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Post-Earthquake Bridge Inspection Guidelines for New York State

by
Jerome S. O'Connor and Sreenivas Alampalli




Technical Report MCEER-12-0003

June 8, 2012

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1 Manager, Bridge Engineering Program, Department of Civil, Structural and Environmental Engineering, University at Buffalo, State University of New York
2 Director, Structures Evaluation Services Bureau, New York State Department of Transportation

MCEER
University at Buffalo, State University of New York
133A Ketter Hall, Buffalo, NY 14260
Phone: (716) 645-3391; Fax (716) 645-3399
E-mail: *mceer@buffalo.edu*; WWW Site: *http://mceer.buffalo.edu*

Preface

MCEER is a national center of excellence dedicated to the discovery and development of new knowledge, tools and technologies that equip communities to become more disaster resilient in the face of earthquakes and other extreme events. MCEER accomplishes this through a system of multidisciplinary, multi-hazard research, in tandem with complimentary education and outreach initiatives.

Headquartered at the University at Buffalo, The State University of New York, MCEER was originally established by the National Science Foundation in 1986, as the first National Center for Earthquake Engineering Research (NCEER). In 1998, it became known as the Multidisciplinary Center for Earthquake Engineering Research (MCEER), from which the current name, MCEER, evolved.

Comprising a consortium of researchers and industry partners from numerous disciplines and institutions throughout the United States, MCEER's mission has expanded from its original focus on earthquake engineering to one which addresses the technical and socio-economic impacts of a variety of hazards, both natural and man-made, on critical infrastructure, facilities, and society.

The Center derives support from several Federal agencies, including the National Science Foundation, Federal Highway Administration, National Institute of Standards and Technology, Department of Homeland Security/Federal Emergency Management Agency, and the State of New York, other state governments, academic institutions, foreign governments and private industry.

This report is a product of an MCEER research project that was funded by New York State Department of Transportation, for its Office of Structures. The project, entitled "Development of Post-Earthquake Bridge Inspection Guidelines," was Research Project C-06-14. The study was accomplished at the University at Buffalo, State University of New York under Cornell Transportation Infrastructure Research Consortium (TIRC) Subcontract 53740-8411. While some other states have produced similar guidance for their bridge inspectors, the project was New York's first such effort. This document is the first published version of these guidelines; it draws heavily from the final report produced for the research project.

This publication adds to a collection of knowledge that is available for NYSDOT to use in the delivery of its Bridge Inspection and Safety Assurance Programs. It is intended to provide enough background to a bridge engineering generalist who may be called upon to conduct bridge inspections after an earthquake. It is meant to help NYSDOT prepare for the scenario of an unlikely, yet potentially destructive earthquake. The procedures developed parallel those that NYSDOT has established for its post-flood inspection program.

This report presents some background on earthquakes and their potential impact on highway bridges. There are recommended procedures that can be relied upon if inspectors are deployed after an earthquake. The guidance is tailored to New York's organizational structure but may also be applicable to other agencies such as local municipalities, bridge authorities and other states. Sample reporting forms are provided, as are post-earthquake repair procedures for bridges.

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EXECUTIVE SUMMARY

This report presents a course of action that can be used by the New York State Department of Transportation (NYSDOT) to respond to an earthquake that may have damaged bridges so that the highway system can be assessed for safety and functionality in an orderly and expeditious manner. It was developed for bridges that are owned and maintained by NYS, but the methodology may also be applicable to other bridges.

If a significant earthquake occurs, residency staff will respond immediately by driving all state highways in the affected area, starting with pre-defined priority routes. They will report their findings to the Resident Engineer (RE) and erect barricades to close badly damaged bridges.

The second phase of the Department's response will consist of detailed bridge inspections. The Regional Structures Engineer (RSE) will mobilize and deploy bridge inspectors according to preliminary damage assessments and data that are available about the proximity, importance and seismic vulnerability of each structure. Several means for prioritizing inspections are offered, including a computer program that uses GPS coordinates that are in the bridge inventory to compute the distance from the epicenter to each bridge.

Action resulting from the damage assessments can be closure, (or reopening of a bridge that was closed during the preliminary assessment as a precaution), restricting traffic (e.g., to allow just emergency traffic), flagging, repair or retrofit, or further investigation.

The proposed Earthquake Response Plan consists of four response levels, delineated by ranges of earthquake magnitude. This is intended to direct an appropriate level of resources toward the response. If the earthquake has a magnitude (M) less than a threshold value of 3.5, a response is not mandatory; the RSE will use his/her prerogative to inspect bridges on a case-by-case basis. For stronger earthquakes, damage assessments are required within a certain radius of the epicenter. For the highest response level, the Department's Incident Command System (ICS) is activated to manage the response and *all* structures within a specified radius are inspected.

Tools needed for implementation of the plan are provided and/or described in this report: a process flowchart, clear lines of responsibility, prioritization methods, reporting forms, lists of necessary resources, sample photos of damage that might occur, strategies for repairing damaged bridges, and training exercises for staff.

ACKNOWLEDGMENTS

This document stems from a research project conducted for New York State Department of Transportation (SPR Project # C-06-14) entitled *Development of Post-Earthquake Bridge Inspection Guidelines* conducted through Cornell Transportation Infrastructure Research Consortium (TIRC) Subcontract 53740-8411. Dr. Sreenivas Alampalli was Project Manager and Mr. Jerome O'Connor was Principal Investigator.

Riyad Aboutaha, Ph. D., Syracuse University, was Project Co-PI and is a contributing author to this report. He was primarily responsible for the sections on repair and retrofit procedures and wrote Section 5.4 and Appendix F.

The authors wish to thank Technical Working Group (TWG) members who were James Flynn, François Ghanem, Michael Sullivan, Rajesh Taneja, and Erica Westhuis. They all provided valuable input to the research team and their guidance truly enhanced the outcome of the project.

This report benefited from numerous technical advisors and peer reviewers. Technical advisors were: Michel Bruneau Ph.D., P. Eng., University at Buffalo; S. Thevanayagan, Ph.D, University at Buffalo; Ken Fishman, Ph.D., McMahon and Mann, PC; and Preston Halstead, VHB Inc.

Peer reviewers were Michel Bruneau, Ph.D,, P. Eng., University at Buffalo, Lucero Mesa, P.E., South Carolina Department of Transportation; Eric Thorkildsen, Greenman-Pederson, PC; Barton Newton, P.E. and Michael Johnson, P.E., California Department of Transportation; Kevin Thompson, P.E., Arora and Associates, PC; Harry Capers Jr., P.E., Arora and Associates, PC, Phil Yen, Ph.D., Federal Highway Administration; and Paul Liles, P.E., Georgia Department of Transportation.

The peer review resulted in many good suggestions for enhancing the report. Most comments have been addressed in this report. Other suggestions would require a more extensive revision and will be given consideration in a possible future edition.

The authors acknowledge the contributions of other state DOTs who have already developed procedures for the post-earthquake safety evaluation of highway bridges, and shared their photos of past damage. The authors also thank the many managers within NYSDOT and with other DOT's who were gracious enough to share their experience and provide their insight during telephone interviews.

Kerry J. B. O'Connor, EIT, conducted many hours of research and report writing during his internship and contributed significantly to the project. His assistance is appreciated.

Joy James used her outstanding word processing skills to prepare the project reports and Jane Stoyle Welch provided the final edit. The authors thank both for their technical expertise.

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Image Sources

The following abbreviations are used in photo credits associated with figures.

CDOT: Colorado Department of Transportation, (2010)

CPHMR: "Caltrans Engineering Service Center PEQIT Report: The Hector Mine Earthquake of October 16, 1999." Jaro Simek and Ganapathy Murugesh.

INDOT: "Field Guide for the Post Earthquake Safety Evaluation of Bridges and Roads," INDOT 2000.

KTC: "Post Earthquake Investigation Field Manual for the State of Kentucky," Sardo, A.G., Sardo, T.E., Harik, I.E., University of Kentucky, Kentucky Transportation Center. 2006.

MCEER: MCEER, University at Buffalo photo archives

MO: "Post Incident Bridge Inspection Training," Missouri Department of Transportation.

NISEE: National Information Service for Earthquake Engineering, EERC, at University of California, Berkeley

NYC: NYC Consortium for Earthquake Loss Mitigation, 2003

PEQIT: "Post Earthquake Investigation Team (PEQIT) Manual," California Department of Transportation (2007).

USDOT: "Effects of Catastrophic Events on Transportation System Management and Operations: Northridge Earthquake - January 17, 1994," U.S. Department of Transportation Research and Special Programs Administration. http://itsdocs.fhwa.dot.gov/jpodocs/repts_te/13775.html

USGS: www.usgs.gov

LIST OF TABLES

LIST OF ACRONYMS

BIN	Bridge Identification Number
BSA	Bridge Safety Assurance
CR	Average Weighted Condition Rating
EERI	Earthquake Engineering Research Institute
ENS	Earthquake Notification Service
ETO	Emergency Transportation Operations
FEMA	Federal Emergency Management Administration
FHWA	Federal Highway Administration
HAZUS	"Hazards-U.S." (FEMA software)
HMS-II	Highway Maintenance Supervisor II
ICS	Incident Command System
MMI	Modified Mercalli Intensity
M	Earthquake Magnitude (M_w, M_b are sometimes used. See Section 6)
MPT	Maintenance and Protection of Traffic
NBIS	National Bridge Inventory System
NYSDOT	New York State Department of Transportation
PGA	Peak Ground Acceleration
RBME	Regional Bridge Maintenance Engineer
RD	Regional Director
RE	Resident Engineer[1]
REDARS	Risks from Earthquake Damage to Roadway Systems (a software program)
RSE	Regional Structures Engineer
SM&I	Structure Maintenance and Investigations (a division within Caltrans)
SR	Sufficiency Rating
STICC	Statewide Transportation Information Coordination Center
TCLEE	Technical Council on Lifeline and Earthquake Engineering
TL	Bridge Inspection Team Leader (ATL is used for Assistant Team Leader)
TMC	Transportation Management Center
VR-S	Vulnerability Rating –Seismic

[1] To fulfill its operational role, NYSDOT divides its regions into residencies, generally a county-wide area. A lead licensed professional engineer, known as the Resident Engineer, is responsible for this territory.

SECTION 1
INTRODUCTION

Is an earthquake response plan needed? Events in recent years have made us cognizant that unexpected natural disasters can occur at any time. Examples are the hurricanes that hit the US Gulf Coast in 2005 (Katrina and Rita) and the extensive flooding that occurred in the US Midwest in 2008. Both of these hazards caused extensive damage to highway bridges over a wide area, similar to what would occur during an earthquake. Although New York does not experience significant earthquakes very often, there is historical evidence that moderate earthquakes do occur in NY, so it would be prudent to have a plan in place ahead of time. In addition, “large earthquakes are possible, albeit rare, in Eastern North America,” (NYCEM 2003). As recently as June 23, 2010, a moderate M 5.0 earthquake struck Southern Ontario, just across the St. Lawrence River, causing shaking in NYS. USGS has stated that there is a “moderate” likelihood of an earthquake in the NYC metropolitan area. Factors such as location and depth of the earthquake, the population density, and stability of infrastructure all influence how earthquakes will affect nearby communities (USGS.gov). This is a concern because “although NYC is a region with *low seismic hazard* (infrequent damaging earthquakes), it actually has *high seismic risk* because of its tremendous assets, concentration of buildings, and the fragility of its structures, most of which haven’t been seismically designed (NYCEM 2003).

Bridges are often considered the most critical link in the highway network. In the event of a damaging earthquake in NYS, DOT management will be responsible for promptly and efficiently deploying resources to assess damage. While *safety* is the primary objective of any post-earthquake bridge inspection program, the need for continued *mobility* is also important. The highway network is needed to provide emergency services, ensure security, provide access for relief and reconstruction, and to facilitate the revitalization of the economy after a devastating event.

Preparedness is the first step toward the mitigation of losses. The Earthquake Response Plan (ERP) proposed herein provides a framework so that, in the event of an earthquake, DOT managers will be prepared to respond quickly and confidently in their deployment of damage assessment teams in an expeditious yet logical fashion that utilizes resources efficiently while attending to the most critical structures first.

The intent of the project and this document is to provide clear guidance to NYSDOT staff so they are prepared to conduct damage assessments of bridges and recommend appropriate action. In particular, it will help ensure the safety of staff and the traveling public, establish when a call-out is needed, how a response is to be conducted, establish clear lines of responsibility, describe appropriate phases and levels of response, what first responders and bridge inspectors should look for, how to report their findings, what training and resources are needed, how to determine appropriate follow-up action (such as closure, restriction of traffic, issuance of structural flags, recommendations for repairs or retrofits), and where to get additional information.

While this was prepared specifically for NYSDOT, local bridge owners and other transportation authorities may also find the information useful for their emergency response planning.

SECTION 2
EARTHQUAKES

2.1 Fundamental Principles

Planet Earth is not a solid sphere. It consists of molten rock at the center with cooler tectonic plates at the surface. The plates form the earth's crust, upon which our civilization is built. Humans feel an earthquake when these plates move or shift in relation to one another. This can release an abundant amount of energy, causing the earth's crust to first bend, then, when the stress exceeds the strength of the rocks, break free, and settle into a new position. We know this to be an *earthquake*.

The *magnitude* (M) of an earthquake describes the absolute size or strength of the event. It is a measure of the energy released by the earthquake, but is not a measure of damage. Generally, a higher magnitude means greater shaking, shaking for a longer time, and over a larger area. Several scales are currently in use to define an earthquake's magnitude. The Moment Magnitude Scale is one and the well-known Richter Scale is another. Both use a logarithmic scale so that an increase of 1.0 on the scale corresponds to a 10-fold increase in magnitude.

Earthquake *intensity* is a subjective expression that describes the damage caused and how it feels to humans. This depends on the magnitude but also upon other factors such as distance to the epicenter and the type of soil through which the seismic waves pass. See Appendix A.

The location on the Earth's surface directly above the point of rupture is called the *epicenter*. Since the *depth* of the rupture has an impact on the damage expected from an earthquake, this dimension is usually of interest too. The point of initiation of the rupture beneath the surface is called the *hypocenter*. In the United States, the U.S. Geological Survey (USGS) is the government agency responsible for tracking and studying earthquakes. Much information is available at www.usgs.gov/hazards/earthquakes/.

During the process of rupture, vibrations or *seismic waves* are generated and transmitted through bedrock. These waves travel outward from the source of the earthquake (the hypocenter) at varying speeds depending on the type of rock or soil through which they are moving. Dense rock transmits these waves very rapidly whereas soil tends to carry the waves more slowly. Layers of soft soil above bedrock tend to magnify the intensity of an earthquake. The soft material causes more shaking on the surface. To help visualize the behavior, soft clays and mud in an earthquake are often likened to a shaken bowl of Jell-O.

Earthquakes of similar magnitude can also cause quite different levels of damage, depending on where they occur. For example, an earthquake in a developed and highly populated area can be devastating while one in a remote region is barely noticed. The 1995 M6.9 earthquake in the city of Kobe, Japan was much more devastating than the 1994 M6.7 Northridge California earthquake because the strongest shaking was in the most densely populated areas of Kobe, whereas the strongest shaking in the Northridge quake was under the sparsely populated mountainous region north of Los Angeles.

Although the focus of the report is on earthquakes, DOT management and staff should be cognizant of the fact that other hazards may result because of the earth's shaking. Some possibilities are:

- Aftershock: These secondary shock waves are usually smaller than the main quake but can be strong enough to do additional damage to a weakened structure.
- Liquefaction: Loss of support may occur when a bridge is founded on granular soils that are saturated with groundwater.
- Tsunami: Although these destructive waves of water have occurred along the coasts of California, Oregon, Washington and Alaska, a tsunami can strike anywhere along the US coastline.
- Landslides: A natural or fill slope can become unstable and fail, especially if the soil is saturated with water, such as after heavy rainfall or a rapid snowmelt.
- Rockfall: boulders can become loose and crash onto a bridge, causing structural damage. (See Figures 2-1 and 2-2)
- Debris Flow, Mud Flow, Huaico: This is an uncommon occurrence but can develop after heavy rainfall or rapid snowmelt. A flowing river of mud can initiate and travel miles, picking up rocks, boulders, and trees along the way.

Figure 2-1. Damage from Rockfall in Peru. (O'Connor)

An earthquake caused rocks to fall from the mountain that was looming over this truss bridge in Peru, causing impact damage to the bottom chord, a primary structural member. In addition to the obvious deformation, cracked welds were discovered.

Figure 2-2. Rockfall in Colorado. (CDOT)

Although not caused by an earthquake, similar rockfall occurred March 2010 along I-70 in Colorado. Depending on local conditions, minor ground shaking can cause major consequences. www.denverpost.com/ci_14633690

Based on historic records and geological evidence of prehistoric earthquakes, seismologists are able to estimate the likelihood of future earthquakes. Engineers sometimes talk about a *return period* for earthquakes, but this is somewhat of a misnomer. The probability of a certain size earthquake is the same each year so a return period of 1,000 years does not mean that if one occurs in your region, another won't occur for another 1,000 years. That size earthquake has the same chance of occurring in each one of the future years.

Experts generally agree that short-term earthquake prediction is not possible and it may be best to assume that an earthquake can occur at any time.

2.2 Seismicity of New York State

The 2008 USGS National Seismic Hazard Map identifies NYS as a region of "low-to-moderate" seismic hazard. (Figure 2-3) The graphic of NYS in Figure 2-4 illustrates the peak ground accelerations (PGA) that have a 2% probability of being exceeded in 50 years. According to this map, the NYC and Adirondack regions are more likely to get an earthquake than the center part of the state. These figures illustrate the fact that the possibility of an earthquake is not solely a west coast concern. Though the frequency of occurrence and the expected ground accelerations may be less, the potential for earthquake damage in or around NYS is still very real.

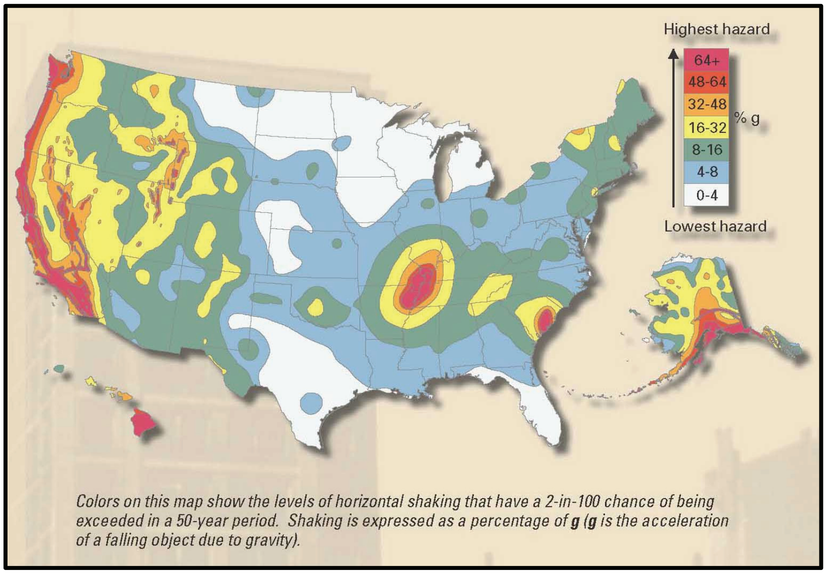


Figure 2-3. United States Seismic Hazard Map (USGS)
(http://www.usgs.gov)

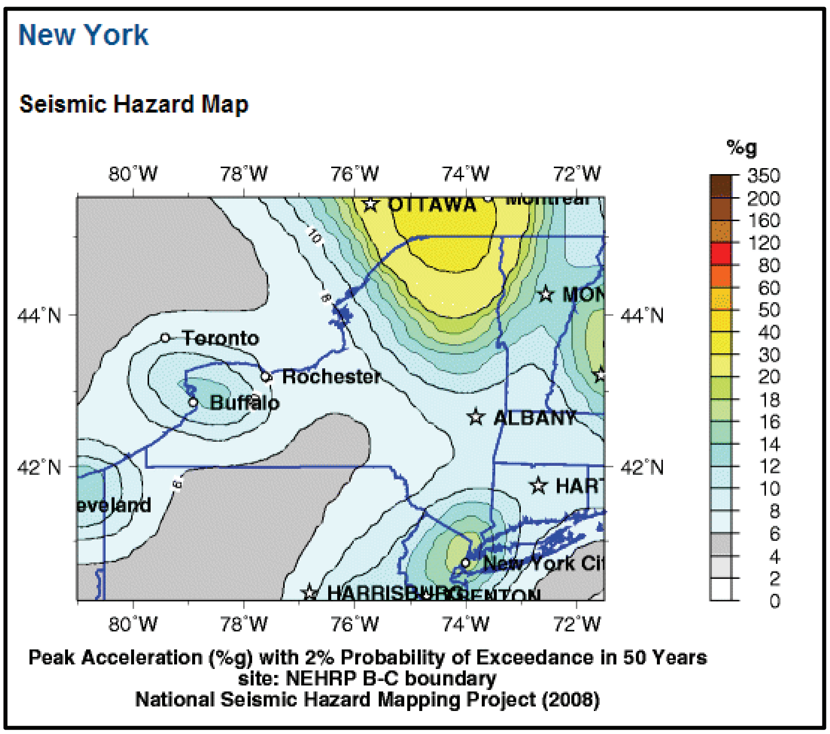


Figure 2-4. New York State's Seismic Hazard (USGS)
(http://earthquake.usgs.gov/regional/states/new_york/hazards.php)

Although infrequent, earthquakes have occurred historically in NYS. Figure 2-5 shows the geographic location of some of these earthquakes.

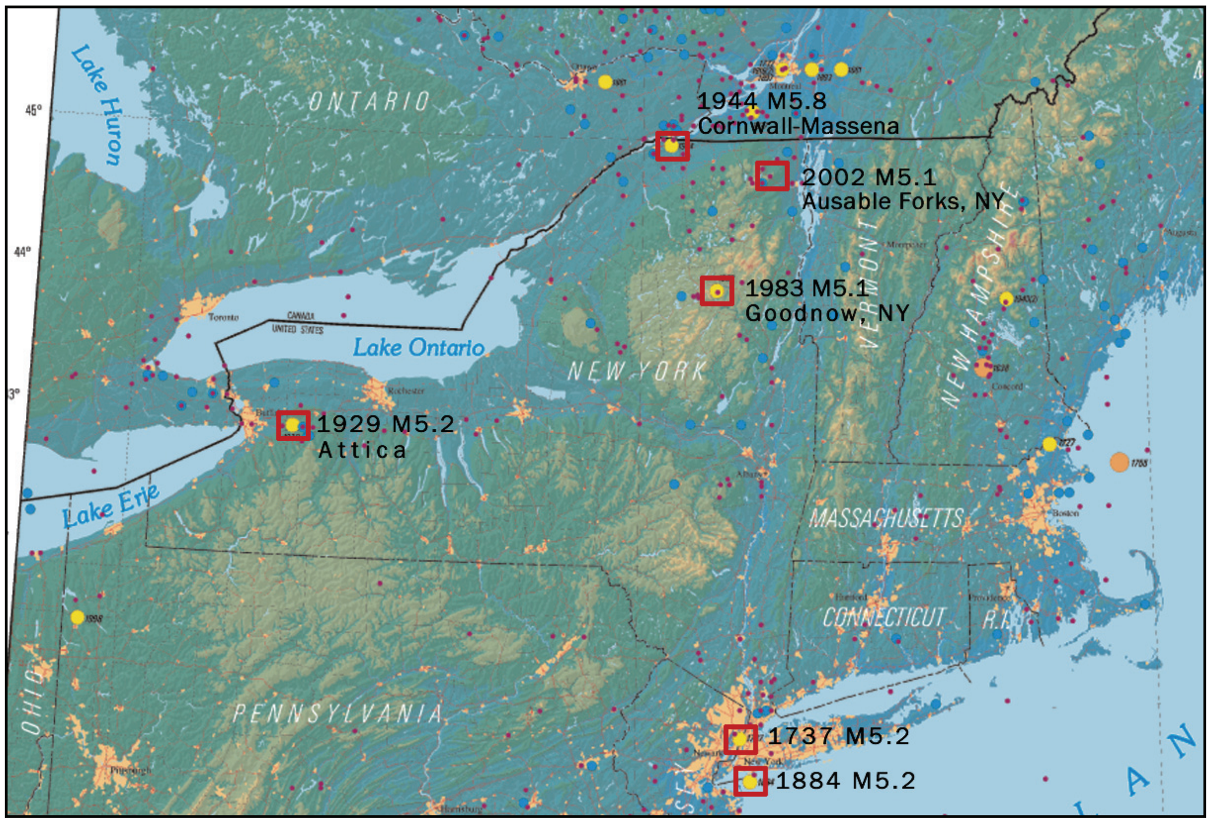


Figure 2-5. History of Earthquakes in NYS (NYCEM 2003)

A few examples of past earthquakes affecting NYS are:

- 1884 – New York City; M5.2-M5.5 (estimated)
- 1929 – Attica, New York; M5.2; Mercalli Intensity VIII
- 1944 – Between Massena, NY and Cornwall, Ontario, Canada; M5.8; VIII
- 1983 – Blue Mountain Lake, New York; M5.1-M5.3 (estimated)
- 2002 – Au Sable Forks (Plattsburgh area), NY; M5.1
- 2002 – Plattsburgh Aftershock; M3.6
- 2002 – Redford, NY; M3.3
- 2010 – Southern Ontario, Canada, within 70 miles of NYS; M5.0
- 2011 – Virginia; M5.8; felt in NYS but no apparent damage

Although the earthquake hazard is rated "low-to-moderate," the risk in NYS can be high because of the potential consequences. Although mild earthquakes occur regularly in and near NYS, and frequently go undetected, a moderate or strong one has the potential to disrupt operation of the highway system, cause injury, and result in major property damage. For instance, a highly developed area like the NYC metropolitan region has many vital structures that carry a large amount of traffic. Considerable damage to any of these structures has potential to severely disrupt traffic and impede recovery from an earthquake. Recognition of this risk is the motivation behind the development of an earthquake response plan.

