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

California Dep. of Transportation
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Part A –
Approach and Theoretical Background

PBEE Application – Part A

Components of Performance Based Earthquake Engineering

- **Hazard Analysis**:

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

- **Structural Analysis:**

  Structural Analysis: Modeling Guidelines & Software

- **Damage Analysis:**

  Displacement, Ductility, & Strain

- **Loss Analysis**

PBEE Application – Part A

1. Hazard Analysis

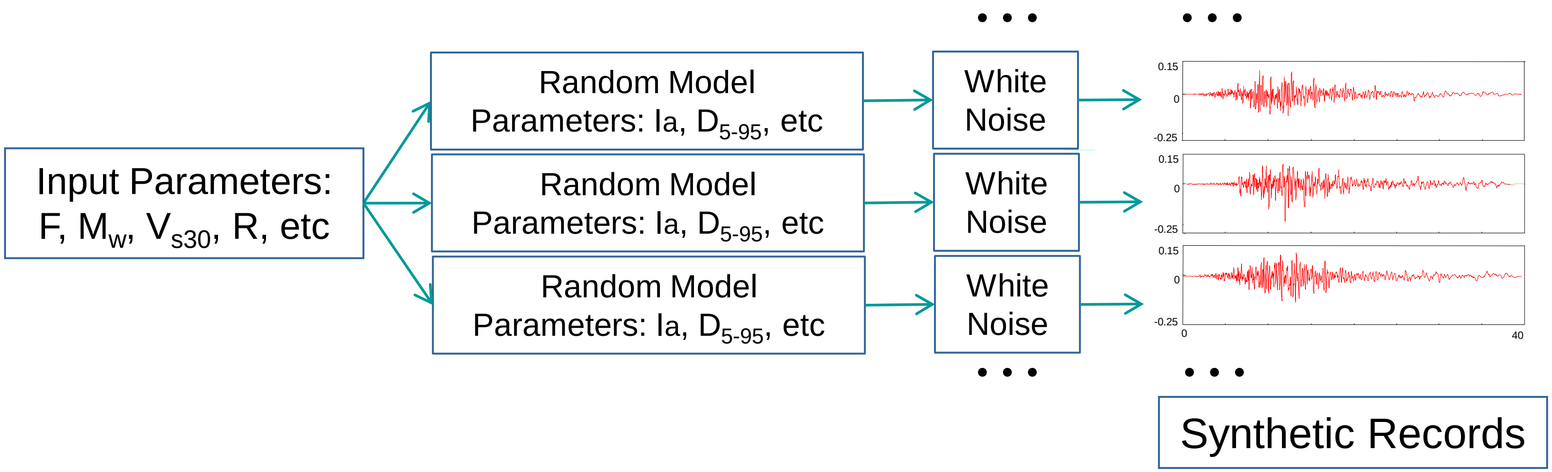
- Linear Spectral Analysis: Acceleration Response Spectra: ARS Online
- NLTHA: Uniform Excitation → Acceleration Time History
  - Basis of Design: Site-Specific Design (Target) ARS obtained from ARS online
  - Synthetic Records (captures important site characteristics)
  - Record Selection (subset of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

PBEE Application – Part A

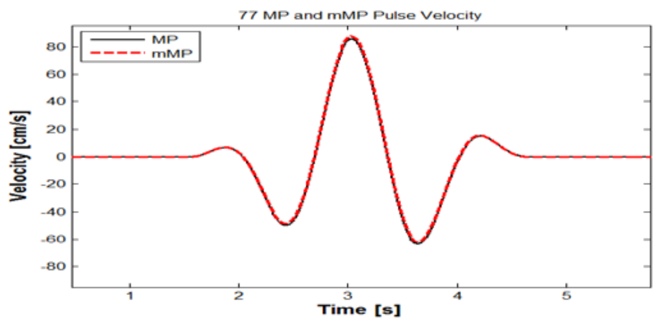
1. Hazard Analysis

Synthetic Record Generation:

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



- Modeling of Velocity Pulse



PBEE Application – Part A

1. Hazard Analysis

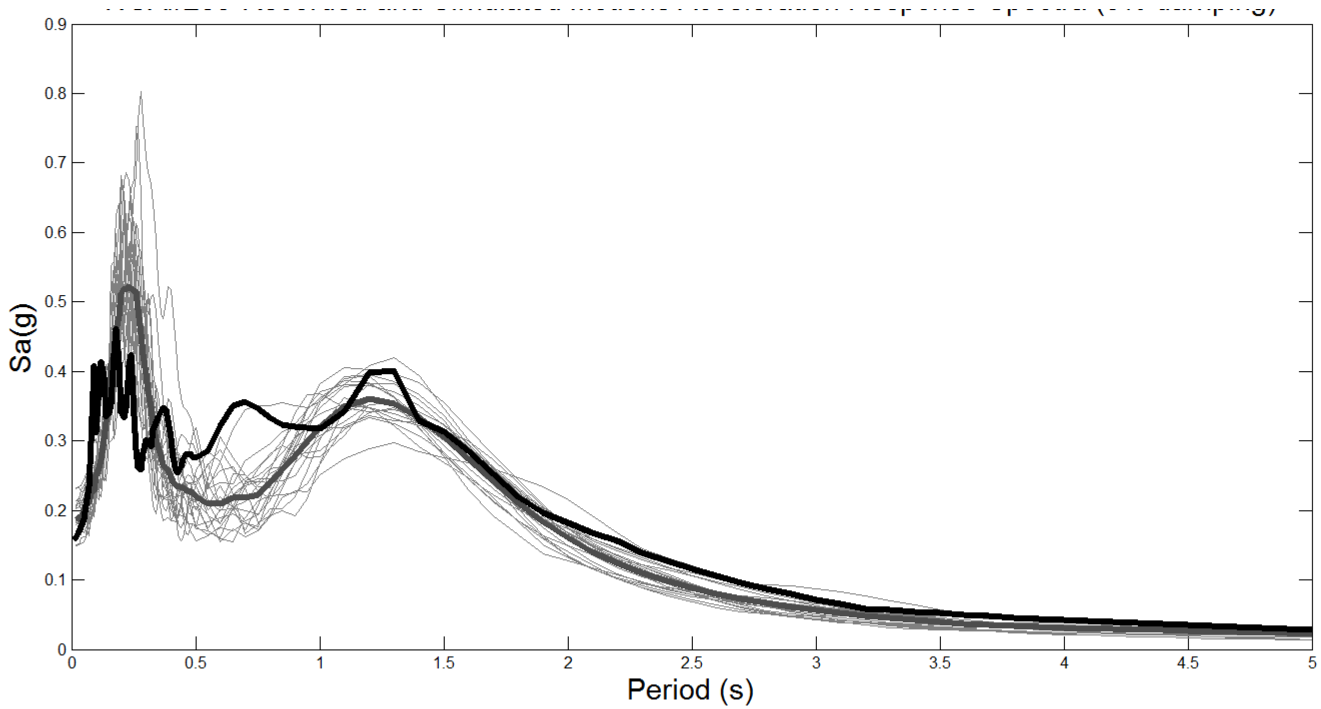
Parameters Needed for Record Generation:

- **Fault Type** : Strike-Slip or Non-Strike-Slip
- **Moment Magnitude, M_w**: Can be chosen between 5.5 to 8
- **Fault Distance, R**: Between 0 km and 30 km
- **Shear Wave Velocity, V_{S30}**: Between 100 m/s and 2100 m/s
- **Directivity Angle, theta**: Between 0 and 90 degrees
- **Distance, S**: Between 0 km and 70 km

