Content

- Philosophy and process
- Screening a bridge inventory
- Evaluation of bridge performance
- Retrofit strategies for deficient bridges
Philosophy and process

Exempt bridges include those that are:

- Near end of service life (≤ 15 years remaining service life)
- Temporary (less than a 15-year life)
- Closed, but not crossing active roads, rail-lines, or waterways
- In the lowest seismic zone (with an exception)
Is Bridge Exempt?

- Yes
  - Screen / prioritize
  - Next bridge

- No
  - Pass
    - Screen / prioritize
    - Next bridge
  - Fail
    - Evaluate
    - Next bridge
Performance-based retrofit

Explicit attempt to satisfy public expectations of bridge performance for earthquakes ranging from small to large...
Performance-based retrofit

Explicit attempt to satisfy public expectations of bridge performance for earthquakes ranging from small to large... for example:

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</table>
Performance-based retrofit

- Application of *performance-based design* to bridge retrofitting
  - two earthquake levels (Lower Level, Upper Level)
  - two bridge types (standard, essential)
  - three service life categories (ASL1,-2,-3)
  - two performance levels (life safety, operational)
Seismic retrofit categories

Seismic Retrofit Categories, SRC, are used to recommend minimum levels of
- screening
- evaluation, and
- retrofitting
Seismic retrofit categories

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If these minima are satisfied, the required performance levels will be satisfied.

Seismic retrofit categories

Seismic Retrofit Categories, SRC, are used to recommend minimum levels of
- screening
- evaluation, and
- retrofitting

If these minima are satisfied, the required performance levels will be satisfied.

SRCs are similar to Seismic Performance Categories (SPC) used in new design
Bridge importance

A bridge is **essential** if it satisfies one or more of the following:
- Provides access for emergency vehicles and is required for secondary life safety
- Would result in major social and / or economic loss if collapsed or was closed
- Required for security / defense
- Crosses an essential route

All other bridges are **standard**
### Bridge Importance
- Anticipated Service Life, ASL
- Spectral Accelerations, Ss and S1
- Soil Factors, Fa and Fv

### Performance Level, PL
- Seismic Hazard Level, SHL

### Seismic Retrofit Category, SRC

#### Service life categories (ASL)

<table>
<thead>
<tr>
<th>Service Life Category</th>
<th>Anticipated Service Life</th>
<th>Age (if not rehabilitated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASL 1</td>
<td>0 - 15 yrs</td>
<td>60 - 75 yrs</td>
</tr>
<tr>
<td>ASL 2</td>
<td>15 - 50 yrs</td>
<td>25 - 60 yrs</td>
</tr>
<tr>
<td>ASL 3</td>
<td>&gt;50 years</td>
<td>&lt; 25 yrs</td>
</tr>
</tbody>
</table>
Performance levels for bridge retrofitting

<table>
<thead>
<tr>
<th>EARTHQUAKE</th>
<th>BRIDGE IMPORTANCE and SERVICE LIFE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Standard</strong></td>
</tr>
<tr>
<td>ASL1</td>
<td>ASL2</td>
</tr>
<tr>
<td><strong>Lower Level</strong></td>
<td>PL0</td>
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<td>ASL2</td>
</tr>
<tr>
<td>Lower Level</td>
<td></td>
<td>PL0</td>
<td>PL3</td>
</tr>
</tbody>
</table>

Performance levels: PL0 and PL3

**PL0**: No minimum performance specified.

**PL3**: Fully Operational: No collapse, no damage, no interruption to traffic flow. No repair required.
Performance levels for bridge retrofitting

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<th>Essential</th>
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<td>ASL2</td>
<td>ASL3</td>
</tr>
<tr>
<td>ASL1</td>
<td>ASL2</td>
<td>ASL3</td>
</tr>
<tr>
<td>Upper Level</td>
<td>PL0</td>
<td>PL1</td>
</tr>
<tr>
<td>PL0</td>
<td>PL1</td>
<td>PL2</td>
</tr>
</tbody>
</table>
Performance levels: PL1 and PL2

- **PL1: Life-safety**: No collapse and life-safety preserved but damage will be severe particularly after UL event. Service is significantly disrupted. Bridge may need replacement after UL event.

- **PL2: Operational**: No collapse, life-safety preserved, damage is minor, almost immediate access for emergency vehicles, repairs feasible but with restrictions on traffic flow.