SECTION 3
BRIDGE PERFORMANCE DURING EARTHQUAKES

3.1 Earthquake Loading and Bridge Response

AASHTO's bridge design specification is accepted in the U.S. as the consensus standard for the design of new bridges. However, it was not until the mid 1970's that the design specification began to include detailed provisions for seismic design. Since the average "year built" for highway bridges in the U.S. is 1969 (Shemaka, 2009), roughly half of existing bridges were built without the benefit of modern earthquake engineering principles and their expected performance in an earthquake is unknown.

The behavior and performance of a bridge structure under earthquake excitation is influenced by *hazard* factors (e.g., magnitude, direction of waves, proximity to epicenter), *site conditions* (e.g., the type of underlying soil supporting the structure) and *response* factors, such as structure type, material, structural details (e.g., connections, foundation fixity, reinforcement details), and condition (e.g., deterioration due to rust).

Seismic waves can cause the ground surface to move horizontally or vertically. Built structures, such as bridges will have a tendency to follow the ground motion but will be inhibited by their own inertia. This causes stress in the bridge because forces are introduced into the structure according to Newton's second law of motion (Force = mass multiplied by acceleration). Since the mass of a bridge is fixed, the force that the bridge is subjected to depends on the acceleration of the ground moving under it. The effect of an earthquake is often expressed in terms of "g" (the acceleration due to gravity), simply because gravity is a concept that we are all familiar with.

Forces induced by ground accelerations may or may not be a problem for a bridge. Even if a bridge was not specifically designed to resist earthquake loads, features such as wind bracing may be adequate to resist some lateral loads. Damage in a bridge element occurs when the seismic *demand* exceeds its *capacity* (or strength). In order for a bridge to perform satisfactorily without damage, its components must remain *elastic*. This means that any structural deformations (called strains) are temporary. With full elastic behavior, the materials return to their original position without an overall change in shape or length.

A bridge must also be able to withstand *displacements* without losing its stability. For instance, high rocker bearings should not move so much that they topple and cause the entire span to drop. Likewise, bridge girders should not move so much that they fall from the pedestal and collapse to the ground. Simply supported spans are particularly susceptible to this type of damage if the ground motions are severe enough. If a bridge is to keep its structural integrity, it needs to be able to resist both the inertial forces and displacement demands. Otherwise, local failure or a collapse of an entire span may occur. Table 3-1 lists possible causes for various conditions resulting from an earthquake (Caltrans 2007).

Table 3-1. Potential Bridge Damage

Bridge Component / Damage	Possible Cause
Approach Slab or Pavement • Raised, lowered, cracked, or buckled	• Longitudinal forces • Lateral spread; Slope failure
Abutment and/or Foundation • Tipping or other displacement • Cracking • Movement of supporting soil	• Movement of soil behind abutment • Loads exceeding shear capacity, especially if superstructure smashes into the backwall, cheekwalls, or shear blocks • Liquefaction
Superstructure • Collapse of one or more spans • Span misalignment • Girder damage • Bowing, dips • Deck damage: spalling, exposed rebar	• Displacement beyond capacity of the bridge seat • Horizontal displacement • Abutment or pier damage or movement • Beam failure due to excessive shear or moment • Superstructures tend to move off a highly skewed seat
Bearings • Toppled • Unseating, misalignment • Sheared or bent anchor bolts	• Use of high, potentially unstable bearings • Frozen (non-functioning) bearings
Restrainers or other Seismic Retrofits • Damage to restrainers	• Insufficient capacity • Improper installation
Joints and Connections • Misalignment, spalling, cracking	• Inadequate development length of longitudinal reinforcement in adjacent member • Poor choice of connection details (insufficient translational restraint for pinned connection, etc.)
Pier (wall, stem, columns or capbeam) • Cracking from flexural or shear failure • Crushing or mushrooming • Longitudinal reinforcement tension failure • Buckling of longitudinal reinforcement • Torsional failure	• Uneven settlement of a footing • Insufficient confinement (number, size or spacing of bars) • Poor reinforcement details (hooks, laps, etc.)
Other • Damage to bridge railing • Pipeline fracture	• Consequence of damage to other elements • Lateral loading or differential displacement

Because modern seismic design standards were introduced fairly recently, and the average age of a bridge in NYS is 45 years, many bridges may be vulnerable to damage because they do not have the features needed to resist the seismically induced forces and displacements. In addition, the physical condition may have changed since the date a bridge was built. For instance, there may be section loss due to rust, or weakness from fatigue or impacts that can reduce a structure's capacity to carry seismic loads. Structural modifications made over the years for different reasons may improve performance or may have the unintended consequence of negatively affecting seismic performance. NYSDOT has developed procedures to identify vulnerable design details and rank bridges by risk using its Seismic Bridge Vulnerability Assessment Manual (NYSDOT 1995), but because of resource constraints, not all bridges in the state have been rated.

While it is fortunate that NYS is rarely subjected to damaging earthquakes, it also means that the robustness of the state's bridges is unproven under this scenario. Engineers must rely on condition inspections, vulnerability assessments, probabilistic scenarios, and detailed analyses of particular bridges to make an educated guess about the fragility of the highway system.

3.2 Vulnerable Structure Types and Details

Bridges must be designed, detailed and built properly to obtain good results in an earthquake. Since the AASHTO design code was changed in the late 1970's, bridges built after 1980 can be considered more seismically resistant than bridges built prior to that year. 'Year Built' data is readily available in the bridge inventory.

Bridges consisting of multiple simply supported spans may be vulnerable because of their lack of structural continuity, combined with an inadequate seat width (also called support length). Non-redundant, fracture critical, curved, and highly skewed bridges are also vulnerable.

Continuous long span (e.g., cable supported) bridges are generally more forgiving because of their inherent flexibility, although age and condition may have an impact on performance. Buried structures may not collapse but they should be checked for shear failure resulting from ground waves.

Additional observations obtained from a literature review are:

- The structural members of an older truss that are intended to take lateral loading should be checked for damage. They were probably not designed for seismic loads. Latticed truss members should also be check carefully.
- Cross bracing diaphragms, especially at the ends of multi-girder bridges, may deform from excessive lateral loads.
- Older substructures made with unreinforced concrete or masonry may experience shear failure under ground motion, causing the superstructure to drop.
- Preexisting conditions, such as scour at a pier footing, or a fatigue crack, may decrease a bridge's ability to withstand an earthquake.
- Weak soils (organic material, sands and silts) amplify the effects of an earthquake.
- With long periods of strong shaking, sandy or silty soils that are saturated may be subject to liquefaction. This could cause the substructure to settle or tilt.

- If a bridge has been retrofitted previously, the performance of the retrofit should be checked to see if it turned out as expected.
- High rocker bearings can overextend and tip, causing the supported span to drop down to the pedestal.
- High piers may allow excessive lateral movement of the bearing, causing an unseating.
- Flagged conditions should be investigated in detail, because by definition, there is a particular aspect of a structural member that is compromised.
- Concrete shear blocks on a bridge seat can prevent the superstructure from moving laterally; lack of such lateral restraint can result in loss of support.
- Details associated with suspended spans (e.g., pin and hangers) or floor beams were not designed to transfer lateral loads, so are vulnerable.
- Reinforced concrete columns can fail from:
    - Insufficient shear capacity
    - Insufficient embedment and/or lap splice of reinforcement
    - Inadequate confinement steel (size of bar, spacing, details)
- Foundation failure can result from:
    - Pile pullout
    - Pile overload
    - Footing concrete shear failure
    - Yielding of footing reinforcement
    - Anchorage failure
    - Pile failure influence or shear
- Utilities on bridges:
    - Collateral damage can occur if utility lines rupture due to earthquake-induced loads, differential displacement or ground settlement.
    - Broken water lines can cause rapid erosion at abutments and approach embankments.
    - Natural gas, petroleum or other flammable products can present an explosion hazard, especially in box girder bridges.

The above is intended to give an overview in general terms. Section 5 of this report provides more detailed guidance, including photos and checklists, and forms.

SECTION 4
EARTHQUAKE RESPONSE PLAN

4.1 Earthquake Notification Service (ENS)

All DOT RE's, RSE's, and RD's will need to subscribe to USGS's ENS at https://sslearthquake.usgs.gov/ens/ since the proposed Earthquake Response Plan (ERP) will be activated upon receipt of an ENS alert. Instructions for subscribing are provided in Appendix B. Detailed information about an event, such as magnitude and location, is usually available within 30 minutes, but if a strong earthquake is felt, the DOT should respond immediately. Sample earthquake data from USGS is shown below (Figure 4-1).

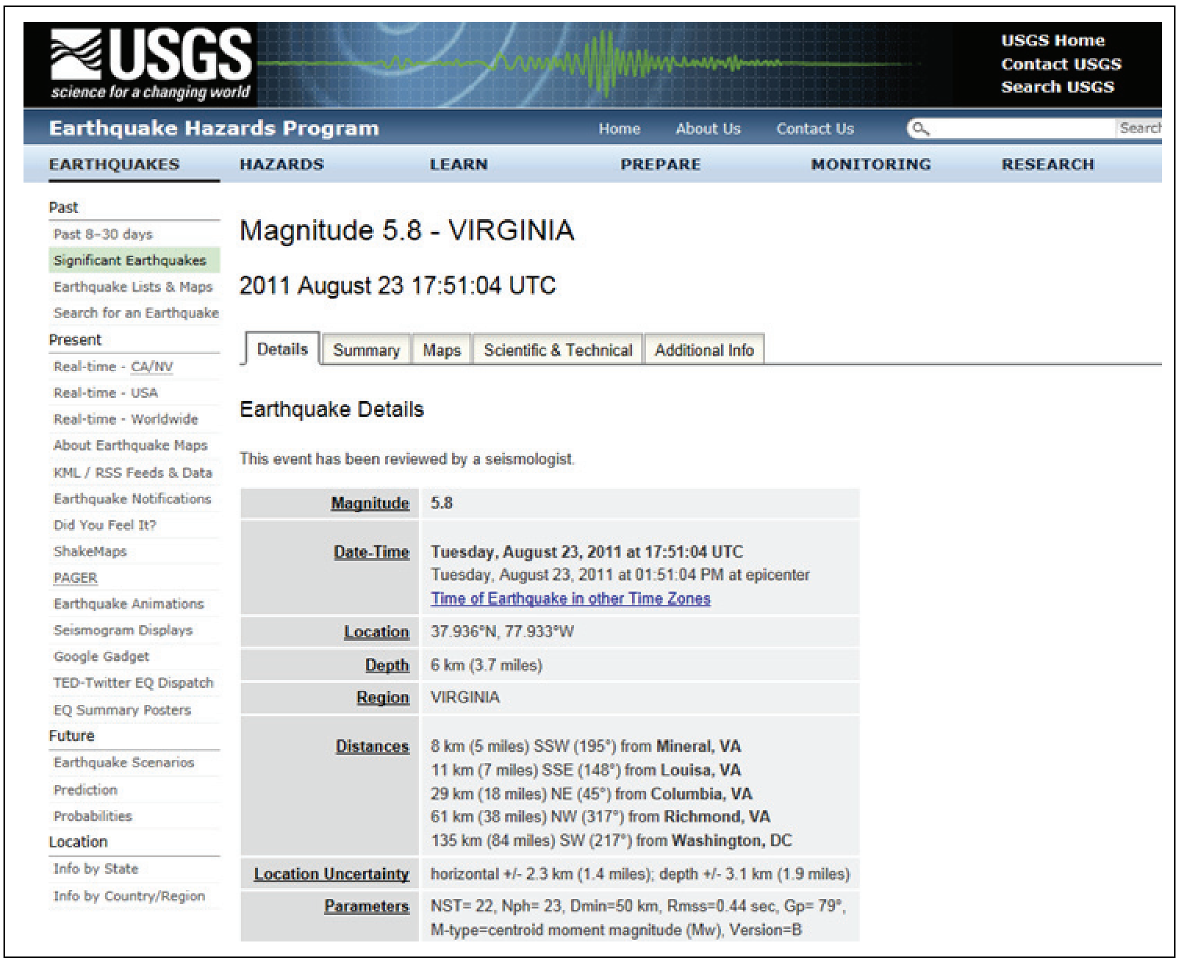


Figure 4-1. USGS Sample Earthquake Notification Alert (USGS)

Other emergency response professionals may also want to subscribe to NYS All-Hazards Alert and Notification (NY-ALERT) at www.nyalert.gov.

4.2 Process Overview

This plan proposes that the Department rely on ENS to trigger a response. The particular response will be dependent on the reported magnitude and the coordinates of the epicenter. An initial damage assessment phase, carried out by residency staff under the direction of the RE, will be accomplished by driving priority routes immediately and continuing until all state routes have been checked. The objective is to determine the extent of damage and to close unsafe bridges. This phase is referred to as the Preliminary Bridge Damage Assessment (PBDA). If the epicenter is in one residency and its impact is felt in an adjacent residency, both RE's will be expected to respond as if their entire residency is in the affected area.

Subsequent to the PBDA, the RSE will oversee a second phase that consists of professional engineers (PE) performing detailed bridge inspections. These Special Post-Earthquake Bridge Inspection (SPEBI) teams will normally be deployed within 8 hours of the event and continue in subsequent weeks until a comprehensive picture of the damage is obtained. Special access equipment, maintenance, and protection of traffic (MPT) support may be needed for these teams. The RSE and the bridge inspectors will prioritize the SPEBI's using findings of the PBDA's, the criticality of bridges in the area, their vulnerability to seismic damage due to structural features, site conditions, and other factors. Geographic Information Systems (GIS) maps, seismic vulnerability ratings, and predefined inspection priority lists, will facilitate the efficient management of these inspections. Additional inspection teams will be brought in from consulting firms, other DOT regions, and Office of Structures in Albany, as necessary.

The bridge inspector will decide what follow-up action is required. Action might consist of flagging a deficient condition, closing (or reopening) a bridge, restricting traffic, writing a repair request, suggesting more substantial remedial work, or requesting further investigation.

Four *response levels* and the associated *radius of concern* (R) are listed in Table 4-1. The response levels are dependent on the magnitude and GPS coordinates of the epicenter which will be available at www.earthquake.usgs.gov.earthquakes/recenteqsus/ normally within 30 minutes after any earthquake.

Response Level I can also be referred to as a *Discretionary Response Level* and Level IV as a *High Level Response*. The listed radius gives an indication of the area around the epicenter that should be investigated. However, if initial reports show that damage is more widespread than anticipated, the RSE has the discretion to expand the radius of concern or elevate the investigation to a higher response level. Figure 4-2 is a process flowchart of the entire ERP.

Table 4-1. Response Levels

Response Level	Earthquake Magnitude	Radius of Concern	Description of Response
I	M < 3.5	-	A broad based response is not planned or required. If there are reports of damage, RE is to notify the RSE. On a case-by-case basis, the RSE will determine if a **Special Post-Earthquake Bridge Inspection (SPEBI)** needs to be done. RSE uses discretion to inspect especially vulnerable or critical bridges close to the epicenter.
II	3.5 ≤ M < 4.5	40 mi	RE will immediately initiate **Preliminary Bridge Damage Assessments (PBDA)**. All state routes within the residency will be driven according to priority and all bridges investigated. Reports of damage or questionable conditions will be called in immediately. Summary reports are to be sent to the RSE at the end of each day. If no damage is discovered during PBDA, the post-earthquake response can be terminated. As soon as possible, RSE will arrange for a **SPEBI** using a RSE-generated prioritized list of seismically vulnerable Bridges. SPEBI will be done on bridges within the radius of concern: ▪ deemed *critically important* by the RSE ▪ where damage was reported in the PBDA ▪ where evaluation by a more trained or experienced person is needed ▪ with a seismic vulnerability rating (VR) of 1or 2. ▪ considered vulnerable or especially important If there are reports of bridge damage outside of the default radius of concern, the RSE will increase the radius and adjust the inspection program accordingly.
III	4.5 ≤ M < 5.5	60 mi	Use the same criteria as Response Level II, but with a larger radius.
IV (High)	M ≥ 5.5	80 mi	NYS's Incident Command System (ICS) will be activated for this High Level Response to ensure coordination of effort among DOT Regions, Main Office and other agencies. RE will conduct **PBDA** on routes immediately and RSE will arrange for **SPEBI** of all bridges that are within the radius of concern as soon as possible.

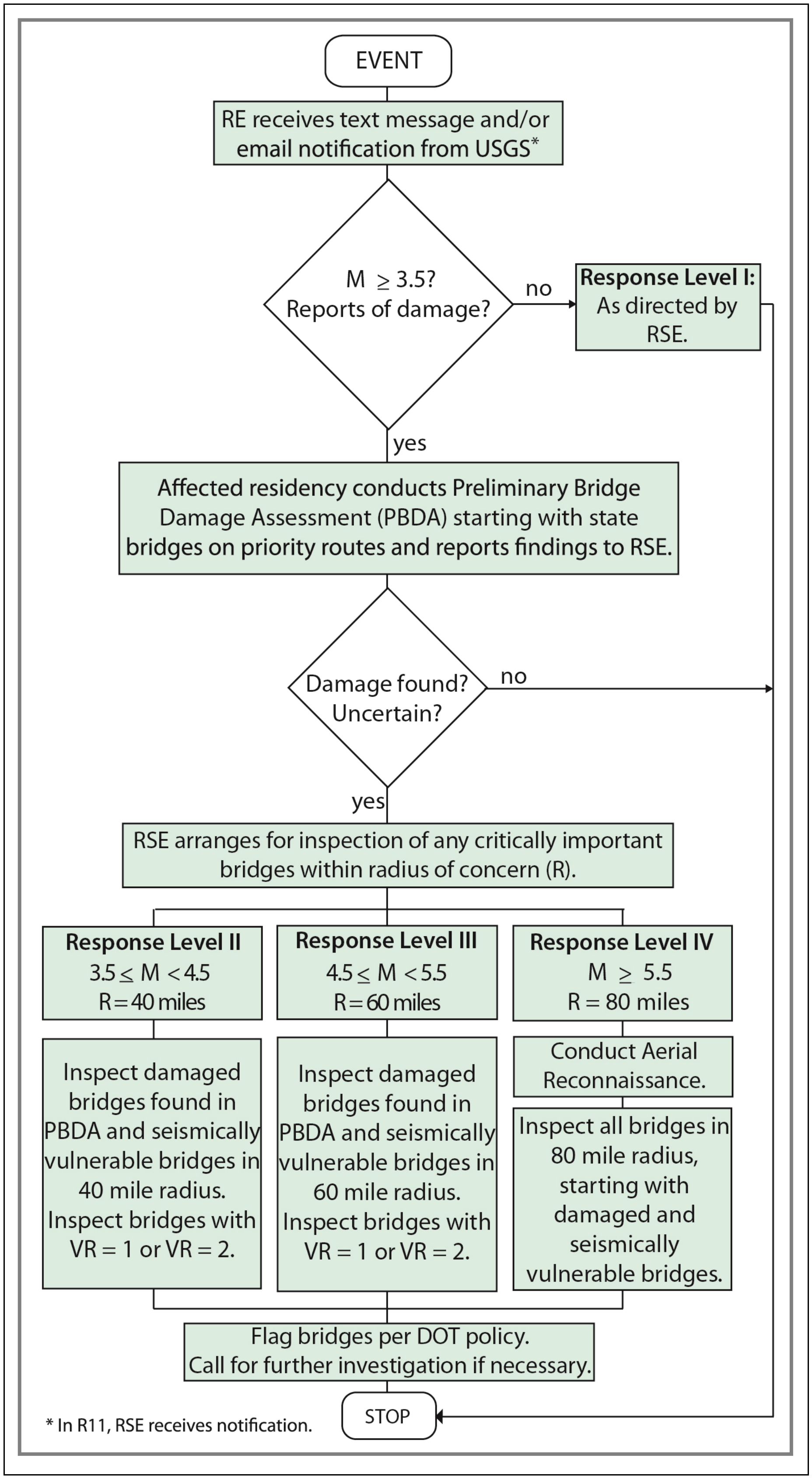


Figure 4-2. Process Flowchart for Earthquake Response Plan

Table 4-2 shows a comparison of the different types of bridge damage assessments, with the most immediate type of assessment on the left, and the more time/labor intensive ones on the right. Obviously, the greater the earthquake magnitude, the more resources will be needed in order to obtain a good understanding of the problem in a reasonable timeframe.

Table 4-2. Types of Post-Earthquake Bridge Damage Assessment

Type	**Aerial Reconnaissance** (Response Level IV)	**Preliminary Bridge Damage Assessment (PBDA)**	**Special Post-Earthquake Bridge Inspection (SPEBI)**	**Further Investigation**
Objective	'Global' perspective	Route reconnaissance	Detailed Post-Earthquake Bridge Inspection	Special study to address a particular concern
Scope	All bridges in affected area	All bridges in affected area, starting with priority routes.	Site-specific. Table 4-1 shows bridges to inspect for a given magnitude.	Site-specific, as needed
Inspection Method	Helicopter or small fixed wing aircraft	Drive-through with quick stop at each bridge	Bridge inspection vans, MPT & special access equipment if needed	Any special equipment that is needed
Personnel	1 or 2 DOT managers	Residency staff	Bridge Inspection Teams with supplemental TL's, if needed	Specialists e.g. Structural, Geotechnical, Metallurgical
Timeframe	Immediate (within 24 hours)	Immediate (within hours)	Start a.s.a.p. (usually within 8 hours) and continue as necessary	Subsequent to a SPEBI
Outcome	▪ Determine the extent of damage ▪ Identify impassible routes & traffic bottlenecks ▪ Locate bridges that have major damage or are obviously unsafe ▪ Suggest priority for ground assessments	▪ Determine the extent of damage ▪ Identify impassible routes & traffic bottlenecks ▪ Close collapsed or dangerous bridges ▪ Recommend SPEBI bridge inspection for damaged or suspect bridges.	▪ Flag if necessary ▪ Close collapsed or dangerous bridges ▪ Recommendations for restriction, repair, or further investigation. ▪ Reopen bridges deemed safe that were closed as a precautionary measure during PBDA	▪ Flag as necessary ▪ Detailed analysis ▪ Provide specific recommendations on necessary restrictions and/or repair ▪ Approximate cost estimate for remedial work
Deliverable	Reconnaissance report with photos and/or video	PBDA Form (one line per bridge)	▪ SPEBI Report ▪ Daily Summary Report (DSR)	Special engineering report

4.3 Preliminary Bridge Damage Assessment (PBDA) Program Steps

The RE in the affected area is responsible for initiating the PBDA program in the event of an earthquake, managing and supporting staff in its execution, working closely with the RSE to implement closures or take other action, and communicating with other DOT managers. Specific steps related to the RE's execution of the PBDA program are:

PBDA Program Steps
1. Provide earthquake awareness training to residency staff, at least annually. 2. Ensure that resources needed for earthquake response are ready for deployment at any time. 3. Personally subscribe to ENS, and assign this responsibility to next in command. 4. Maintain a map and/or list of priority routes in the residency. 5. Maintain a map and/or list of all bridges in the residency, with an identification of bridges considered most critical. 6. Immediately commence PBDA on all routes in the residency whenever: a. The epicenter of the earthquake is within the radius of concern of any part of the residency. (The radius of concern varies according to the earthquake magnitude.) b. There are reports of earthquake damage to bridges, buildings, or slopes, within the residency. 7. Deploy two-person PBDA teams. 8. RE responds to questions from field teams and provides any necessary support. 9. Collect and review daily reports from field teams. Summarize findings and send a daily report to RSE with digital photos of any damage. Provide the data electronically (i.e. in a spreadsheet), if possible. 10. Verbally report any significant bridge damage to the RSE immediately. 11. Immediately close and barricade any bridges that appear to be unsafe. 12. If there is any uncertainty about a bridge's condition, request that the RSE conduct a bridge inspection (SPEBI). 13. After SPEBI's are completed, close or reopen bridges as requested by the RSE. 14. Arrange for immediate repair of damage that does not require any analysis (e.g., damaged approach). Document all activities with photographs and inform RSE.

4.4 Special Post-Earthquake Bridge Damage Assessment (SPEBI) Program Steps

The RSE in the affected area is responsible for accomplishing detailed inspections in an expeditious manner, with an effort that is commensurate with the severity of the event. The RSE will also direct follow-up action, such as conducting detailed investigations, structural or geotechnical analysis, designing repair or retrofit schemes, or initiating long-term replacement or rehabilitation. Program steps include:

SPEBI Program Steps
1. Annually provide earthquake awareness training to bridge inspectors and other staff who might be called into service after an earthquake. The RSE may want to maintain a contact list of PE's in the region who are qualified to do post-earthquake bridge inspections. 2. Ensure that resources needed for an earthquake response are ready for deployment at any time. Prepare a response that can be carried out even if there is no power or typical communication equipment (e.g. landline phones, cell phones or internet). 3. Personally subscribe to ENS. 4. Communicate with regional GIS and emergency response staff, and share data that is required to maintain a current: a. map and list of priority routes in the region that can be used as lifeline routes. b. map and list of all bridges in the region, with an identification of bridges considered most critical, those that are flagged, and if possible, those considered seismically vulnerable. This would also include an accurate inventory of potentially dangerous pipelines and other utilities carried on bridges. c. lists with emergency contact numbers for bridge inspectors and office staff who may need to be involved in post-earthquake response. 5. Notify local County Highway Superintendents, authorities, and other bridge owners whenever any significant earthquake occurs and advise of appropriate action. 6. Refer to ERP, determine which *response level* and *radius of concern* is appropriate and communicate to others. Organize bridge inspection teams and commence SPEBI's, preferably within 8 hours. 7. Generate a prioritized list of bridges to inspect and print GIS maps with these bridges located on it. Provide to bridge inspection teams. (The RSE should always have a standing list that is available within minutes of an earthquake. After an event, this list can be refined using up-to-date data, as time permits. A standing list may be based on static data, but it would prevent a delay in the mobilization and deployment of inspectors in the immediate aftermath after an earthquake.) 8. Inspectors are to submit Daily Summary Reports (DSR) at the end of each day when SPEBI's were done. Collect and review daily reports from field teams. Summarize findings and send a report to RD and Director - Office of Structures, the Incident Commander and STICC as appropriate. 9. Review SPEBI reports. Determine if any bridges should be closed or restricted (weight restricted, reduced number of lanes, or open to just emergency vehicles). Give

authorization to reopen bridges that were closed as a precaution during the PBDA phase if it is appropriate to do so. Track resolution of any structural flags.

