A MANUAL FOR THE PERFORMANCE-BASED SEISMIC RETROFITTING OF HIGHWAY BRIDGES

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Abstract

In 2006 the Federal Highway Administration (FHWA) published a major revision to the 'Seismic Retrofitting Manual for Highway Bridges', published ten years ago in 1995 (FHWA, 1995). This new edition expanded the coverage of the previous publication by including procedures for evaluating and retrofitting retaining structures, slopes, tunnels, culverts, and pavements, in addition to bridges. It is published in two parts as follows:

Part 1: Bridges
Part 2: Retaining Structures, Slopes, Tunnels, Culverts, and Pavements

Whereas Part 1 maintains the basic format of the retrofitting process described in the 1995 Report, major changes have been made in this revision to include current advances in earthquake engineering, field experience with retrofitting highway bridges, and the performance of bridges in recent earthquakes in California and elsewhere. It is the result of several years of research with contributions from a multidisciplinary team of researchers and practitioners.

In particular, a performance-based retrofit philosophy is introduced similar to that used for the performance-based design of new buildings and bridges. Performance criteria are given for two earthquake ground motions with different return periods, 100 and 1000 years. A higher level of performance is required for the event with the shorter return period (the lower level earthquake ground motion) than for the longer return period (the upper level earthquake ground motion). Criteria are recommended according to bridge importance and anticipated service life, with more rigorous performance being required for important, relatively new bridges, and a lesser level for standard bridges nearing the end of their useful life.

This paper describes the methodology used to implement a performance-based retrofit philosophy for highway bridges in the 2006 edition of the FHWA Manual (FHWA, 2006).

Introduction

It has been common practice to design new bridges and buildings for a single-level of earthquake ground motion. This ground motion, often called the *design earthquake*, represents the largest motion that can be reasonably expected during the life of the bridge. Implied in such a statement is the fact that ground motions larger than the *design earthquake* may occur during the life of the bridge, but the likelihood of this

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happening is small. This likelihood is usually expressed as the *probability of exceedance*, and it may also be described by a *return period* in years. When setting the seismic hazard level, most design specifications that are intended for regions of varying seismicity use the same probability of exceedance from one region to another. This 'uniform hazard' approach is considered to be more rational than using the maximum historical event for each region.

The *Standard Specification for Highway Bridges* (AASHTO, 2002) in the United States adopted a uniform hazard approach following the 1989 Loma Prieta earthquake, and chose a level of hazard that had a 10 percent probability of exceedance in a 50-year exposure period (the assumed life of a bridge). This corresponded to a ground motion with a return period of about 500 years. During the development of the *AASHTO LRFD Specification* in the mid-nineties, the life of the average highway bridge was reassessed at 75 years and the exposure period was adjusted accordingly (AASHTO, 1998). The probability of exceedance was then raised to 15 percent to maintain (approximately) the same return period (500 years).

At the same time as adopting this uniform hazard approach, a corresponding set of performance standards was included in the philosophy of the 1992 *AASHTO Specifications* (AASHTO, 2002). These are given in Art. 1.1 of the Specification and summarized below:

- Small to moderate earthquakes should be resisted within the elastic range, without significant damage.
- Realistic seismic ground motion intensities and forces be used in the design procedures.
- Exposure to shaking from large earthquakes should not cause collapse of all or part of the bridge. Where possible, damage that does occur should be readily detectable and accessible for inspection and repair.

A set of basic concepts for seismic design was derived from this philosophy (Art. 1.3, AASHTO, 2002), and is summarized below:

- Hazard to life is minimized.
- Bridges may suffer damage but should have a low probability of collapse.
- Function of essential bridges is maintained.
- Ground motions used in design should have a low probability of being exceeded in the normal lifetime of the bridge.

While characterized by a lack of specificity, these criteria were a significant advance over the then prevailing requirements for seismic design.

In like manner, previous retrofit guidelines and manuals have also used a single-level of earthquake ground motion (a 500-year event) for representing the earthquake hazard, and adopted the same performance criteria as in the then current AASHTO Specifications for bridge design.

