FHWA’S 2005 SEISMIC RETROFITTING MANUAL,
PART I: BRIDGES

Phil Yen, PhD, P.E.1, John O’Fallon, P.E.2, Jerome O’Connor, P.E.3

ABSTRACT
In 2005, the Federal Highway Administration (FHWA) will issue its Seismic Retrofitting Manual for Highway Structures, Part I: Bridges. This updates suggested practice for mitigating the seismic vulnerability of existing bridges. The manual, recently completed by the Multidisciplinary Center for Earthquake Engineering Research (MCEER), replaces the 1995 Seismic Retrofitting Manual for Highway Bridges and offers better guidance on screening, prioritizing, evaluating, and retrofitting regular bridges. The paper gives an overview of the performance based philosophy presented in the manual and describes procedures for implementing it. It specifically addresses two levels of seismic hazard that are used, bridge importance, anticipated service life, soil site classes and amplification factors, performance levels, and selection of retrofit categories. It then provides strategies for improving structural response through several approaches and a wide selection of structural retrofit measures. It also summarizes recent philosophy on hazardous sites (e.g. near a fault) and geotechnical and foundation issues such as potential for liquefaction and lateral spreading.

KEYWORDS
seismic, retrofit, bridge, earthquake, hazard, structures, liquefaction

INTRODUCTION
In 2005, the Federal Highway Administration (FHWA) will release a new publication for the seismic retrofitting of highway structures. It is called: Seismic Retrofitting Manual for Highway Structures, Part I: Bridges and Part II: Retaining Structures, Slopes, Tunnels, Culverts, and Pavements. (FHWA/MCEER, 2005) This paper pertains only to Part I: Bridges.

The manual has been prepared by the University at Buffalo’s Multidisciplinary Center for Earthquake Engineering Research (MCEER) under the direction of the Seismic Research Team at FHWA’s Turner-Fairbank Research Facility. It is authored by experts in the field to reflect the latest information on assessing the risk of earthquake damage to existing bridges and to give guidance on retrofitting when warranted. The manual is intended for use nationwide by state departments of transportation (DOT’s) and their engineers for regions of low, moderate, or high

1. Research Structural Engineer, Federal Highway Administration, wen-huei.yen@fhwa.dot.gov
2. Research Structural Engineer, Federal Highway Administration, John.O’Fallon@fhwa.dot.gov
3. Senior Program Officer, Transportation Research, Multidisciplinary Center for Earthquake Engineering Research, University at Buffalo, State University of New York, jso7@buffalo.edu
seismicity. It targets regular bridges, which as defined by American Association of State Highway and Transportation Officials (AASHTO) are less than 150m long (500 ft.). Agencies dealing with special bridges such as long span bridges or those with unique structure types may benefit from the concepts presented in the manual but they will need to use additional care in application of the concepts.

The new manual builds heavily on previous editions issued by FHWA by supplementing previous material with improved knowledge, analysis techniques, and retrofit measures. The new manual benefits from experience gained from observation of existing bridges in actual seismic events in both the U.S. and abroad. FHWA has also sponsored extensive research that has led to a better understanding of the behavior of existing bridges and new ways to improve their performance to make them safer in the event of an earthquake. The manual benefits from the lead role that FHWA has taken in fostering international collaboration. This has led to an improvement in design criteria used in the U.S. and also benefited our world neighbors. The FHWA has established relationships with earthquake professionals in Japan, Taiwan, New Zealand, China, Turkey, Korea as well as other countries facing natural hazards.

The new retrofitting manual uses the concept of performance based design and sets performance objectives for two levels of earthquakes according to categories determined from the relative importance of the bridge, its anticipated service life, and site conditions. It contains new information on geotechnical hazards caused by earthquakes.