10. Prepare plans for repair, retrofit or replacement as appropriate and work with Structures Asset Management Team to program remedial work.
11. Defer any communication with the media to the RD's designee.

4.5 Training and Preparation

As part of the implementation of this plan, anyone who will be expected to respond to an earthquake should either attend a one-day workshop on post-earthquake damage assessments or take a computer based training (CBT) course to familiarize them with the same material. Annually afterwards, they should take a one hour CBT presentation to refresh their memory. The purpose of the training is twofold: to reinforce the required post-earthquake inspection procedures, and to familiarize them with basic earthquake principles and types of bridge damage that could occur. The training courses will include photographs of possible earthquake damage.

Since ICS will be activated for a large earthquake, those who will be involved in a response should also go to http://www.fema.gov/emergency/nims/NIMSTrainingCourses.shtm. Through this site, one can access free on-line ICS training.

Scenario exercises are a useful tool for ensuring that key players fully understand their responsibilities. The DOT can test its readiness under different earthquake scenarios by dedicating a day to dramatizing the action steps that would be required in an actual event. This will ensure that personnel understand their roles and that the plan can be executed as intended. These simulations have been used successfully by other DOT's and by NYS for other hazards. Since these emergency response scenarios consume resources, it is only recommended that a field or tabletop exercise be conducted once every four years.

At least annually, the RD should insure that the contact information for managers and others who will be involved in an earthquake response is up to date. The list should contain office and personal phone numbers, and e-mail addresses. Although the lists may be maintained electronically, a hardcopy should also be kept on file just in case computers are down or electricity is not available after an earthquake. Emergency contact information needs to be current and on a regular basis distributed to the people who need it.

If an earthquake occurs during normal working hours,

- All employees shall make themselves available for possible assignment and immediately begin to prepare for deployment. Fuel up vehicles; check phone, camera and flashlight batteries; gather maps, manuals, reporting forms, etc.; check two-way radios; and pick up basic tools (e.g., tape measure).
- Preliminary Bridge Damage Assessments (PBDA's) will begin as soon as possible after the event, starting with pre-defined priority routes. If there are incoming damage reports, the RE may consider adjusting the response accordingly.

- In the event of a strong earthquake, DOT office buildings may need to be evacuated and assessed for damage. When preparing local procedures, an alternate site should be designated as a staging area, for use when the regular facilities are not accessible.

If an earthquake occurs while employees are not at work, DOT staff will respond as follows:

- Prepare to report to work if called and await a phone call for assignment.
- If possible, contact supervisor.

4.6 Communication, Damage Summaries and After-Event Review

If an earthquake occurs, the RSE is to provide initial notice to the RD and the Director – Office of Structures verbally. This will occur as soon as possible after the event. Over the course of the earthquake response, detailed verbal reports shall be provided regularly to insure that management has a good understanding of the situation. These reports will describe affected areas, the impact that the earthquake has had on traffic operations, and identification of any closed or flagged bridges, detailed counts of damaged bridges, inspected bridges, and damage cost estimates, if requested.

A communication technique that has been used successfully by California DOT (Caltrans) is to hold a brief meeting (15 minute) daily while post-earthquake inspections and repairs are being conducted. These frequent updates keep a clear line of communication open between the people engaged in emergency response and those that need to know what is happening (e.g., RD and Commissioner level).

The RD and the Director – Office of Structures will coordinate with the Commissioner's office and other agencies, levels of government and nearby states if necessary. Field staff should also defer to the RD for communication with the public and communications media.

As teams inspect bridges immediately after an earthquake, it will be necessary to create concise summaries of findings for the Regional Director, Incident Commander and the Director – Office of Structures. During post-earthquake investigations, each RE and TL will be asked to provide a Damage Summary Report (DSR) to the RSE daily. The RSE will compile results into one document and disseminate. This will give an indication of the overall progress of the inspection program and an overview of the findings. A template for this report is given in Appendix E. The DSR form is essentially a concise summary of the SPEBI form. It allows bridges to be listed line-by-line along with the damage state, status, work needed, and actions taken.

In addition to DSR's, the RSE will also document any meetings. The minutes will include a brief summary of important discussions, decisions, agreements, and assignments. After NYSDOT response has been terminated, each affected region will complete a review report that includes a summary of all damage found. This summary may then be used to analyze earthquake bridge damage to see if any conclusions can be drawn that can be used to modify NYS design and/or retrofit practices.

After a seismic event, NYSDOT will benefit from a formal evaluation of the operation to determine if the Department's goals were met. The objective of this review is to assess the effectiveness of the post-earthquake response, in order to determine what aspects of the response plan could be improved and what parts worked well. This review of lessons learned will include gathering the opinions of ICS staff, NYSDOT main office and regional staff, and possibly community members affected by the event. It is suggested that an after-action meeting or conference call be held with all key players involved. In the spirit of continuous improvement, a report will be written that summarizes recommended modifications to the earthquake response plan and procedures. The Director – Office of Structures is responsible for making any revisions to the ERP.

SECTION 5
TECHNICAL GUIDANCE

5.1 Preliminary Bridge Damage Assessment (PBDA)

A PBDA is a quick condition assessment of a bridge obtained by residency staff during a route reconnaissance within a few hours of an earthquake. It is a cursory visual inspection with the primary objective being *to identify and close any unsafe bridges*. The team is expected to stop at each bridge and look for any damage that might have been caused by the earthquake. Once all routes are surveyed, DOT management will have a better handle on the extent of highway damage caused by the earthquake and will be in a better position to respond. Reporting requirements for a PBDA are minimal so as not to deter efforts on the ground.

Since these assessments will be done by operational staff without an educational background in engineering or structures, some extra reference materials have been prepared. Section 6 is a glossary of important terms that are fundamental to the discussion of bridges. Figure 6-1 is a Bridge Terminology Reference Sheet, labeled with the components of a typical bridge. Figures 6-2 through 6-12 illustrate various types of bridges that might be encountered. Appendix A provides some discussion of basic earthquake principles. Appendix D lists tools, equipment and reference material that will be necessary.

5.1.1 PBDA Procedures

The RE will oversee the operation. PBDA procedures for staff are as follows:

PBDA Procedure
1. Report to the residency and prepare for departure in two-person teams. Review safety procedures.
2. Collect necessary equipment, maps, communications devices, camera, etc.
3. Drive assigned state routes in priority order.
4. At each bridge, stop and record the date and arrival time, BIN#, Feature Carried, and Feature Crossed using forms provided in Appendix E.
5. Begin by inspecting approaches and continue in the order listed in the inspection form. Using the PBDA form as a checklist, evaluate the condition of the bridge. Complete items 1 through 6 on the form with the comments “Yes” or “No”, using the Bridge Terminology Reference Sheet or Technical Guidance presented later in this section of the report, as necessary. If unsure about the status, call the RE or check the last box in the row so that an inspection can be arranged.
6. A one line report is all that is expected for each bridge, but if there is significant damage, record the condition, take a photograph, and report it to the RE immediately.
7. If the bridge is obviously unsafe, (either already failed or in imminent danger of collapse) immediately close the bridge by erecting barricades and appropriate signage.

Keep personal safety the priority. Approach the bridge with caution and never walk directly under or over the bridge immediately upon arrival. Do not cross the bridge without giving it a cursory assessment by first sighting down the curb/rail line and checking the underside for structural damage. Use caution when proceeding under or across a bridge structure, as aftershocks may further shift or cause collapse of an already precarious structure. The PBDA team members should remain reasonably separated from each other and never go underneath the bridge at the same time. Although the assessment is primarily visual, listen carefully for possible indications of damage to utility pipelines carried on the bridge.

If any bridge span is totally collapsed or completely nonfunctional, there is no need to proceed with the step-by-step procedure. The bridge should be closed immediately and the residency should be called to request backup support, if needed. When assistance arrives, proceed with the remaining PBDAs.

If any hazardous condition is encountered while driving the highways within the residency, the RE and/or appropriate authorities should be contacted in order to secure the area. This includes reporting downed power lines, faulty traffic control devices, slope failures, or other roadway obstructions. Although these are not always bridge related, they are a safety concern and will hinder DOT's overall response, so they should be reported as soon as possible.

Upon completion of the assigned route reconnaissance, deliver the results to the RE and prepare for the possibility of assignment to another route.

5.1.2 Sample PDBA

This section presents a hypothetical highway bridge after a moderate earthquake. It illustrates how the bridge should be systematically evaluated, the form filled in and photographs taken of changed conditions and the findings reported.

Begin by first filling in the fields for the BIN#, Feature Carried, Feature Crossed, and time.

Upon approaching the bridge, it is apparent that traffic is still using the bridge (Mark "Yes" or "Y" in the appropriate column) and there are no collapsed or partially collapsed spans. Note this with a "No" or "N" in the "Span Collapse" column.

Since there is minor settling at the approach at one end, enter "Yes" in column #6. (Figure 5-1a)

After determining that the bridge is not in immediate danger of collapse, proceed to examine elements of the superstructure such as the deck, joints, and girders. The deck exhibits minor cracking, but the cracks do not appear to be new. There does not appear to be damage to the girders but there is debris on the deck and some separation at the expansion/contraction joint so enter "Yes" in column #1. This may be an indication of more serious problems with the bearings underneath. (Figure 5-1b)

When evaluating the substructure, there is no visible damage to piers or pier caps. (Figure 5-1c) There is no abutment cracking or other evidence of that the superstructure had pounded against the abutment. Record a "No" in column 2. When examining the bearings, it seems that several anchor bolts have sheared off recently. Note this concern by marking a "Yes" in column #3. (Figure 5-1d)

Soil around the abutment has apparently moved, given the fresh gap at the base (Figure 5-1e), so mark "Yes" on the form for column #5. Check for other soil damage that might be a more serious problem or immediate danger. If none is found, move on.

Step back and check for any other damage. A leaking waterline can cause serious erosion in a short time. The bridge carries what seems to be a water line but it does not appear to have suffered any damage or caused any damage to the bridge. Check for damage to the abutment wingwalls. In this case, there is exposed rebar, indicating a deficiency in the wingwall (Figure 5-1f). However, notice the rebar is already rusted; this is not new damage. As observed in the first image (Figure 5-1a), no damage to the railing or curb was observed, so mark "No" for column 4.

Since some damage was discovered and you think some follow-up by a trained bridge inspector is warranted, request a SPEBI by answering "Yes" in the last column.

a. PBDA Column #6
Approach

b. PBDA Column #1:
Superstructure Damage

c. PBDA Column #2
Substructure Damage

d. PBDA Column #3
Bearing Damage

e. PBDA Column #5
Soil Problems

f. PBDA Column #4
Secondary Systems

Figure 5-1. Photographic examples of bridge damage for inclusion in a Preliminary Bridge Damage Assessment (PBDA) – (NISEE)

The PBDA for this bridge is now complete; the one line report should appear similar to the following (Figure 5-2).

New York State Department of Transportation Post-Earthquake Damage Assessment

Preliminary Bridge Damage Assessment (PBDA) Form

Region 5

County Erie

Date: 1/22/2013

Name(s): T. Smith

					Changed condition: Respond 'Yes' or 'No'											
BIN	**Feature Carried**	**Feature Crossed**	**Arrival Time**	**Is bridge open to traffic?**	**Span Collapse?**	**Is any damage apparent?**	**1. Superstructure Damage** girders, joints, deck	**2. Substructure Damage** damaged or tipped columns, cracked pier cap, abutments	**3. Bearings** displaced, damaged?	**4. Secondary Systems** wingwalls, bridge railing, utilities, pipleines OK?	**5. Soil Problems** sloughing, fissure, differential settlement, liquefaction?	**6. Approaches** settlement, cracking, voids under?	**Other Observations**	**Does it need to be closed?** (If so, call it in immediately)	**Does a Bridge Inspector need to look at it?**
1006550	I-990	Arthur St.	13:30	Y	N	Y	Y	N	Y	N	Y	Y			Y

form PBDA rev 2/2012

Figure 5-2. Preliminary Bridge Damage Assessment (PBDA) Form – Completed for One Bridge

5.2 Special Post-Earthquake Bridge Inspection (SPEBI)

The RSE is responsible for orchestrating a program of detailed inspections whenever necessary. The main goal of a SPEBI is to assess the structural integrity of a bridge after an earthquake, with the focus being on the assessment of its seismic performance. A professional engineer will lead these inspections and typically be supported by trained, fully equipped bridge inspection teams who can supply traffic control, special access equipment, specialized tools or whatever else is necessary to do the job in a satisfactory and safe manner.

In addition to evaluating bridges to determine if flagging or closure is necessary, the inspecting engineer may need to judge whether a bridge that has been closed as a precaution during the PBDA phase is actually safe, and can be put back into operation. The inspector may also recommend that it be kept open but restricted to emergency vehicles at slow speeds or with a reduced number of lanes. Secondary objectives of the SPEBI are to provide information to program repair or retrofit work, estimate the value of damage and to gain lessons that might help improve the performance of future structures.

5.2.1 SPEBI Procedures

The SPEBI program is to be done under the direction of the RSE in the affected region. A team leader will follow these steps:

SPEBI Procedure
1. Report to the regional office to confer with the RSE. In some cases, an alternate dispatch station may be used or instructions received by telephone. 2. Determine the inspection priority in collaboration with the RSE. 3. Over the course of the SPEBI program, do not spend time at a bridge that has already collapsed. As long as it is officially closed and barricaded, it is best to move on and inspect others on the list. Time is better spent at bridges that are still standing but are potentially unsafe for traffic. 4. Collect necessary equipment, maps, communications devices, camera, etc. (Appendix D) Utilize a laptop with available databases (such as WinBOLTS and BIPPI), if possible. 5. Review safety procedures with all team members. 6. Examine information provided in the PBDA report, if available. 7. Use one SPEBI form for each bridge inspected. These are provided in Appendix E. Complete the heading information about the bridge, including route, BIN#, and date/time. 8. Conduct an overall assessment first and then progress to individual components. 9. Proceed with the bridge inspection, noting the observed damage by checking the appropriate boxes. The SPEBI form contains five main categories of damage related to different elements of the bridge.

10. For any box checked to indicate damage, make a note of the severity of the damage in the space provided and take a photograph of the damage. Immediately report significant damage to the RSE. Flag as appropriate.
11. After each bridge component has been inspected, proceed to the section 'Overall Damage State'. Summarize the damage observed in the box labeled "General Description of Damage" and make a note on the overall condition of the bridge by checking the appropriate box for 'Overall Damage State.' When making a decision on the overall damage state, it is important to consider the importance of the structural member, the number of members damaged, and the severity of damage that each has incurred.
12. If possible, indicate the probable cause(s) of damage by checking the appropriate box on Page 2 of the form.
13. Use the section "Action" to indicate which measures were taken or need to be taken to ensure the safety of the bridge.
    a. If the conclusion is reached that the bridge should be closed, flag it, contact the RSE and RE immediately, and make a note on the form.
    b. If any boxes were checked in the Damage Checklist under the 'Geotechnical' heading, recommend a geotechnical investigation.
    c. If moderate damage is observed but the bridge is deemed safe for traffic, it may be advisable to recommend further investigation or detailed Load Rating in the space provided.
    d. The team may also recommend that a bridge closed during PBDA may be put back into service as-is, or after some repair, or with some restriction. Check the box 'Repair or retrofit details' and 'Recommend further investigation.' Consult with RSE.
14. Note any additional recommendations in the space provided at the end of the form. Map out major cracks, provide sketches and photos to record all observations. Since the condition of a damaged structure may worsen due to aftershocks or gravity, larger cracks should be monitored in order to provide a more definite means of assessing whether crack size is changing over time.

The form for reporting an SPEBI is provided in Appendix E. Technical guidance on what to look for is provided in subsequent sections of this report.

5.2.2 Prioritizing SPEBIs

The RSE is in charge of the overall inspection program so will be assigning SPEBI's to individual inspectors and prioritizing the order in which the inspections should be done. Since many team leaders have extensive personal knowledge of the bridges in their territory, they will also have valuable input that they can share with the RSE when an order is being determined. The information in this section is provided as an aide to remind the RSE and TLs of various factors to consider and what tools they have available to them when prioritizing.

Certain routes are defined as *lifeline routes* because they are critical links in the highway network. Though a region should have these clearly defined ahead of time, they are also identifiable by their functional classification and high traffic volumes (AADT).

The intensity of an earthquake will be greatest at the location that has experienced the highest ground acceleration (PGA). USGS has a tool called ShakeCast that maps locations of high PGA making it easier for an agency like NYSDOT to know where to focus their inspection efforts. Since this is not currently available in NYS, the proposed ERP relies upon the location of the epicenter. GIS can be used to identify all bridges that lie within a certain radius of the epicenter, so that an inspector can easily identify which bridges may need inspection. Appendix C describes a program that was developed to automatically compute the distance from each bridge to the epicenter and use the information when listing the bridges in priority order. Appendix C also describes other possible tools for generating priority lists.

In addition to proximity, the RSE will want to use other criteria to prioritize the damage assessments:

- PBDA reports

- Initial reports from the media or the general public

- Structural vulnerability. Seismic vulnerability ratings may be available for certain bridges but at the time of this report, because of competing priorities, not all bridges have been rated for seismic vulnerability. For this reason, it will not be possible to use them consistently on a statewide basis. Region 11, however, has assessed bridges in NYC that are on or above routes that they have identified as critical and these ratings should be used to prioritize post-earthquake bridge inspections. The program presented in Appendix C has provisions for prioritizing post-earthquake bridge inspections according to these ratings.

  Among other factors, NYS's vulnerability assessment process uses design criteria (year built is used as an indicator of design sufficiency) to determine a vulnerability rating (VR-S). Structural characteristics that increase the likelihood of failure from an earthquake include: superstructure discontinuities (simply supported spans instead of a superstructure with continuity), skew angle, bearing type and height, lack of lateral bracing, deteriorated condition (as reflected in the condition ratings, especially the primary and secondary structural members), seat length and width, lack of restraint from lateral displacement, vulnerable structure type (e.g., trusses), redundancy, poor seismic detailing of concrete reinforcement, etc.

- Mode of Failure. Although the VR is intended to *anticipate* bridges that might fail catastrophically, the same criteria can be used for planning post-earthquake procedures. Bridges with a failure mode labeled as catastrophic should be kept higher on the prioritized list of bridge inspections than a bridge whose failure would not be considered catastrophic.

- Geological vulnerability. Bridges founded on granular soil in an area with a high water table may be at risk of failure from soil liquefaction, especially if ground shaking is severe or prolonged. This possibility is most likely in coastal settings. Slope failures and lateral spread are other potential consequences.

- Flagged conditions. Since the conditions identified by red or yellow structural flags can compromise a bridge's performance in an earthquake, it is important to consider the presence of flags when prioritizing. The Department's database of flagged bridges is dynamic; it changes almost daily, depending on findings of bridge inspectors. It might be necessary for the RSE to use personal knowledge to supplement computer generated lists.

- Condition. Inspection prioritization tools used on the west coast are frequently based on the assumption that a bridge is in the same condition that it was in when it was designed and built. This is often not the case for NYS bridges. Since the general population of bridges is older, there is usually more deterioration, such as corrosion and fatigue, and this can have an impact on seismic performance. In addition, repairs or modifications from original construction could have been made. For instance, end diaphragms of steel bridges help transfer lateral loads to the substructure. If these have section loss due to rust, they cannot effectively perform that function. Elements with condition ratings between 1 and 3 are in poor condition due to deterioration or are not functioning as designed. These elements are more likely to be damaged in an earthquake and bridges with them should be placed higher on the list of bridges to be inspected. Structural members considered *secondary* may, in fact, be very important with respect to seismic performance.

- Structures carrying essential utilities would also be considered more important than a comparable bridge without utilities.

- Consideration of road closures, construction project, proximity of bridges to one another.

5.2.3 SPEBI Damage Assessment

Since the NYSDOT Bridge Inspection Manual (NYSDOT 1999) gives detailed guidance for completing a typical bridge inspection, this section only gives guidance on seismic issues and completion of the SPEBI form. A checklist approach is used for the post-earthquake inspections to facilitate the job and reduce the possibility of skipping an important item that should be evaluated. Additional considerations are presented below.

Geotechnical

- Look for ground cracks, slope displacements, liquefaction, slides, settlement around the foundation, or exposed piles.
- Have there been any geological failures, evidenced by sloughing, ground cracking, or sand-boils?
- Are all substructure units fully supported? Has there been movement? Have conditions changed?

- If there is any doubt about changed soil conditions, the bridge should be looked at by a geotechnical engineer.

Foundation & Substructure

- Unreinforced concrete or masonry abutments or piers are especially vulnerable to failure. Are there fresh cracks or evidence of movement?
- Are columns plumb? Is there evidence of tipping of the piers or abutments?
- Has the abutment backwall experienced longitudinal pounding from longitudinal movement of the superstructure?
- Be wary of bridges that have piers of varying heights. They are more vulnerable than a similar bridge with piers of consistent height.
- Devise a way to monitor fresh cracks in case there is additional movement from an aftershock.
- Has concrete cover been lost? Is reinforcing steel exposed? Has it pulled out of the concrete or yielded?
- Look critically at the top and bottom of concrete columns that are often intended to be the weak link in the load path. Modern design allows for plastic hinging in this zone to help avoid damage to parts of the bridge, such as the superstructure and deck, that would be harder to inspect and repair. Look for evidence of hidden damage such as cracking, distortion, or an out-of-plumb column. Call for further investigation if a diving inspection, exposure of piles, or other special inspection techniques are warranted.

Superstructure. Look for

- Structural cracks, deformation, displacements and failures. If possible, comment on the type of distress; e.g., bending, shear, or compression.
- Deformation of secondary structural members that might have carried lateral loads (e.g. bent or buckled bracing, end diaphragms).
- Cracked welds, especially if the bridge has a history of flags related to fatigue or weld details.
- Sheared, bent or missing rivets or bolts, especially at connections between structural members.
- Significant cracking or spalling of concrete. Note possible causes: shear, flexural torsion, or pounding.
- Scrape marks, dents, holes, spalls, etc., indicating structural elements sliding or impacting against other elements.
- Condition of restrainers, shear blocks, or other modifications that have been made in an effort to improve seismic performance
- Evidence of movement at hinges, joints, railing, curbs. Provide measurements whenever possible.

Joints & Bearings

- Deformed or displaced bearings.
- Bent, sheared, or missing anchor bolts or evidence of unusual movement.
- Note direction and degree of leaning or tilting.

Approach

- Is the pavement safe for traffic or has it cracked badly, settled, heaved or buckled?
- Is the approach slab still fully supported on soil?
- Have the abutments exerted pressure on the soil behind it and left a gap?
- Is the approach embankment intact or has it sloughed down or cracked badly?
- Is the approach railing safe or has it been displaced or lost support?
- Is there damage to approach retaining walls or mechanically stabilized earth (MSE) systems?

Appurtenances & Utilities

- Are utility lines intact? A leaking water line could cause subsequent damage such as undermining or erosion.
- Are there any alignment issues or discontinuities?
- Have sound walls been damaged? Are they still securely attached? Note that the connections between concrete barrier and sound wall may not have been designed for seismic loading.

For moveable bridges, in addition to assessing the extent of typical structural damage, the mechanical and electrical systems should be carefully inspected for signs of misalignment, damage, or malfunction. After a thorough inspection, the bridge tender should test out the mechanisms, listening for any unusual noises. If the span was in a closed position and then, after operating, in an open position, it should again be inspected to look for damage that may have been hidden.

Non-destructive evaluation (NDE) or structural health monitoring (SHM) techniques may be necessary to detect hidden damage. This could involve the use of thermographic infrared cameras, crack monitoring, load tests, etc. to supplement visual inspections. If it is not feasible to conduct these tests during the post-earthquake inspection, the engineer should suggest *further investigation* on page 2 of the SPEBI form and note the specific recommendation.

The SBEPI form should be complete and clear. Describe the precise location of any damage and provide labeled photographs. Immediately report any significant damage to the RSE.

5.2.4 Sample SPEBI

Below is an example of a completed SPEBI. Figures 5-3 through 5-5 are photos taken to accompany the completed SPEBI form (Figure 5-6). The images demonstrate the documentation of damage that should accompany the written portion of the form. For any damage noted on the form there should be an accompanying visual exhibit, whether it be a photograph or sketch.

Figure 5-3. Settlement at Approach: Spalling (NISEE)

Figure 5-4. Evidence of Longitudinal Pounding (NISEE)

Figure 5-5. Spalling and Splice Failures at Column Base (NISEE)

Special Post-Earthquake Bridge Inspection (SPEBI) Form — NYSDOT

R/C 53
BIN 1040817

Name of Engineer T. SMITH
Date and Time 10/18/2008 7:42 PM

Overall Damage State

- [ ] No earthquake damage
- [ ] Minor damage
- [X] Moderate damage
- [ ] Major damage
- [ ] Collapsed

General description of damage:
MODERATE POUNDING & SPALLING DAMAGE.
MINOR SETTLEMENT AT SOUTH APPROACH.

Describe performance of any previous seismic retrofit:
(NONE)

Earthquake Damage Checklist: Include Description and Photo Documentation

Geotechnical

- [ ] Slope failure
- [ ] Liquefaction
- [ ] Lateral spreading of slopes
- [ ] Ground faulting
- [X] Approach settlement — 2" at SOUTH END
- [ ] Other

Foundation

- [ ] Visible damage or displacement
- [ ] Other

Superstructure

- [ ] Horizontal displacement
- [ ] Collapsed span(s)
- [ ] Partially dropped span
- [X] Longitudinal pounding — MODERATE, AT HINGE JOINT
- [ ] Deformed diaphragms or lateral bracing
- [ ] Damaged primary member
- [X] Cracked or damaged deck — MINOR CRACKING (SEE SKETCH)
- [ ] Damage to critical element (hinge, hanger, suspender, cable)
- [ ] Railing or barrier misalignment
- [ ] Damage to utility lines, lighting, etc.
- [X] Other — SPALLING ON barrier RAIL (MINOR)

Substructure

- [X] Spalled columns — MODERATE SPALLING + SPLICE FAILURE AT BASE OF EAST COLUMN
- [ ] Plastic hinging of columns
- [ ] Shear failure
- [ ] Reinforcement pullout
- [ ] Damage to pier cap
- [ ] Displacement or damage to abutment, backwall, wingwall
- [ ] Damaged steel, concrete, or FRP jacket
- [ ] Tipped pier
- [ ] Other

Joints & Bearings

- [ ] Toppled
- [ ] Excessive deformation or displacement
- [ ] Broken or damaged anchor bolts
- [ ] Damaged or malfunctioning joint
- [ ] Other?