The assumption is made in single-level design and retrofit, that if performance under the *design earthquake* is satisfactory, it will be satisfactory at all other levels of ground motion, both smaller and larger. Such an assumption is generally not true as seen in recent earthquakes in California, Costa Rica, Japan, Turkey and Taiwan (Figures 1 to 4). It would be true for a smaller event if elastic performance was required at the design ground motion, and it may also be true for a larger event, if it exceeded the design ground motion by only a small margin (i.e., less than 50 percent), and there was a sufficient reserve of strength in the bridge to accommodate this higher demand.

However, in many areas of the United States, these larger ground motions can be three or four times the design ground motions and may cause instability and collapse. Although such ground motions rarely happen, their occurrence should be explicitly considered in the design and retrofit process and a ‘multi-level’ rather ‘single-level’ design process should be used. In addition, performance requirements should be adjusted for ground motions of different sizes, with higher levels of performance being expected for smaller motions and lesser levels of performance for larger motions.

Performance-based design provides a format for addressing these needs in a rational manner. It explicitly allows for different performance expectations for bridges of varying importance while subject to different levels of seismic hazard. Accordingly, this manual recommends a performance-based approach to the seismic retrofitting of highway bridges in the United States.

This relationship is shown in Figure 5. Representation of the hazard and performance expectations by discrete zones (or levels) is necessary given the current state-of-the-art, and this leads to the bar chart shown in this Figure. Nevertheless, the trends are the same: high performance standards in high hazard zones imply higher costs.

Seismic Performance Criteria

Performance Levels

As noted in the previous section, this manual presents a performance-based approach to the seismic retrofitting of highway bridges. This means that the expected performance of the retrofitted bridge is explicitly recommended for different levels of earthquake ground motion. In this manual, performance criteria are defined for four performance levels. These are given as follows:

Performance Level 0 (PL0):	No minimum level of performance is recommended.
Performance Level 1 (PL1):	Life safety. Significant damage is sustained during an earthquake and service is significantly disrupted, but life safety is assured. The bridge may need to be replaced after a large earthquake.

Figure 1 (right).
Collapse of the link span at Tower E9 of the San Francisco Oakland Bay bridge due to inadequate seat lengths and anchor bolts.

Loma Prieta earthquake, 1989

Figure 2 (left).
Collapse of the two-level Cypress Viaduct on I-880 in Oakland due to brittle shear failure at the connection between the upper and lower levels of the viaduct.

Loma Prieta earthquake, 1989

Figure 3 (right).
Collapse of end spans in the Shi Wei bridge in Taichung, due to ground failure and nearby fault rupture.

Chi Chi earthquake, 1999

Figure 4 (left).
Diagonal shear crack in lightly reinforced concrete pier of the Wu Shu bridge in Taichung.