PBEE Application – Part A

1. Hazard Analysis

Synthetic Record Generation - Example



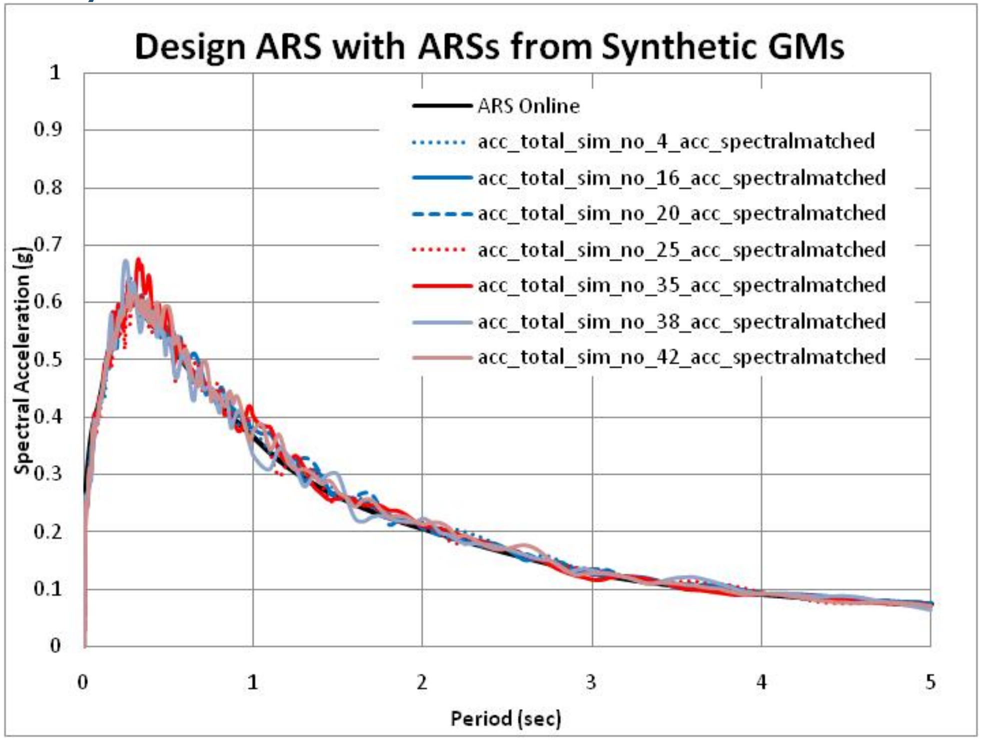
Pseudo-acceleration response spectra at 5% damping of the NGA record #285 (black thick line), of 20 simulated ground motions using the fitted parameters (grey lines), and their geometric mean (thick grey line)

PBEE Application – Part A

1. Hazard Analysis

Record Selection:

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



TDSMatch

PBEE Application – Part A

1. Hazard Analysis

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 $0.5 \leq T \leq 3.0$ seconds
- Scale Records: Use TDSMatch to adjust the 7 selected records to the target ARS
- Use the adjusted records for analysis

PBEE Application – Part A

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

PBEE Application – Part A

2. Structural Analysis

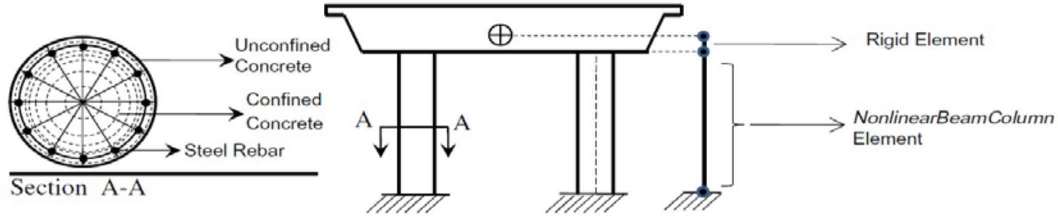
What is needed for Nonlinear Time History Analysis:

- 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.

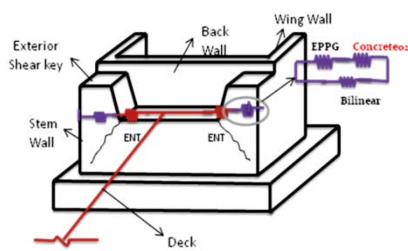
PBEE Application – Part A

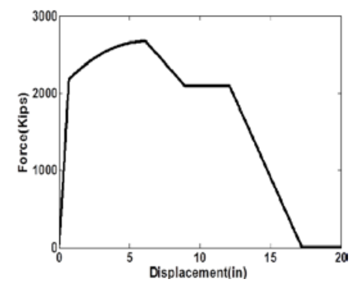
2. Structural Analysis
Modeling Nonlinear Behavior:

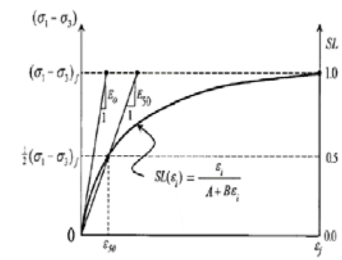
- Column Hinge



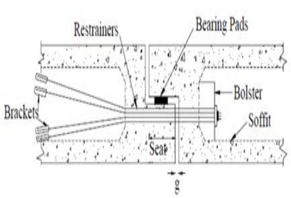
- Abutment Springs

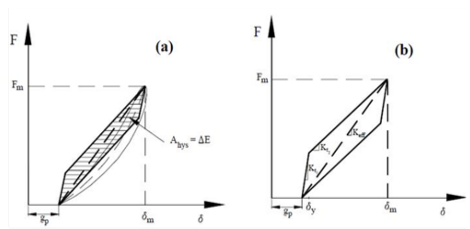


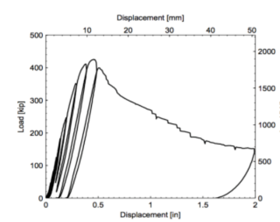


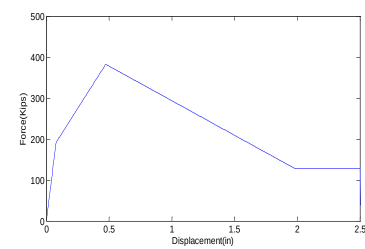


- Hinge impact & Shear key

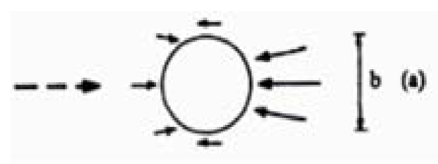


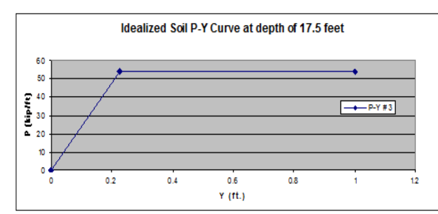






- Soil Structure Interaction (p-y, t-z, & q-z)





PBEE Application – Part A

2. Structural Analysis

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

PBEE Application – Part A

3. Damage Analysis

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
  - $\mu_{d.col} = \Delta_{demand} / \Delta_y$; $\mu_{c.col} = \Delta_{capacity} / \Delta_y$
  - $\Delta_{demand} \leq \Delta_{capacity}$ &
  - $\mu_{d.col} \leq 4$ (single column) or 5 (multi-column) &
  - $\mu_{c.col} \geq 3$

PBEE Application – Part A

3. Damage Analysis

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: ϕ_c / $\phi_y \geq 10$ (using SDC values)
- Identify Damage Index:
  - Curvature demand → Max strain demand → Damage Index

PBEE Application – Part A

3. Damage Analysis

Possible Future Acceptance Criteria / Damage Assessment:

Damage State (DS) Index with Associated Strain Threshold and Repair Cost
Based on the work by 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 – Part A

Summary

- **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 Application – Part A

Continue to Part B..

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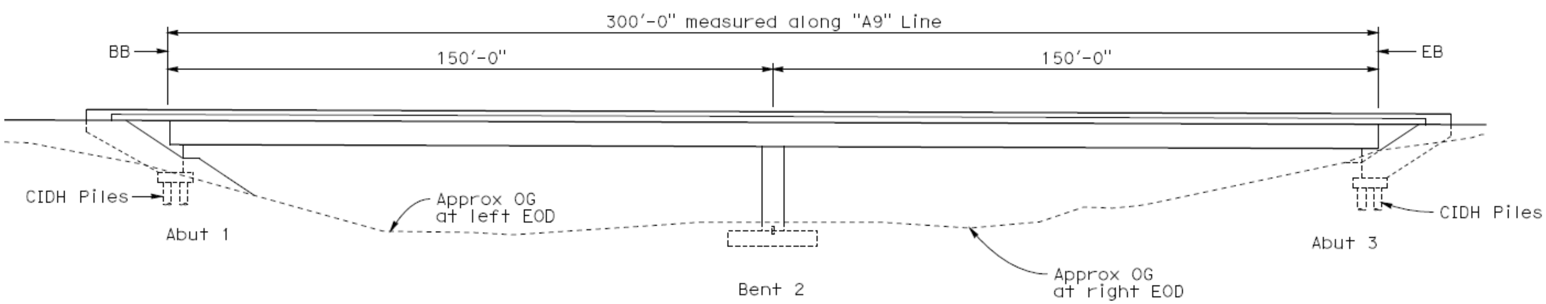
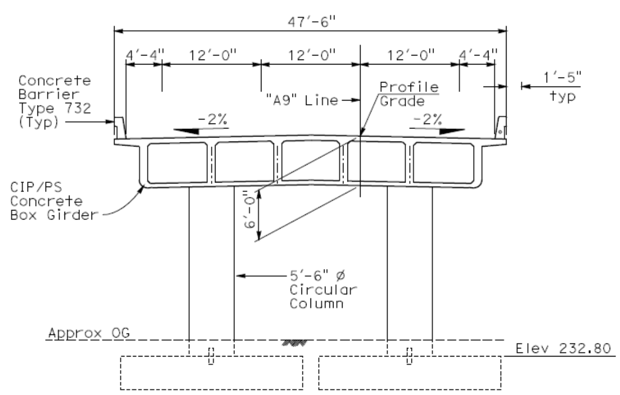
Part B –
Illustrative Example

PBEE Application – Part B

Design Scenario: An Ordinary Standard Bridge will be located in Bay Area, near San Mateo, at junction of highway 82 and 92. The bridge is a CIP/PT box girder bridge with two spans of 150 feet each. The bent consists of two 5'-6" diameter reinforced concrete columns. The footing is founded on competent rock.