Page 1 of 2

Figure 5-6. Special Post-Earthquake Bridge Inspection Form (page 1)

Probable Cause of Undesireable Performance

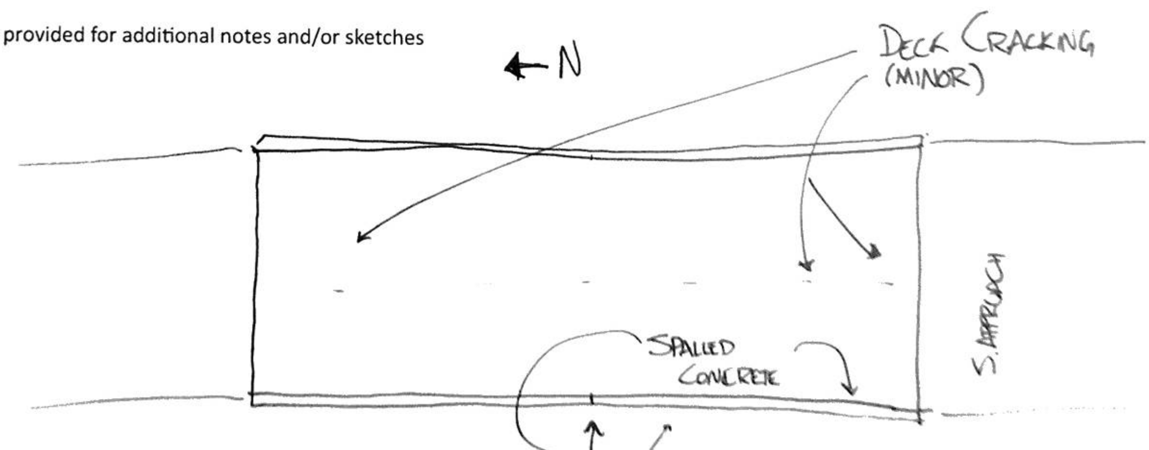
- [ ] NA
- [ ] Deteriorated condition (e.g. corrosion)
- [ ] Discontinuity of reinforcement (e.g. insufficient lap)
- [x] Ground settlement/movement
- [ ] Inadequate confinement steel
- [ ] Instability of bearings (e.g. rocker bearings)
- [ ] Insufficient shear capacity
- [ ] Insufficient support length (seat width)
- [ ] Lack of continuity
- [ ] Lack of redundancy
- [ ] Large skew
- [x] Non-seismic design (pre 1975)
- [ ] Retrofit measure did not perform as intended
- [ ] Secondary hazard (scour, fire, etc.)
- [ ] Steel deficiency due to historic fatigue cycles
- [ ] Uplift
- [ ] Varying column heights (different stiffness)

Notes:

Action

- [ ] Flagged (see flag report for detail)
- [x] Repair Request: REPAIR DAMAGE TO EAST COLUMN and POUNDING DAMAGE AT HINGE JOINT
- [x] Recommendations: CLEAR DEBRIS FROM SPALLING – CURRENTLY A HAZARD TO TRAFFIC
- [x] Further investigation needed:
  - [ ] Special Structural Investigation and Analysis
  - [x] Repair or retrofit details
  - [ ] Level 1 Load Rating
  - [ ] Geotechnical Investigation

Space provided for additional notes and/or sketches



Signature of Engineer

Page 2 of 2

Figure 5-6. Special Post-Earthquake Bridge Inspection Form (page 2)

5.3 Photographs of Bridge Damage

This section gives photographic examples of earthquake damage.

<u>Approach</u>

Approaches to bridges can undergo settlement (Figures 5-7 through 5-9), cracking, heaving, and/or lateral movement. If the vertical settlement is greater than 6 inches, the condition represents a significant hazard to the traffic. In this case, the condition should be considered “severe damage.” Although closure of the bridge may be warranted, it would be best to consult with the RE before doing so. For operational reasons, it may be necessary to keep the bridge open to restricted traffic (e.g., for emergency use only or traffic reduced to 5 mph). If the settlement is 2 to 6 inches, the condition may be considered moderate. Most vehicles could safely cross the bridge after a complete stop at the settlement location. Minor Damage is less than two inches of settlement and noted on the PBDA form. Spalling and cracking of the approach slab should be noted as well.

Settlement of the approach slab is often a result of soil movement around the abutments (lateral spread or liquefaction). Hence, if the approach has settled, particular attention should be given to evaluating the condition of the foundation and substructure.

Figure 5-7. Moderate Damage: Approach Slab Settlement (Sardo, A. G., et al., 2006). Note the cracking of the concrete barrier as well.

Figure 5-8. Approach Damage Considered Moderate to Major (Northridge Earthquake) (PEQIT)

Figure 5-9. Settlement of Bridge Approach, Considered Major Damage (KTC)

Geotechnical Problems

All bridges (except floating bridges) are founded on soil or rock and any bridge is only as strong as its foundation. Earthquakes create ground shaking that can damage the substructure and superstructure, but can also cause soil problems. For instance, a seismic event can result in a loss of shear strength in loose, cohesionless soil when the water table is high – called liquefaction.

Soil liquefaction and lateral spread are common ground failures that can accompany earthquakes, especially strong ones or ones with a long duration. A loss of bearing capacity caused by soil liquefaction can cause foundation failure, settlement, or tilting of abutments and piers. Settlement can result in a discontinuity in the superstructure between spans or between the bridge deck and the approach slab. An inspector should be aware of the range of ground failures that can occur and be able to identify them. Bridges in coastal areas and those without piles are especially susceptible. Figure 5-10 illustrates what liquefied soil might appear like, although it appears that this bridge did not suffer major damage. In other cases, the pier may be left tilted. Slope failure could be the cause of the condition found in Figure 5-11. Discovery of this situation should prompt the inspector to investigate the supporting embankment.

Figure 5-10. Evidence of Liquefaction near a Pier (NISEE)

Figure 5-11. Settlement at the Bridge Approach, Likely Caused by Soil Settlement around the Abutment (Northridge EQ) (NISEE)

Primary and Secondary Structural Members

The girders (which are also called stringers or beams) should be inspected for any damage as well as shifting or misalignment. Concrete spans in particular should be inspected for flexural cracks, shear cracks and spalling at the bearings (Figures 5-12, 5-13). Excessive deflection should also be noted, as this may indicate the span is not capable of supporting legal live loads. Although extreme uplift forces are not typical in an earthquake, if they occur, there can be damage from the unanticipated negative bending, especially to prestressed beams. This type of damage was discovered after Hurricane Katrina (O'Connor & McAnany, 2008).

Steel spans require more careful inspection since the damage may not be immediately noticeable as it is in concrete components. The primary structural members should be checked for local damage, such as buckling. However, often the secondary members fail or deform due to unanticipated lateral loading so diagonals, diaphragms, and end cross frames should be checked carefully (Figure 5-14). All plates, hangers, and assemblies should also be examined. It is helpful to look for chipped paint or exposed primer, often of a different color, as this can indicate localized damage to a steel member (Figures 5-15, 5-16). All connections and areas that were subjected to unusual stresses should be inspected thoroughly. Look for cracked paint and cracks in the welds. Look for anchor bolts that are sheared or elongated; all bolts should be intact and nuts tight (Figure 5-17). The girders should be inspected for any misalignment, cracking or cracked welds (Figures 5-18, 5-19), especially fatigue sensitive details. Especially crucial are the "pins and hangers" used to support suspended spans of a steel girder bridge. This detail is considered a seismic vulnerability since damage or displacement can lead to complete loss of span support.

Figure 5-12. Moderate Damage: Spalled Concrete (WSDOT)

Figure 5-13. Moderate Damage: Flexural Cracking of Concrete Girder (KTC)

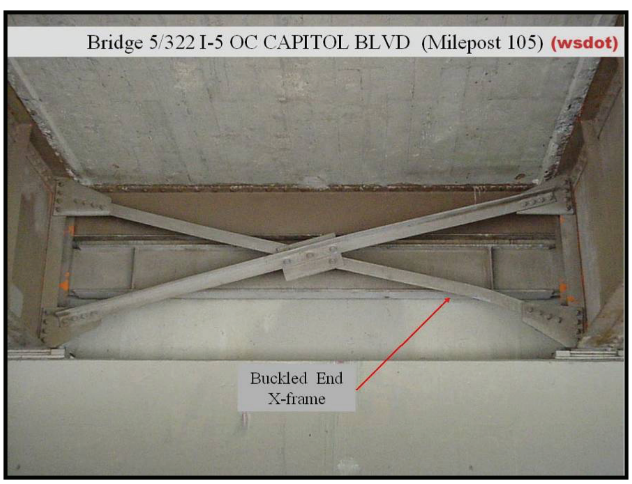


Figure 5-14. Minor Damage: Buckled Bracing Element . (WSDOT)

Figure 5-15. Minor Damage: Web Stiffener Damage. Note that the paint has flaked off recently. (MCEER)

Figure 5-16. Moderate Damage: Crack in Web of Steel Girder. Note that this may be a red flag condition if it is in the primary member. (CPHMR)

Figure 5-17. Minor Damage: Damage to Anchor Bolts (MCEER)

Figure 5-18. Moderate Damage: Fracture of Lower Lateral Bracing (MCEER)

Figure 5-19. Severe Damage: Steel Girder Buckling (MCEER)

Many multiple-span bridges were constructed as a series of simply supported spans so the superstructure is not continuous over the piers. Earthquake induced motion can lead to loss of support at the end of a beam, leading to a collapse of a span. In general, continuous girder bridges perform better. Likewise, single span bridges generally do well because the abutments provide a certain amount of longitudinal and lateral restraint.

Deck Damage

The bridge deck often reveals valuable information as to whether the structure has experienced forces or movement sufficient to cause damage. Major deck spalling, displacement at joints and deflections within spans are indicative of superstructure and/or substructure damage. Displacement of joints indicates that displacements likely occurred at the top of the piers. During seismic events, bridges, especially those with large skews, will commonly experience lateral movement perpendicular to the span, which will open joints or show evidence of misalignment in the pavement striping. Longitudinal motion may cause *pounding* of one span against an adjacent span, which can cause spalling of the deck, barrier and/or curb concrete. Sometimes this type of damage does not represent a structural problem itself, but the debris may jeopardize the safety of the traveling public (Figure 5-20). A slight drop of the deck at a joint illustrated in Figure 5-21, may be classified as moderate. Determination of the cause requires more investigation. There may be additional damage visible from below. Figures 5-22 through 5-24 illustrate severe failures.

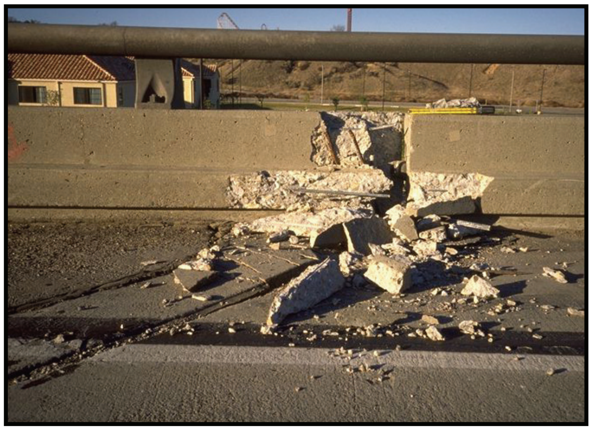


Figure 5-20. Minor Damage: Parapet Crushing / Spalling (NISEE)

Figure 5-21. Minor to Moderate Damage: Vertical and Horizontal Movement at Joint (NISEE)

Figure 5-22. Severe Damage: Deck Collapse (KTC)

Figure 5-23. Severe Damage: Deck collapse (USDOT)

I-10 and SR 118 Damage from Northridge EQ
http://itsdocs.fhwa.dot.gov/jpodocs/repts_te/13775.html

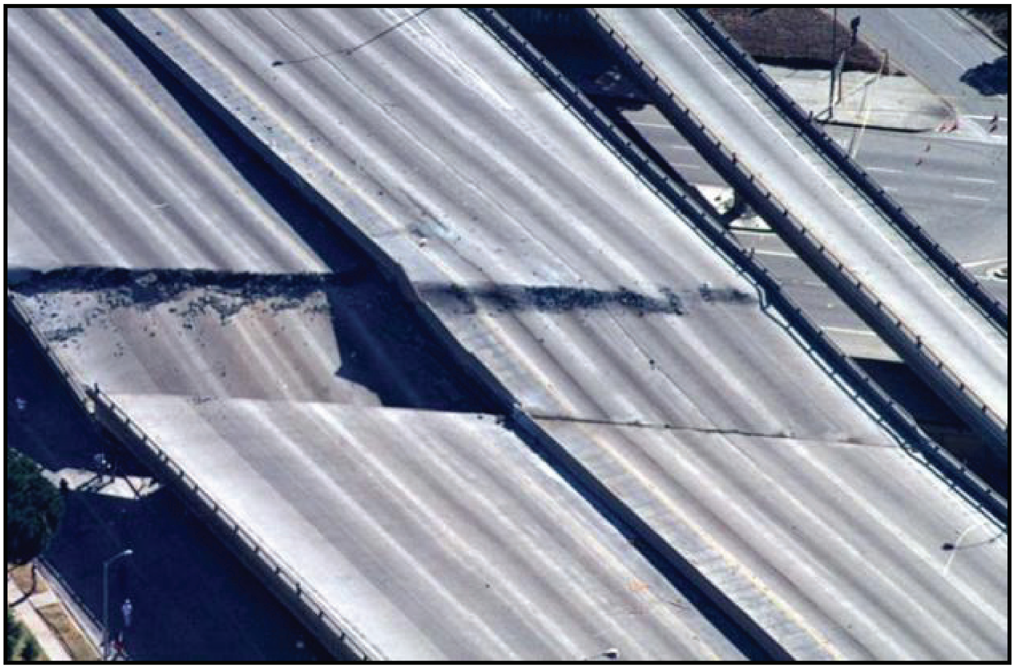


Figure 5-24. Severe Damage: Deck Collapse (USDOT)

(I-10 and SR 118 Damage from Northridge EQ
http://itsdocs.fhwa.dot.gov/jpodocs/repts_te/13775.html)

Piers and Columns

Concrete piers or columns may show flexural and/or shear cracks after an earthquake. If the cracks are superficial and if the concrete cover spalls over a limited area, the damage is minor but must still be noted on the PBDA. If the concrete cover spalls over a large area and the cracks penetrate into the core of the column (defined by the area within the limits of the lateral confining steel, such as hoops, ties or spirals), the damage should be considered moderate or severe and this should be noted on the form. There is not much room for judgment between the categories of moderate and severe. If a majority of the cracks are diagonal (indicating shear failure), the condition should be assessed as severe, until further inspection can be completed. Buckled or fractured reinforcement is also indicative of severe damage. More often than not, the noted damage will be at the top or bottom of the columns or piers. The top of the columns should be investigated for damage to the concrete and bearing. The bottom of the columns should be investigated for damage to the concrete and reinforcement but also for dislocated soil, liquefaction, fissures, and differential settlements as an indication of foundation movement and possible damage to the footings. (Figures 5-10 and 5-25) Figures 5-6, 5-25 through 5-35, and 5-53 show columns in various damage states.

Figure 5-25. Ground Movement Indicating Possible Foundation Problem (MCEER)

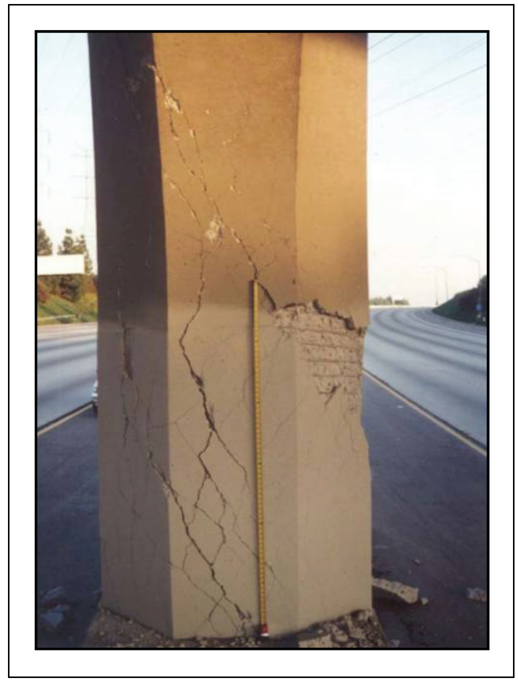


Figure 5-26. Minor Damage: Cracking and Spalling of the Concrete Cover at the Column Base (KTC)

Figure 5-27. Moderate Damage: Compression Failure at Top of Concrete Column (INDOT)

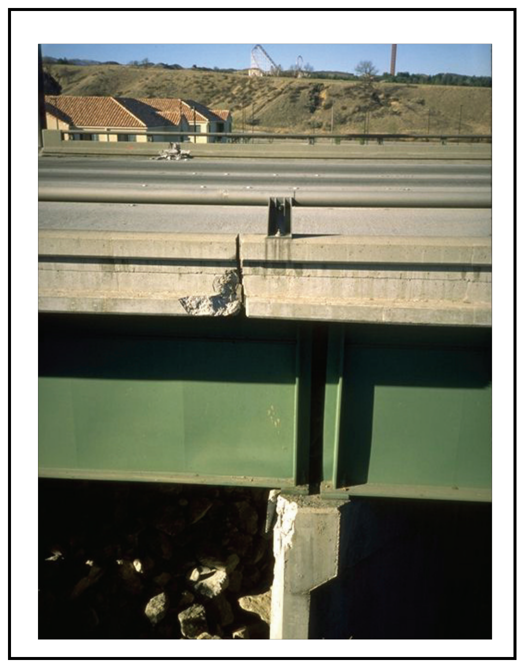


Figure 5-28. Moderate Damage: Support Damage at Top of Pier. Minor Damage: Fascia Concrete (MCEER)

Figure 5-29. Severe Damage: Mid-height Flexural Damage (PEQIT)

Figure 5-30.
Moderate to Severe Damage: Spalled Column; Buckling of Primary Reinforcement (MCEER)

Figure 5-31.
Severe Damage: Confinement Failure (MCEER)

Figure 5-32.
Moderate Damage: Column Shear (NISEE)

Figure 5-33.
Severe Damage: Brittle Shear Failure (NISEE)

Figure 5-34. Severe Damage: Weld Failure of Column Longitudinal Reinforcement (MCEER)

Figure 5-35. Severe Damage: Shear Failure (1971 San Fernando Earthquake) (MCEER)

Joints

Relative displacement of spans is often evident at joints. (Figures 5-36 through 5-38) This can result in joints that do not function as intended but may also mean that there is more serious damage underneath. For instance, a vertical displacement at the joint may mean that a bearing has toppled or been damaged. To know conclusively, the area must be examined from below the deck.

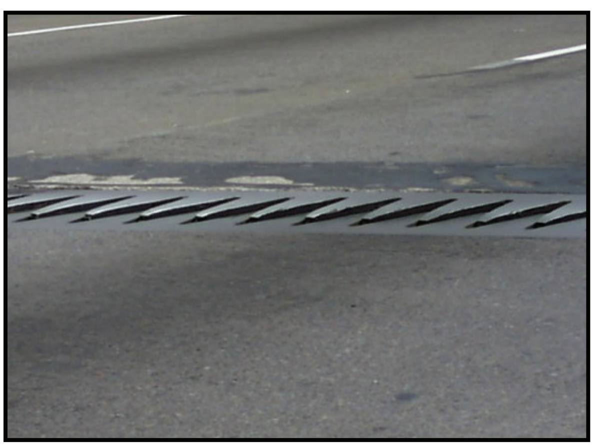


Figure 5-36: Minor Damage: Misaligned Finger Joint (MO)

Figure 5-37: Minor Damage: Transverse Movement Along the Centerline (COHMR)

Figure 5-38: Moderate Damage: Differential Settlement and Expansion Joint Damage (PEQIT)

Bearings

Bearings at the abutments and piers should be inspected for toppled assemblies, sheared or loosened bolts, sheared keeper plates and movement. Spans supported by tall rocker bearings such as those shown in Figure 5-39 are subject to large vertical drops. Cracked or spalled concrete at pedestals may also indicate damage to bearing assemblies (Figure 5-40). In addition, the bridge seats should be checked for adequate seat width to support the adjoining spans. If there is a changed condition such that less than 4 inches is available, this should be noted. Figures 5-41 through 5-44 show situations with severe damage to bearings.

Figure 5-39. No Damage: Tilted Rocker Bearings, Movement Due to Thermal Loads (INDOT)

Figure 5-40. Minor Damage – Cracks Induced by Steel Bearing (CPHMR)

Figure 5-41. Moderate Damage: Abutment Rocker Bearings. (MCEE)

Figure 5-42. Severe Damage: Toppled Rocker Bearing (MO)

Figure 5-43. Severe Damage: Rocker Bearing Failure (MO)

Figure 5-44. Severe Damage: Missing Abutment Bearing after Northridge (PEQIT)

Abutments

Transverse movement may displace or crack the cheek-walls, wing-walls (Figures 5-45, 5-46) and any abutment shear blocks. Longitudinal movement during an earthquake may damage the abutment stem and/or backwall (Figure 5-47). Examine abutment backwall and wing-walls for flexural or shear cracks, which may be less obvious than abutment movement. Loose or settled fill, slope failures, liquefaction, fissures and differential settlements at the base of the abutments may be observed as evidence of foundation movement and possible damage. If any evidence of cracking or displacement is observed, be sure to note it on the form and specify the location in the 'Comments' field.

Figure 5-45. Minor Damage: Shear Cracking at the Abutment Wing-wall (KTC)

Figure 5-46. Moderate Damage: Abutment Slumping and Rotation Failure (NISEE)

Figure 5-47. Moderate Damage: Spalling and Cracking of Abutment, Movement at Ground Level (MO)
Note that the rebar is not rusting, an indication that damage is recent.

Figure 5-48. Moderate Damage: Bowing of Parapet and Railing (MO)

Secondary Systems

During a damage assessment, it is important to examine secondary systems because even nonstructural elements can provide insight as to the extent of damage. While the bowing of the railing in Figure 5-48 or the misalignment in Figure 5-49 or 5-51 may not be immediate cause for alarm in itself, the problem may indicate a more serious problem with the bridge substructure or footing. Concrete barrier (also called a parapet) can often be inspected for fresh cracks that might indicate the recent movement.

When examining secondary systems, take care to investigate all of the following elements for potential problems:

- Bridge Rail
- Curb (alignment)
- Power Lines
- Lighting and Lamp Posts
- Piping (bridges often carry water lines, gas lines, or conduit for telecommunications wiring, or electric cable). See Figure 5-50.

Figure 5-49. Misalignment of Curb Line and Bowing of Railing. Notice that the white edge line is slightly shifted at the joint. (MO)

Figure 5-50. Movement of Trusses at Pier 23 of the San Francisco Oakland Bay Bridge during the Loma Prieta Earthquake. The shoe (at the right) hit two pipes that carried electric wires and dented them. These dents indicated that there was at least 3 to 4 inches of movement. (NISEE)

Figures 5-51 and 5-52 further illustrate conditions that may be encountered. While these changed conditions may not be cause for alarm, they should be noted in the inspector's report.

Figure 5-51. Moderate Damage: Transverse Movement of the Abutment Wing-wall (CPHMR)

Figure 5-52. Minor Damage: Wing-wall and End-wall (CPHMR)

5.4 Repair and Retrofit of Earthquake Damaged Bridges

5.4.1 Introduction

As with any bridge inspection, earthquake response procedures call for immediate closure of a bridge that is deemed unsafe. Since closures cause inconvenience in normal times, they can be expected to be very disruptive in the aftermath of a damaging earthquake since a closed route will deter response and recovery efforts. Tenders of moveable bridges will need to carefully test out the operation of their structures to be sure no misalignment or hidden damage has occurred. Additionally, a critical bridge may need to be temporarily shored or repaired so it can be functional for restricted traffic such as emergency vehicles.

This section provides guidance on the repair and retrofit of bridges that have been damaged by an earthquake. The retrofits are categorized as immediate, short term and long term since the amount of effort, time required and expense can vary greatly, depending on the level of serviceability needed. Its use will provide a systematic means of considering various repair or retrofit strategies, given observed deficiencies and level of damage.

Post-earthquake retrofit can be classified into three categories, as follows: (1) Immediate, (2) Short-term, and (3) Long-term retrofit. An immediate retrofit is intended to stabilize the bridge and reduce the likelihood of further damage or progressive collapse, particularly during aftershocks. It is also intended to make the site safer for further detailed inspection and retrofit. The short-term retrofit is intended to make the bridge safe for light emergency traffic (police cars, and ambulances), heavy emergency traffic (fire trucks) at limited speed, or all traffic. In some cases, immediate and short-term retrofit may overlap, where the immediate retrofit may serve as a short-term retrofit. A long-term retrofit is intended to restore the bridge to its original condition, and possibly strengthen the bridge to improve its seismic performance.

None of these strategies should be undertaken without the guidance of a professional engineer. Repairs and retrofits, especially those being considered under emergency situations, require extreme caution and careful design. For instance, a bridge that has been weakened by an earthquake may be vulnerable to aftershocks as well as other hazards. Even temporary repair measures need to account for situations that may not be routinely expected. Traffic loadings may be different than is normally assumed. The presence of damage and unusual circumstances will require the use of good engineering judgment during development of a repair scheme and when it is implemented.

Short-term retrofits could be performed by DOT Bridge Maintenance crews or by contractors but may have to be strengthened or modified at a later date to ensure satisfactory long term performance. Contractors are frequently called upon to help respond to an emergency, with the state reimbursing them for time, materials and equipment rental. In some instances, the region may have stand-by contracts in place, in anticipation of a situation where their own crews do not have the resources to complete the job. These are sometimes called “where & when” contracts. Long-term retrofits will usually be done through a normal contract letting process. The solutions presented in this report are the same, regardless of how they are accomplished.