BACKGROUND
Until 1971, the AASHTO seismic provisions for the design of new bridges required an equivalent lateral force, usually applied at the deck level, which was from two to six percent of the superstructure dead load, depending on whether the footings were spread footings or were supported on piles. Experience has shown that these methods were not sufficient to prevent serious damage to bridges. The 1971 San Fernando earthquake in California brought on a new effort to find better ways to identify the risk and improve the performance of large structures after it became evident that current provisions were not adequately protecting highway bridges from damage and collapse. In 1973, the California Department of Transportation (Caltrans) issued new seismic criteria for the design of new or replacement bridges in California. This was the first attempt in the U.S. to relate peak ground accelerations shown on seismic hazard maps to different soil types at bridge sites and the dynamic-response characteristics of structures, including inelastic behavior. The California seismic design criteria formed the basis for the national seismic provisions in the 1977 AASHTO Standard Specifications for Highway Bridges.

While Caltrans and AASHTO took the lead promulgating criteria for the seismic design of new bridges, FHWA saw the need for similar guidance for existing bridges. The AASHTO bridge design specifications have never included any provisions for seismic retrofitting; FHWA has taken responsibility for this. Early versions of FHWA’s retrofitting manual (listed below) were based on the specifications that stemmed from California’s experiences, lessons learned, and subsequent modifications to the design code.

*Retrofitting Guidelines for Highway Bridges* (FHWA-RD-83-007) (FHWA, 1983), and *
In order to address the most immediate problems first, the emphasis of early retrofit designs was to guarantee span support at piers. Restrainer cables or bars were added to restrict relative movement of multiple superstructure spans at expansion joints and to keep them supported by the piers. Later it became apparent that the transfer of loading to columns necessitated the addition of steel jackets to insure adequate confinement. Vulnerable structural configurations such as single column piers and multiple decked bridges were also found to be in need of special attention. Since it is cost prohibitive and administratively impossible to improve all existing bridges at once, it was also necessary to develop some means to assess a large population of bridges and to prioritize them according to risk and the subsequent urgency of the need for retrofit. Eventually, it became apparent that a philosophy of performance based design and detailing was needed. The new manual addresses these issues.

**PHILOSOPHY AND CONCEPTS**

**Retrofitting Program**
Although retrofitting is a common method for improving performance, the cost of improving a structure may be so prohibitive that replacing it altogether with a new structure may be the preferred alternative. Alternatively, doing nothing, accepting the risk and the consequences of damage is another possible option. The decision to retrofit, abandon, replace, or do-nothing, requires that both the importance and degree of vulnerability of the structure be carefully understood. A transportation agency’s population of bridges needs to be looked at as a whole to insure that scarce resources are directed toward bridges in greatest need. The retrofit program process depicted in Figure 1 will generally be used so that the most deficient bridges can be identified and prioritized, with important bridges in high seismic zones and high vulnerability being given the first priority for retrofitting.

![Retrofit Program Diagram](image)

**Figure 1: A typical retrofit program**

In the first phase of a retrofit program, bridge inventories are screened to identify those structures that are seismically deficient so that they can be prioritized in order of need. Such a process is intended to be rapid, easy to apply and intrinsically conservative. Although three methods for
screening and prioritization are described in the manual, a state may use any system it chooses to conduct this vulnerability assessment. Several screening and prioritization methods have been proposed in the past decade. One example is that used by New York State Department of Transportation. (O’Connell, 2002).

Most methods develop a seismic vulnerability and rating system first, and then use the results of this rating exercise to prioritize the inventory. Factors considered in the rating usually include specific structural vulnerabilities, prevailing seismic and geotechnical hazards, bridge importance, network redundancy, political and social issues, and the economic context in which the retrofit program is being conducted. Regardless of the process used to develop the final prioritized list, all bridges should be subject to detailed evaluation before actual retrofitting is undertaken, to confirm the identified structural deficiencies and determine the cost and benefits of retrofitting. Bridges found to be deficient at this stage are subject to detailed evaluation at the next step, and any that are later found to be satisfactory are excluded from further study at that time.

**Seismic Hazard**
Performance is obviously most dependent on the magnitude of the earthquake. The previous edition of the manual employs only one design earthquake with a 500 year return period. The new edition uses a performance based approach that calls for evaluation of the effects of two different seismic events (termed the lower level earthquake and the upper level earthquake). This stems from the recognition that it is not economically feasible to upgrade all bridges to such a condition that no damage will ever occur. Since low intensity earthquakes are a relatively frequent occurrence throughout the world, all bridges should be able to withstand them without significant damage. At the same time, there are rarer, stronger, earthquakes that will impose damage despite attempts at mitigation. Thus, the impact of at least two levels of seismic intensity need to be investigated; a lower level that is routinely handled by the bridge, and a somewhat arbitrary higher level at which we intend that the worst of damage is avoided.

