Quantifying the Vulnerability of Vermont Bridges to Seismic Loading

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Acknowledgement of Support

- VTrans Research Grants Cooperative Agreement Project
  - UVM Transportation Research Center
• Motivation

• Analysis

• Findings
Mineral, VA Earthquake

Magnitude 5.8 Earthquake – August 2011

Images: USGS
Example Case History

Virginia Department of Transportation Response to the 5.8 Magnitude Earthquake on August 23, 2011 Status of Seismic Event Inspection

Claude S. Napier, Jr.
Assistant State Structure and Bridge Engineer
Session 786: Seismic Design and Analysis of Bridges in Low to Moderate Seismic Regions
January 25, 2012
Magnitude 5.1 Earthquake – April 2002 (near Plattsburg, NY)
Tropical Storm Irene, August 2011

Photo credit: Lars Gange & Mansfield Heliflight
Seismic Hazard – PGA - 7% in 75 year probability of exceedance, ~1,000 year return period

How many bridges in low to moderate seismic regions?
## AASHTO Seismic Loading Requirements through 1981

<table>
<thead>
<tr>
<th>Year</th>
<th>Reference</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1931</td>
<td>AASHTO(^1) 1st Ed.</td>
<td>None (Earthquakes not mentioned)</td>
</tr>
<tr>
<td>1953</td>
<td>AASHTO(^1) 6th Ed.</td>
<td>Earthquakes mentioned but no quantifications given</td>
</tr>
<tr>
<td>1961</td>
<td>AASHTO(^1) 8th Ed.</td>
<td>EQ = ((C)(D)) provides lateral force at c.g. of structure; where (C = 0.02/0.04/0.06) depending on supporting soil (i.e., spread footing bearing pressure or if piles are used), D = dead load (Live load may be neglected)</td>
</tr>
<tr>
<td>1973</td>
<td>AASHTO(^1) 11th Ed.</td>
<td>Same as 1961</td>
</tr>
<tr>
<td>1977</td>
<td>AASHTO(^1) 12th Ed.</td>
<td>EQ = ((C)(F)(W)); where (C = (A)(R)(S)/(Z)), F = framing factor (either 1.0 or 0.8), W = total dead weight of structure (lb.), A = max acceleration of bedrock (using risk map), R = normalized rock response, S = soil amplification spectral ratio, Z = reduction for ductility and risk assessment; Design of Restraining Features: EQ = ((0.25) * (\text{contributing DL})) - column shears due to EQ</td>
</tr>
<tr>
<td>1981</td>
<td>FHWA(^2)</td>
<td>Numerous classifications and factors.</td>
</tr>
</tbody>
</table>

1. *Standard Specifications for Highway Bridges*
2. Federal Highway Administration, *Seismic Design Guidelines for Highway Bridges*
2013 Survey of DOT Seismic Vulnerability Screening Practices

<table>
<thead>
<tr>
<th>Region</th>
<th>Number of States in Region</th>
<th>States Responding to Online Survey</th>
<th>Responding States Which Use a Screening System</th>
<th>Screening System Being Used and Year in Which Applied</th>
<th>States in Region Performing Full Seismic Vulnerability Ratings and/or Screening*</th>
</tr>
</thead>
<tbody>
<tr>
<td>West</td>
<td>13</td>
<td>4 (31%)</td>
<td>2</td>
<td>FHWA 1983 – Applied 1991</td>
<td>7 (54%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FHWA 1995 – Applied 1995</td>
<td></td>
</tr>
<tr>
<td>Central</td>
<td>20</td>
<td>9 (45%)</td>
<td>1</td>
<td>FHWA 2006 – Applied to major rehab projects, case-by-case</td>
<td>4 (20%)</td>
</tr>
<tr>
<td>East</td>
<td>17</td>
<td>9 (52%)</td>
<td>2</td>
<td>Modified FHWA 1995 Partial use since 1995</td>
<td>4 (24%)</td>
</tr>
</tbody>
</table>

* Based on data obtained in addition to survey responses.
Motivation Summary

✓ Need for quantifying risk (Risk = Probability x Consequences)

✓ Tangible benefits = asset management, post-EQ response

✓ Limited DOT resources available for “extra” work

✓ Limited “off-the-shelf” tools and precedents
Analysis
Current Screening Tools

System-wide rating algorithm – NYSDoT

Screening Methods (FHWA 2006 Seismic Retrofit)

Fragility Curves
Systems-Level Rating Algorithm

Ratings based on vulnerable characteristics

NYSDoT Example

Figure 1-1. Overview of the retrofitting process for highway bridges.
Seismic Retrofitting Manual for Highway Structures: Part 1 – Bridges

PUBLICATION NO. FHWA/HRT-06/032

JANUARY 2006

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296
Fragility Curve Method

Fragility curve for concrete piers at steel girder bridge (Pan et al. 2010)
Multiple Span Bridge Count for Entire U.S.