In order to select a retrofit system for a seismically damaged bridge member, it is very important to understand the behavior of the bridge, identify the load path(s), and understand the purpose of each bridge element/sub-element. A good field assessment will lead to a cost-effective and efficient retrofit system.

A basic, but powerful, method for assessing structural members is identification of the purpose of the damaged element or sub-element. For example, a fracture of a column stirrup (transverse reinforcement) means the column has (1) lost some if not all of its shear strength resisted by steel, (2) lost lateral confinement of column section, and/or (3) lost some longitudinal bracing against intended to protect against buckling of the longitudinal reinforcement. Knowing the purpose of the stirrups (Figure 5-53) in a column makes it easier for inspectors and engineers to identify the discontinuity of the load path, and select a proper retrofit system.

5.4.2 Materials

Several construction materials could be used for post-earthquake retrofit of bridges. They include but are not limited to: steel, concrete, polymers, polymer concrete, and fiber reinforced polymer (FRP) composites. Timber has also been used effectively as cribbing to shore up a damaged span. The selection of a particular material depends on the application, state of stresses in the damaged member, condition of the bridge, and speed of repair.

Figure 5-53. Earthquake Damage to Reinforced Concrete Bridge Column (Aboutaha)

Steel

Steel elements used for post-earthquake repair of bridges come in various forms; prestressing steel, steel plates, steel jackets, steel collars, bolts, structural elements.

External prestressing is the most efficient method used to close cracks opened resulting from overload, as it produces active compressive pressure across the crack. Prestressing steel used for post-earthquake repair of bridges comes in two forms, prestressing strand and bars. The stands are applicable for various applications, while the bars are used for straight member applications. The ultimate strength of low-relaxation prestressing strands is about 270 ksi, while for prestressing bars it is about 150 ksi. Figure 5-54 shows application of external post-tensioning of a pier cap beam.

For bridge retrofit applications, steel plates have been used in the form of steel jackets to provide shear resistance, confine the column section, and confine short lap splices in longitudinal bars.

Structural shapes, e.g., W-shapes, could be used to shore a bridge superstructure. This would be done to guard against failure initiated by damage to superstructure girders or bearings. In addition, small sections of structural shapes could be used to restrain/control the lateral movement of bridge girders, as shown in Figure 5-55.

FRP Composites

For seismic retrofit applications, FRP composites could be used for confining bridge columns, provide shear resistance, and confine short lap splices in longitudinal bars. Their application for post-earthquake repair should be adopted with caution near cracked sections, as they are very sensitive to stress concentrations.

Polymer Modified Concrete

Polymer modified concrete, which is a regular Portland cement concrete modified with polymer emulsion, could be used to restore the shape of damaged concrete members before wrapping with FRP composite jackets or steel jackets.

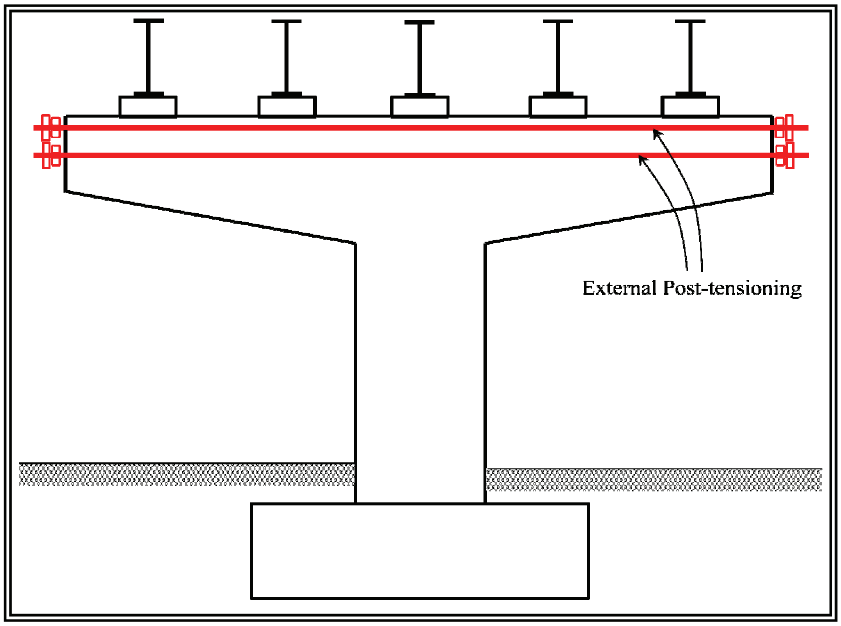


Figure 5-54: External Post-tensioning of Pier Cap Beam (Aboutaha, 1993)

<u>Polymer Concrete</u>
Polymer concrete, which consists of polymer and fillers, has high compressive and bond strength. It could be used for restoration of small but critically damaged concrete sections. It also has the advantage of rapid set and cure time. This will be beneficial in situations where it is important to get a bridge back in service as quickly as possible.

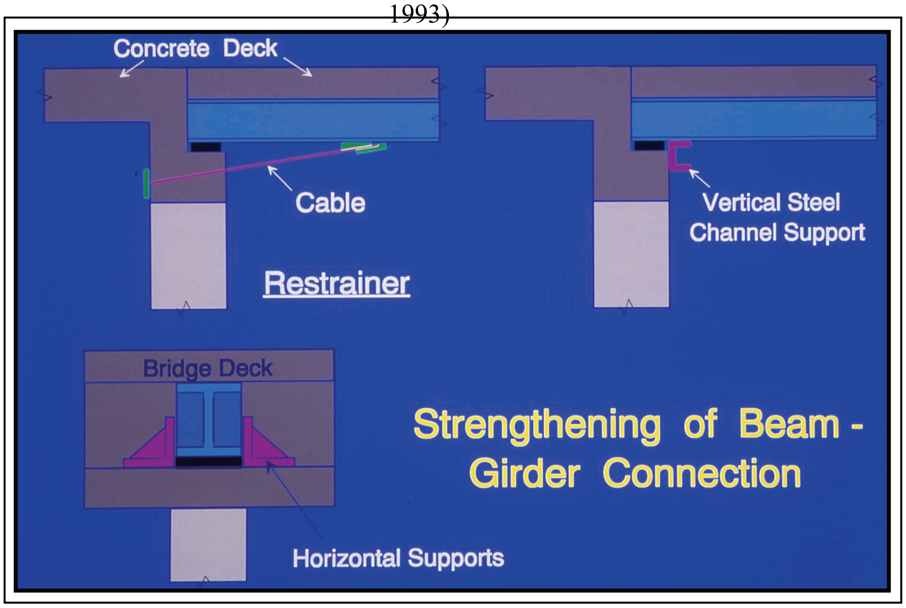


Figure 5-55. Use of Structural Shapes for Seismic Retrofit of Bridge Superstructure (Aboutaha, 1993)

<u>Non-Shrink Grout</u>

To ensure transfer of loads between concrete and structural steel members used for retrofit and shoring, a non-shrink grout is used to fill the gap at the interface. In general, non-shrink grout has high compressive strength, and high flowability. It can either be a cementitious or epoxy grout.

Several other repair materials could be used as part of a structural retrofit system, which includes but is not limited to: regular Portland cement concrete, adhesive and end-bearing anchor bolts, welding electrodes, elastomeric bearing pads, and hydraulic flat jacks and cylinders.

5.4.3 Bridge Elements

This section presents several retrofit techniques that could be adopted for post-earthquake repair of damaged bridge elements. For every type of bridge element, recommendations for immediate, short-term, and long-term retrofit are presented. While retrofitting a damaged bridge after a seismic event, it is important to remember that the objective is to maintain the continuity of the load path by restoring the damaged elements and sub-elements.

Retrofit of Damaged Approach Roadway

Approach damage is classified minor, moderate, or severe based on the amount of settlement of the approach slab, pavement or embankment. By itself, the settlement may not pose a serious safety hazard, however, it would pose a driving hazard that may affect traffic safety.

For severe settlements exceeding six inches, the wing-walls should be examined, as mentioned in previous sections. It is also possible that the soil will have collapsed around the wing-wall without causing a wing-wall failure.

The pavement of the approach wall could be refilled/repaved, as found appropriate by the pavement engineer.

Retrofit of Damaged Bridge Decks

Bridge deck damage is usually caused by damage in the components of the superstructure system, girders and bearings. It may range from minor joint damage due to adjacent spans pounding at the deck joint to a more severe damage due to severe tilting or toppling of rocker bearings. Minor damage in the bridge deck could be easily repaired with polymer modified Portland cement concrete. Localized minor damage of the deck joint may involve replacement of the joint, and the use of polymer concrete for repair of the joint edge. For immediate retrofit, a slightly damaged/misaligned bridge joint may be covered with a one-inch thick steel plate. This would allow the bridge to be opened to restricted emergency traffic.

Severe deck damage may require replacement of the bridge deck. In some cases, replacement/repair of the superstructure system may also be necessary. A thorough inspection will be required.

Retrofit of Damaged Bridge Girders

The majority of bridge girders are made of steel or reinforced/prestressed concrete. For steel girders, seismic damage may result in local buckling at the most critical sections, and at the connections, including the bearings. A slight local buckling might be classified as minor damage, and as a result, no immediate retrofit is needed. However, moderate and severe local buckling would require welding of a stiffener to the buckled region. If it falls over a bearing, the stiffener should be the full depth of the girder web.

Fracture of part of a section of a steel girder is considered severe as the crack may propagate suddenly causing a more critical condition. Repair of fractured steel elements will require some analysis and input from a materials/welding specialist. It is possible that the damaged section can be removed and replaced by welding in a new plate of the same material and dimensions. In other cases, re-welding of a crack may be sufficient. Expert opinion is needed.

For reinforced concrete girders, minor flexural cracks do not affect the flexural strength of the girder, and no immediate retrofit is needed. However, in order to maintain the girder in good durable condition for the rest of its service life, the cracks should be sealed. For moderate flexural cracks, FRP composite sheets could be bonded to the tension side of the girder (Figure 5-56), and for severe flexural cracks, external post-tensioning might be needed for short and long-term retrofits.

For reinforced concrete girders, regardless of the size of the crack, a shear crack is considered severe damage, and requires structural retrofit. Minor and moderate cracks could be repaired with FRP sheets, and major shear cracks with external post-tensioning. (American Concrete Institute 2, VSL Systems 2010).

For prestressed concrete girders, regardless of the size of the crack, all flexural and shear cracks are considered severe damage, and must receive immediate structural repair. An in-depth analysis of the damaged beam may also be required, depending on the type and extent of damage. If there is loss of prestressing in a beam, it may be possible to restore it to service by installing an external prestressing system that uses steel or carbon FRP (CFRP). (American Concrete Institute 2, VSL Systems 2010).

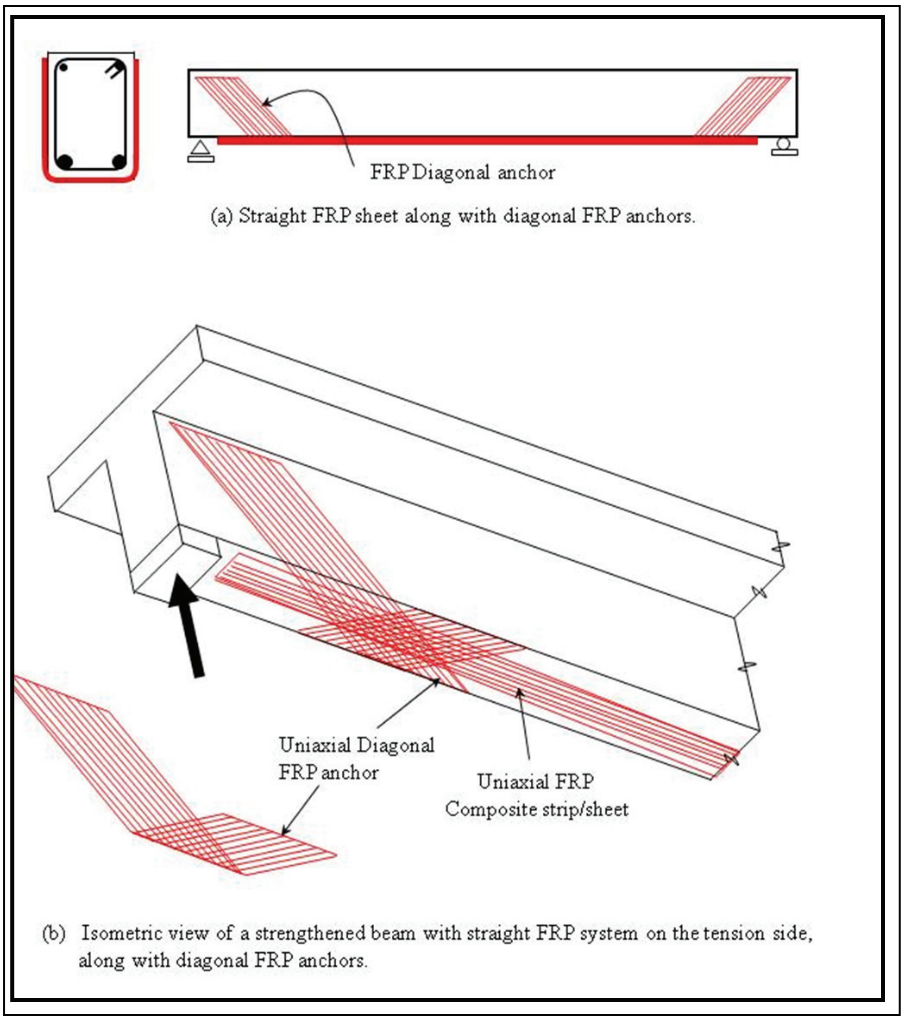


Figure 5-56. Retrofit of Bridge Girder with FRP Composite Sheets (Aboutaha, 2004)

During a seismic event, concrete girders may experience damage at the end sections, near the bearings. This is a critical situation in prestressed concrete girders as the end of the girder is the prestress transfer zone. Any concrete damage in the transfer zone affects the bond between the prestressing steel strands and the surrounding concrete. Such damage should be repaired with epoxy mortar to restore the bond between the prestressing strands and the surrounding concrete. If the concrete damage is very severe in the transfer zone, then transverse clamping might be needed along with epoxy mortar or polymer modified concrete.

Figure 5-57. Seismic Retrofit of a Bridge Column Using a Steel Jacket (Aboutaha, 1994)

Retrofit of Damaged Bridge Piers and Columns

Bridge piers and columns are the primary lateral and gravity load resisting systems. Depending on the magnitude of the earthquake, and the details of the bridge piers/columns, seismic forces/deformations may produce minor to severe shear cracks, fracture of transverse reinforcement, crushing of the concrete in the plastic hinge regions, failure of lap splices in the longitudinal bars, buckling of longitudinal bars, and/or spalling of the concrete cover.

Any shear crack makes a bridge column vulnerable to seismic aftershocks. Therefore, shear cracks in columns should be repaired before the bridge is open for unrestricted emergency traffic. If the shear cracks are minor, then the bridge could remain open for restricted emergency traffic. However, it is recommended that FRP wrapping be used to retrofit immediately columns that have even minor shear cracks. Alternatives to FRP wraps are straps consisting of high strength steel, CFRP, flexible flat stock or rebar. An example of high tensile steel strapping can be found at http://www.americanstrapping.com/asc/asc.html. Collars made of steel angles would be suitable for rectangular columns. For columns with yielded stirrups and/or fractured stirrups, FRP wrapping/steel jacketing is required before the bridge is opened to traffic. Figure 5-57 shows seismic strengthening of a bridge column using a steel jacket.

Spalling of concrete cover reduces the shear strength of the column, exposes the reinforcing bars, and partially damages the bond between the steel reinforcing bars and the surrounding concrete. In spite of these facts, just spalling of the concrete cover causes minor concern so the bridge may remain open to restricted emergency traffic until repairs are made. Repair of columns with spalled concrete cover involves removal of all loose concrete (without chipping concrete behind the steel reinforcing bars), replacement of concrete cover, then wrapping the column with FRP composites, as shown in Figure 5-58.

Failure of lap splices in the longitudinal reinforcement makes the column very vulnerable to seismic forces/deformations, as it destroys the bending resistance of the column. Lap splice failure results in bond failure between the spliced bars and the surrounding concrete. It is typically associated with cracks in the lap splice region parallel to the spliced bars. Moderate aftershocks may cause the complete collapse of the bridge column with damaged lap splices, and consequently the whole superstructure. Therefore, columns with visual evidence of lap-splice failure should be repaired carefully to restore the integrity of the splice and the bond between the

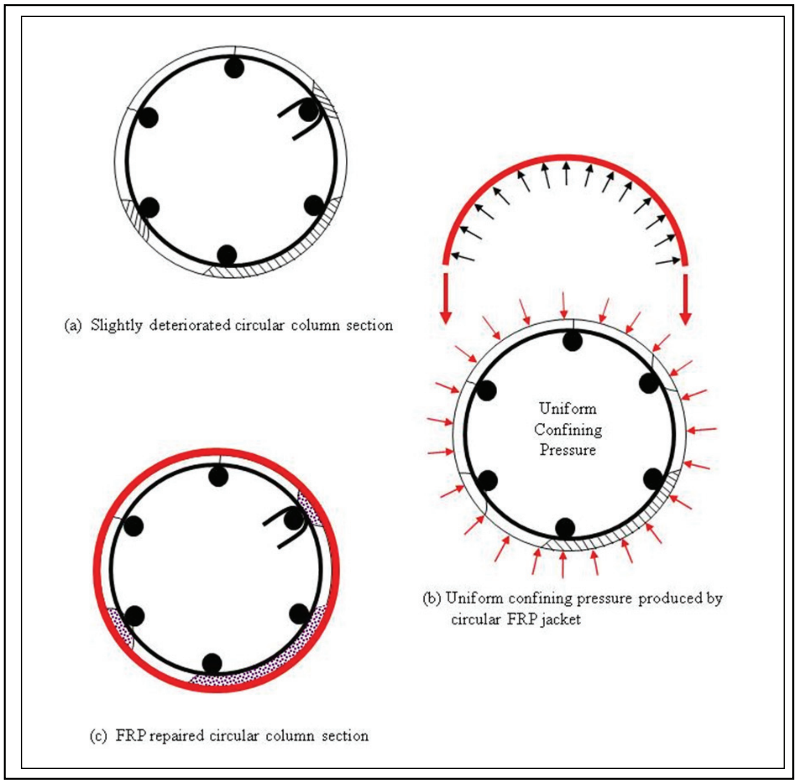


Figure 5-58. Seismic Retrofit of Bridge Column with FRP Composites (Aboutaha, 2004)

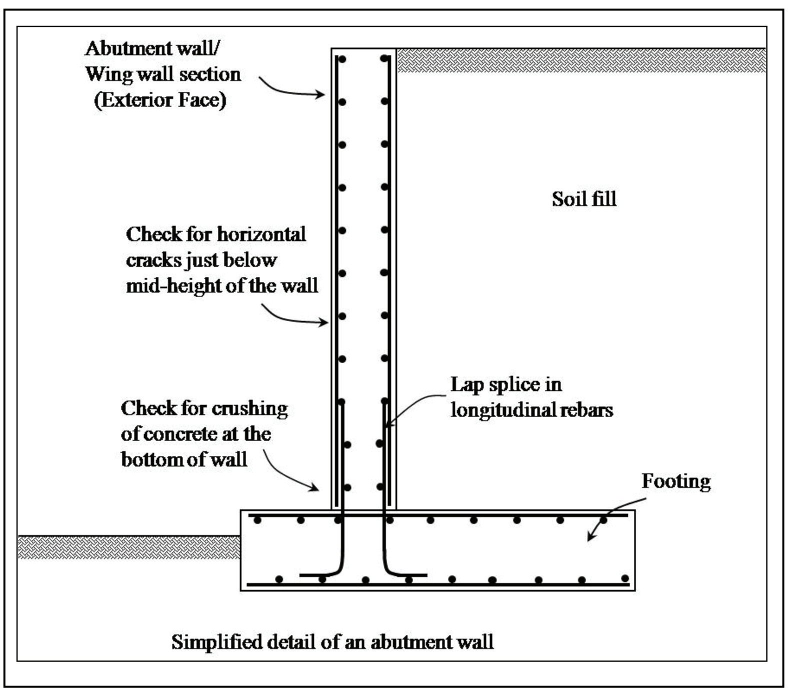


Figure 5-59. Typical Cross Section of an Abutment/Wing-wall, (Aboutaha, 2004)

lap-spliced bars and the surrounding concrete. Such repair may involve removal of all loose concrete, chipping about ¾" concrete behind the spliced bars, welding the longitudinal bars (depending on the type of steel) and then replacing the removed concrete with polymer modified concrete. To ensure good performance during future seismic events, the column section over the lap splice region should be wrapped with FRP composite sheets.

Retrofit of Damaged Bridge Abutments

Concrete crushing at the bottom of the exterior surface of the wing-wall might be caused by flexural failure of the wing-wall (Figure 5-59). In this case, the wall should be braced with diagonal structural members as an immediate and short-term retrofit. For long-term retrofit, the wall might need welding of the lap splice in the longitudinal bars at the base of the wing-wall, and the damaged concrete might need replacement.

Horizontal cracks at or near mid-height of an abutment wall might be caused by flexural failure of the wall, particularly if associated with concrete crushing at the bottom of the wall. If the cracks at the mid-height of the wall are minor, and the wall does not exhibit major deformation, then just sealing of the crack is adequate. Otherwise, the superstructure might need shoring in preparation for major retrofit of the abutment.

Retrofit of Damaged Bridge Bearings

Seismic forces/deformation may cause sliding/shifting, tilting, or complete failure of the bridge bearings, especially rocker bearings. These modes of failure are usually associated with cracking and damage of the pedestals/concrete pier cap beam. In addition, bearing failure might be associated with fracture of the anchor-bolts connecting the bearing assembly and the pedestal/pier cap beam.

The repair of bridge bearings starts with shoring the superstructure using hydraulic flat jacks or cylinders, as the space between the bottom of the superstructure and the top of the pier cap beam would permit, and depending on the severity of the bearing damage. (WADOT 2001)

Retrofit of Damaged Bridge Footings

Foundation damage, as shown in Figure 5-60, is more difficult to inspect than other bridge elements. In addition, the mode of failure may vary depending on the detail of the foundation and the type of soil.

Tilting of a pier, flexural cracking of the column, sloughing of the fill around a footing, pulling away of the fill from a footing, etc. are indications of foundation distress or possible failure. To thoroughly assess the extent of damage, it may be necessary to excavate along the footing and/or piles to visually inspect their integrity. Structural cracks in either the footing or piles would be cause for concern.

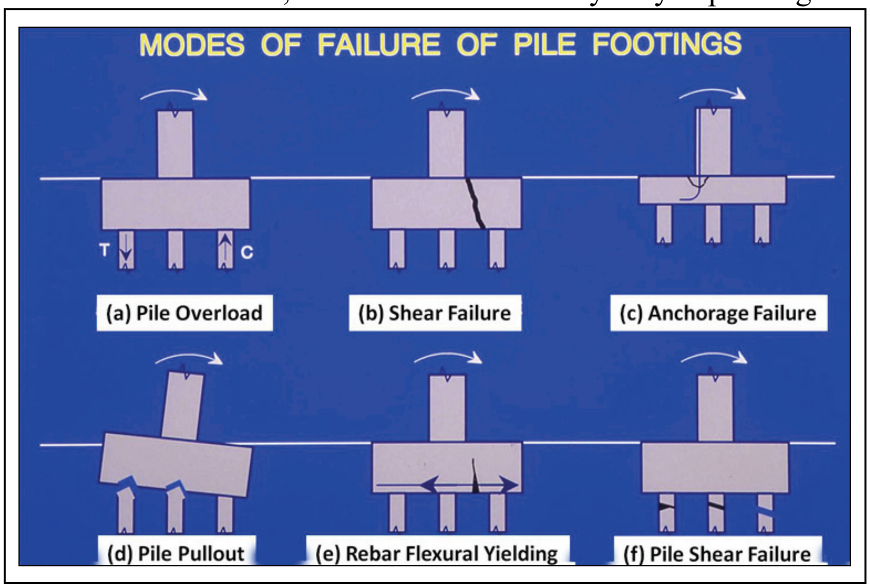


Figure 5-60. Modes of Failure of Pile Footings, (Aboutaha, 1993)

Figure 5-60 illustrates the potential modes of failure of pile footings during a major seismic event. These modes of failure could be summarized as follows:

- Pile Overload may cause yielding of the main longitudinal steel bars of the pile, transverse cracking of the concrete pile, and friction failure of friction piles. This mode of failure may not cause collapse of the bridge pier, however, it will probably be associated with settlement of the pile cap, and will affect long-term durability.
- Shear failure of the pile cap could be easily detected by inspecting the elevation of the top surface of the pile cap, as it causes movement of one side relative to the other. Such mode of failure is associated with a crack along the full width of the pile cap.
- Anchorage Failure is caused by pullout of the column main longitudinal bars from the pile cap, as well as concrete conical failure at individual bars.

- Pile Pullout is caused by anchorage failure of the pile main longitudinal bar due to inadequate embedment into the pile cap. Such mode of failure is associated with tilting of the pile cap.
- Rebar Yielding is a flexural mode of failure that causes the yielding of the main longitudinal bars in the pile cap. It is associated with localized concrete crushing of the top surface of the pile cap, near the pier column.
- Pile Shear Failure is caused by lateral movement of the pile cap and inadequate pile shear strength due to lack of adequate shear reinforcement. This mode of failure is associated with lateral movement of the pile cap.

In general, foundation retrofit would involve stabilization of the soil, restoration of the concrete, restoring continuity of rebars and load path, and possible enlargement of the foundation. Possible repair techniques for these types of failure as well as others discussed in this report can be found in the FHWA retrofit manual. (FHWA, 2008)

Information presented in the above sections has been used to compile a reference entitled *Strategies for Earthquake Damaged Bridges*, included in this report as Appendix F. An inspector can use this reference chart to systematically consider possible repair or retrofit strategies for various bridge components, given observed types and levels of damage. The repair schemes recommended depend on the purpose at hand (immediate repair vs. a short or long-term timeframe).