PBEE Application – Part B

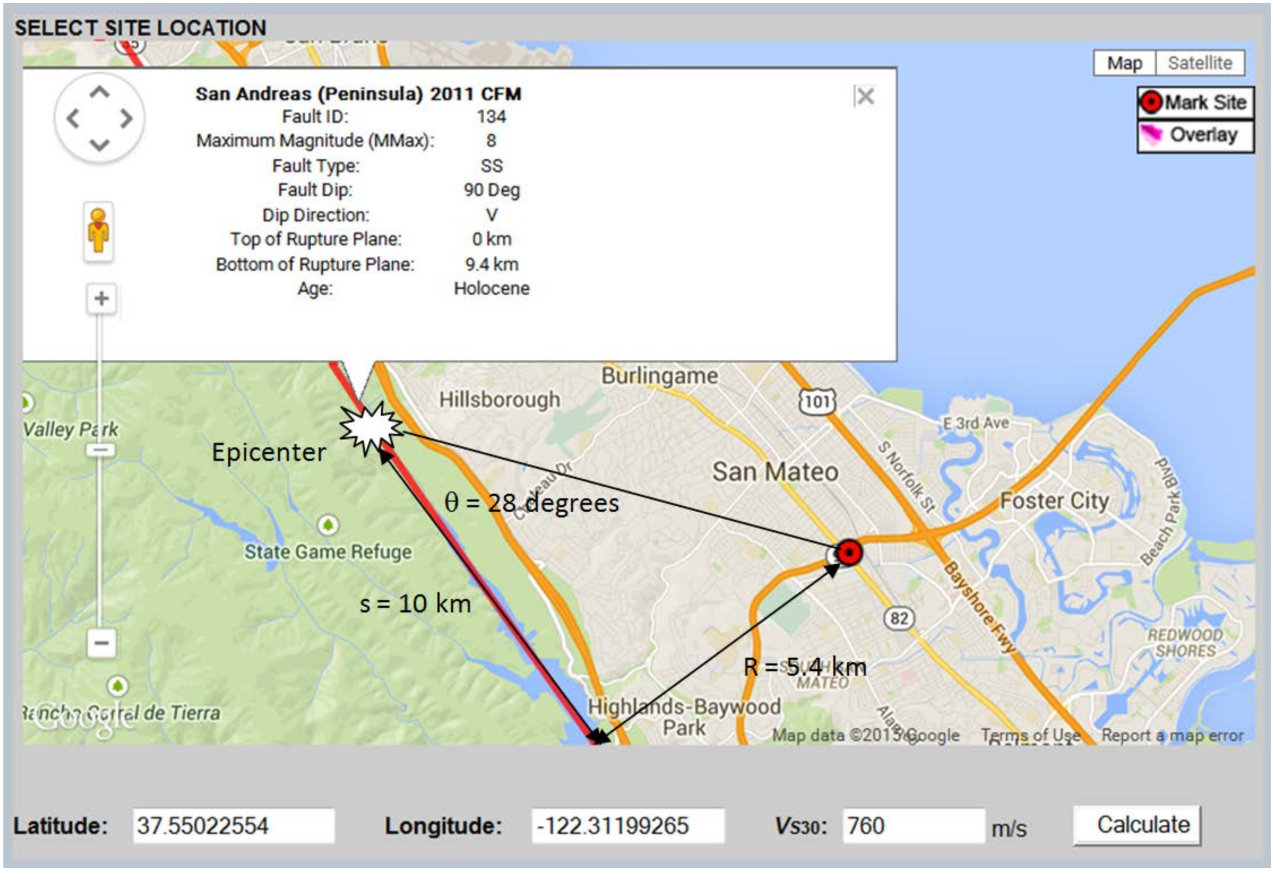
Step 1: Acceleration Record Generation & Selection

Step 2: Structural Analysis for Demand

Step 3: Structural Analysis for Capacity & Damage Assessment

PBEE Application – Part B

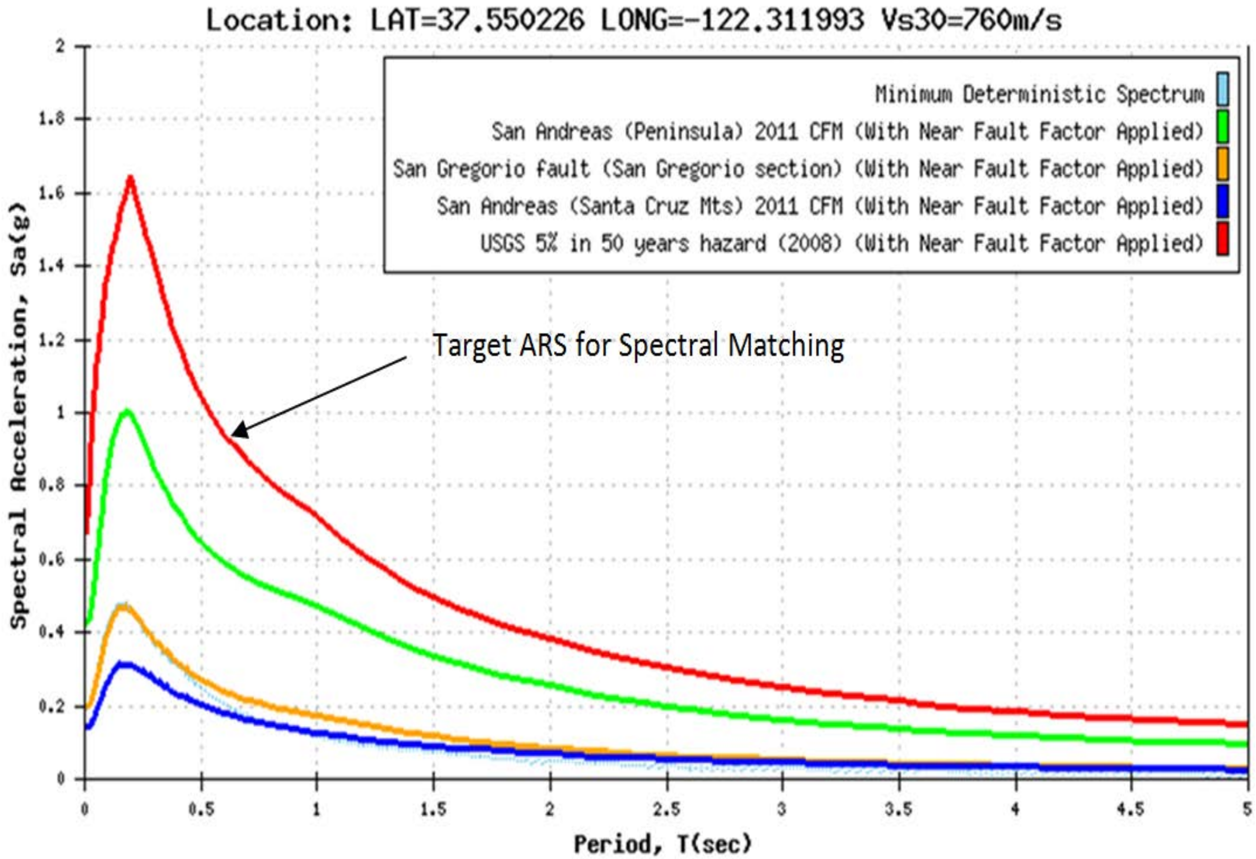
Step 1a: Acceleration Record Generation - Determine Target ARS from ARS Online and Obtain Parameters for Synthetic Ground Motion Generation.