Bridge Type

Multiple Span Bridge Count for Entire U.S.

- Multi-girder: 55.0%
- Slab: 26.3%
- Tee Beam: 8.7%
- Multiple Box beams - single: 6.8%
- Girder and Floor Beam: 3.5%
- Trusses: 2.1%
- Single Span: 1.4%
- Frame: 1.2%
- Arches: 0.8%
- Other: 0.4%
- Movable: 0.3%
- Segmental Box: 0.3%
- Suspension: 0.1%
- Orthotropic: 0.03%
- Stayed Girders: 0.03%
- Mixed type approach spans: 0.02%
- Tunnels: 0.01%
- Others: 0.002%
## Bridge Pier Heights, Span Lengths, and Natural Periods

<table>
<thead>
<tr>
<th>Span Length, Feet</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.14</td>
<td>0.21</td>
<td>0.29</td>
<td>0.38</td>
<td>0.48</td>
</tr>
<tr>
<td>40</td>
<td>0.15</td>
<td>0.23</td>
<td>0.32</td>
<td>0.42</td>
<td>0.52</td>
</tr>
<tr>
<td>50</td>
<td>0.17</td>
<td>0.25</td>
<td>0.35</td>
<td>0.45</td>
<td>0.56</td>
</tr>
<tr>
<td><strong>60 (52N)</strong></td>
<td>0.18</td>
<td><strong>0.27</strong></td>
<td><strong>0.37</strong></td>
<td><strong>0.48</strong></td>
<td><strong>0.51</strong></td>
</tr>
<tr>
<td>70</td>
<td>0.19</td>
<td><strong>0.28</strong></td>
<td><strong>0.39</strong></td>
<td><strong>0.51</strong></td>
<td>0.64</td>
</tr>
<tr>
<td>80</td>
<td>0.20</td>
<td><strong>0.30</strong></td>
<td><strong>0.41</strong></td>
<td>0.54</td>
<td>0.68</td>
</tr>
<tr>
<td>90</td>
<td>0.21</td>
<td><strong>0.32</strong></td>
<td><strong>0.43</strong></td>
<td>0.57</td>
<td>0.71</td>
</tr>
<tr>
<td>100</td>
<td>0.22</td>
<td><strong>0.33</strong></td>
<td><strong>0.45</strong></td>
<td>0.59</td>
<td>0.74</td>
</tr>
<tr>
<td>110</td>
<td>0.23</td>
<td><strong>0.34</strong></td>
<td><strong>0.47</strong></td>
<td>0.62</td>
<td>0.77</td>
</tr>
<tr>
<td><strong>120 (91)</strong></td>
<td>0.24</td>
<td><strong>0.35</strong></td>
<td><strong>0.36</strong></td>
<td><strong>0.48</strong></td>
<td><strong>0.49</strong></td>
</tr>
<tr>
<td>130</td>
<td>0.24</td>
<td>0.37</td>
<td>0.51</td>
<td>0.66</td>
<td>0.83</td>
</tr>
<tr>
<td>140</td>
<td>0.25</td>
<td>0.38</td>
<td>0.53</td>
<td>0.68</td>
<td>0.86</td>
</tr>
<tr>
<td>150</td>
<td>0.26</td>
<td>0.39</td>
<td>0.54</td>
<td>0.71</td>
<td>0.88</td>
</tr>
</tbody>
</table>

*Tn values computed for transverse stiffness of concrete bent frame with no contribution from adjacent span sections accounted for.*
Individual Bridge Analyses

Non-linear finite element time-history analysis using SAP 2000 structural analysis program
Bridge non-linear seismic analysis

Structure models with non-linear material properties

Location and seismic site class based target spectra

Ground Motion Time-History Records Matched to Target Spectra

Force and Displacement Output
Time-History and Bridge Type/Condition Analysis Combinations