Upper and lower level earthquakes

- **Lower Level earthquake (LL)**: 100-year return period (50% probability of exceedance in 75 years)

- **Upper Level earthquake (UL)**: 1000-year return period (7% probability of exceedance in 75 years)
### Performance levels for bridge retrofitting

<table>
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<tr>
<th>EARTHQUAKE</th>
<th>BRIDGE IMPORTANCE and SERVICE LIFE</th>
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</tr>
<tr>
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</tr>
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</table>

- **Bridge Importance**
- **Anticipated Service Life, ASL**
- **Spectral Accelerations, Ss and S1**
- **Soil Factors, Fa and Fv**

- **Performance Level, PL**
- **Seismic Hazard Level, SHL**
- **Seismic Retrofit Category, SRC**
USGS hazard maps

Spectral accelerations, Ss and S1

\[ S_{DS} = F_a \times S_s \quad \text{and} \quad S_{D1} = F_v \times S_1 \]
Soil factor, Fa

Table 1-4. Site factors $F_a$ and $F_v$.
(a) Values of $F_a$ as a function of site class and short-period (0.2 second) response spectral acceleration, $S_a$.

<table>
<thead>
<tr>
<th>SITE CLASS</th>
<th>$S_a \leq 0.25$</th>
<th>$S_a = 0.50$</th>
<th>$S_a = 0.75$</th>
<th>$S_a = 1.00$</th>
<th>$S_a \geq 1.25$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>B</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>C</td>
<td>1.2</td>
<td>1.2</td>
<td>1.1</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>D</td>
<td>1.6</td>
<td>1.4</td>
<td>1.2</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>E</td>
<td>2.5</td>
<td>1.7</td>
<td>1.2</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>F</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

Notes:
1. Use straight-line interpolation for intermediate values of $S_a$.
2. Site-specific geotechnical investigation and dynamic site response analysis should be performed for all sites in Site Class F.
Soil factor, $F_v$

---

(b) Values of $F_v$ as a function of site class and long-period (1.0 second) response spectral acceleration, $S_1$

<table>
<thead>
<tr>
<th>SITE CLASS</th>
<th>Spectral Acceleration at Long Period (1.0 sec.), $S_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$S_1 \leq 0.1$</td>
</tr>
<tr>
<td>A</td>
<td>0.8</td>
</tr>
<tr>
<td>B</td>
<td>1.0</td>
</tr>
<tr>
<td>C</td>
<td>1.7</td>
</tr>
<tr>
<td>D</td>
<td>2.4</td>
</tr>
<tr>
<td>E</td>
<td>3.5</td>
</tr>
<tr>
<td>F</td>
<td>*</td>
</tr>
</tbody>
</table>

Notes:
1. Use straight-line interpolation for intermediate values of $S_1$.
2. Site-specific geotechnical investigation and dynamic site response analysis should be performed for all sites in Site Class F.

Site classes: A – F

---

<table>
<thead>
<tr>
<th>SITE CLASS</th>
<th>SOIL TYPE and PROFILE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Hard rock with measured shear wave velocity, $V_s &gt; 1500$ m/sec (5,000 ft/sec).</td>
</tr>
<tr>
<td>B</td>
<td>Rock with 760 m/sec $&lt; V_s \leq 1500$ m/sec (2,500 ft/sec $&lt; V_s \leq 5,000$ ft/sec).</td>
</tr>
<tr>
<td>C</td>
<td>Very dense soil and soil rock with $360$ m/sec $&lt; V_s \leq 760$ m/sec (1,200 ft/sec $&lt; V_s \leq 2,500$ ft/sec) or with either $N &gt; 50$ blows/0.30m (50 blows/ft) or $\sigma_{uv} &gt; 100$ kPa (2,000 psf).</td>
</tr>
<tr>
<td>D</td>
<td>Stiff soil with $180$ m/sec $&lt; V_s \leq 360$ m/sec (600 ft/sec $&lt; V_s \leq 1,200$ ft/sec) or with either $15 \leq N \leq 50$ blows/0.30m (15 $\leq N \leq 50$ blows/ft) or $50$ kPa $\leq \sigma_{uv} \leq 100$ kPa (1,000 $\leq \sigma_{uv} \leq 2,000$ psf).</td>
</tr>
<tr>
<td>E</td>
<td>Soil profile with $V_s &lt; 180$ m/sec (600 ft/sec) or with either $N &lt; 15$ blows/0.30m ($N &lt; 15$ blows/ft) or $\sigma_{uv} &lt; 50$ kPa (1,000 psf), or any profile with more than $3$ m (10 ft) of soft clay defined as soil with $PI &gt; 20$, $w \geq 40$ percent and $\sigma_{uv} &lt; 25$ kPa (500 psf).</td>
</tr>
</tbody>
</table>
| F          | Soils requiring site-specific evaluations, such as:
1. Peats or highly organic clays ($H > 3$ m [10 ft] of peat or highly organic clay where $H = $ thickness of soil).
2. Very high plasticity clays ($H > 8$ m [25 ft] with $PI > 75$).
3. Very thick soft/medium stiff clays ($H > 30$ m [120 ft]). |
Seismic hazard levels: I - IV