Fault : Strike-Slip
Mw : 8.0
R : 5.4 km
V_{S30}: 760 m/sec
θ: 28 deg
s: 10 km

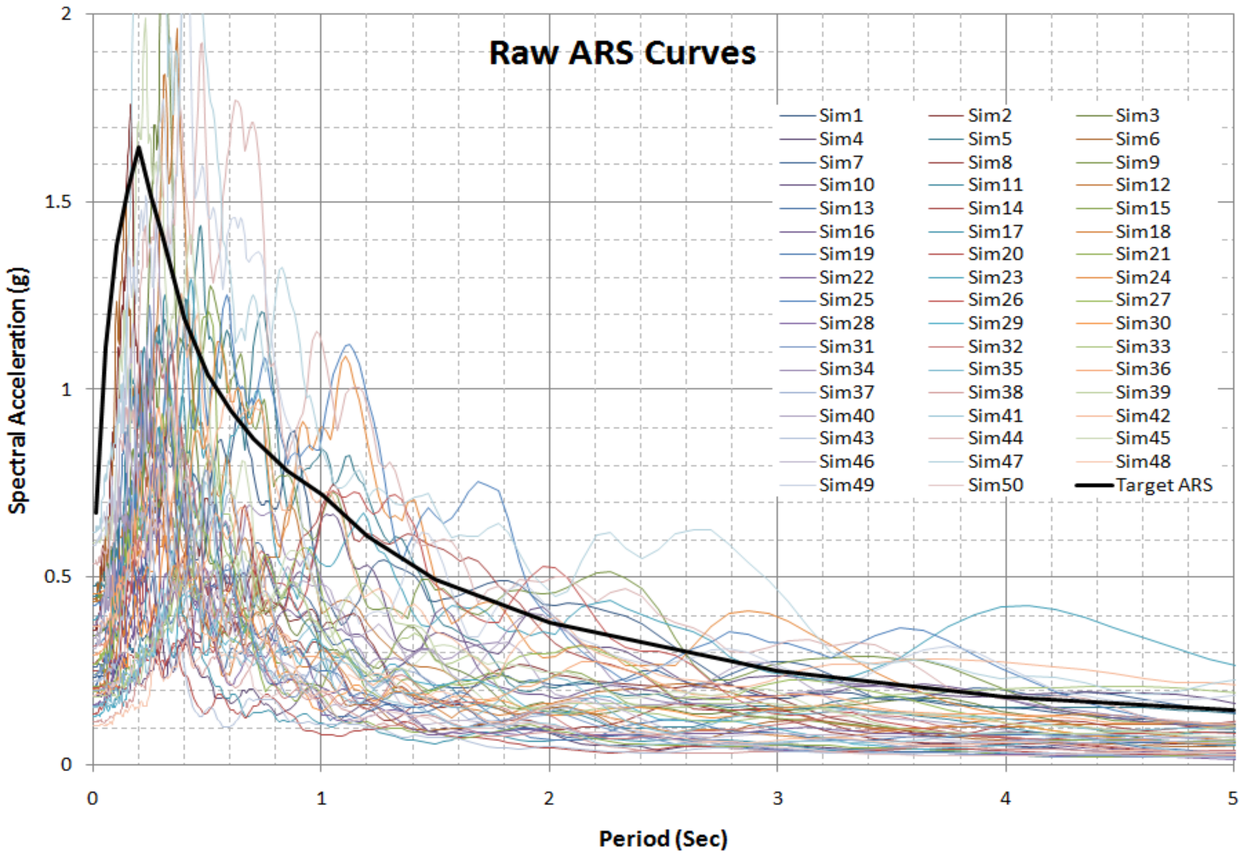
PBEE Application – Part B

Step 1a: Acceleration Record Generation - Determine Target ARS from ARS Online and Obtain Parameters for Synthetic Ground Motion Generation.



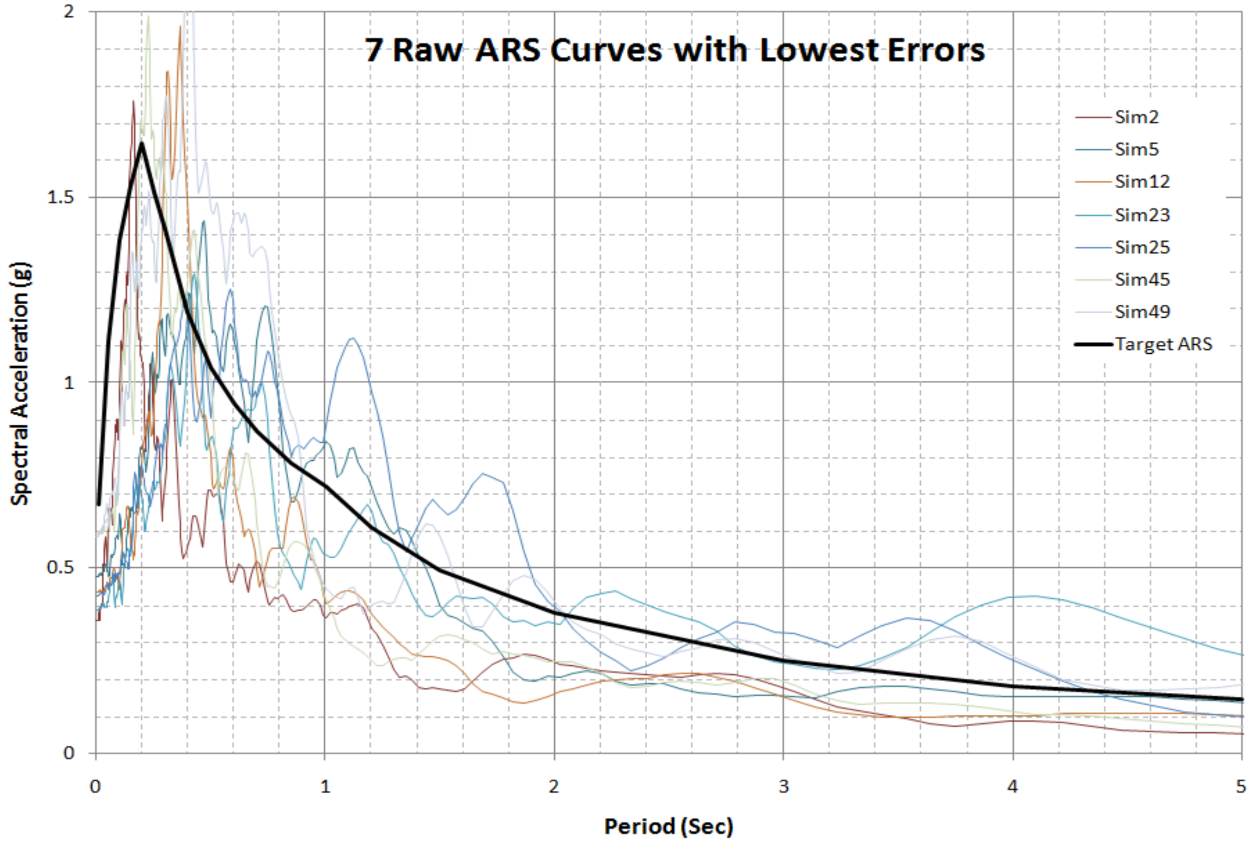
PBEE Application – Part B

Step 1b: Acceleration Record Generation - Generate 50 ground motions.