Though the selection of an appropriate recurrence interval for each of these seismic events is difficult, setting a mark provides a means for comparing bridge performance on a uniform basis. For the sake of consistency with the evolving criteria for the design of new bridges, the new manual suggests a recurrence interval of 100 years for the lower level event and 1000 years for the upper level earthquake. A higher upper level event may be employed at the discretion of the engineer or because of stricter local codes. All bridges are intended to perform elastically during the lower level earthquake so that no damage occurs and the bridge is useable immediately after an event. Because of the prohibitive expense of upgrading a whole population of bridges all at once, expected performance of bridges during an upper level event is not uniform. The degree of retrofit effort and therefore the performance requirement is determined according to the anticipated service life and importance of the bridge. By having performance objectives set as a function of these factors, the use of resources is prioritized and applied where it does the most good. Better performance is demanded of structures that are deemed important and/or expected to be in service for a long time. Although a bridge may be expected to sustain damage at the upper level earthquake, it is planned that all bridges will avoid collapse and function well enough to prevent the loss of life.
Geotechnical Hazard
In addition to the hazard presented directly from the earthquake induced shaking, serious damage can result from scenarios classified as geotechnical hazards. These include soil liquefaction, lateral spreading, soil settlement, surface fault rupture and flooding. These situations can have consequences as devastating as shaking, such as the loss of the foundation that could result in the collapse of a structure. Since liquefaction has been a significant cause of damage to bridges during past earthquakes, the new version of the manual gives added attention to these risks.

Bridge Importance
Although an argument can be made for the importance of every bridge, bridges serving as critical links in the transportation network are judged to be higher priority because of the severe repercussions that damage to them would have on emergency response and regional commerce. The concept of performance based retrofit consequently calls for certain bridges are identified as essential. All others are considered standard.

Because previous attempts to classify bridges using completely objective criteria have not been successful, the assignment of importance is left to the agency. It is made using less tangible socioeconomic factors as well as factual data.

The manual defines an essential bridge as one that is expected to function after an earthquake or which crosses a route that is expected to remain open immediately following an earthquake. An essential bridge meets one or more of the following conditions:

- The bridge is necessary to provide secondary life safety (i.e. it provides access to local emergency services such as hospitals, or crosses such routes, or the bridge carries lifelines such as electric power, gas, or water supply pipelines.)
- Loss of the bridge would lead to severe economic impact (i.e. it is a major link in the transportation network, one that is vital to the economic recovery of the region, or services an area that has a major impact on the local economy)
- The bridge is included in a local emergency plan as being critical (i.e. it enables emergency responders, fire departments, health agencies to respond to disasters, or it is on an identified emergency evacuation route)
- The bridge is a critical link in the national defense network or necessary for the nation’s security. (e.g. routes that service military installations, strategic industries, etc)

Any bridge that is not classified as essential by the transportation agency is considered standard.

Anticipated Service Life (ASL)
There are other factors but anticipated service life is related mainly to the age and condition of a structure. It is intuitive that younger bridges will be in service for a long time and will be exposed longer to the risk of an earthquake for a longer period of time. It therefore follows that these bridges should be made more resistant to earthquake-induced forces without suffering irreparable damage. Retrofitting a bridge with a short service life is more difficult to justify in view of the very low likelihood that a damaging earthquake will occur during the remaining life of the structure. Table 2 categorizes bridges by age. This is a useful ASL selection guide, even though other, less tangible factors may also influence the decision.
### Table 2: Anticipated Service Life Categories

<table>
<thead>
<tr>
<th>Service Life Category</th>
<th>Approximate Remaining Service Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASL1</td>
<td>0 – 15 yrs</td>
</tr>
<tr>
<td>ASL2</td>
<td>16 – 50 yrs</td>
</tr>
<tr>
<td>ASL3</td>
<td>&gt;50 yrs</td>
</tr>
</tbody>
</table>

Bridges in category ASL 1 are considered to be near the end of their service life and retrofitting may not be economically justified. These bridges need not be retrofitted and are assigned to a default seismic retrofit category, i.e. category A. At the other end of the spectrum are bridges in category ASL 3. These are almost new and retrofitting to the standard of a new design may be justified. Those in category ASL 2 fall between these two extremes and a lesser standard is both technically and fiscally responsible.