Search and Obtain 70 Unique Ground Motion Time-History Records from PEER NGA West 2 Database

--- Site Class E - North Hero
--- Site Class E - Brattleboro
--- Site Class B - North Hero
--- Site Class B - Brattleboro

North Hero E 100 Analyses
Brattleboro E 104 Analyses
North Hero B 88 Analyses
Brattleboro B 88 Analyses

380 Total Analyses
Accounting for Deterioration

Spalled Concrete Cover

Bridge 91
Concrete Beams

Bridge 52N
Concrete Columns
Bridge 52N – Two 30-foot-high square columns at 3-feet-wide with 60 foot span
Bridge 52N – Two 30-foot-high square columns at 3-feet-wide with 60 foot span
Bridge 91 – Three 20 foot-high round columns at 3-feet diameter with 115 foot span
Bridge 91 – Three 20 foot-high round columns at 3-feet diameter with 115 foot span
Findings
Pushover Capacity for Pristine and Spalled Conditions

The graph shows the pushover capacity for Br 91 and Br 52 in both pristine and spalled conditions. The x-axis represents displacement in feet, while the y-axis represents pushover force in kips. The graph compares the performance of the bridges under different conditions.
Maximum Displacement vs. Maximum Base Shear

Maximum Displacement, feet

Maximum Base Shear (kips)

4 collapse cases - Bridge 91 Pristine

- Bridge 52 N - Spalled-Max Displacement (ft)
- Bridge 52 N - Pristine-Max Displacement (ft)
- Bridge 91 - Spalled-Max Displacement (ft)
- Bridge 91 - Pristine-Max Displacement (ft)
- Bridge 52 N - Spalled-Pushover
- Bridge 52 N - Pristine-Pushover
- Bridge 91 - Spalled-Pushover
- Bridge 91 - Pristine-Pushover
Binned Damage Index vs. Site Class/Location
Seismic Hazard

\[ DI_{\text{total}} = DI \text{ (displacement)} + DI \text{ (energy)} \]

Percent of total of hazard category motions

Site Class B - Brattleboro
Site Class B - North Hero
Site Class E - Brattleboro
Site Class E - North Hero
Binned Damage Index vs. Bridge Type and Condition

\[ DI_{\text{total}} = DI \text{ (displacement)} + DI \text{ (energy)} \]
<table>
<thead>
<tr>
<th>Item</th>
<th>Characteristic</th>
<th>NBI Item Number</th>
<th>Item Name</th>
<th>Item Description</th>
<th>NBI Item Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>Span vulnerability</td>
<td>43A</td>
<td>Kind of Material and/or Design</td>
<td>Is this a continuous span bridge?</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Simple</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N.A.</td>
</tr>
<tr>
<td>V2</td>
<td>Bearing type(s)</td>
<td>224</td>
<td>Type of Expansion Bearing Device</td>
<td>Are the bearings readily subject to toppling?</td>
<td>All others</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Note 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N.A.</td>
</tr>
<tr>
<td>V2</td>
<td>Span Skew</td>
<td>34</td>
<td>Skew</td>
<td>Does the bridge skew create more chance of span unseating?</td>
<td>&lt;20 degrees</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt;20 degrees</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N.A.</td>
</tr>
<tr>
<td>V2</td>
<td>Span Type</td>
<td>43B</td>
<td>Type of Design and/or Construction</td>
<td>Does this bridge have girder and floor beam spans?</td>
<td>Not this type</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>This type</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N.A.</td>
</tr>
<tr>
<td>V3</td>
<td>Structural Condition Rating</td>
<td>239</td>
<td>Deficiency Status of Structure</td>
<td>Is this structure cataloged as structurally deficient?</td>
<td>Not SD</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SD</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N.A.</td>
</tr>
<tr>
<td>V3</td>
<td>Fracture Criticality of Structure</td>
<td>801</td>
<td>FCM Detail</td>
<td>Are fracture critical members present?</td>
<td>None present</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Present</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N.A.</td>
</tr>
<tr>
<td>Liquefaction</td>
<td>Foundation Stability</td>
<td>225 A-G</td>
<td>Type of Foundation at (Abutment, Pier)</td>
<td>Are foundations likely directly on rock?</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>E</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>E</td>
</tr>
<tr>
<td>Column Vulnerability</td>
<td>Column Ductility</td>
<td>N.A.</td>
<td>Seismic Retrofit Category per FHWA 2006</td>
<td>Is this Seismic Retrofit Category A or B?</td>
<td>A or B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C or D</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N.A.</td>
</tr>
<tr>
<td>Abutment</td>
<td>Abutment damage potential</td>
<td>N.A.</td>
<td>Seismic Retrofit Category per FHWA 2006</td>
<td>Is this above or below Seismic Retrofit Category D?</td>
<td>&lt;D</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>D</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N.A.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>34</td>
<td>Skew</td>
<td>Is the span skew greater than 40 degrees?</td>
<td>&lt;40 degrees</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt;40 degrees</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N.A.</td>
</tr>
</tbody>
</table>
Histogram
Vulnerability Ratings for Vermont Multiple Span Bridges