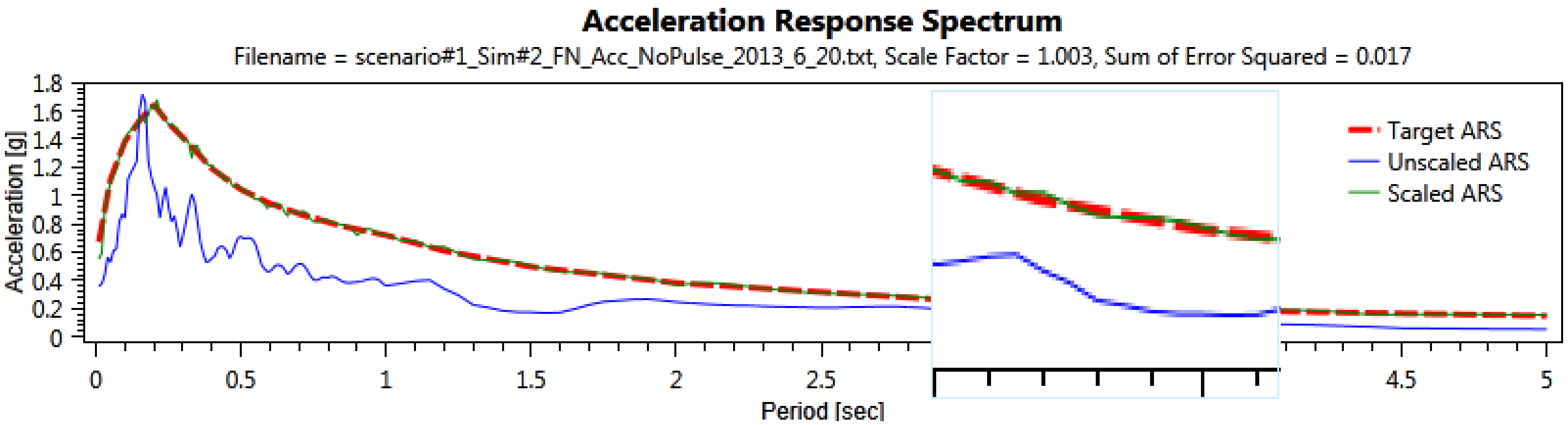
PBEE Application – Part B

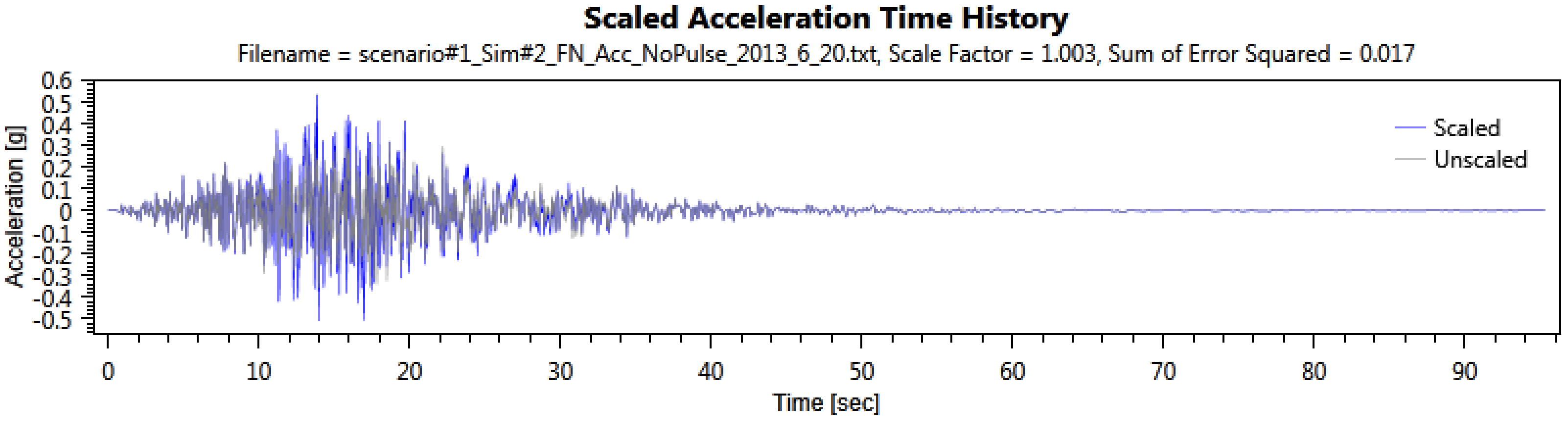
Step 1c: Acceleration Record Selection - Find 7 motions with lowest deviations from Target ARS.



PBEE Application – Part B

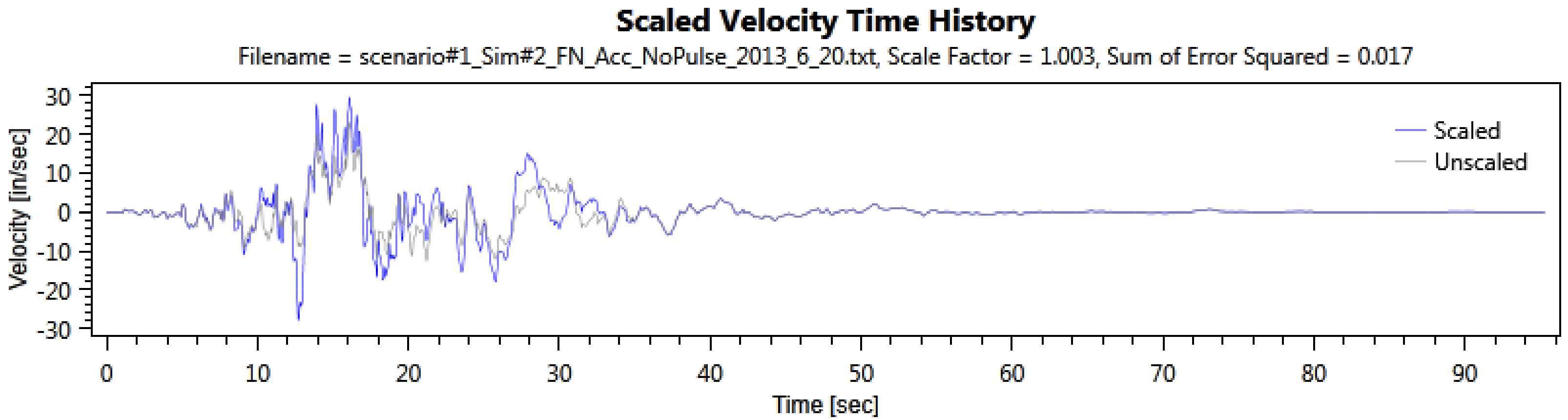
Step 1d: Acceleration Record Selection - Conduct Spectral Matching of 7 Motions to Target ARS.