### Performance Levels

Three levels of performance objectives have been defined. See Table 3. Working with the most vulnerable bridges first, a transportation agency will determine which ones are considered essential and estimate the remaining service life so it can be put into an ASL category. Table 3 can then be used to determine the minimum performance level for the lower and upper level earthquake. An agency is, of course, free to set the performance level higher than these recommended minimums.

### Table 3 Assignment of Performance Level

<table>
<thead>
<tr>
<th>EARTHQUAKE</th>
<th>BRIDGE IMPORTANCE and SERVICE LIFE CATEGORY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Standard</td>
</tr>
<tr>
<td></td>
<td>ASL1</td>
</tr>
<tr>
<td><strong>Lower Level Earthquake</strong></td>
<td></td>
</tr>
<tr>
<td>A return period of approximately 100 years</td>
<td>PL0</td>
</tr>
<tr>
<td><strong>Upper Level Earthquake</strong></td>
<td></td>
</tr>
<tr>
<td>A return period of approximately 1000 years</td>
<td>PL0</td>
</tr>
</tbody>
</table>

Where:

- PL0 (No minimum): No minimum level of performance
- PL1 (Life Safety): Life safety is assured. There may be significant damage as a result of the upper level earthquake and service will probably be disrupted but collapse is avoided so lives are not lost.
- PL2 (Operational): Sustained damage is minimal and limited service for emergency vehicles is available after inspection and clearance of debris. The bridge is repairable but there may be restrictions to traffic.
- PL3 (Fully Operational): The bridge behaves elastically and no damage is sustained. Full service is available for all vehicles immediately after an earthquake.
Soil Class and Site Factors
The behavior of a bridge during an earthquake is strongly related to the soil conditions at the site. Soft soils can amplify ground motions in the underlying rock, sometimes by factors of 2 or more. The extent of this amplification is dependent on the stiffness of the soil and rock and the intensity of shaking in the rock below. The manual classifies sites by type (site class A-E) and profile for the purpose of defining the overall seismic hazard. The seismic hazard level is then quantified as the product of the soil amplification and the intensity of shaking in the underlying rock. Site classification F is for situations that require a site specific evaluation.

Factors are provided for each of the soil classes. Site class B (soft rock) is taken to be the reference site category for the USGS ground shaking maps so the site factor is 1.0. Site classes A, C, D, and E have separate sets of site factors for the short-period range (site factor $F_a$) and long-period range (site factor $F_v$). These site factors are greater for soils that are softer (increasing from site class A to E) because they quantify the amplification that occurs when rock is covered by softer soils.

Design Response Spectrum
The manual uses a two point method to characterize earthquake ground motion and draw a design response spectrum as shown in Figure 2. The two points used to define the spectrum are spectral ordinates (peak structural accelerations) in bridges with periods of 0.2 and 1.0 second. For bridges on rock, (site class B), these ordinates are identified as $S_s$ and $S_1$ respectively. For other site conditions, the response spectral accelerations are modified with the site factors discussed above to obtain a value for short period (0.2 sec.) design spectral acceleration ($S_{DS}$) and for long period (1.0 sec.) design spectral acceleration ($S_{D1}$). The variation of these ordinates throughout the United States has been mapped for various return periods by the US Geological Survey (USGS). Maps are available on the USGS web site or on the CD provided with the manual. If a transportation agency so desires, state ground motion maps may be generated and supplied to designers as a substitute for the national ground motion maps.

Figure 2: Construction of the seismic design response spectrum
Seismic Hazard Levels (SHL)
Each bridge is assigned to one of four seismic hazard levels (I through IV) using the spectral ordinates and soil factors mentioned above. See Table 4. If two different hazard levels are derived for the same bridge because of differing soil conditions, the higher level should be used.