Chi Chi earthquake, 1999

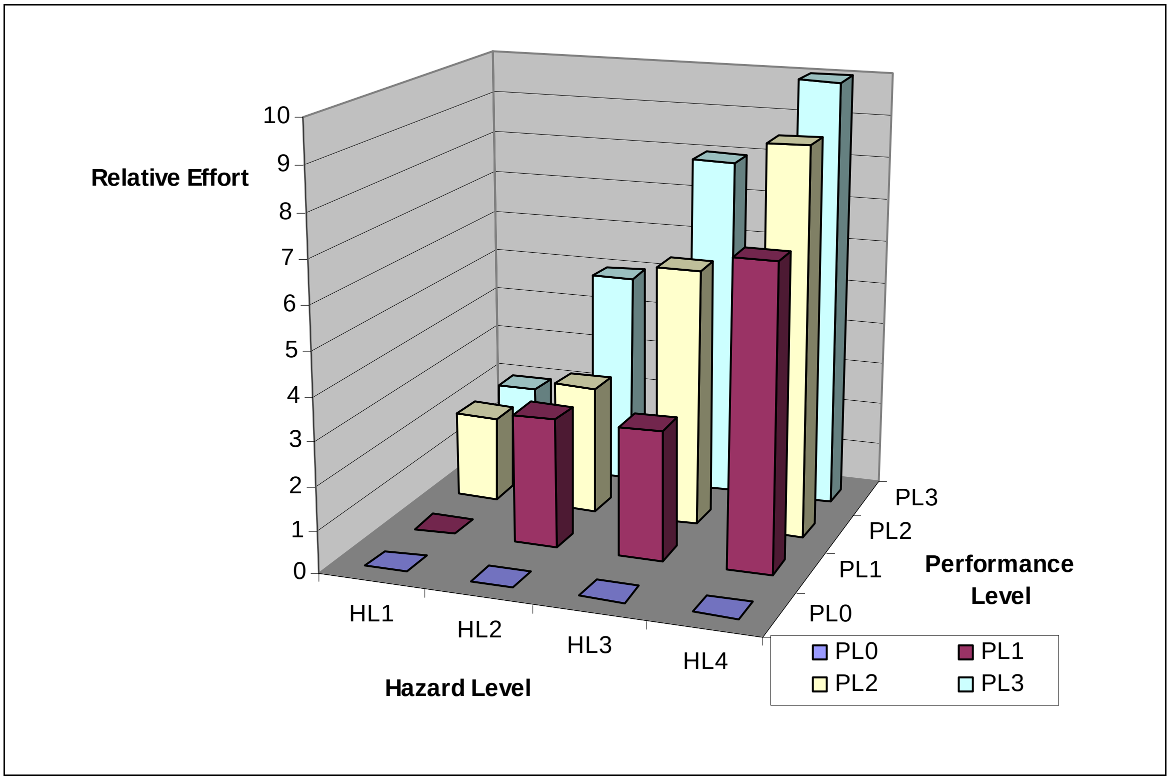

Figure 5. Conceptual relationship between relative effort, increasing hazard and performance criteria implied in this paper.

Performance Level 2 (PL2): Operational. Damage sustained is minimal and full service for emergency vehicles should be available after inspection and clearance of debris. Bridge should be reparable with or without restrictions on traffic flow.

Performance Level 3 (PL3): Fully Operational. No damage is sustained and full service is available for all vehicles immediately after the earthquake. No repairs are required.

The terms *minimal* damage and *significant* damage are used in the above performance criteria. These terms are explained below:

- Minimal damage includes minor inelastic response and narrow flexural cracking in concrete. Permanent deformations are not apparent and repairs can be made under non-emergency conditions with the possible exception of superstructure expansion joints which may need removal and temporary replacement.

- Significant damage includes permanent offsets and cracking, yielded reinforcement, and major spalling of concrete, which may require closure to repair. Partial or complete replacement of columns may be required. Beams may be unseated from bearings but no span should collapse. Similarly, foundations are not damaged except in the event of large lateral flows due to liquefaction, in which case inelastic deformation in piles may be evident.

Higher levels of performance may be specified by the owner. For example, the following criteria might be used for extremely important bridges:

- Sustained damage is negligible and full service to all traffic is available after inspection and clearance of debris. Damage that does occur is reparable without interruption to traffic flow. Negligible damage includes evidence of movement, and/or minor damage to nonstructural components, but no evidence of inelastic response in structural members or permanent deformations of any kind.

Generally, the performance criteria vary with level of earthquake ground motion, bridge importance and anticipated service life. In this manual, these objectives are defined for two ground motion levels (a *lower* and an *upper* level), two importance classifications (*standard* and *essential*), and three service life categories (ASL l, 2 and 3), as discussed below.

Earthquake Ground Motion Levels

The *lower level* (LL) earthquake ground motion is one that has a reasonable likelihood of occurrence within the life of the bridge (assumed to be 75 years), i.e., it represents a relatively small but likely ground motion[2]. It is common practice to use a probability of exceedance to characterize the motion, as noted above. Accordingly, the lower level motion has a relatively high probability of exceedance within the life of a bridge, and a figure of 50 percent is recommended for retrofit design. A 50 percent probability of exceedance in 75 years corresponds to a return period of about 100 years.