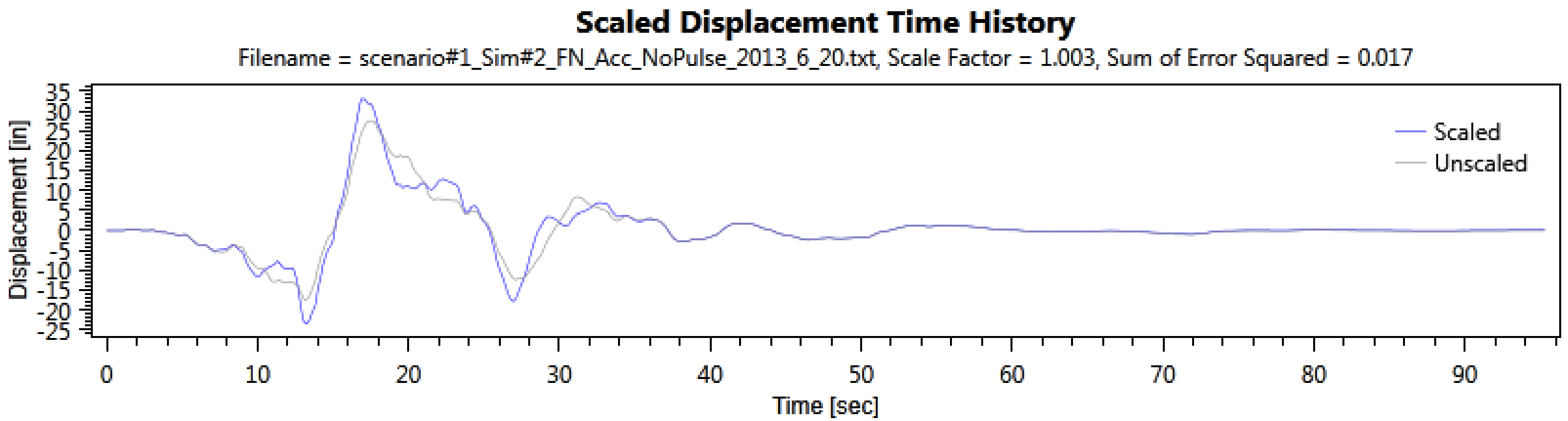




PBEE Application – Part B

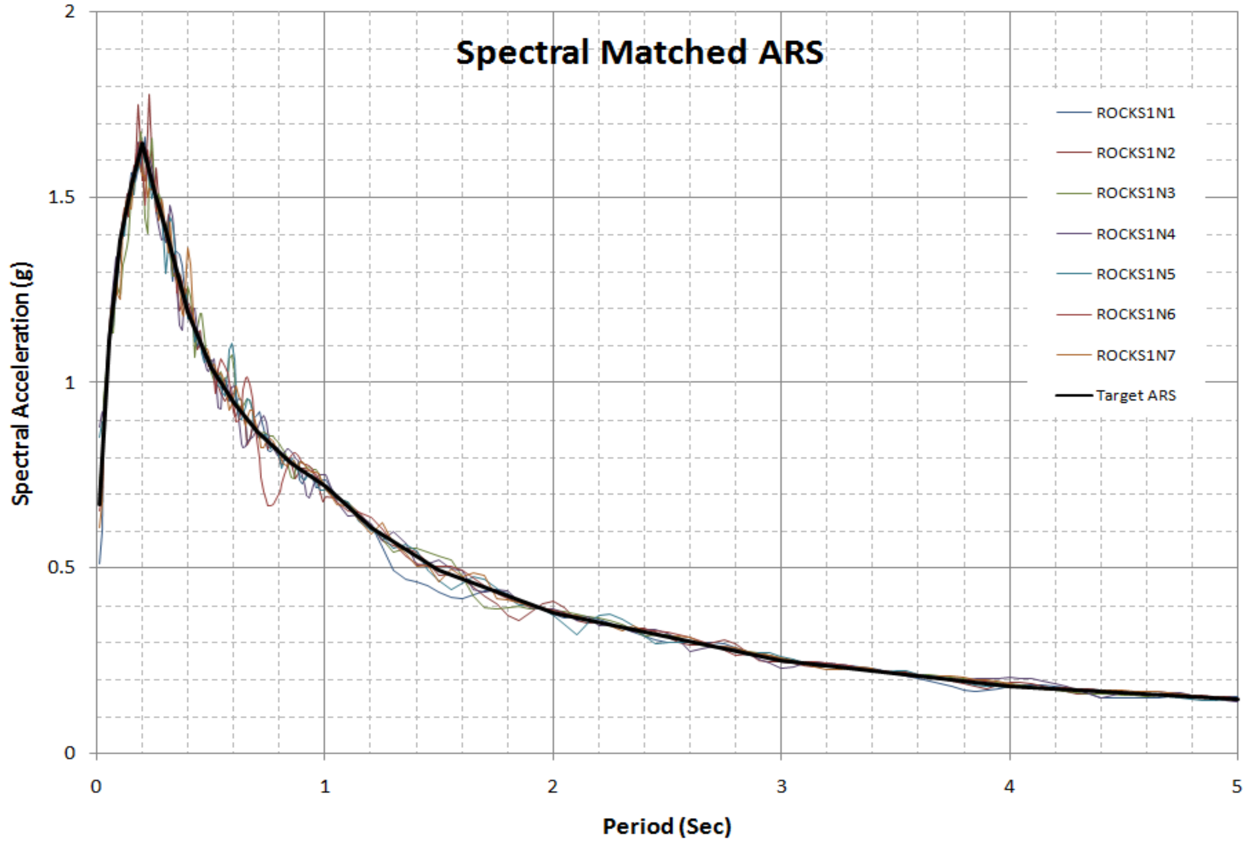
Step 1d: Acceleration Record Selection - Conduct Spectral Matching of 7 Motions to Target ARS.





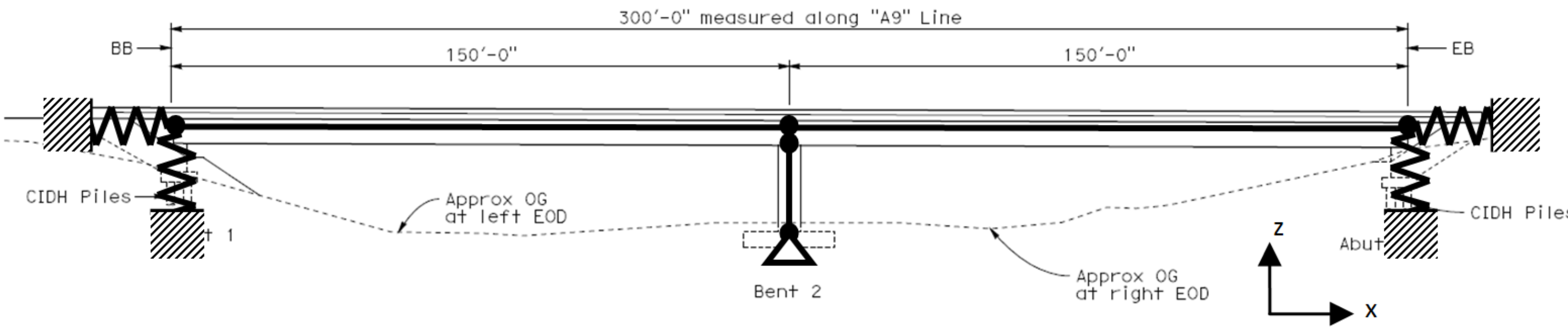
PBEE Application – Part B

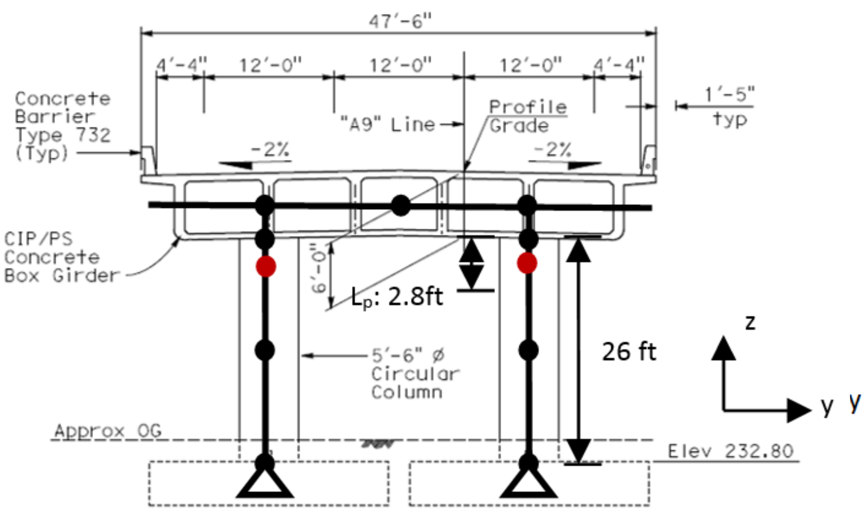
Step 1d: Acceleration Record Selection - Conduct Spectral Matching of 7 Motions to Target ARS.