<table>
<thead>
<tr>
<th>HAZARD LEVEL</th>
<th>Using $S_{D1} = F_v S_1$</th>
<th>Using $S_{DS} = F_a S_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$S_{D1} \leq 0.15$</td>
<td>$S_{DS} \leq 0.15$</td>
</tr>
<tr>
<td>II</td>
<td>$0.15 &lt; S_{D1} \leq 0.25$</td>
<td>$0.15 &lt; S_{DS} \leq 0.35$</td>
</tr>
<tr>
<td>III</td>
<td>$0.25 &lt; S_{D1} \leq 0.40$</td>
<td>$0.35 &lt; S_{DS} \leq 0.60$</td>
</tr>
<tr>
<td>IV</td>
<td>$0.40 &lt; S_{D1}$</td>
<td>$0.60 &lt; S_{DS}$</td>
</tr>
</tbody>
</table>

Notes:
1. For the purposes of determining the Seismic Hazard Level for Site Class E Soils, the value of $F_v$ and $F_a$ need not be taken larger than 2.4 and 1.6 respectively, when $S_1$ is less than or equal to 0.10 and $S_s$ is less than 0.25.
2. For the purposes of determining the Seismic Hazard Level for Site Class F Soils, $F_v$ and $F_a$ values for Site Class E soils may be used with the adjustment described in Note 1 above.

Seismic Retrofit Categories (SRC)
Once the bridge importance, anticipated service life, and seismic hazard are defined, each bridge can be classified and assigned to a particular seismic retrofit category. Assignment to one of the four categories provides guidance on the level of analysis required when evaluating the structure and which retrofitting measures should be employed. Bridges in Seismic Retrofit Category A do not need retrofitting, regardless of their structural deficiencies or level of hazard. These are usually located in areas where the overall risk of a damaging earthquake is low.

Since each bridge is subject to a lower level and an upper level earthquake, there are two performance levels and two seismic hazard levels for each bridge. The more rigorous category is taken as the controlling requirement, and the associated earthquake becomes the design earthquake for later use in screening, evaluation and designing retrofit measures. In all but the most seismically hazardous situations, the upper level event will govern design. For this reason, emphasis in the manual is on the procedures needed for evaluating response to and protecting against the upper level event. Table 5 shows seismic retrofit categories for the upper level event, given a particular performance level and hazard level.

EVALUATION METHODS
Chapters 5-7 of the manual are dedicated to the detailed analyses that may be necessary for component by component assessment. These are sometimes needed for both structural and geotechnical issues. Methods presented are: simple minimum capacity checks, component capacity-demand (C/D) checks using elastic dynamic analysis methods, structure C/D analysis using capacity-demand spectra, structure C/D methods using a nonlinear static procedure or pushover analysis, and a nonlinear dynamic method using inelastic time history analysis.
Table 5: Seismic Retrofit Categories for Upper Level Event

<table>
<thead>
<tr>
<th>HAZARD LEVEL</th>
<th>PERFORMANCE LEVEL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PL0: No Minimum Level</td>
</tr>
<tr>
<td>I</td>
<td>A</td>
</tr>
<tr>
<td>II</td>
<td>A</td>
</tr>
<tr>
<td>III</td>
<td>A</td>
</tr>
<tr>
<td>IV</td>
<td>A</td>
</tr>
</tbody>
</table>

SRC A: No evaluation or retrofit is required.
SRC B: Assess without a detailed evaluation.
SRC C and SRC D: Rigorous standards for evaluation and retrofit.

Note: These categories are essentially the same as the seismic performance categories used in previous editions of the manual. The terminology was modified to distinguish them from the performance categories employed by AASHTO for the design of new bridges.

RETROFITTING PROCESS

Retrofitting strategies, approaches and measures
Once a bridge is found to be seismically deficient, the next step is to decide what, if anything, should be done to correct the deficiencies. Decision-making may be formalized by exploring retrofit options and the associated cost implications. The manual discusses the selection of a retrofit strategy, development a retrofit approach, and identification of appropriate retrofitting measures.

A Retrofit Strategy is the overall plan for the seismic retrofit of a bridge. This plan can employ more than one retrofit approach and retrofit measures. Identification of a retrofit strategy is considered analogous to the ‘structure type selection’ process for a new bridge.