R-value Bins (in 10's inclusive)

Count

Low

High

All Multiple Span Bridges
Only Multi-Girder Multiple Span Bridges
General Initial Observations

• Multiple beam/girder bridges are the most common of multiple span bridges

• Seismic screening in L-M seismic regions is uncommon

• Seismic screening provides benefits for emergency response after earthquakes
Overall Findings and Applicability

- Limited capacity loss with concrete cover spalling
- Limited (but not zero) seismic damage potential for typical MS-MB/G bridges
- Screening algorithm using NBI data is useful for asset management and can be enhanced during inspections
Thank you for your attention
Binned Maximum Base Shear vs. Site Class/Location Seismic Hazard
Recommendations

- Review VeRSSA findings
- Investigate additions to NBI-VT database
- Broadcast findings within VTrans
Single Span Bridges- Histogram of VeRSSA R-ratings
Histogram of Maximum Span Lengths in NEUS

<table>
<thead>
<tr>
<th>Maximum Span Length Bins, Meters</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>4%</td>
</tr>
<tr>
<td>20</td>
<td>27%</td>
</tr>
<tr>
<td>30</td>
<td>35%</td>
</tr>
<tr>
<td>40</td>
<td>20%</td>
</tr>
<tr>
<td>50</td>
<td>9%</td>
</tr>
<tr>
<td>60</td>
<td>3%</td>
</tr>
<tr>
<td>70</td>
<td>1%</td>
</tr>
<tr>
<td>80</td>
<td>1%</td>
</tr>
</tbody>
</table>

86% of the bridges fall within the maximum span length range of 20 meters to 30 meters.
Historically Vulnerable Features

- Rocker Bearing
- Roller Bearing
- Pin and Link Bearing

Bearing Types
- None: 382
- Favorable: 12
- Unfavorable: 53
- Timber Block: 882
- Thin Fabric Type: 896
- Unknown: 586
Historically Vulnerable Features

Simple Spans

Simple Spans with Skewed Substructures

2 Girder Spans

Span Type

- Simple Span: 391
- Continuous: 2413
- Timber: 7

The University of Vermont
How many bridges in low to moderate seismic regions?
CEUS Declustered Earthquakes 1997-2006

Mblg > 3
Status of Seismic Event Inspection
Route 1 over Hazel Run

Column Cracking

Horizontal cracks in Column 4 at Pier 1

Horizontal crack in Column 3 at Pier 1 (close-up)
Status of Seismic Event Inspection
Route 683 (Parrish Road) over I-64

Spalling
Status of Seismic Event Inspection

Route 683 – Parrish Road over I-64

Concrete Spalling

Shearing of Anchor Bolt
Quantifying the Seismic Risk for Bridges in Low to Moderate Seismicity Regions

Why?

\[ \omega_n = \sqrt{\frac{k}{m}} \]

\[ T_n = \frac{2\pi}{\omega_n} \]

Plot of Spectral Acceleration (Sa) vs. Period (Tn)

Design Response Spectra per AASHTO LRFD 7th Ed. Section 3.10.4.1 (5% damping)

Minimum horizontal connection restraint required in the absence of seismic analysis

Seismic Site Class E
Quantifying the **Seismic Risk** for Bridges in Low to Moderate Seismicity Regions

Bridge seismic analysis and/or design methods:

**Elastic analysis:**
(non-exempt)

\[ \rho_e = S_a \times \frac{W}{L} \]

Equivalent static seismic loading, in force/unit length of bridge

**Non-linear time history analysis:**

Structure model with non-linear material properties
Multispan Bridges by Type - Entire U.S.
Multispan Bridges by Type - Northeast U.S.

