FHWA Seismic Retrofitting Seminar

Indianapolis, IN

October 19-20, 2010
Agenda

Seminar Overview
Lesson 1 - Introduction to Seismic Retrofitting Manual
  – Philosophy
  – Methods for Screening
  – Evaluation Methods
Lesson 2 - Seismic Ground Motion Hazards and Geotechnical Hazards
  – Develop Response Spectrum
  – Discuss Geotechnical Hazards including Liquefaction
Lesson 3 - Retrofitting Methods for Superstructures
Lesson 4 - Retrofitting Methods for Substructures
Lesson 5 - Retrofitting Methods for Abutments & Footings
Questions and Answers Session and Final Exam
Instructors

• Tom Saad, PE, Structural Engineer, FHWA Resource Center

• Justice Maswoswe, PE, Geotechnical Engineer, FHWA Resource Center

• Derrell Manceaux, PE, Structural Engineer, FHWA Resource Center
Seismic retrofitting manuals for highway bridges

- 1983: Seismic Retrofitting Guidelines for Highway Bridges (FHWA Report 83/007)
- 2006: Seismic Retrofitting Manual for Highway Structures (FHWA Report …)
  - Part 1: Bridges
  - Part 2: Tunnels, walls, slopes, culverts..

PUBLICATION NO. FHWA-HRT-05-067

AUGUST 2004
FHWA Manual and AASHTO Specifications
Terminology and Philosophy

- FHWA Seismic Retrofit Manual
  - Dual level ground motions (100 and 1000 yr. event)
  - Seismic Retrofit Category A to D (SHL and SRC)

- AASHTO LRFD Seismic Design Provision (2008)
  - 1000 yr. design event
  - Seismic Zones 1-4

- AASHTO Seismic Design Guide Specification
  - 1000 yr. design event
  - Seismic Design Category A to D

- Standard Specifications
  - 500 yr. event
  - SPC A-D
State Earthquake Activity Ranking

[Map showing earthquake activity ranking across the United States with different states color-coded to indicate the number of events in 30 years. Legend: At least 1 event in 30 years, 0 events in 30 years.]

U.S. Department of Transportation
Federal Highway Administration
Resource Center
Common EQ Failure Mechanisms

- Unseating (most common)
- Column Shear
- Column Confinement
- Reinforcing Embedment and Laps
- Inadequate Foundation Capacity
Unseating

Large displacements encountered during EQ can lead to superstructure unseating.
Unseating
Unseating
Unseating
Column Shear

Large shear forces encountered during EQ can lead to column shear failure.
Column Shear
Loss of Confinement

Large compressive stresses encountered during EQ can lead to concrete crushing and eventual loss of confinement.
Loss of Confinement

Is this a failure?
Inadequate Reinforcing Embedments & Laps

Large forces encountered during EQ can lead to pull out of reinforcing.
Inadequate foundation capacity

- Pile Overload
- Concrete Shear Failure
- Flexural Yielding of Reinforcing
- Pile Pullout
- Anchorage Failure
- Pile Flexural and/or Shear Failure
Inadequate foundation capacity

Collapse due to liquefaction
Learning Outcomes

• Explain the philosophy for seismic retrofitting structures in accordance with the FHWA manual
• Develop a design response spectrum to determine the demand on the structure
• Understand when liquefaction may be a consideration and discuss mitigation measures
• Explain strategies for increasing capacity of existing structures
• Explain strategies for decreasing demand on existing structures
• Establish State-wide policy and procedure for retrofitting structures
FHWA/NHI Bridge Design and Analysis Courses (www.nhi.fhwa.dot.gov)

- **NHI Course 130081**: LRFD for Bridge Superstructures
- **NHI Course 130082**: LRFD for Bridge Substructures and ERS
- **NHI Course 130092**: LRFR for Highway Bridges
- **NHI Course 130093**: LRFD Seismic Analysis and Design of Bridges
- **NHI Course 130094**: LRFD Seismic Analysis and Design of Tunnels, Walls and other Geotechnical Features
- **NHI Course 130095**: LRFD: Design and Analysis of Skewed and Horizontally Curved Steel Bridges
Audience Expectations
Lesson 1 – Introduction to FHWA Seismic Retrofitting Manual
Is Bridge Exempt?

- Yes
  - Pass
    - Screen / prioritize
  - Fail
    - Evaluate
      - Pass
        - Screen / prioritize
      - Fail
        - Review

- No
  - Pass
    - Screen / prioritize
  - Fail
    - Retrofit
      - Review
Exempt bridges include those that are:

- Near end of service life ($\leq$ 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
Performance-based retrofit

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

<table>
<thead>
<tr>
<th>Performance</th>
<th>Earthquake</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Small</td>
</tr>
<tr>
<td>No interruption</td>
<td>√</td>
</tr>
<tr>
<td>Limited access</td>
<td></td>
</tr>
<tr>
<td>Closed for repairs</td>
<td></td>
</tr>
</tbody>
</table>
Seismic Retrofit Philosophy

Small to Moderate Earthquakes:
- resisted in the elastic range
- no significant structural damage

Large Earthquakes:
- avoid collapse
- damage rapidly detected & accessible for inspection and repair
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-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 (ASL 1,-2,-3)
- two performance levels (life safety, operational)
Seismic retrofit categories

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

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

SRCs are similar to Seismic Design Categories (SDC) 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**
## 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>
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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
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

<table>
<thead>
<tr>
<th>EARTHQUAKE</th>
<th>BRI DGE I MPORTANCE and SERVICE L I FE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Standard</td>
</tr>
<tr>
<td></td>
<td>ASL1</td>
</tr>
<tr>
<td>Lower Level</td>
<td>PL0</td>
</tr>
</tbody>
</table>