<table>
<thead>
<tr>
<th>HAZARD LEVEL</th>
<th>Using $S_{oi} = F_v S_i$</th>
<th>Using $S_{os} = F_a S_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$S_{oi} \leq 0.15$</td>
<td>$S_{os} \leq 0.15$</td>
</tr>
<tr>
<td>II</td>
<td>$0.15 &lt; S_{oi} \leq 0.25$</td>
<td>$0.15 &lt; S_{os} \leq 0.35$</td>
</tr>
<tr>
<td>III</td>
<td>$0.25 &lt; S_{oi} \leq 0.40$</td>
<td>$0.35 &lt; S_{os} \leq 0.60$</td>
</tr>
<tr>
<td>IV</td>
<td>$0.40 &lt; S_{oi}$</td>
<td>$0.60 &lt; S_{os}$</td>
</tr>
</tbody>
</table>

Notes:

1. For the purposes of determining the Seismic Hazard Level for Site Class F soils, the value of $F_v$ and $F_a$ need not be taken larger than 2.4 and 1.6 respectively, when $S_i$ is less than or equal to 0.10 and $S_s$ is less than 0.25.
2. For the purposes of determining the Seismic Hazard Level for Site Class E soils, $F_v$ and $F_a$ values for Site Class F soils may be used with the adjustment described in Note 1 above.
Geotechnical hazards

- Soil liquefaction
- Soil settlement
- Surface fault rupture
- Flooding

Bridge Importance

Anticipated Service Life, ASL

Spectral Accelerations, Ss and S1

Soil Factors, Fa and Fv

PERFORMANCE LEVEL, PL

SEISMIC HAZARD LEVEL, SHL

SEISMIC RETROFIT CATEGORY, SRC
Seismic retrofit category

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<td></td>
<td>PL0: No min.</td>
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<tr>
<td>I</td>
<td>A</td>
</tr>
<tr>
<td>II</td>
<td>A</td>
</tr>
<tr>
<td>III</td>
<td>A</td>
</tr>
<tr>
<td>IV</td>
<td>A</td>
</tr>
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Minimum requirements

Minimum retrofit requirements determined by *seismic retrofit category* (SRC)

- A: retrofitting not required
- B: seats + connections + liquefaction
- C: seats + connections + columns + footings + liquefaction
- D: seats + connections + columns + footings + abutments + liquefaction
Minimum requirements continued

<table>
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<tr>
<th>ACTION</th>
<th>SEISMIC RETROFIT CATEGORY</th>
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<tbody>
<tr>
<td></td>
<td>A</td>
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<tr>
<td>Screening/Retrofitting</td>
<td>NR</td>
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Example:

**Given:** Essential bridge, 30-year service life, Salt Lake City (84112), dense soils ($v_s=1000$ ft/sec).
Find seismic retrofit category, upper level earthquake.

**Step 1:** ASL2; site class C (T1-1, 1-3)

**Step 2:** Essential bridge; therefore Performance criteria (UL) = PL1 (T1-2)
Example continued

Step 3: (T1-4, 1-5, 1-6)
- For zip code 84112,
  \( S_s = 1.11 \) and \( S_1 = 0.39 \)
- For site class C, and \( S_s, S_1 \):
  \( F_a = 1.0 \) and \( F_v = 1.4 \)
- Hence \( F_a \cdot S_s = 1.11 \) and \( F_v \cdot S_1 = 0.55 \)
  and \( SHL = IV \) (T1-5)
- For PL1, \( SHL = IV \), and
  Seismic retrofit category is C (T1-6)

Information required for performance-based retrofitting

---

Anticipated Service Life

Performance Objectives

Bridge Inventory

Seismic Hazard
  - Ground motions
  - Site effects

Seismic retrofit category
Retrofit process for two earthquake levels

- Two-step process
  1. Screen, evaluate, retrofit for performance required during Lower Level earthquake
  2. Screen, evaluate, retrofit, for performance required during Upper Level earthquake

- Performance required
  - Lower Level: PL3
  - Upper Level: PL1, PL2
Exempt?

- Are near end of service life (<15 years remaining life)
- Temporary (expected life less than 15 years)
- Closed, but not crossing active roads, rail lines or waterways
LOWER LEVEL EARTHQUAKE

1. Screen
2. Evaluate
3. Retrofit

Exempt?

Next bridge

SRC = A?