- Multi-girder: 66.7%
- Slab: 4.2%
- Tee Beam: 3.5%
- Box beams - multiple: 6.5%
- Box beams - single: 0.0%
- Channel beam: 2.4%
- Girder and Floor Beam: 3.4%
- Box beams - multiple: 3.6%
- Trusses: 3.1%
- All others: 0.0%
- Arches: 6.5%
Quantifying the **Seismic Risk** for Bridges in Low to Moderate Seismicity Regions

How to analyze 470,000 bridges for seismic vulnerability?

System-Level Rating Systems:

![Diagram of the retrofitting process for highway bridges](image-url)

*Figure 1-1. Overview of the retrofitting process for highway bridges.*
1000-year return period PGA overlay on 2800 State Long Bridges in VTrans NBI.
Earthquakes in NE United States and Canada 1990 - 2010

Probability of Exceeding Damage Index Value

- Bridge 52N Pristine: 14.7% 7.4% 7.4% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0%
- Bridge 52N Spalled: 17.9% 8.4% 6.3% 2.1% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0%
- Bridge 91 Pristine: 44.2% 7.4% 6.3% 5.3% 5.3% 4.2% 4.2% 4.2% 4.2% 3.2% 0.0%
- Bridge 91 Spalled: 48.4% 10.5% 7.4% 2.1% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0%

Damage Index, DI (binned by 0.1 increments)
Quantifying the Seismic Risk for Bridges in Low to Moderate Seismicity Regions

How vulnerable are they to earthquakes?

Earthquake Risk and U.S. Highway Infrastructure: Frequently Asked Questions

June 5, 2013
1. How vulnerable is the U.S. highway system to earthquakes?

2. How vulnerable are highway bridges to earthquakes?

3. What are the options to improving...seismic resilience...?

4. How much would it cost to retrofit vulnerable ...infrastructure?

1. Don’t know. No national database exists on status of seismic design and retrofit.

2. Difficult to quantify. Some are designed for seismic hazards. Many bridges predate seismic design standards. Seismic hazard knowledge is always evolving.

3. That decision is left up to state governments…regarding how to spend funds....

4. Don’t know since no national database exists.....
Energy Relationships in Hinge Rotations

Hysteretic Energy, \( HE = \oint M(\Theta) \, d\Theta \)

Where \( M(\Theta) \) is the hinge moment vs. hinge rotation, \( \Theta \)

Pushover Energy Capacity

\( PE = \oint F(\delta) \, d\delta \)

\( PE = \sum \oint M(\Theta) \, d\Theta \)
Schematic illustration of Damage Index (DI) distribution function relationships with deterioration

\[ \text{DI}_{A10, A20, A30} + \text{DI}_{S10, S20, S30} = \text{DI}_{T10, T20, T30} \]

\( f_d \) is a critical level of damage such as near collapse, or similar high risk conditions.

\( \text{DI}_{cr} \) is a critical level of damage such as near collapse, or similar high risk conditions.
SAP 2000 3-D model of Steel Girder Bridge with Concrete Piers
Vermont Seismic Screening Algorithm - VeRSSA

Vermont NBI database in MS Excel
Spalling in UVM model
Spalling Examples

Spalling in UVM model

More spalling than UVM model
Binned Maximum Base Shear vs. Site Class/Location Seismic Hazard

Percent of total of hazard category motions

- Site Class B - Brattleboro
- Site Class B - North Hero
- Site Class E - Brattleboro
- Site Class E - North Hero
Binned Maximum Base Shear vs. Bridge Type and Condition

- Bridge 52N Pristine
- Bridge 52N Spalled
- Bridge 91 Pristine
- Bridge 91 Spalled
Time-History and Bridge Type/Condition Analysis Combinations

- **Seismic Site Class B**
  - 22 ground motions
  - 4 bridge cases
  - 88 Analyses

- **Seismic Site Class E**
  - 26 ground motions
  - 4 bridge cases
  - 104 Analyses

- **Seismic Site Class B**
  - 22 ground motions
  - 4 bridge cases
  - 88 Analyses

- **Seismic Site Class E**
  - 25 ground motions
  - 4 bridge cases
  - 100 Analyses

---

380 Total Analyses