A Retrofit Approach is the philosophy of seismic enhancement adopted for a bridge. Strengthening is one of several retrofit approaches can be employed to improve the seismic performance of a bridge. A summary of approaches are: strengthening; displacement capacity enhancement; force limitation; response modification; site remediation by ground improvement; acceptance or control of damage to specific components; and partial replacement.
A Retrofit Measure is the physical modification of a component in a bridge for the purpose of enhancing overall seismic performance. For example, the addition of a steel or fiber reinforced polymer (FRP) shell to confine a reinforced concrete column is a retrofit measure. Retrofit measures for superstructure, substructure, and foundation components that are presented in the manual include: Diaphragm strengthening; Energy dissipating ductile diaphragms; Provision of longitudinal continuity to simply supported spans; Bearing replacement; Seismic isolation bearings; Energy dissipaters; Seat width extensions and catcher blocks at girder supports and intermediate hinges; Restrainers at girder supports and intermediate hinges; Column replacement; Column jacketing with concrete shells, steel jackets, or FRP wraps; Infill shear walls in bents; Cap beam strengthening using pre-stressing; Super girders; Anchor slabs behind abutments; Soil and gravity anchors; Abutment shear keys; Footing replacement; Footing overlays; Pile tie-down enhancement; Supplemental piles; Articulation for fault crossings; and Site remediation for unstable slopes and liquefaction, and vibro-replacement of soils and stone columns.

The manual tabulates appropriate levels of intensity for the screening, evaluation and actual retrofitting of a bridge according to the seismic retrofit category identified. For example, a bridge with a SRC of A needs no particular assessment of its component vulnerabilities, whereas a bridge in SRC D warrants a check of seat widths, connections, columns, walls, footings, abutments, and liquefaction potential. Likewise, the evaluation methods used for a SRC D bridge are the most rigorous and labor intensive.

CONCLUSION
FHWA’s 2005 Seismic Retrofitting Manual for Highway Structures is intended to be applicable nationwide so it is written to give an appropriate amount of emphasis to structure types found in other regions as well as those found in California. Part I is dedicated to existing, regular highway bridges. Part II (not addressed in this paper) deals with other typical structure types such as culverts and retaining walls.

The manual provides new information on the seismic hazard and the geotechnical hazards that are likely to occur at two levels of earthquake, a lower level that has a 100 year return period and 1000 years for the less frequent, stronger event. These events were selected with consideration of recent developments in the evolution of criteria being developed for the design of new bridges. They provide a somewhat higher level of protection than those criteria developed for the previously used 500 year event.

The new manual provides methods for screening and prioritizing bridges for retrofit and gives increasingly rigorous means of evaluation when the effort is warranted. It discusses different approaches for reducing the risk of failure and gives numerous specific measures that can be taken as part of a retrofitting project.

Part I not only expands material presented in earlier versions; it also introduces the concept of performance based retrofitting. Chapter 1 of the manual conveniently summarizes the entire process and tabulates the level of effort necessary for component screening, evaluation and retrofitting a bridge after consideration of numerous parameters.
ACKNOWLEDGMENTS
Development of the retrofitting manual was funded by FHWA / MCEER Highway Project 106 under the direction of Contract Officer Technical Representative John O’Fallon. The manual was produced by an MCEER team of numerous authors and reviewers headed by Project Director George Lee, University at Buffalo.

Credit for substantial portions of the manual or other significant contribution is given to: Ian Buckle, who assumed the role of lead author, Ian Friedland, Jeffery Ger, E.V. Leyendecker, Derrel Manceaux, John Mander, Geoff Martin, Richard Nutt, Peter Osborn, Gokhan Pekcan, Maury Power, and Vikas Wagh. MCEER’s Highway Seismic Research Council provided oversight and review throughout the process. Jane Stoyle, MCEER Publications editor deserves special thanks for her diligence and tenacity as does Hector Velasco who is responsible for the many graphics.

DISCAIMER
The contents of this paper are the sole responsibility of the authors and do not constitute official FHWA or MCEER policy or recommendations.

REFERENCES