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Federal Highway Administration
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.
Performance levels for bridge retrofitting

<table>
<thead>
<tr>
<th>EARTHQUAKE</th>
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<tr>
<td></td>
<td>ASL1 ASL2 ASL3</td>
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</tr>
<tr>
<td>Lower Level</td>
<td>PL0 PL3 PL3</td>
<td>PL0 PL3 PL3</td>
</tr>
<tr>
<td>Upper Level</td>
<td>PL0 PL1 PL1</td>
<td>PL0 PL1 PL2</td>
</tr>
</tbody>
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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

U.S. Geological Survey
National Seismic Hazard Mapping Project

ion map of the 48 conterminous states for the 0.2 sec horizontal spectral response acceler
# Seismic hazard levels: I - IV

<table>
<thead>
<tr>
<th>HAZARD LEVEL</th>
<th>Using $S_{DI} = F_v S_I$</th>
<th>Using $S_{DS} = F_a S_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$S_{DI} \leq 0.15$</td>
<td>$S_{DS} \leq 0.15$</td>
</tr>
<tr>
<td>II</td>
<td>$0.15 &lt; S_{DI} \leq 0.25$</td>
<td>$0.15 &lt; S_{DS} \leq 0.35$</td>
</tr>
<tr>
<td>III</td>
<td>$0.25 &lt; S_{DI} \leq 0.40$</td>
<td>$0.35 &lt; S_{DS} \leq 0.60$</td>
</tr>
<tr>
<td>IV</td>
<td>$0.40 &lt; S_{DI}$</td>
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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 (SRC)

<table>
<thead>
<tr>
<th>HAZARD LEVEL</th>
<th>PERFORMANCE LEVEL</th>
<th>Upper Level EQ</th>
<th>Lower Level EQ</th>
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<tbody>
<tr>
<td></td>
<td>PL0: No min.</td>
<td>PL1: Life-safety</td>
<td>PL2: Operational</td>
</tr>
<tr>
<td>I</td>
<td>A</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
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<td>A</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>III</td>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>IV</td>
<td>A</td>
<td>C</td>
<td>D</td>
</tr>
</tbody>
</table>
# Minimum requirements

<table>
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<tr>
<th>ACTION</th>
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<tr>
<td>Screening/Retrofitting</td>
<td>NR</td>
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U.S. Department of Transportation
Federal Highway Administration

RESOURCE CENTER
Example:

Data:

Essential bridge
30-year service life remaining
Bridge City
Dense soils ($v_s = 1000$ ft/sec)

Find:

Seismic Retrofit Category, upper level earthquake.
### Example:

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**Step 1:** ASL2; site class C
### Step 2: Essential bridge; therefore Performance criteria (UL) = PL1

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<td>PL2</td>
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**BRIDGE IMPORTANCE**

**and SERVICE LIFE**
**Step 3:**

\[ S_1 = 0.39g \] and \[ S_S = 1.11g \]

- For site class C:
  \[ F_v = 1.4 \] and \[ F_a = 1.0 \]

  \[ F_v \cdot S_1 = 0.55g \] and \[ F_a \cdot S_S = 1.11g \]

  and \[ SHL = IV \]

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**Step 4:** For PL1, SHL = IV, and Seismic retrofit category is SRC = “C”

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### Step 5: Minimum Requirements

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Screening & Prioritization

Screen / prioritize

Evaluate

Retrofit
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 
  \[ F = F_a S_s W = S_{DS} W \]
- If \( F < \) both \( F_{\text{wind}} \) and \( F_{\text{braking}} \), bridge passes
- If \( F > \) 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 (cont’d)

Detailed evaluation - Step 1

- Calculate transverse and longitudinal periods of bridge
- Calculate $S_{aT}$ and $S_{aL}$
- Calculate $F_T = S_{aT} W$ and $F_L = S_{aL} W$
- If $F_T < F_{wind}$ and $F_L < F_{braking}$ bridge passes, otherwise go to Step 2
Process for Lower Level earthquake (cont’d)

● 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 (cont’d)

**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.
Process for Upper Level EQ
Process for Upper Level earthquake

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

Three methods:

- **Indices Method (FHWA 1995)**
  - Indices used for vulnerable components and hazards and combined for single rating.

- **Expected Damage Method (new)**
  - Compares severity of damage including economic loss.

- **Seismic Risk Assessment Method (new)**
  - Uses network models and fragility functions rank is based on direct and indirect losses, uses REDARS software.
Evaluation of Performance

Screen / prioritize
Evaluate
Retrofit
Methods of evaluation

In general, all evaluation methods involve:

- 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
Methods of evaluation (cont’d)

Three categories, six methods:

I. No demand analysis

1. Method A (capacity checks made for seats and connections- 10% to 25% vertical reaction)
2. Method B (capacity checks made for seats connections, columns, and footings- 25% vertical reaction)

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 (cont’d)

III. Structure C/D evaluation

4. Method D1 (*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)
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:
- 100-40% Rule
Member strength capacities

- Flexural and shear strength of reinforced concrete *columns and beams*
  - Design vs. Actual flexural strength
  - Design vs. Actual shear strength
  - Flexural *overstrength*
  - Flexural strength of columns with lap-splices in plastic hinge zones
Member deformation capacities – Chapter 7

- 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 (cont’d)

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 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 (cont’d)

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
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 (cont’d)

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

- SRCs are equivalent to **Seismic Design Categories (SDC)** used in new design

- SRCs are based on hazard level and desired performance level
Summary (cont’d)

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

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
What questions do you have?