PBEE Application – Part B

Step 2a: Structural Analysis – Idealize Bridge Model





Column Fixity

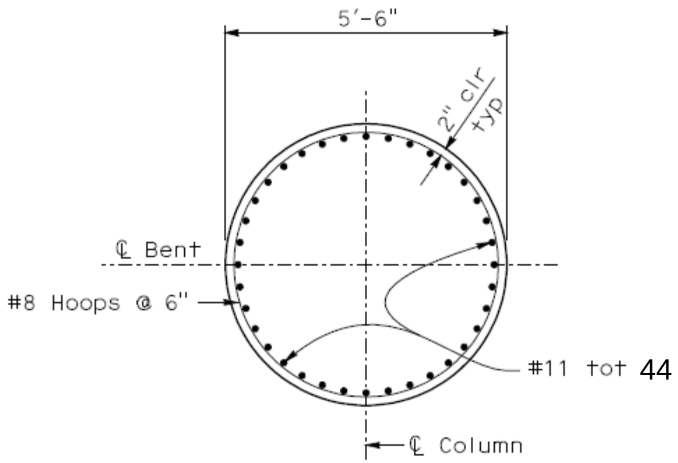
Fix at top & Pin at Bottom

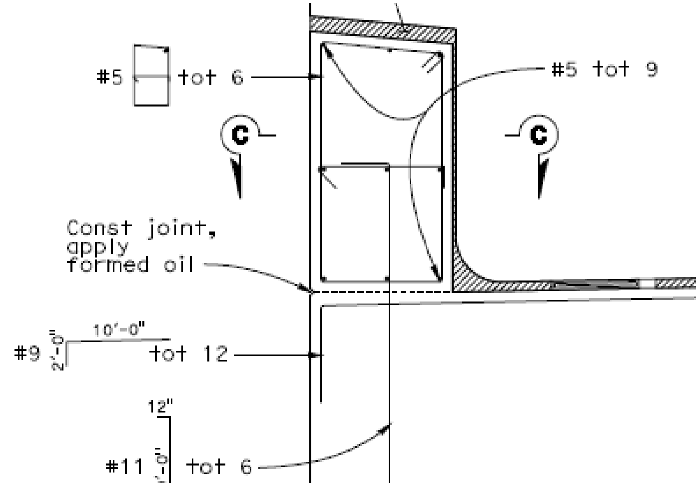
Geometry & Material Properties

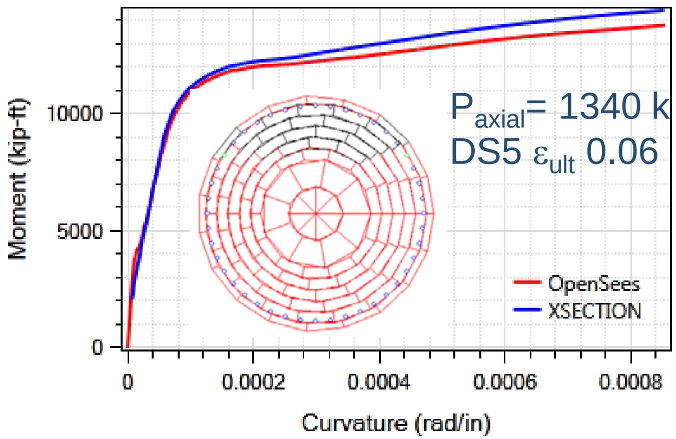
	Deck	Bentcap
E (ksi)	4287	4287
G (ksi)	1786	1786
f'_{ce} (ksi)	5	5
$A_{CrossSection}$	79	79
I_{xx} (ft^4)	-	156
I_{yy} (ft^4)	418	-
I_{zz} (ft^4)	13307	325

PBEE Application – Part B

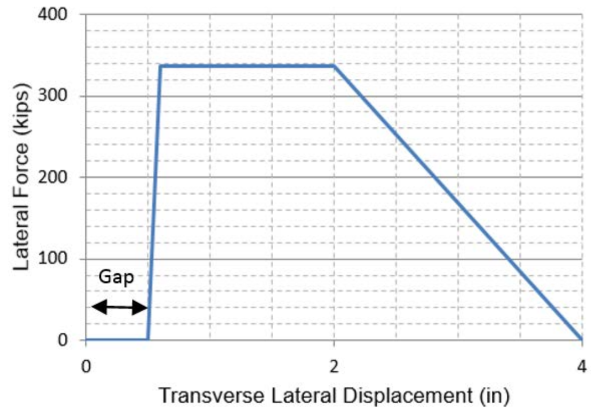
Step 2a: Structural Analysis – Idealize Bridge Model







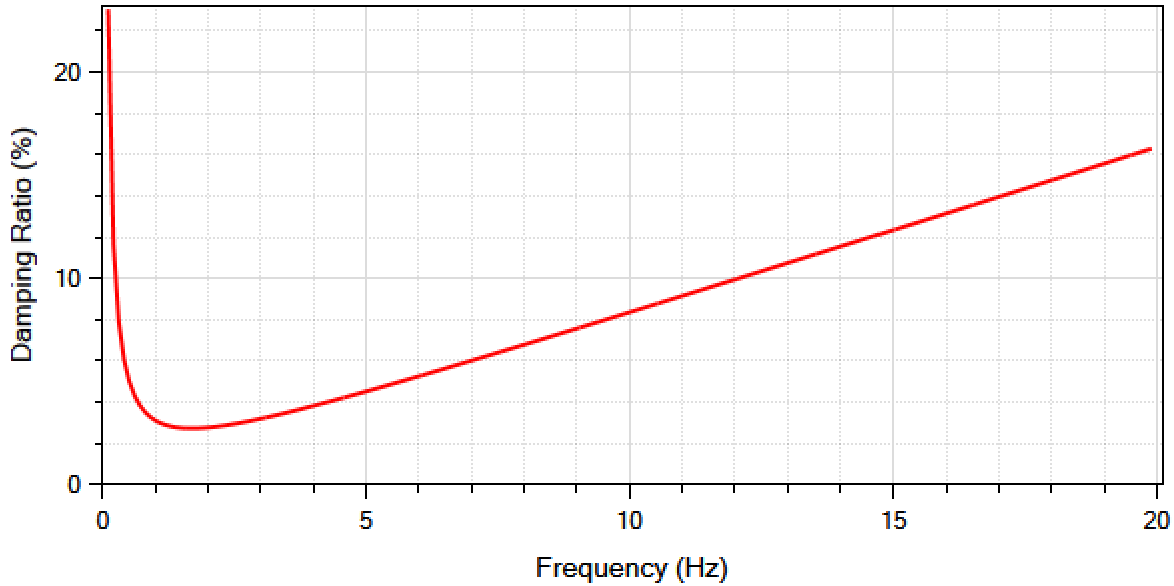
Column Plastic Hinge
Fiber Model



Shear Key F-Δ

PBEE Application – Part B

Step 2a: Structural Analysis – Idealize Bridge Model



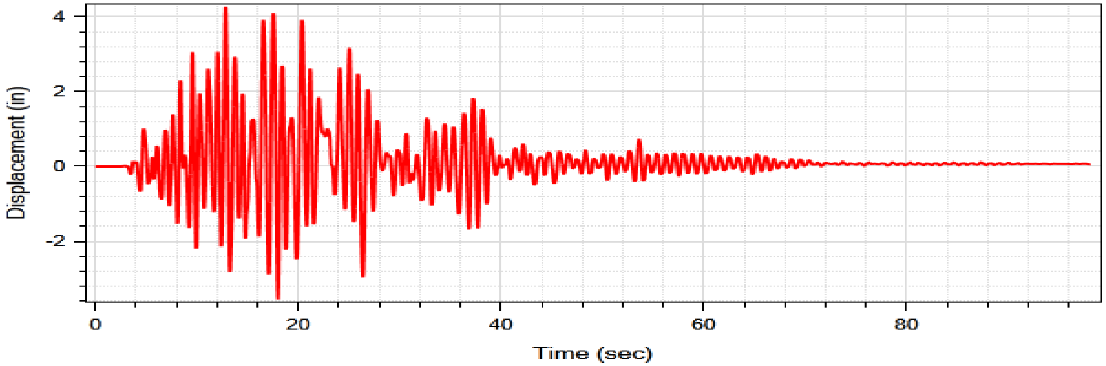
Rayleigh Damping:
5 % damping @ T = 0.17 & 2 sec (f = 0.5 & 5.88 Hz)

Integration Type:
Newmark

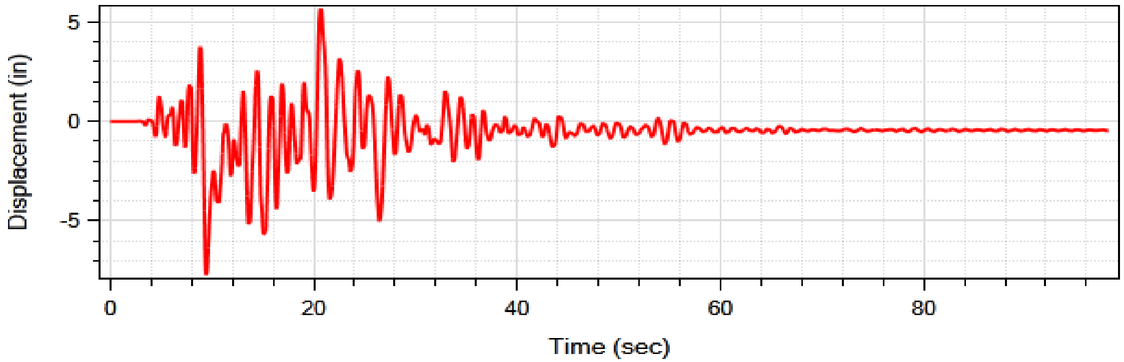
Algorithm:
Modified Newton

PBEE Application – Part B

Step 2b: Structural Analysis – Perform TH Analysis using 7 Spectrally Matched Motions.