Yes

No
**Process for Lower Level earthquake**

**Screening and prioritization**
- Quick screen based on comparison of basic earthquake load against wind and braking loads where earthquake load is taken as $F = F_aS_sW = S_dS_wW$
- If $F < \text{both } F_{\text{wind}}$ and $F_{\text{braking}}$, bridge passes
- If $F > \text{either } F_{\text{wind}}$ or $F_{\text{braking}}$, detailed evaluation required
- Prioritization for further evaluation based on severity of shortfall in strength
Process for Lower Level earthquake continued

Detailed evaluation - Step 1

- Calculate transverse and longitudinal periods of bridge (ULM, MSM...)
- Calculate $S_{aT}$ and $S_{aL}$
- Calculate $F_T = S_{aT} \cdot W$ and $F_L = S_{aL} \cdot W$
- If $F_T < F_{\text{wing}}$ and $F_L < F_{\text{braking}}$ bridge passes, otherwise go to Step 2

Process for Lower Level earthquake continued

Detailed evaluation - Step 2

- Calculate elastic, unfactored, strengths in transverse and longitudinal directions, $F_{\text{capT}}$ and $F_{\text{capL}}$
- If $F_T < F_{\text{capT}}$ and $F_L < F_{\text{capL}}$ bridge passes, otherwise retrofit is required for Lower Level earthquake
Process for Lower Level earthquake continued

- Retrofit strategy, approach, measures

**Strategy:** consider ‘do-nothing’ and ‘full-replacement’ options; identify relevant approaches (if more than one)

**Approach:** Decide most effective combination of techniques (measures) to satisfy performance requirement (PL3)

**Measures:** Devise retrofit measures... using conventional strength-based methodology.

---

Flowchart:

**LOWER LEVEL EARTHQUAKE**
- Exempt? (Yes/No)
  - Yes: Next bridge
  - No: Screen → Evaluate → Pass → Retrofit

**UPPER LEVEL EARTHQUAKE**
- Screen → Evaluate → Pass
- SRC = A? (Yes/No)
  - Yes: Retrofit
  - No: Screen → Evaluate → Pass
Process for Upper Level earthquake

- Screening and prioritization
- Detailed evaluation
- Retrofit strategy and related approaches and measures

Screening & Prioritization

1. Screen / prioritize
2. Evaluate
3. Retrofit
Screening and prioritization

- Purpose is to screen an existing inventory of bridges for seismic deficiencies and prioritize the inventory for seismic retrofitting based on vulnerability, hazard, and non-structural factors.
- Screening methods are expected to be quick and conservative; bridges that ‘fail’ are passed to a second level of screening i.e. ‘detailed evaluation’.

Factors considered

- Structural vulnerability
- Seismic and geotechnical hazards
- Other
  - Importance
  - Network redundancy
  - Age and physical condition
Screening and prioritization

\[ P = f(R, \text{importance, non-seismic and socioeconomic factors}) \]

where: 
P = assigned priority  
R = bridge rating (or rank)  
based on hazard and vulnerability

Three methods:
- *Expected Damage Method* (new, uses bridge fragility functions, rank is based on direct losses due to damage)
- *Seismic Risk Assessment Method* (new, uses network models and fragility functions, rank is based on direct and indirect losses, uses REDARS software)
Detailed Evaluation

- Screen / prioritize
- Evaluate
- Retrofit

Detailed evaluation

- Methods of Evaluation
- Geotechnical Modeling
- Structural Modeling
Methods of evaluation

In general, all evaluation methods involve (figure 1-13):

- Demand analysis
- Capacity assessment
- Calculation of a capacity / demand ratio either
  - for each critical component in a bridge or
  - for bridge as a complete system

Exceptions exist

Methods of evaluation continued

Three categories, six methods:

I. No demand analysis
   1. Method A1/A2 (capacity checks made for seats and connections)
   2. Method B (capacity checks made for seats connections, columns, and footings)

II. Component C/D evaluation
   3. Method C (elastic analysis: uniform load method, multimode spectral analysis; prescriptive rules given for calculation of component capacity)
Methods of evaluation continued

III. Structure C/D evaluation

4. Method D1 (*capacity-spectrum method*: elastic analysis for demands, simplified models for calculation of capacity;

5. Method D2 (*pushover method*: elastic analysis for demands, nonlinear static analysis used for calculation of pier capacity)

6. Method E (nonlinear time history analysis for calculation of both demand and capacity)

Geotechnical modeling

*Geotechnical Modeling and Capacity Assessment*

- Foundation Modeling
  - Shallow footings
  - Piles and pile groups
  - Abutments