5.4.4 Examples of Post-Earthquake Steel Jacketed Bridge Columns

Jacketing of post-earthquake damaged bridge columns is the most efficient and practical seismic retrofit technique. As damaged columns have cracked sections and irregular surfaces after a major seismic event that might be harmful to FRP wrapping due to its sensitivity to stress concentrations, a steel jacket may be the preferable jacketing alternative. If concrete damage can be patched and smoothed out, FRP wrapping may be feasible. (American Concrete Institute 1) Many columns in California and elsewhere have been retrofitted with FRP and specifications for the work are available.

For circular columns, a circular steel jacket works quite well for all types of column deficiencies and damages; shear, confinement, and lap-splice in the longitudinal reinforcement. A circular steel jacket produces uniform confining pressure on a circular column section, and as a result is effective for retrofit of columns with inadequate lap splices in the longitudinal reinforcement. Figure 5-61 and 5-62 show details of circular steel jackets for strengthening of circular concrete columns.

For rectangular concrete columns, a rectangular steel jacket is effective in providing high shear resistance; however, due to its poor out of plane flexural stiffness, it is not effective in confining columns with inadequate lap splices in the longitudinal reinforcement. In such cases, a circular or elliptical steel jacket is recommended. In addition, rectangular steel jackets do not require rounding the corners of the column section, a time consuming operation, which allows fast post-earthquake retrofit of bridge columns. Figure 5-63 shows details of rectangular concrete columns retrofitted with steel jackets.

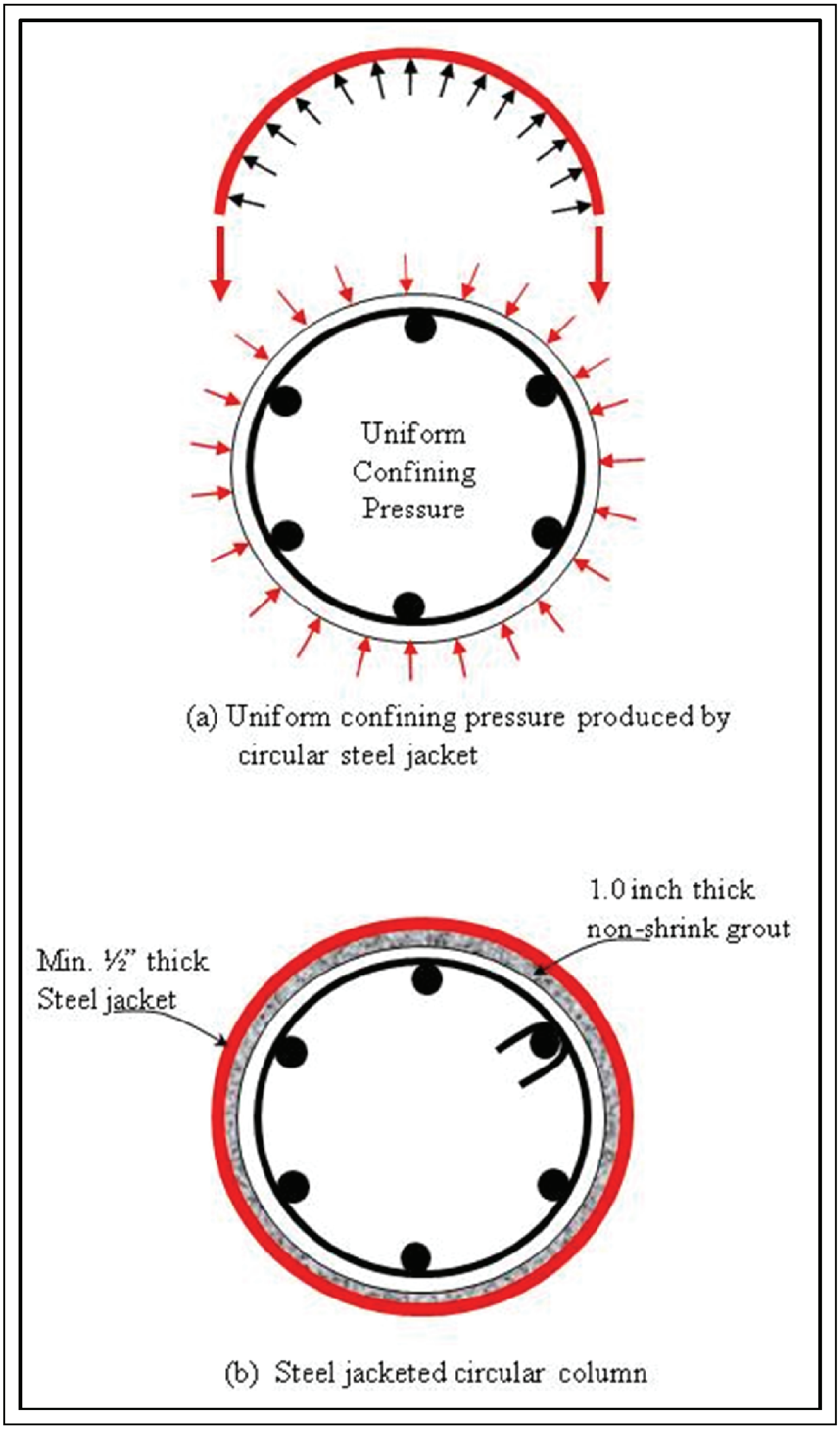


Figure 5-61. Seismic Retrofit of a Circular Concrete Column with Circular Steel Jacket (Aboutaha, 1996)

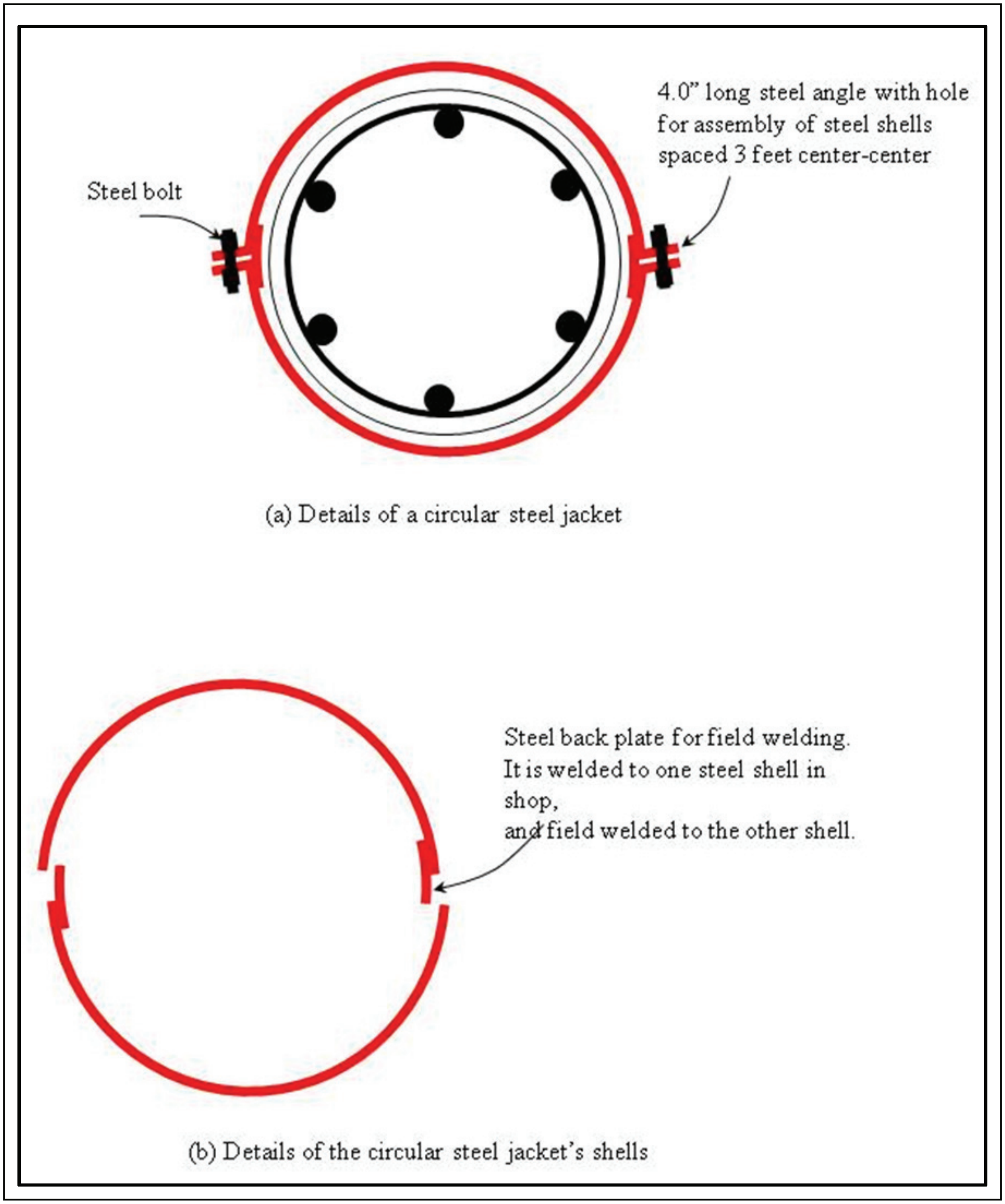


Figure 5-62. Details of a Circular Steel Jacket (Aboutaha, 1996)

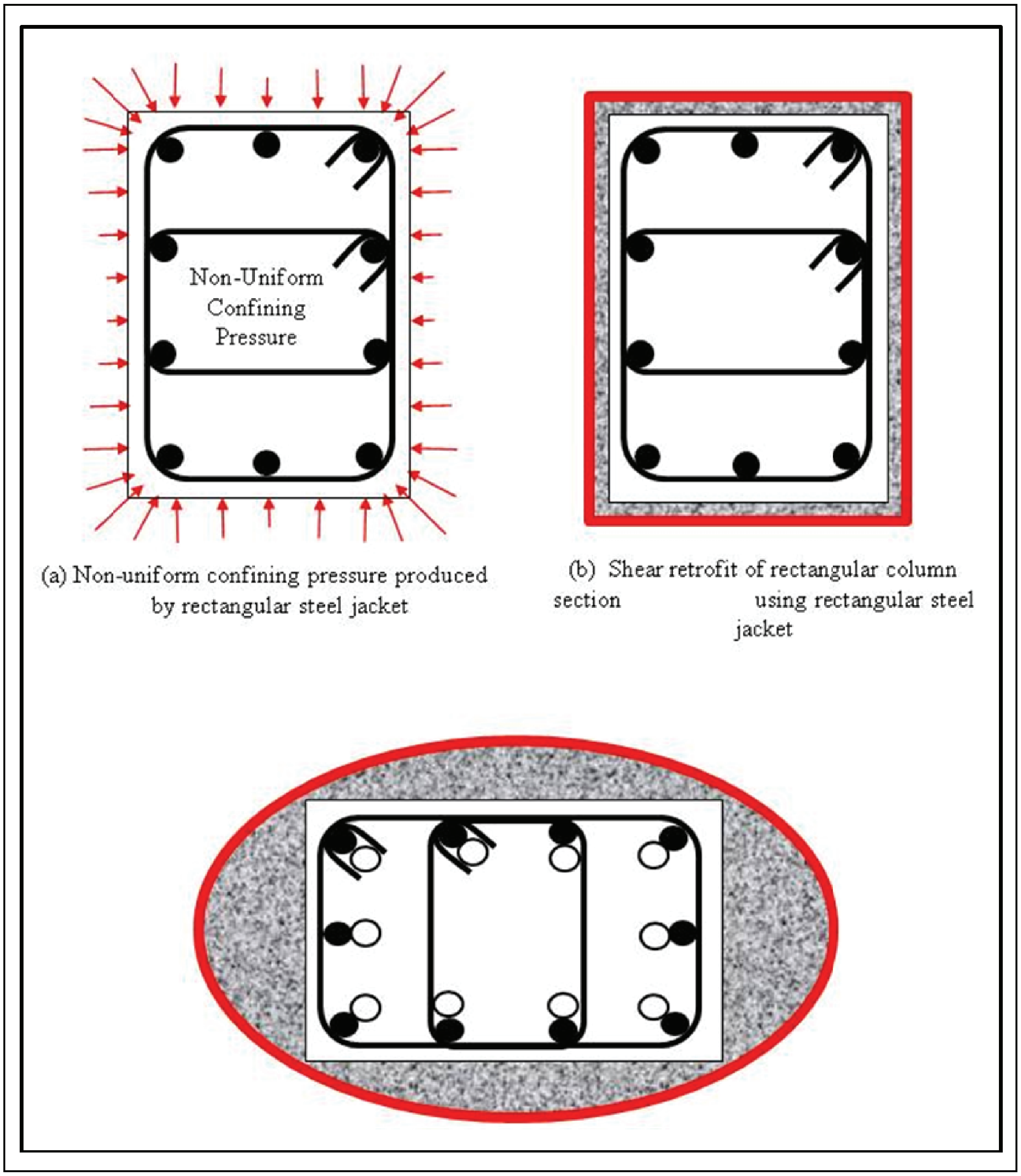


Figure 5-63. Seismic Retrofit of Rectangular Concrete columns with Steel Jackets (Aboutaha, 1996)

5.4.5 Summary

Post-earthquake retrofit of bridges has been classified into three categories: (1) Immediate retrofit to stabilize the bridge from further damage or collapse during aftershocks, (2) Short-term retrofit to open the bridge to restricted or all traffic, and (3) Long-term retrofit to restore the original strength of the bridge, and possibly upgrade the bridge for better performance during future earthquakes. Regardless of the category, all retrofit work should be done under the supervision of a professional engineer so that it can be properly designed and implemented.

Seismic retrofit systems should ensure continuity of load path, repair damage caused by the earthquake, and strengthen any deficiency in the original bridge member. Such deficiencies could be lack of shear strength, lack of flexural ductility, poor lap splices in columns, insufficient seat length for bridge superstructure, etc.

Shoring of a bridge superstructure could be the best immediate retrofit alternative. However, it is not practical as a short and long-term solution.

Because FRP composites are very sensitive to stress concentrations caused by sharp edges of fractured concrete, care must be taken if FRP wrapping is to be used to retrofit columns. Steel jackets, on the other hand, are very forgiving. While circular and elliptical steel jackets are effective in retrofit of all types of bridge columns and damages, rectangular steel jackets are effective in shear retrofit of rectangular columns, only.

An inspector in the field can use Appendix F to systematically review the deficiencies and damage states for various bridge elements. Depending on the observed level of damage and the intended duration of the fix, repair or retrofit alternatives are listed.

SECTION 6
GLOSSARY

Bridge Terminology Reference Sheet: A graphic used to illustrate the names of bridge components for Operational employees not intimately familiar with bridges

Daily Summary Report (DSR): A bridge inspector's brief compilation of findings for a day, used to summarize SPEBI detailed reports**.** The RSE will submit a compilation of inspectors' DSR and transmit to regional management and the Director – Office of Structures.

Emergency (NYSDOT definition): Any hurricane, tornado, thunderstorm, snowstorm, ice storm, blizzard, sandstorm, high water, tidal wave, tsunami, earthquake, volcanic eruption, mudslide, drought, forest fire, explosion, blackout, or other occurrence, natural or manmade, which interrupts the delivery of essential services (such as electricity, medical care, sewer, water, telecommunications) or essential supplies (such as food and fuel) or otherwise immediately threatens human life or public welfare.

Epicenter: The point on the earth's surface directly above the hypocenter of an earthquake.

Fault: A break in the earth along which movement occurs. Sudden movement along a fault can produce an earthquake because ground waves emanate from this location, causing shaking on the earth's surface.

Focus: That point within the earth from which originates the first motion of an earthquake and its elastic waves. This is also referred to as the hypocenter.

Hypocenter: The calculated location of where the earthquake originated (i.e., its focus).

Incident Command System (ICS): The ICS is a widely applicable management system designed to enable efficient incident management by integrating a combination of facilities, equipment, personnel, procedures, and communications operating within a common organizational structure. The Incident Command System (ICS) is a standardized, on-scene, all-hazards incident management approach that enables a coordinated response among various jurisdictions and functional agencies, both public and private.

Incident Commander: The Incident Commander is technically not a part of either the General or Command Staff. The Incident Commander is responsible for overall incident management.

Intensity: Intensity is a qualitative description of the effects of ground shaking (vs. magnitude which is a measure of the energy released). While an earthquake is described by a single magnitude, it will produce a range of shaking intensities across an area. Because the intensity scale describes what the shaking feels like and how it affects different types of structures, they are terms that most people understand (Table A-1). Intensity is usually greatest near the earthquake epicenter, and less away from the epicenter, but it can increase in certain areas of poor soil.

Keeper plate: A steel restrainer welded to the bottom girder flange around the sole plate at the top of the bearing.

Key (or shear key): An element typically made of reinforced concrete, that is intended to limit superstructure movement.

Lateral bracing: Members attached between steel girders to restrict out-of-plane displacements caused by lateral loads caused by erection, wind and/or earthquakes. A *diaphragm* also performs this function.

Liquefaction - A seismically induced loss of shear strength in loose, cohesionless soil that results from a build-up of pore water pressure in the soil as it tries to consolidate during strong ground shaking.

Magnitude (M): The magnitude of an earthquake describes the absolute size of the event. It is a measure of the energy released by the earthquake. Generally, higher magnitude earthquakes have greater shaking intensities at the epicenter, shake for a longer time, and affect a larger area. A number of magnitude scales exist, including the Moment Magnitude Scale and Richter Magnitude Scale. If a subscript appears on the M, such as M_w, it simply denotes the method used to calculate the magnitude and is of no interest to the user of the procedures presented in this document. NYSDOT and other states use the magnitude provided by USGS (M or M_b).

PGA (peak ground acceleration): maximum acceleration experienced at a site. It is not a measure of the total magnitude of the earthquake but how hard the earthquake shakes in a given geographic area.

PGD (peak ground displacement): An earthquake causes shaking or displacement of the earth; PGD is the maximum amount that the earth moves at a given site.

Preliminary Bridge Damage Assessment (PBDA) Form: a checklist used by Operational employees when conducting the initial route survey in a residency

Preliminary Bridge Damage Assessment (PBDA): A cursory assessment of a bridge's condition by residency or other operational staff. The time required is whatever time is needed to get out of the vehicle, walk the bridge to look for irregularities, quickly look underneath, and report findings on one line of a report. This provides an initial understanding of the earthquake's impact on the highway network while accomplishing the main objective, which is to close any unsafe bridges.

Radius of concern (R): for a given magnitude is a general guideline for the geographic region around the epicenter where NYSDOT will investigate for bridge damage. The RSE has the prerogative to increase the radius to encompass more bridges, if in his/her judgment, further investigation is warranted.

Response Level: One of four categories used to insure that an appropriate level of resources is assigned to the event.

Restrainer: A cable or steel rod used to limit the relative displacement at a movement joint in a bridge superstructure to decrease the likelihood of the superstructure becoming unseated at that joint during an earthquake.

Richter Scale: A magnitude scale that assigns a number to quantify the amount of seismic energy released by an earthquake. It is a base ten logarithmic scale, meaning, for example, that an earthquake that measures 6.0 is has a shaking amplitude ten times larger than one that measures M = 5.0. Though the Richter is the mostly widely recognized scale, there are other scales used for the same purpose (e.g. Moment Magnitude Scale).

Scenario exercise, also referred to as a **simulation exercise** or **table-top exercise**: A step-by-step office exercise used to train and assess the understanding of post-earthquake response procedures.

Shake Map: A map produced by USGS after an earthquake that uses color codes to show areas of earthquake intensity.

Special Post-Earthquake Bridge Inspection (SPEBI): A detailed bridge inspection led by a professional engineer, focusing on the structure's seismic response and any seismically sensitive details. Special access, MPT, etc is provided if necessary.

Substructure: The part of any construction which supports the superstructure. The piers, pedestals, and abutments are parts of the substructure:

> **Abutment:** The vertical structure supporting either end of a bridge and retaining the earth.
>
> **Anchor bolt:** A round, steel bolt embedded in concrete or masonry to secure the bearings.
>
> **Approach:** Typically a concrete slab that carries traffic from the land to the bridge deck.
>
> **Column:** A vertical, structural element, designed to be strong in compression.
>
> **Embankment:** Earth fill with side slopes that meet original ground.
>
> **Footing:** The foundation of the bridge. The footing is the component of the substructure that rests directly on the soil, bedrock or piles. It is usually below grade and is not visible.
>
> **Foundation:** Steel, concrete or timber piles supporting the footing. This is typically concealed by earth.
>
> **Pedestals:** Typically a concrete block which supports the bearing and girder and transfers load to the abutment or pier.
>
> **Pier (bent, column):** An intermediate support for the superstructure between abutments. A typical pier in NYS consists of reinforced concrete (RC) columns with a RC horizontal beam called a cap beam carrying the pedestals, bearings and girders.
>
> **Pier cap (cap beam, bent cap):** Horizontal structural member that connects columns or piers at the top and holds them in position.
>
> **Piles:** Long columns driven deep into the ground to form part of a foundation or substructure. Rows of piles with a pile cap to hold the row in place are called pile bents.
>
> **Wingwall:** One of the side walls of an abutment extending outward from the abutment stem in order to hold back the slope of the approach embankment.

Superstructure: The parts of a bridge that are above the bottom of the girders. Girders, bridge deck, and bridge railing are parts of the superstructure:

> **Diaphragm:** A transverse beam or frame between primary structural members to give the system additional lateral support and rigidity.
>
> **Fascia:** Vertical face on both sides of a bridge span.
>
> **Girder:** A horizontal structural member supporting vertical loads by resisting bending. The ends of girders are supported by the piers or abutments that they rest on. A girder is a

large beam, sometimes made of multiple metal plates that are riveted or welded together. It is sometimes called a beam or stringer.

Joint (often called an expansion joint): The meeting point between two spans or an end span and the abutment, which is designed to allow for expansion and contraction of the superstructure due to temperature and moisture changes while protecting the parts from damage.

Wearing surface: The topmost layer of material applied upon a roadway to receive the traffic loads, typically concrete or asphalt, although a thin layer of polymer concrete is increasingly used to protect the deck from the elements.

For a visual impression of certain bridge terms and types of bridges, refer to the following Bridge Terminology Reference Sheet and Figures 6-1 through 6-12.

For an English-Spanish translation of relevant bridge and earthquake terms, see O’Connor et al. (2007).

Figure 6-1. Bridge Terminology Reference Sheet (O'Connor)

BRIDGE TYPES

New York State has a wide variety of bridge structures on the highway transportation system. Some common structural types are shown in the images below (Figures 6-2 through 6-12).

Figure 6-2. Steel Multi-Girder

Figure 6-3. Prestressed Concrete Girder

Figure 6-4. Steel Box Girder

Figure 6-5. Reinforced Concrete Arch

Figure 6-6. Steel Through Truss

Figure 6-7. Adjacent Prestressed Concrete Box Beams

(O'Connor)

Figure 6-8. Steel Pony Truss

Figure 6-9. Timber Girder

Figure 6-10. Moveable Bridge

Figure 6-11. Concrete Box Culvert

Figure 6-12. Thru-Girder

(O'Connor)

SECTION 7
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APPENDIX A
EARTHQUAKE FUNDAMENTALS

APPENDIX A
EARTHQUAKE FUNDAMENTALS

The Severity of an Earthquake (USGS-c)
The severity of an earthquake can be expressed in terms of both *intensity* and *magnitude*. However, the two terms are quite different, and they are often confused. Intensity is based on the observed effects of ground shaking on people, buildings, and natural features. It varies from place to place within the disturbed region depending on the location of the observer with respect to the earthquake epicenter.

Magnitude (M) is related to the amount of seismic energy released at the hypocenter of the earthquake. It is based on the amplitude of the earthquake waves recorded on instruments which have a common calibration. The magnitude of an earthquake is thus represented by a single, instrumentally determined value.

Earthquakes are the result of forces deep within the Earth's interior that continuously affect the surface of the Earth. The energy from these forces is stored in a variety of ways within the rocks. When this energy is released suddenly, for example by shearing movements along faults in the crust of the Earth, an earthquake results. The area of the fault where the sudden rupture takes place is called the *focus* or *hypocenter* of the earthquake. The point on the Earth's surface directly above the focus is called the *epicenter* of the earthquake.

The Richter Magnitude Scale
Seismic waves are the vibrations from earthquakes that travel through the Earth; they are recorded on instruments called seismographs. Seismographs record a zig-zag trace that shows the varying amplitude of ground oscillations beneath the instrument. Sensitive seismographs, which greatly magnify these ground motions, can detect strong earthquakes from sources anywhere in the world. The time, location, and magnitude of an earthquake can be determined from the data recorded by seismograph stations.

The Richter Magnitude Scale was developed in 1935 by Charles F. Richter of the California Institute of Technology as a mathematical device to compare the size of earthquakes. The magnitude of an earthquake is determined from the logarithm of the amplitude of waves recorded by seismographs. Adjustments are included in the magnitude formula to compensate for the variation in the distance between the various seismographs and the epicenter of the earthquakes. On the Richter Scale, magnitude is expressed in whole numbers and decimal fractions. For example, a magnitude of 5.3 might be computed for a moderate earthquake, and a strong earthquake might be rated as magnitude 6.3. Because of the logarithmic basis of the scale, each whole number increase in magnitude represents a tenfold increase in measured amplitude; as an estimate of energy, each whole number step in the magnitude scale corresponds to the release of about 31 times more energy than the amount associated with the preceding whole number value.
At first, the Richter Scale could be applied only to the records from instruments of identical manufacture. Now, instruments are carefully calibrated with respect to each other. Thus, magnitude can be computed from the record of any calibrated seismograph. Earthquakes with

magnitude of about 2.0 or less are usually called micro-earthquakes; they are not commonly felt by people and are generally recorded only on local seismographs. Events with magnitudes of about 4.5 or greater--there are several thousand such shocks annually--are strong enough to be recorded by sensitive seismographs all over the world. Great earthquakes, such as the 1964 Good Friday earthquake in Alaska, have magnitudes of 8.0 or higher. On the average, one earthquake of such size occurs somewhere in the world each year. Although the Richter Scale has no upper limit, the largest known shocks have had magnitudes in the 8.8 to 8.9 range. Recently, another scale called the Moment Magnitude Scale has been devised for more precise study of great earthquakes. The Richter Scale is not used to express damage. An earthquake in a densely populated area which results in many deaths and considerable damage may have the same magnitude as a shock in a remote area that does nothing more than frighten the wildlife. Large-magnitude earthquakes that occur beneath the oceans may not even be felt by humans.