in longitudinal direction

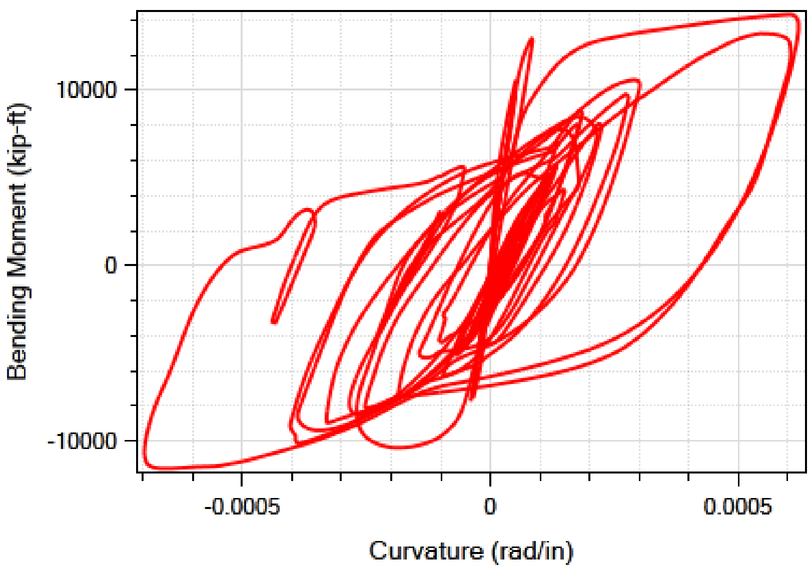


in transverse direction

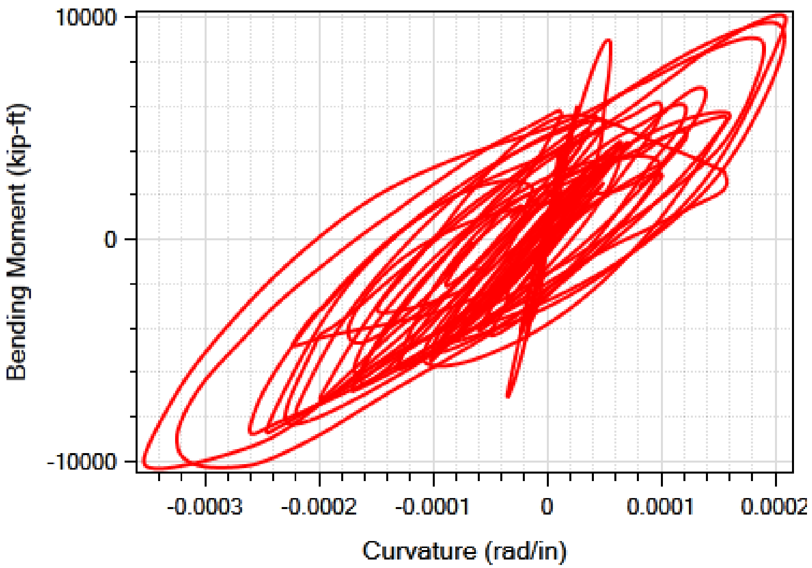
Displacement time history
@ column top subjected Motion Rock2

PBEE Application – Part B

Step 2b: Structural Analysis – Perform TH Analysis using 7 Spectrally Matched Motions.



in transverse direction

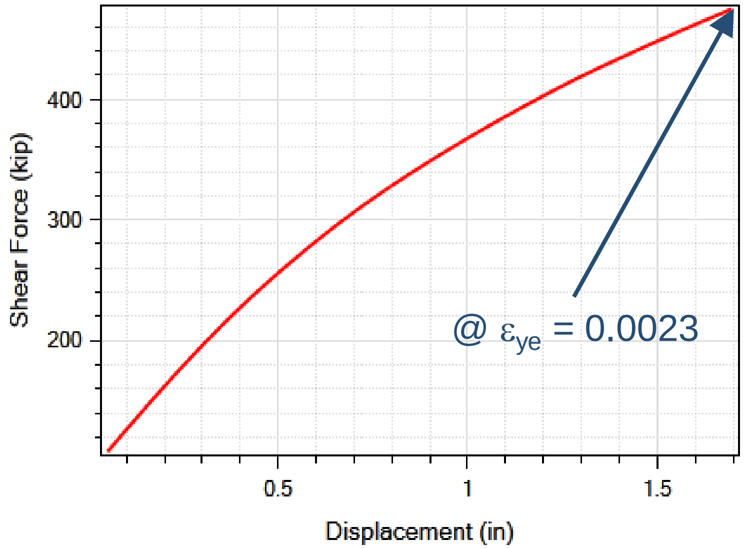


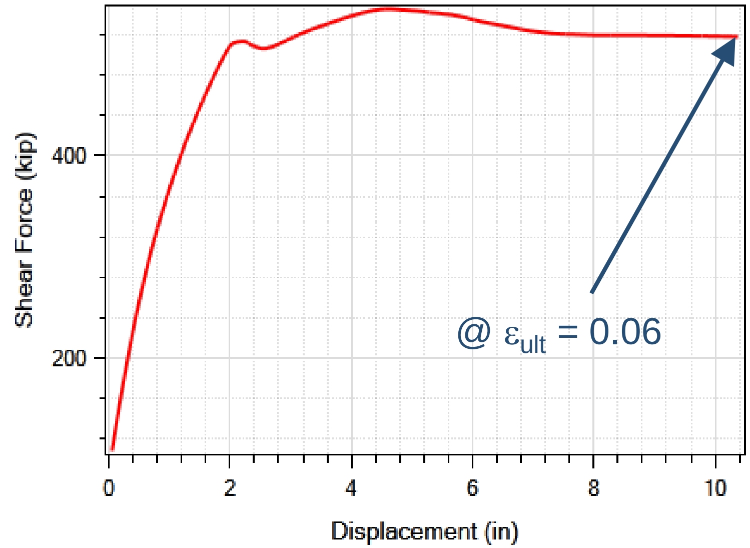
in longitudinal direction

Moment - Curvature History
@ column top subjected Motion Rock2

PBEE Application – Part B

Step 3a: Structural Analysis for Capacity – Conduct Push-over Analysis to determine Displacement & Curvature Capacity





Pushover results in transverse direction

Damage State	Δ_y (in)		Δ_c (in)		ϕ_y (rad/in)		ϕ_c (rad/in)	
	Long Dir	Trans Dir	Long Dir	Trans Dir	Long Dir	Trans Dir	Long Dir	Trans Dir
5 (ε_{ult} = 0.06)	2.3	1.8	12.9	10.4	6.6E-5	7E-5	1.3E-3	9.1E-4

PBEE Application – Part B

Step 3b: Acceptance Criteria / Damage Assessment

Displacement Based

Motion ID	Δ_d (in)		μ_d (in)	
	Long Dir	Trans Dir	Long Dir	Trans Dir
ROCK1	4	9	1.7	5.0
ROCK2	4.3	7.8	1.9	4.3
ROCK3	3.9	6.7	1.7	3.7
ROCK4	3.5	6.1	1.5	3.4
ROCK5	4.7	7.1	2.0	3.9
ROCK6	3	11.6	1.3	6.4
ROCK7	5.4	6.6	2.3	3.7
Avg	**4.1 < Δ_c**	**7.8 < Δ_c**	**1.8 < 5**	**4.3 < 5**
Δ_c	**12.9**	**10.4**	-	-
μ_c	-	-	**5.6 > 3**	**5.8 > 3**

PBEE Application – Part B

Step 3c: Alternate Acceptance Criteria / Damage Assessment

Curvature Based

Motion ID	ϕ_d (in) @ Col 1		ϕ_d (in) @ Col 2	
	Long Dir	Trans Dir	Long Dir	Trans Dir
ROCK1	2.8E-04	8.6E-04	3.4E-04	7.7E-04
ROCK2	3.5E-04	8.2E-04	3.5E-04	7.0E-04
ROCK3	3.3E-04	8.4E-04	3.1E-04	5.8E-04
ROCK4	2.9E-04	6.8E-04	2.7E-04	7.3E-04
ROCK5	4.5E-04	6.8E-04	5.1E-04	8.5E-04
ROCK6	3.8E-04	9.1E-04	3.6E-04	1.1E-03
ROCK7	4.5E-04	7.0E-04	4.5E-04	6.9E-04
Avg	**3.6E-04 < ϕ_c**	**7.8E-04 < ϕ_c**	**3.7E-04 < ϕ_c**	**7.7E-04 < ϕ_c**
ϕ_c	**1.3E-3**	**9.1E-4**	**1.3E-3**	**9.1E-4**
ϕ_c / ϕ_y	**19.7 > 10**	**13.0 > 10**	**19.7 > 10**	**13.0 > 10**

PBEE Application – Part B

The above example was performed applying the motions in bridge longitudinal and transverse directions only. The complete analysis can be made repeating steps 2 & 3 by orienting the ground motions at different orientations (30 & 60 deg) per MTD 20-17.

PBEE Application – Part B

Question?