By contrast, the *upper level* (UL) earthquake ground motion has a finite, but remote, probability of occurrence within the life of the bridge; i.e., it represents a large but unlikely ground motion[3]. Just as for the lower level motion, it is common practice to use a probability of exceedance to characterize this motion. Thus the upper level earthquake ground motion has a relatively low probability of exceedance within the life of a bridge. In this manual, the upper level motion has a 7 percent probability of exceedance in 75 years, which corresponds to a return period of about 1,000 years.

Spectral ordinates and peak ground accelerations for both the lower and upper level ground motions may be found using maps published by the US Geological Survey or from a CD-ROM by Frankel and Leyendecker (2001). A copy of this CD is included

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[2] This ground motion is sometimes called the *frequent* earthquake. In the *NCHRP 12-49 Recommended LRFD Guidelines for Seismic Design* (ATC/MCEER, 2003) it is called the *expected* earthquake, and in the *Caltrans Seismic Design Methodology* (Caltrans, 1999) it is called the *functional evaluation earthquake (FEE).*

[3] This ground motion is sometimes called the *rare* earthquake. In the *NCHRP 12-49 Recommended LRFD Guidelines for Seismic Design* (ATC/MCEER, 2003) it is the *maximum considered earthquake (MCE)*, and in the *Caltrans Seismic Design Methodology* (Caltrans, 1999) it is the *safety evaluation earthquake (SEE).*

in the revised Manual (FHWA ,2006)[4]. Bridge sites may be identified by zip code or, more accurately, by latitude and longitude. However, values given on this CD are in terms of an exposure period of 50 years rather than the 75-year bridge life assumed above. Therefore, equivalent exceedance probabilities for a 50-year life are required to use this CD, as follows:

- The return period for an earthquake ground motion with a 50 percent probability of exceedance in 75 years is 108 years. However, this return period is only 72 years for a ground motion with a 50 percent probability of exceeedance in 50 years. For the purpose of this manual, this lesser return period is considered to be close enough to the specified value of 100 years, and that values for the 50-year life may be used. Therefore, for the lower level ground motions, use data from the CD for 50 percent probability of exceedance in 50 years.

- The return period for an earthquake ground motion with a seven percent probability of exceedance in 75 years is approximately the same as that for a ground motion with five percent probability of exceedance in 50 years (both are about 1,000 years). Therefore, for the upper level ground motions, use data from the CD for five percent probability of exceedance in 50 years.

Alternatively, spectral ordinates and peak ground accelerations may be obtained for the upper level ground motion from the following web site maintained by the U.S. Geological Survey: *http://eqhazmaps.usgs.gov*. Mapped values are given for regions within the United States, and numerical values are given for specific locations according to zip code, or longitude and latitude. As with the CD-ROM, these values are expressed in terms of a 50-year bridge life and equivalent exceedance probabilities must be found to use this site, as described for the CD. At this time, this site does not give spectral ordinates and accelerations for the lower level ground motions (100 years) and the only known, readily available, source of this data is the CD-ROM included with this manual.

Some performance-based specifications for bridges and buildings have recommended a three percent probability of exceedance in 75 years for the upper level ground motions; but these specifications are for new construction and not necessarily appropriate for the retrofit of existing structures. Seismic resistance is much easier to provide in new structures than in existing ones. The selection of the reduced upper level motions for retrofitting is a compromise between the need to provide life safety and adequate performance for these less frequent motions and the limited resources of the owner. Note that these performance criteria are general recommendations and subject to change by the owner (or engineer) when specific circumstances of a particular bridge make it necessary.

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[4] This CD contains the seismic hazard maps and curves published by USGS in 1996. Updated maps were published in 2002 but not for the 1000-year return period.