The Modified Mercalli Intensity Scale

The effect of an earthquake on the Earth's surface is called the intensity. The intensity scale consists of a series of certain key responses such as people awakening, movement of furniture, damage to chimneys, and finally--total destruction. Although numerous intensity scales have been developed over the last several hundred years to evaluate the effects of earthquakes, the one currently used in the United States is the Modified Mercalli Intensity Scale. It was developed in 1931 by the American seismologists Harry Wood and Frank Neumann. This scale, composed of 12 increasing levels of intensity that range from imperceptible shaking to catastrophic destruction, is designated by Roman numerals. It does not have a mathematical basis; instead it is an arbitrary ranking based on observed effects. The Modified Mercalli Intensity value assigned to a specific site after an earthquake has a more meaningful measure of severity to the nonscientist than the magnitude because intensity refers to the effects actually experienced at that place. After the occurrence of widely-felt earthquakes, the Geological Survey mails questionnaires to postmasters in the disturbed area requesting the information so that intensity values can be assigned. The results of this postal canvass and information furnished by other sources are used to assign an intensity value, and to compile isoseismal maps that show the extent of various levels of intensity within the felt area. The maximum observed intensity generally occurs near the epicenter.

Table A-1. Guide to Modified Mercalli Earthquake Intensity (USGS-c)

I	Not felt except by a very few.
II	Felt only by a few persons, especially on upper floors of buildings. Suspended objects may swing.
III	Felt noticeably by persons indoors. Many people do not recognize it as an earthquake. Standing cars may rock slightly. Vibration similar to the passing of a truck.
IV	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned.
VI	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII	Damage negligible in buildings of good design. Slight damage to moderate in well-built ordinary structures. Considerable damage in poorly built or badly designed structures. Some chimneys broken.
VIII	Considerable damage in ordinary buildings, with partial collapse. Damage great in poorly built structures. Damage slight in specially designed structures Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X	Some well-built wooden structures destroyed. Most masonry and frame structures destroyed with foundations. Rails bent.
XI	Few, if any masonry structures remain standing. Bridges destroyed. Rails bent greatly.
XII	Damage total. Lines of sight and level are distorted. Objects thrown into the air.

Earthquake Basics (Alesch 2004)

There are characteristics of earthquakes and their risks that you must be clear about yourself before you start talking about them to others. Over the years, earth scientists, engineers, and others who spend much of their time studying earthquakes have developed a set of terms relating to earthquakes that have very precise meanings, but which are often confusing or meaningless to those outside the field. This brief highlights some of the key concepts that commonly arise in discussions about seismic safety.

Every Earthquake is Unique

Each earthquake is a unique combination of characteristics: location, magnitude, depth, type of fault, mechanism of fault rupture, and direction of rupture. In addition, the soils in the area determine how fast seismic waves move, how quickly their energy dissipates, and whether or not they focus on particular sites. Thus, although we like to draw lessons by comparing one earthquake to another, these comparisons can only go so far.

Magnitude is the Usual Measure of an Earthquake

The magnitude of an earthquake describes the absolute size of the event. It is a measure of the energy released by the earthquake. Generally, higher magnitude earthquakes have greater shaking intensities at the epicenter, shake for a longer time, and affect a larger area. Several magnitude scales are currently in use, and they are all different, especially for larger earthquakes. The well-known Richter scale is one magnitude scale, but seismologists have increasingly begun to favor the *moment magnitude scale* because it gives more reliable results for larger earthquakes and those more distant from recording devices.

Intensity is Another Way to Describe an Earthquake's Size

Earthquake intensity scales qualitatively describe the effects of ground shaking rather than the energy released. While an earthquake is described by a single magnitude, it will produce a range of shaking intensities across an area. Because the intensities describe what the shaking feels like and how it affects different types of structures, they are terms that most people understand. In the United States we use a scale that ranges from Intensity I ("Not felt except by a very few under especially favorable conditions") to Intensity XII ("Damage total"). Intensity is usually greatest near the earthquake epicenter, and less away from the epicenter, but it can increase in certain areas of poor soil.

Earthquakes of Similar Magnitudes May Have Different Effects

Two earthquakes of magnitude 6.5 can cause dramatically different levels of ground shaking because they may differ in depth or mechanism of fault rupture. The 2001 magnitude 6.8 Nisqually earthquake, for example, shook a wide area near Seattle but caused much less damage than the 1994 magnitude 6.7 Northridge earthquake in Los Angeles because the Nisqually earthquake was extremely deep and did not cause severe shaking at the earth's surface. Earthquakes of similar magnitude can also cause differing levels of damage according to their proximity to populated areas. The 1995 magnitude 6.9 earthquake in Kobe, Japan, was much more devastating than the Northridge quake because the strongest shaking was in the most densely populated areas of Kobe, whereas the strongest shaking in the Northridge quake was under the mountains north of Los Angeles.

Smaller Earthquakes Can Cause Damage and Injuries
Earthquake damage at any given point depends on magnitude, distance to the rupture, the local soil conditions, and the building types, so even smaller magnitude earthquakes (between 5 and 6) can cause considerable damage and injuries in particular localities.

Softer Soils are usually Less Safe than Firm Ground
Generally speaking, softer soils shake more than firmer soils. Sandy and water-saturated soils can also experience *liquefaction*, in which the ground turns to mush during the shaking and loses its ability to support structures.

It's not only about the Fault Line
Everyone in a seismically active region should be concerned, not just those located "on the fault line." Because earthquake waves radiate out from faults and cause damages over large areas, seismic safety precautions are important region-wide. It is more important to worry about overall seismicity of an area than to know only the location of faults. The most current U.S. Geological Survey seismic hazard maps of the U.S. are at http://geohazards.cr.usgs.gov/eq/.

Unknown Faults often Cause Earthquakes
Earthquakes can strike on faults that were previously unrecognized. Many such earthquakes, for example the 1994 Northridge quake, have been extremely damaging. Because, by definition, earthquakes on unknown faults can't be anticipated, it is more prudent to focus on an area's overall seismicity in determining its earthquake risks.

Seismologists can Estimate Long-term Earthquake Probabilities
Based on historic earthquakes and evidence of prehistoric earthquakes, seismologists are able to estimate the long-term probabilities of earthquakes in seismically active areas. These estimates, however, are only approximate, because we do not have enough years of records to make statistically reliable estimates. The estimates are useful as a basis for seismic building codes, as well as for comparing hazard between regions, and do give some indication of the likelihood of future damaging earthquakes

We know where large earthquakes have occurred in the United States in the past few hundred years. We know that similarly large earthquakes will occur again, and in some places they are more probable than in others. We do not know precisely where or when they will happen or how strong they will be. When addressing a lay audience, earth scientists typically say something like "An earthquake of this magnitude in this area has about a 50% chance of happening sometime in the next 30 years."

Short-term Earthquake Prediction is not Possible
Seismologists are not able to predict imminent earthquakes, as a weather forecaster can predict a hurricane. Due to the physical characteristics of fault rupture, such predictions

may never be possible. Because earthquakes occur without warning, increased seismic safety is vital.

An Earthquake can Occur at Any Time

If seismologists say that a damaging earthquake has a 50% chance of occurring in your region during the next 30 years, that can be translated to mean that it has approximately a 2% chance of occurring in any given year. The probability is the same this year as it will be next year or two years from now. People often speak of earthquakes occurring sometime in the future, but the truth is that they can happen *right now*. Because earthquakes occur without warning, communities must be prepared in advance. There are many options for a community. They can take steps to reduce the number of unsafe old buildings or move people out of them. They can adopt codes that ensure new buildings will be earthquake-resistant. They can strengthen vulnerable buildings. They can modernize their infrastructure and make it more damage-resistant. Or they can reduce the financial consequences of damages through insurance.

What is Infrastructure?

A community is served by many networks utilities, transportation routes and systems, and communications systems that support the daily flow of life and commerce. These infrastructure elements are frequently damaged in earthquakes and, when they are, can threaten lives and property, and seriously disrupt the routines of community life. Fires can result from downed electrical wires or ruptured gas mains. Interruptions to water, sewer, electrical power or gas service will affect the lives of everyone, very negatively over time. Interruptions to communications will quickly have large personal and business impacts. Broken transportation links make it difficult or impossible for life or commerce to flow anywhere. Damage to one or two infrastructure elements poses a problem that most communities can work around, but damage to all or most of the elements is a disaster that will grind everything to a halt. Protecting infrastructure against earthquake damage is very important and can be accomplished either through retrofit or replacement.

APPENDIX B
REGISTERING FOR USGS'S EARTHQUAKE NOTIFICATION SERVICE (ENS)

APPENDIX B
REGISTERING FOR USGS'S EARTHQUAKE NOTIFICATION SERVICE (ENS)

USGS Earthquake Notification Service (ENS)

Setting Up ENS

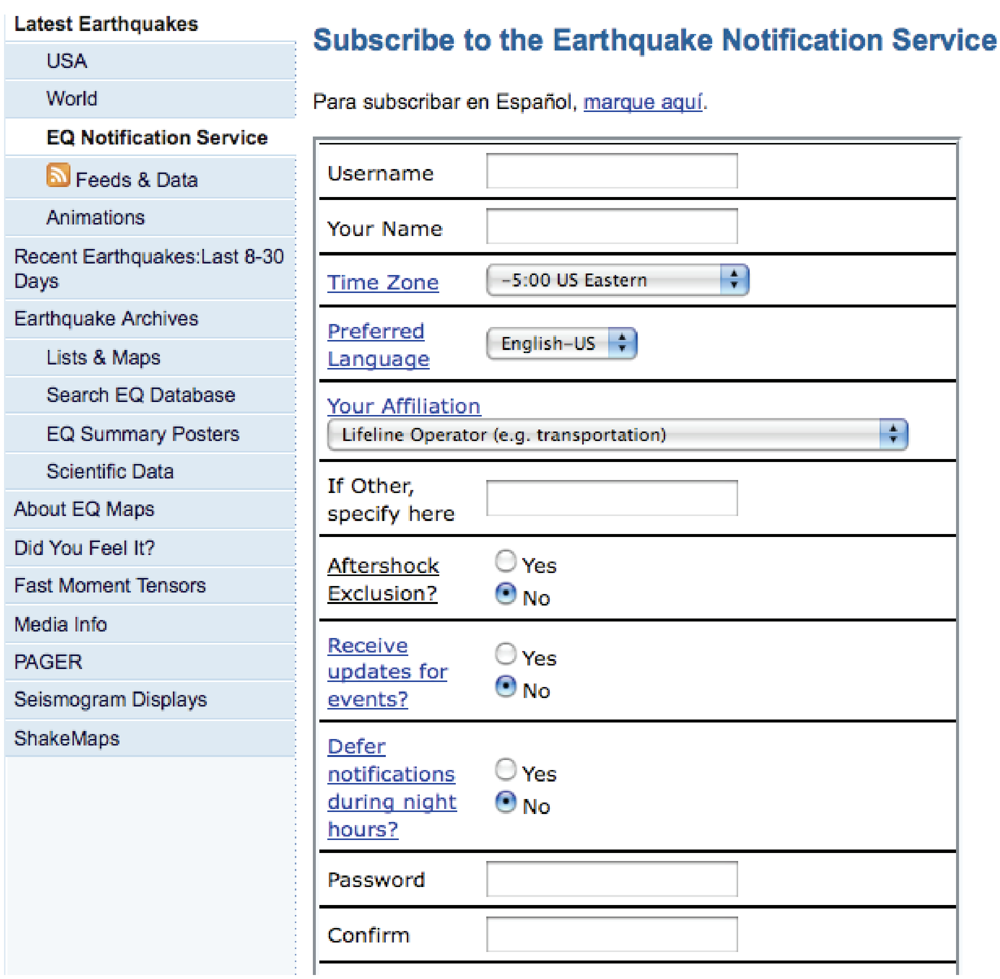
1 Click on the following or type it into your browser: https://sslearthquake.usgs.gov/ens/

or

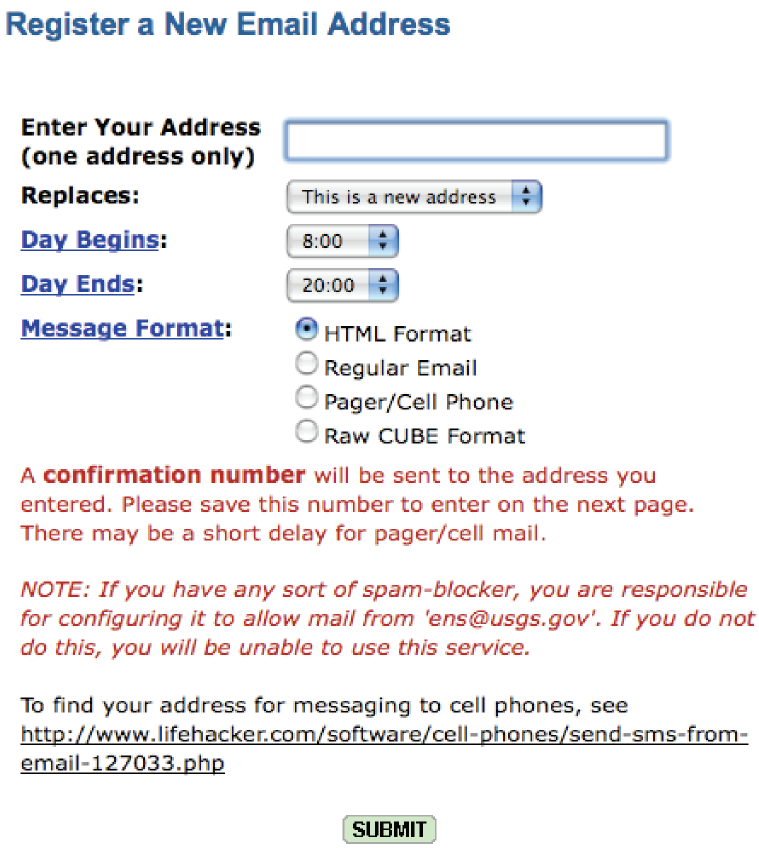
Visit http://www.usgs.gov and navigate by clicking 'Earthquakes' then 'Earthquake Hazards Program' then 'ENS – EQ Notification Service'.

2 Click 'Subscribe to ENS'.

3 Fill in your desired username and complete the rest of the information as indicated below:



4 Enter the email address you check most frequently. Use the default values for other fields.



Register a New Email Address

Enter Your Address (one address only)
Replaces: This is a new address
Day Begins: 8:00
Day Ends: 20:00
Message Format: HTML Format / Regular Email / Pager/Cell Phone / Raw CUBE Format

A **confirmation number** will be sent to the address you entered. Please save this number to enter on the next page. There may be a short delay for pager/cell mail.

NOTE: If you have any sort of spam-blocker, you are responsible for configuring it to allow mail from 'ens@usgs.gov'. If you do not do this, you will be unable to use this service.

To find your address for messaging to cell phones, see http://www.lifehacker.com/software/cell-phones/send-sms-from-email-127033.php

SUBMIT

5 Confirm your USGS registration by retrieving your confirmation number from your email account. Enter the code and click 'Confirm.'

6 Next, register your phone to receive notifications. Enter your phone number in the address field using one of the following formats depending on your cellular service provider:

Verizon	phonenumber@vtext.com
AT&T	phonenumber@txt.att.net
T-Mobile	phonenumber@tmomail.net
Virgin Mobile	phonenumber@vmobl.com
Sprint	phonenumber@messaging.sprintpcs.com
Nextel	phonenumber@messaging.nextel.com
US Cellular	phonnumber@email.uscc.net
Boost	phonenumber@myboostmobile.com
Alltel	phonenumber@message.alltel.com
(Cingular	phonenumber@cingularme.com)

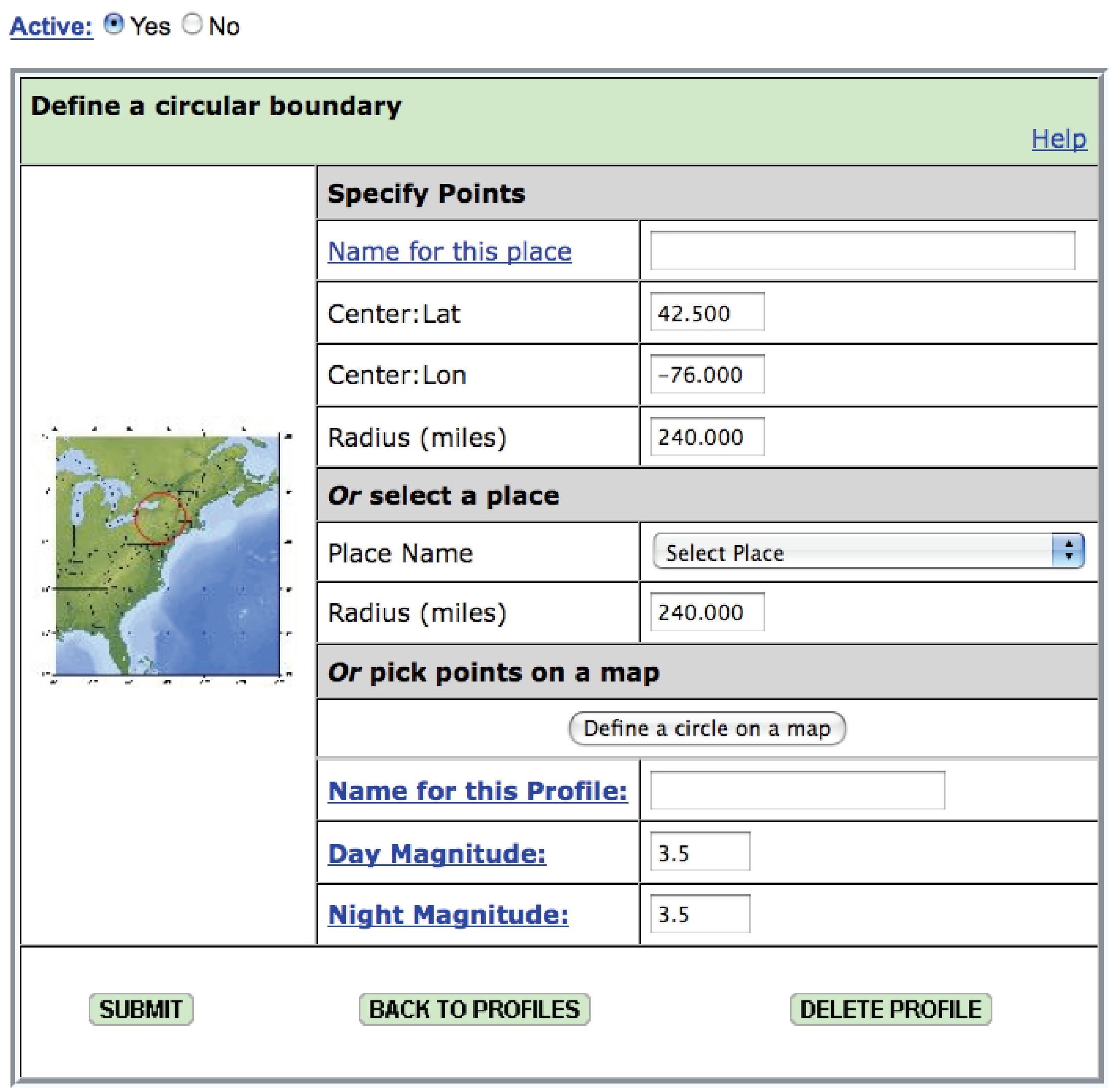
Be sure to select 'Pager/Cell Phone' for the message format. If you are sure your phone can support HTML messages, choose HTML format. Click 'Submit'.

7 You will receive a text notification on your phone that contains a code. Confirm the registration by entering this code on the USGS website and clicking ‘Confirm’.

8 Click ‘My ENS profiles on the left-side bar. Delete both profiles, ‘Default World’ and ‘United States’.

9 On the left-side bar, click ‘Circle Profile’

10 Enter the parameters indicated below.



11 Make sure that both the email and phone addresses are checked. Click ‘Submit’.

12 ENS setup is complete.

APPENDIX C
PRIORITIZING SPECIAL POST-EARTHQUAKE BRIDGE INSPECTIONS (SPEBI)

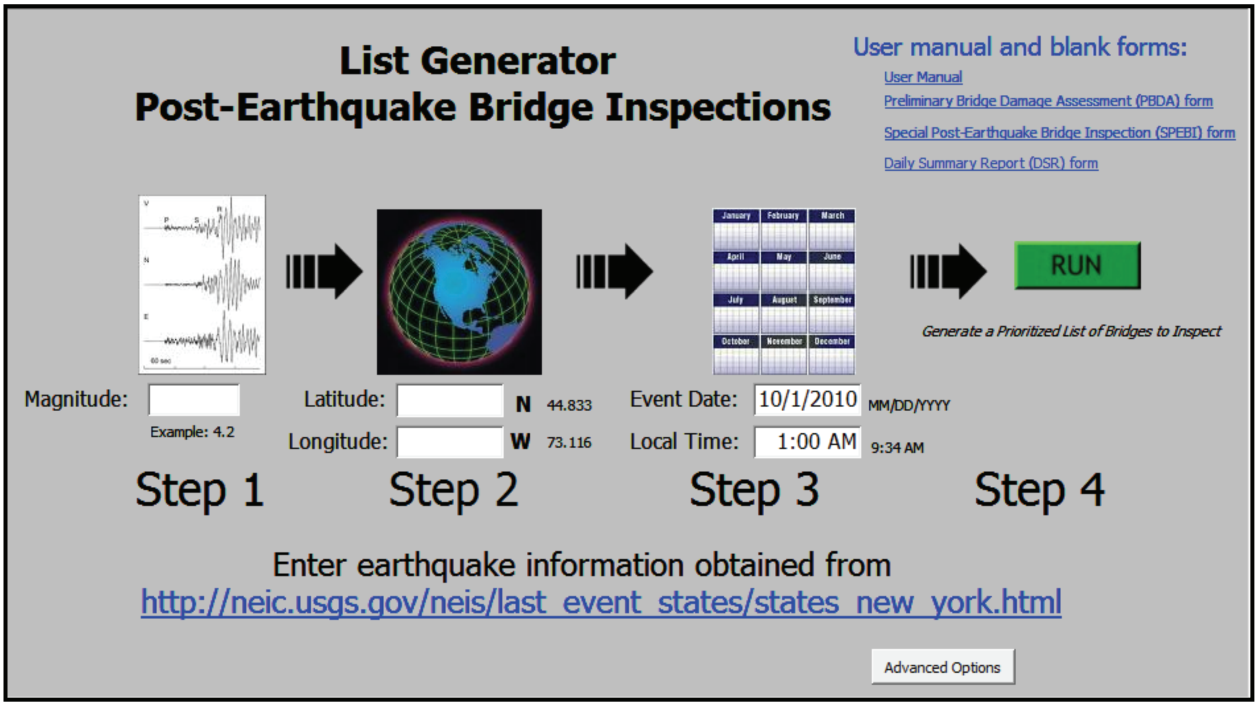
APPENDIX C
PRIORITIZING SPECIAL POST-EARTHQUAKE BRIDGE INSPECTIONS (SPEBI)

Special Post-earthquake Bridge Inspections (SPEBI) are to be conducted according to a priority established by the RSE, in contrast to Preliminary Bridge Damage Assessments (PBDA) which done according to the importance of the route that the bridges are on. It is recommended that the RSE generate and annually update a hardcopy of a priority list for SPEBI so it is immediately available in the aftermath of an earthquake. A more refined list, that considers the location of the epicenter and the most recent inspection data, can be produced when time permits.

As mentioned in Section 5.2.2 of this report, the RSE has several methods that can be used to determine the order in which to inspect the bridges. A brief description of the alternatives follows.

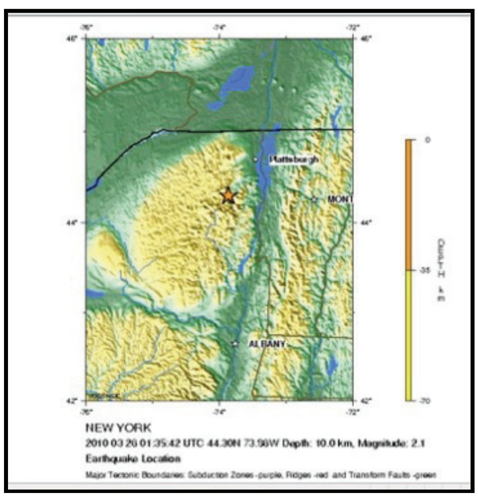
1. NYSDOT's List Generator for Post-Earthquake Bridge Inspections

NYSDOT has a Microsoft Access database application produced by University at Buffalo (O'Connor 2010). The application is intended to provide a prioritized list of bridges that will need to be inspected for damage after an earthquake. As a computer-generated tool, it has limitations and good judgment on the part of the user will need to be applied. The priority lists that the program generates are based strictly on the data that is stored in the inventory, inspection, and flag databases that it has available to it. Some other factors that may affect the order in which bridges are inspected are: immediate reports of damage received from the public or media, the bridge inspector's personal knowledge of bridges in the vicinity of the epicenter, regional and local definitions of essential and critical routes (these are not recorded in the bridge databases), geotechnical issues (e.g., liquefaction and lateral spread) since there is very limited site specific soil data available in useable form (e.g., water levels, depth of rock, soil type). It relies primarily on data contained in the DOT's WinBolts database. The interface for the application is shown on the following page.



