col}$ of each column
  - $\Delta_{capacity}$ = From Push-over analysis of bent or frame
- Damage Index Evaluation:
  - PDCA: Column damage index based on strain

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3. Damage Analysis: Where we are headed (Research Needs):

Possible Future Acceptance Criteria / Damage Assessment:

- No Push-over Analysis needed, instead calculate the ultimate curvature for each plastic hinge
- Compare Curvature demand and capacity:
  - Yield curvature = ϕ_y, based on SDC idealized M-ϕ curve
  - Curvature demand = ϕ_d = Average of maximum curvatures of the 7 analysis cases
  - Curvature capacity = ϕ_c (based on SDC strain limits), i.e.: $\phi_d \leq \phi_c$
  - Curvature Ductility: $\phi_c / \phi_y \geq 10$ (using SDC values)
- Identify Damage Index:
  - Curvature demand → Max strain demand → Damage Index

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4. Loss/Cost Analysis – Where we are headed (Research Needs):

Possible Future Acceptance Criteria / Damage Assessment:

Damage State (DS) Index with Associated Strain Threshold and Repair Cost (Saini and Saiidi, 2014)

Damage State (DS)	Description	Trigger	Trigger Value				Item - Strategy	Units	Cost
			Concrete Cover Strain	Concrete Core Strain	Main Steel Strain	Confinement Steel Strain			
1	Surface cracks	Strain	<= 0.002	na	<= 0.002	<= 0.002	OK	na	0
2	First spalling	Strain	0.002< ε <= 0.005	na	0.002< ε <= 0.005	0.002< ε <= 0.005	Patch Concrete	SQFT	$400 $250 $100 $50
							Epoxy Inject	LF	$62
3	Major spalling	Strain	Spalled to core strain height	0.005< ε <= 0.008	0.005< ε <= 0.010	0.005< ε <= 0.010	Patch Concrete	SQFT	$400 $250 $100 $50
							Epoxy Inject	LF	$62
4	Exposed reinf.	Strain	spalled off	0.008< ε <= 0.010	0.010< ε <= 0.025	0.010< ε <= 0.015	Steel Column Casing	EA	$61,200
5	Core shedding	Strain	spalled off	0.010< ε <= 0.020[(1)]	0.025< ε <= 0.06[(2)]	0.015< ε <= 0.120[(2)]	Replace Column	EA	$138,055
6	Failure (rupture)	Strain & Displ.	spalled off	> 0.020[(1)]	> 0.06[(2)]	> 0.120[(2)]	Replace Superstructure and Columns	EA	$1,455,840

PBEE Application

Summary – Current Status

- **Hazard Analysis** - Loading (Input motions):
  - Generate 50 synthetic records (Include near-field effect if needed)
  - Select 7 records that best match design ARS in range $0.5s \leq T \leq 3.0s$
  - Use TDSMatch to adjust selected records to design ARS

- **Structural Analysis** - Modeling: Include major nonlinearities:
  - Column plastic hinge, abutment spring, shaft p-y, & span hinge

- Structural Analysis - Analysis: CSIBridge, OpenSees, or Misdas-Civil, etc.
  - Perform Nonlinear analysis in long./transverse (and maybe more) directions
  - Calculate maximum displacement demand (average of 7 motions)

- **Damage Analysis** - Acceptance Criteria:
  - Perform Push-over analysis, obtain displacement capacity
  - Compare displacement demand vs. capacity (Current SDC)
  - Future: Compare curvature demand vs. capacity

PBEE - Bridges

4. Loss Analysis / Performance Measure – Future

4.1: Loss quantification

Function of Interest Rate ?

4.2: Performance Measure

Cost

Time

Fatalities

Sustainability (Mackie)