- Ground Displacement Demands
  - Settlement
  - Liquefaction Induced Lateral Spreads
Structural modeling

- Load path
- Modeling recommendations
- Combination of seismic forces
- Member strength capacities
- Member deformation capacities

Load path

- Identify clear load path for lateral loads:
  - Deck slab and connectors (studs)
  - Cross frames (diaphragms)
  - Longitudinal beams (girders)
  - Bearings and anchorages
  - Pier (cap beam, columns, walls)
  - Abutments and foundations (back wall, footing, piles)
  - Soils
Structural modeling recommendations

- Distribution of mass
- Distribution of stiffness and strength
- Damping
- In-span Hinges
  - Substructures
  - Superstructures

Combination of seismic forces

- Loading in 2- or 3-orthogonal directions:
  - SRSS Rule
  - 100-40% Rule

- Response quantities in biaxial design:
  - SRSS Rule
  - 100-40% Rule
Member strength capacities

- Flexural and shear strength of reinforced concrete columns and beams
  - Expected flexural strength
  - Flexural overstrength
  - Flexural strength of columns with lap-splices in plastic hinge zones
  - Initial shear strength
  - Final shear strength

Strength capacities continued

- Shear strength of reinforced concrete beam-column joints
  - Maximum beam-column joint strength
  - Cracked beam-column joint strength
Member deformation capacities

- Plastic curvature & hinge rotations
- Deformation-based limit states
  - Compression failure of confined and unconfined concrete
  - Buckling longitudinal bars
  - Tensile fracture longitudinal bars
  - Low-cycle fatigue longitudinal bars
  - Failure in lap-splice zone

Retrofit Strategies, Approaches, and Measures

1. Screen / prioritize
2. Evaluate
3. Retrofit
Retrofit strategies, approaches, and measures

**Retrofit Measure**: a device or technique such as a *restrainer, column jacket, stone column*.

**Retrofit Approach**: One or more measures used together to achieve an improvement in performance such as *strengthening* using restrainers and jackets...

Retrofit strategies, approaches and measures continued

**Retrofit Strategy (one of the following)**:

- One or more approaches used together to achieve desired level of improvement in performance such as *strengthening and site remediation*.
- Partial or full replacement
- Do-nothing (retrofitting not justified)
Retrofit approaches

- **Approaches:** one or more measures to achieve:
  - Strengthening
  - Displacement capacity enhancement
  - Force limitation
  - Response modification
  - Site remediation
  - Partial replacement
  - Damage acceptance or control

Retrofit matrix

- For a given seismic deficiency, matrix identifies possible *approaches*, and for each approach, matrix recommends possible *measures* for consideration
### Retrofit matrix: approaches/measures

<table>
<thead>
<tr>
<th>Deficiencies</th>
<th>Measures (techniques)</th>
</tr>
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#### Retrofit measures

- **Superstructure measures:**
  - Restrainers
  - Seat width extensions, catcher blocks
  - Continuous simple spans
  - Bearing side-bar restraints, shear keys, stoppers
  - Isolation bearings and energy dissipators, including ductile-end-diaphragms
Retrofit measures continued

Substructure measures
- Column jacketing, using steel, fiber composites, or concrete shells
- Infill walls
- Column replacements

Retrofit measures for foundations and hazardous sites

Retrofit Measures for
- Abutments, Footings and Foundations
- Hazardous sites including
  - near active faults
  - unstable slopes
  - liquefiable sites.
Summary

- Performance-based philosophy (methodology):
  - two earthquake levels (Lower Level, Upper Level)
  - two bridge types (standard, essential)
  - three service life categories (ASL1,-2,-3)
  - two performance levels (life safety, operational)

- Three-stage process for each earthquake level:
  - screening,
  - evaluation, and
  - retrofit
Summary continued

- *Seismic Retrofit Categories, SRC*, are used to recommend minimum levels of screening, evaluation, and retrofitting.
- SRCs are equivalent to *Seismic Performance Categories (SPC)* used in new design.
- SRCs are based on hazard level and desired performance level.

Summary continued

- Three screening methods
- Six evaluation methods
- Retrofit phase divided into three steps
  - Decide *strategy*
  - Select *approach* (7)
  - Design and install component retrofit *measures* (25)
Summary continued

- **Step 1.** For Lower Level earthquake:
  screen, evaluate, retrofit (controlled by service loads such as wind and braking...)

- **Step 2.** For Upper Level earthquake:
  - Calculate seismic retrofit category
  - Screen and prioritize

For bridges that do not pass screen:
  - Conduct detailed analysis for demand and evaluate capacity
  - Decide retrofit strategy, select approach, and design & install retrofit measures

Thank you!