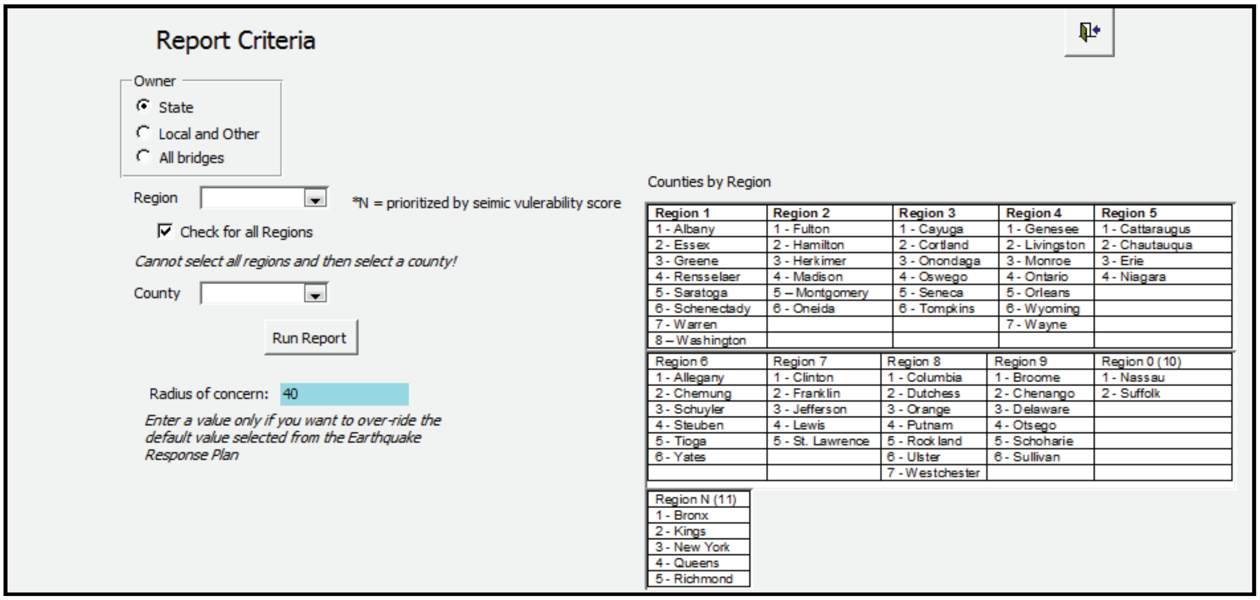
Information about the earthquake can be found by clicking on the link at the bottom of the screen: http://neic.usgs.gov/neis/last_event_states/states_new_york.html

A map similar to the one below will appear with the necessary information (the magnitude, date, time and GPS coordinates in latitude and longitude).



Once the earthquake information is entered, the program is ready to calculate the distance of each bridge to the epicenter and rank the bridges in priority order. Bridges that should be inspected first will appear at the top of the list. The default report includes all state bridges within a certain radius of concern. The radius used can be found in the Earthquake Response Plan (See Table 4-1 in Section 4.2 of this report.) and depends on the magnitude. Although no response is mandated when an earthquake is less than M3.5, the program allows the user to generate a list and in this case uses a radius of 40 miles.

If the *Advanced Options* button at the bottom right of the program's main screen is selected, a second screen will appear, similar to the one below.



Although the list of state bridges generated by the main screen is expected to be suitable for most situations, the *Advanced Options* allows the user to customize results and generate a list of

- non-state bridges within the radius of concern
- all bridges within the radius of concern
- bridges within just one region or county

It also allows the Regional Structures Engineer to use a radius of concern that is different from the default value found in the Earthquake Response Plan. For instance, the RSE may decide to increase the radius if damage is discovered outside of the default value.

The default list contains state bridges only, whereas this screen can be used to choose all bridges, just non-state bridges, or just bridges in one region by selecting the radio button for *State, Local* or *All* bridges and then selecting *Region* if desired.

Since an earthquake does not know political or regional boundaries, it is not necessary to give a region number. In most cases, the *all regions* box (see below) should remain checked. Although it is not necessary to select a region, the option is made available in case a list of only one region's bridges is desired. Select the region by pulling down the arrow to the right of the input box for Region and uncheck the box labeled *check for all regions*.

A sample of the report based on a sample seismic event follows.

Total Bridges: 215

Post Earthquake Bridge Inspections   State Bridges

3/26/2010   1:35 PM   Longitude: 73.86   Latitude: 44.30

Magnitude: 4.0   Radius of concern: 40

R/C	BIN	GPS		Feature	Feature	Year Built:	S-VR	Mi from epicenter	AADT	Length	# spans	GTMS	Posting	CR	SR:	Pri	Sec	Brgs
7/2	1000790	44.32	75.34	PEDESTRI AN WALK	3 3 72051250	1957		13		120	3	02	0	5.667		6	6	6
8/3	1078590			Ramp NS	Ramp L	2009		0		159	2	02		6.652	92	7	7	7
8/7	1078700			Ramp I	Mamarone ck River	2009		0		22	1	07		7	98	8	8	8
5/3	1078850			Route 5	Outer Harbor Dr	2009		0		60	1	07		7	100	8	8	8
5/3	1079100			RTE 5	SERVICE RD 'D'	2009		0		35	1	00		7	84.6	8	8	8
5/3	1079110			RTE 5	Tifft Nat Presv	2009		0		60	1	00		7	93	8	8	8
7/1	7033970	44.64	77.85	DELAWAR E & HUDSON	87I 87I710511 07	1959		29		381	4	03	0	4.667		5	5	5
7/1	7033980	44.66	77.88	DELAWAR E & HUDSON	87I 87I710511 24	1959		31		219	4	03	0	4.879		5	5	5
7/2	7714460	44.32	75.28	ADIROND ACK SCENIC	WOODRU FF STREET	1930		13		38	1	02	0	4.627		5	5	8
1/2	7715350	44.27	82.96	ADIROND ACK	CHUBB RIVER	1900		6		58	2	02	0	4.866		5	5	3

The report header above shows the earthquake information you provided on the first screen. In the top right corner, the report shows the total number of state bridges in the vicinity of the earthquake.

This radius should only be changed if the RSE decides that a wider area needs to be investigated. For instance, this may be advisable if damage is discovered outside of the default radius found in the ERP. In most instances, this value would not be reduced. The program uses this number to calculate the distance of each bridge from the earthquake epicenter. If the radius is reduced, the report would not include all of the bridges that may need to be investigated.

Since Region 11 (NYC) has conducted a seismic vulnerability assessment of its bridges, an alternate method for prioritizing inspections is provided to take advantage of the information available from these assessments.

To utilize the vulnerability rating scores to prioritize inspections, it is necessary to go to *Advanced Options* and select Region “*N”. When this is selected, the program does not calculate distances from the epicenter. Instead, it uses seismic vulnerability information and places bridges with the highest vulnerability rating score highest on the priority list. When two bridges have the same vulnerability rating score, the type of failure (catastrophic, partial. or structural damage) and potential for liquefaction (high, medium, or low) are used to break the tie.

The report below is obtained by choosing the region code “*N” on the pull down box. The report is based only on the data provided in the table “R11 Seismic Vulnerability.xls.

Bridges in NYC by Seismic Vulnerability

County	BIN No	Rating	Score	Structure Name	Superstructure	Substructure
3	2232167	1	20	Park and Promenade over FDR	Slab, Girder and Floorbeams	Gravity Concrete, Conc. Columns, Steel Column
5	1067760	1	20	909 (Richmond Pkwy) over SIE	Multi-stringer	Multi-column
4	105591A	1	20	S/B Whitestone Exwy over Relief Ramp	Multi-stringer	Concrete Rigid Frame
1	1066809	1	20	87I/149th Street	Multi Stringer\Cross Girder	Dual Steel Columns
2	2231429	1	20	907C / BEDFORD AVE	Stringer/Multi-Beam or Girder	Solid Concrete, Concrete Columns
4	1075239	1	20	908B / 907M	Arch, Deck	Other / N/A
3	2232019	1	20	907L 907LX4M12008	Girder/Floorbeam	Steel Rigid Frames
2	1065439	1	20	278I over FLUSHING AVENUE	Frame	N/A
3	1077040	1	20	907P 907PX4M12022	Stringer/Multi-Beam or Girder	Hammerhead

Additional information about the program is provided in (O'Connor 2010). The program can be modified by the DOT if the factors or weighting of each needs to be changed. This is to be done only under the direction of the Director, Office of Structures and only if it is determined that a better method of prioritization is possible.

2. Inventory Query

NYSDOT's bridge inventory data can be used to select bridges having particular characteristics such as multi-girders with simply supported spans or high traffic volumes. This can provide a quick method to hone in on vulnerable structure types.

3. Distance from Epicenter

Once the location of the epicenter is known, NYSDOT's GIS capabilities can easily plot bridges within a given radius of concern. If the presumption is made that the worst damage will occur near the epicenter, inspections can start there and fan out until no damage is found. The simplicity of this approach is one of its merits.

4. USGS ShakeCast

USGS's ShakeCast can be used in a way that is similar to the above method. ShakeCast is a more refined approach because it uses measured ground acceleration data. Since the intensity of the earthquake is what matters, it is better than a purely geographical approach.

5. REDARS

This damage assessment and prioritization software was developed for FHWA by MCEER, University at Buffalo (Werner 2006). It is a comprehensive tool for network analysis, though it may take a concentrated effort for an agency to implement and maintain.

APPENDIX D
RESOURCES AND EQUIPMENT

APPENDIX D
RESOURCES AND EQUIPMENT

Equipment

An effective post-earthquake evaluation depends on preparation, organization, coordination, communication and cooperation. The highway system may very well be a dangerous location after an earthquake and the safety of NYSDOT personnel is the first priority. PBDA and SPEBI teams should consist of individuals who have participated in routine practice drills prior to the post-earthquake investigation. To ensure that each PBDA and SPEBI team is adequately prepared to travel into the field, each team will assemble a seismic inspection kit that should consist of as many of the following items as practical:

The following information and equipment is an example of what will be needed by field teams:

- First-Aid kit
- Basic safety gear such as hard hats and vests
- Cones, signs and other traffic safety equipment
- Earthquake Response Plan (Section 4 of this report)
- Reporting forms (Appendix E of this report)
- Bridge Inspection Technical Guidance (Section 5 of this report)
- Bridge Element Reference Sheet (Appendix D of this report)
- Clipboard, forms and writing supplies
- GPS and navigation software. This will be especially useful to inspectors from another region that may need to locate bridges by coordinates.
- Vehicle with two-way radios, AM/FM/Satellite radio
- Cell phone. Do not assume that cell phone service will be available; towers may be down and circuits will probably be overloaded.
- Digital camera with extra batteries and storage media.
- USB drive and/or other data storage devices
- Laptop computer with Google Earth and Google Maps for accessing route numbers, political boundaries, geographical features, etc.
- Maps with priority routes marked
- GIS maps (paper maps as well as computer files) with all bridges shown, including those that are flagged, posted, restricted, under construction, or considered critical or seismically vulnerable. Also, lists with GPS coordinates for each bridge, locations of hospitals and other important facilities.

- Portable generator or power inverter so AC equipment can be run off a vehicle's DC power outlet. Also, be sure to check that all batteries (for camera, cell phones, etc.) are charged and you have spare batteries, if possible.
- Other tools such as 100 foot measuring tape, stringline, plumb bob, pocket knife, sounding hammer, flashlight and batteries, hand level, watch, thermometer, AM/FM radio, traffic cones, shovel, ladder, crack width gauges, shovel, wire brush, inspection mirror on swivel head, binoculars, calipers, axe, PVC coated gloves or leather gloves, tool belts and/or tool box, boots,
- Access equipment (ladders, boats, etc)
- Fire Extinguisher
- Piano wire or another device for measuring crack depth
- Magnifying glass for inspecting small cracks at connections or welds
- Dye penetrant kit

After a major earthquake, it is likely that power and telephone/internet communication will not be available. Preparation should include the anticipation of this scenario.

Maps & GIS

In the immediate aftermath of an earthquake, the following mapping tool may be useful to a person without formal training in geographic information systems (GIS): http://earth.google.com/

After an earthquake event, the RSE will request that the regional GIS coordinator produce a map that shows the geographical area of the earthquake and the applicable radius of concern. This map and an accompanying list will be useful to teams for conducting SPEBIs and should be obtained before heading into the field, if at all possible. In addition to route numbers, political boundaries, etc, the maps should contain information relevant to post-earthquake inspections, including

- The epicenter of the earthquake
- The radius of concern for the earthquake magnitude
- All state bridges within this radius with the seismically vulnerable bridges clearly marked
- GPS coordinates for each bridge
- Notations about restricted bridges or ones with structural flags
- Other available attributes relevant to a seismic investigation

A prioritized list of bridge inspections from the program described in Appendix C will also be useful during inspections. It will give the distance of each bridge to the epicenter and some inventory information that may be useful to the inspector. GPS coordinates that are listed may assist in locating bridges in the field.

Communication Devices

Teams must have several communication devices with them in the field. Team members should carry cellular phones with extra batteries. Since cellular service may not be available because of downed towers or the system working at capacity, cell phones should have text messaging capabilities. For a high level event where cellular service may be disrupted, texting may be available when voice communication is not.

Two-way radios should be on hand in the event that cell phones are not able to be used. Staff should receive annual refresher training so they are ready to use the radios, if necessary.

Satellite phones, cell priority service, or microwave communication may be available as options, and should be investigated by the Department as part of their emergency response preparation.

In the event that all communication devices fail, employees should follow established protocol for responding to emergencies. The normal managerial chain of command is to be followed until an ICS organization is established.

APPENDIX E
FORMS FOR FIELD TEAMS

Preliminary Bridge Damage Assessment (PBDA) Form

Region ___________
County ___________
Date: ___________

Name(s): ______________________________
____

					Changed condition: Respond 'Yes' or 'No'										
BIN	**Feature Carried**	**Feature Crossed**	**Arrival Time**	**Is bridge open to traffic?**	**Span Collapse?**	**Is any damage apparent?**	**1. Superstructure Damage** girders, joints, deck	**2. Substructure Damage** damaged or tipped columns, cracked pier cap, abutments	**3. Bearings** displaced, damaged?	**4. Secondary Systems** wingwalls, bridge railing, utilities, pipleines OK?	**5. Soil Problems** sloughing, fissure, differential settlement, liquefaction?	**6. Approaches** settlement, cracking, voids under?	**Other Observations**	**Does it need to be closed?** (If so, call it in immediately)	**Does a Bridge Inspector need to look at it?**

form PBDA rev 2/2012

Special Post-Earthquake Bridge Inspection (SPEBI) Form — NYSDOT

R/C ______________ **Name of Engineer** ______________________

BIN ______________ **Date and Time** ______________________

Instructions: Use standard bridge inspection forms (TP349 & 350) to report only changed conditions. In addition, use this form to provide extra information specifically about earthquake damage. Use photos and extra sheets as needed to thoroughly describe damage.

Overall Damage State

- ☐ No earthquake damage
- ☐ Minor damage
- ☐ Moderate damage
- ☐ Major damage
- ☐ Collapsed

General description of damage:

Describe performance of any previous seismic retrofit:

Overall Operational State

- ☐ Open to all traffic
- ☐ Partially open or open with restrictions
- ☐ Open but temporary shoring is in place
- ☐ Closed to all traffic

Earthquake Damage Checklist: Include Description and Photo Documentation

Geotechnical & Approach

- ☐ Slope failure ______
- ☐ Liquefaction ______
- ☐ Lateral spreading of slopes ______
- ☐ Ground faulting ______
- ☐ Approach settlement ______
- ☐ Other ______

Superstructure

- ☐ Horizontal displacement ______
- ☐ Collapsed span(s) ______
- ☐ Partially dropped span ______
- ☐ Longitudinal pounding ______
- ☐ Deformed diaphrams or lateral bracing ______
- ☐ Damaged primary member ______
- ☐ Cracked or damaged deck ______
- ☐ Damage to critical element (hinge, hanger, suspender, cable) ______
- ☐ Railing or barrier misalignment ______
- ☐ Damage to utility lines, lighting, etc. ______
- ☐ Other ______

Foundation & Substructure

- ☐ Visible damage or displacement ______
- ☐ Spalled columns ______
- ☐ Plastic hinging of columns ______
- ☐ Shear failure ______
- ☐ Reinforcement pullout ______
- ☐ Damage to pier cap ______
- ☐ Displacement or damage to abutment, backwall, wingwall ______
- ☐ Damaged steel, concrete, or FRP jacket ______
- ☐ Tipped pier ______
- ☐ Other ______

Joints & Bearings

- ☐ Toppled
- ☐ Excessive deformation or displacement
- ☐ Broken or damaged anchor bolts
- ☐ Damaged or malfunctioning joint
- ☐ Other?

Utilities and Appurtenances

- ☐ Damaged signs or poles
- ☐ Leaking or damaged pipeline
- ☐ Utility damage

Probable Cause of Undesirable Performance

- ☐ NA
- ☐ Deteriorated condition (e.g. corrosion)
- ☐ Discontinuity of reinforcement (e.g. insufficient lap)
- ☐ Ground settlement/movement
- ☐ Inadequate confinement steel
- ☐ Instability of bearings (e.g. rocker bearings)
- ☐ Insufficient shear capacity
- ☐ Insufficient support length (seat width)
- ☐ Lack of continuity
- ☐ Lack of redundancy
- ☐ Large skew
- ☐ Non-seismic design (pre 1975)
- ☐ Retrofit measure did not perform as intended
- ☐ Secondary hazard (scour, fire, etc.)
- ☐ Steel deficiency due to historic fatigue cycles
- ☐ Uplift
- ☐ Varying column heights (different stiffness)

Notes:

Action

- ☐ Close immediately (or retain closure)
- ☐ Was closed but is OK to reopen

- ☐ Flagged (see flag report for detail)
- ☐ Repair Request: ____________________
- ☐ Recommendations: ____________________
- ☐ Further investigation needed:
  - ☐ Special Structural Investigation and Analysis
  - ☐ Repair or retrofit details
  - ☐ Level 1 Load Rating
  - ☐ Geotechnical Investigation
  - ☐ ____________________

Space provided for additional notes and/or sketches

Signature of Engineer ____________________

Daily Summary Report (DSR) of Special Post-Earthquake Bridge Inspections

Region # ___

Date: ______________________

Name of Engineer: ______________________

Inspection Date	**R/C**	**BIN**	**Feature Carried**	**Feature Crossed**	**Team Leader** (initials)	**Overall Damage State** (NA, Minor, Moderate, Major, Collapsed)	**Overall Operational State** (Open, Restricted, Open but shored, Closed)	**Most Failed Element** (substructure, primary members, secondaries…)	**Probable Cause of Failure** (e.g. support length, high bearings, shear loads…)	**Action** (e.g. Red PIA, Red, Yellow, Repair Request)	**Further Investigation Required?** (e.g. by Structural Specialist or	**Closed to Traffic?**	**Comments**	**Previous General Rec**	**New General Rec**

APPENDIX F
STRATEGIES FOR EARTHQUAKE DAMAGED BRIDGES
(Aboutaha)

Strategies for Earthquake Damaged Bridges

Bridge Element	Types of Deficiency	Type of Damage	Level of Damage	Purpose[1]	Possible Action / Retrofit System[2]
Approach	Unstable soil Weak abutment/wingwall	Settlement of approach	Minor	I	Post low speed/ warning sign
				ST	Repave/refill
				LT	Repave/refill
			Moderate	I	Fill with soil and cover with steel plate, Post warning signs
				ST	Repave/refill
				LT	Repave/refill
			Severe (Check abutment /wingwalls)	I	Fill with Portland cement mixed soil and cover with steel plate.
				ST	Repave/refill
				LT	Repave/refill
Pier Columns (Shear failure)	Shear Failure (Diagonal cracks) Insufficient transverse reinforcement Large spacing between stirrups	Fine Shear cracks	Minor	I	Install steel straps (e.g. flat stock ¼"x 3", welded)
				ST	Wrap with FRP (carbon or glass design)
				LT	Wrap with FRP (carbon or glass design)
		Spalling of concrete cover Very visible Shear cracks Exposed transverse and main bars	Moderate	I	Install steel straps
				ST	Patch with Polymer Modified Concrete, and wrap with FRP
				LT	Patch with Polymer Modified Concrete, and wrap with FRP
		Spalling of concrete cover Steep shear cracks Exposed transverse and main bars Fractured transverse ties	Severe	I	Shore the superstructure Use steel collars
				ST	Shore the superstructure Install steel jacket
				LT	Shore the superstructure Install steel jacket
Pier Columns (Flexural failure)	Flexural Failure (column ends) Short lap splice in longitudinal bars Poor confinement (lack of transverse reinforcement)	Small transverse cracks at the column ends (without longitudinal cracks)	Minor	I	None
				ST	Remove loose concrete, and patch with polymer modified concrete or polymer concrete.
				LT	Replace damaged/loose concrete and then: If the column has adequate shear strength, then wrap at the ends only with FRP. If the column does not have adequate shear strength, then wrap the column with FRP along its full height.
		Spalling of concrete cover Exposed rebars Fine short vertical cracks Localized crushing of concrete	Moderate	I	Replace damaged concrete and then install steel straps
				ST	Patch with Polymer Modified Concrete, and wrap with FRP
				LT	Same as "Minor" damage
		Vertical cracks along lap splice Exposed rebars Bond failure Crushing of concrete cover	Severe	IR	Shore the superstructure Replace damaged concrete Use steel collars
				STR	Shore the superstructure Replace damaged concrete Install steel jacket
				LT	Shore the superstructure Restore splice integrity by welding the spliced bars Replace damaged concrete, completely embedding splice Wrap column with FRP, designing for shear, flexural or lap splice retrofit.
Concrete Bridge Deck	Crushing of Concrete Misalignment of joints Punching failure	Localized crushing of concrete at joints Very slight misalignment of joints	Minor	I	None
				ST	Repair damaged joints
				LT	Identify source of misalignment & fix Repair damaged joints
		Limited crushing of concrete over the full length of joint Misalignment of joints Shifting of bearings, but still supported on pedestals Slight settlement across joints	Moderate	I	Stabilize bearings and superstructure girders Cover joints with steel plates
				ST	Stabilize bearings and superstructure girders Repair damaged joints
				LT	Repair bearings and superstructure girders Repair damaged joints
		Crushing of concrete over the full length of joint, or within the span Misalignment of joints Bearing/superstructure Failure Differential settlement of deck panels Punching failure (in this case always close the bridge)	Severe	I	Close the bridge
				ST	Shore the superstructure Stabilize superstructure Replace damaged deck panels with precast
				LT	Shore the superstructure Repair bearings and superstructure girders Replace damaged deck panels

[1] I = Immediate Retrofit; ST = Short-term Retrofit; LT= Long-term Retrofit

[2] With proper design, FRP column wraps can be glass (GFRP) or carbon (CFRP)

Bridge Element	Types of Deficiency	Type of Damage	Level of Damage	Purpose[1]	Possible Action / Retrofit System[2]
Prestressed Concrete Girders	Laterally unrestrained Corrosion of strands at girder ends Lack of sufficient amount of strands Shear deficiency	Fine closed flexural cracks Slight shifting over bearings Localized spalling of concrete cover near ends	Minor	I	None
				ST	Patch spalled concrete cover near ends
				LT	Fix the bearing Patch spalled concrete cover near ends Inject cracks with epoxy resin
		Closed flexural cracks Fine closed shear cracks Localized spalling of concrete cover Localized crushing of concrete Shifting over the bearings	Moderate	I	Stabilize bearings If shear cracks open under traffic, then close the bridge
				ST	Fix the bearings Repair damaged concrete Install longitudinal bonded CFRP sheets
				LT	Fix the bearings Repair damaged concrete Install longitudinal bonded CFRP sheets
		Crushing of concrete Open flexural cracks Shear cracks Spalling of concrete cover and exposed strands at girder ends Unseated bearings	Severe	I	Close the bridge over damaged girders
				ST	Fix the bearings Repair damaged concrete Install prestressed longitudinal bonded CFRP sheets, or external steel prestressed system
				LT	Replace the girder
Steel Girders	Laterally unrestrained Corrosion Lack of stiffeners at critical section Fatigue fracture cracks Lack of lateral restrainers Lack of joint seating with adequate length	Minor flange buckling Slight shifting over bearings Slightly buckled lateral bracing	Minor	I	None
				ST	Provide restrainers
				LT	Fix the bearing Fix the buckled sections/members
		Buckling of flanges and web Small fracture of flange extended over no more than 1.0" Fracture of a bracing member Localized yielding of bolt-holes, at bolted connections Shifting over the bearings	Moderate	I	Weld the fractured flange Stabilize bearings
				ST	Weld the fractured flange Weld the fractured bracing Fix bearings Provide restrainers Add cables to bracing system
				LT	Weld the fractured flange Straighten buckled sections, may need to add steel sections Replace the fractured bracing Fix bearings Provide restrainers
		Major buckling of flanges and web Serious fracture of flange extended over ¼ of the flange width Fracture of a critical bracing member Unseated of its bearings Sheared bolts at bolted connections	Severe	I	Close the bridge over the damaged girders
				ST	Weld the fractured flange Straighten buckled sections, may need to be cut out and replaced Replace the fractured bracing Fix bearings Provide restrainers Replace bolts
				LT	Replace the girder
Bridge Abutment / Wingwalls	Unstable Soil Short lap splice in longitudinal bars Corrosion of rebars / bearings Poor drainage behind the wall Old bridges: micro-cracking due to alkali-silica reaction (ASR)	Fine inclined cracks in wingwall Localized damage of pedestals due to slight movement of bearings Inclined cracking of wingwall Localized spalling of concrete cover Damage of pedestals, and exposed anchor-bolts Cracking of side walls Cracking of backwall Minor shear cracks in wingwall	Minor	I	None
				ST	Brace bearings
				LT	Fix the bearing Patch spalled concrete cover near ends Inject cracks with epoxy resin
			Moderate	I	Stabilize bearings Check settlement of approach road under heavy truck, if major settlement, then repair back and wingwalls
				ST	Fix the bearings Repair damaged concrete Install bonded CFRP sheets
				LT	Fix the bearings Repair damaged concrete Install bonded CFRP sheets
		Tilting or sliding of the wall Major horizontal cracks near mid-height of wall Crushing of concrete at the bottom section of the wall Major inclined flexural and shear cracking in wing wall Major damage of back and side walls	Severe	I	Close the bridge
				ST	Fix the bearings Repair damaged concrete Install prestressed bonded CFRP sheets, or external steel prestressed system
				LT	Replace the wall

[1] I = Immediate Retrofit; ST = Short-term Retrofit; LT= Long-term Retrofit

[2] With proper design, FRP column wraps can be glass (GFRP) or carbon (CFRP)

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University at Buffalo, The State University of New York
133A Ketter Hall ▪ Buffalo, New York 14260-4300
Phone: (716) 645-3391 ▪ Fax: (716) 645-3399
Email: *mceer@buffalo.edu* ▪ Web: *http://mceer.buffalo.edu*

University at Buffalo *The State University of New York*

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