Bridge Importance

Classification of bridge importance based on traffic counts and detour lengths has been proposed in the past and importance indices developed. But such quantitative methods do not usually include many non-technical issues that directly affect importance and are loosely called socio- economic factors. Instead, a broad classification based on engineering judgment is preferred, and in this manual two such classes are recommended: essential and standard. *Essential* bridges are those that are expected to function after an earthquake or which cross routes that are expected to remain open immediately following an earthquake. All other bridges are classified as *standard*. The determination of importance is therefore subjective and consideration should be given to societal/survival and security/defense requirements when making this judgment.

An *essential* bridge is, therefore, one that satisfies one or more of the following conditions:

- A bridge that is required to provide secondary life safety; e.g., one that provides access to local emergency services such as hospitals. This category also includes those bridges that cross routes that provide secondary life safety, and bridges that carry lifelines such as electric power and water supply pipelines.

- A bridge whose loss would create a major economic impact; e.g., one that serves as a major link in a transportation system, or one that is essential for the economic recovery of the affected region.

- A bridge that is formally defined by a local emergency plan as critical; e.g., one that enables civil defense, fire departments, and public health agencies to respond immediately to disaster situations. This category also includes those bridges that cross routes that are defined as critical in a local emergency response plan and those that are located on identified evacuation routes.

- A bridge that serves as a critical link in the security and/or defense roadway network. Security and defense requirements may be evaluated using the 1973 Federal-aid Highway Act, which required that a plan for defense highways be developed by each state. Now called STRAHNET, this defense highway network provides connecting routes to military installations, industries, and resources and is part of the National Highway System.

Anticipated Service Life

An important factor in deciding the extent to which a bridge should be retrofitted is the anticipated service life (ASL). Retrofitting a bridge with a short service life is difficult to justify for two reasons: it is not economical and the design earthquake is unlikely to occur during the remaining life of the structure. On the other hand, a bridge that is almost new or being rehabilitated to extend its service life, should be retrofitted for the longer remaining service life.

Estimating remaining life is not an exact science and depends on many factors such as age, structural condition, specification used for design, and capacity to handle current and future traffic. Nevertheless, estimates can be made, at least within broad ranges, for the purpose of determining a bridge's remaining service life and, subsequently, a retrofit category. Three such categories are used in this manual, as defined in Table 1. When setting these categories, it was noted that new bridges are assumed to have a service life of 75 years in the *AASHTO LRFD Specification* (AASHTO, 1998), and this life span was then divided into three categories for the purpose of assigning retrofit levels (retrofit categories) according to age and remaining life. It is recognized that many long-span bridges have service lives far greater than 75 years, but these are outside the scope of this manual. Bridges in benign climates and those located on low-density routes may also have service lives in excess of 75 years.

Bridges in category ASL 1 are considered to be near the end of their service life and retrofitting may not be economically justified. Thus, these bridges need not be retrofitted and are assigned to the lowest seismic retrofit category. Bridges in category ASL 3 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 acceptable. However, the owner may always choose to retrofit to a higher standard as circumstances permit.

Table 1. Service life categories.

SERVICE LIFE CATEGORY	ANTICIPATED SERVICE LIFE	AGE (if not rehabilitated)[1]
ASL 1	0 - 15 yrs	60 - 75 yrs
ASL 2	16 - 50 yrs	25 - 60 yrs
ASL 3	> 50 yrs	< 25 yrs

Note: 1. Age is calculated assuming total service life is 75 years and the bridge has not been rehabilitated in its lifetime to date.

Bridges are often rehabilitated toward the end of their service life to address deficiencies that have accumulated over time (e.g., deteriorated deck slabs, frozen bearings and damaged expansion joints), improve safety, and to accommodate increased traffic volume. As a consequence, a bridge with 15 years, or less, of life may, after rehabilitation, have a new service life of 35 years, and in so doing, the service life category (ASL) for the bridge has been lifted from ASL 1 to ASL 2 (Table 1). The bridge should now be reevaluated for seismic performance, which should be done at the same time as planning the other rehabilitation. In this way, retrofit measures (if needed) can be implemented at the same time. By taking advantage of the contractor being on site, the cost of the seismic retrofit may be significantly reduced.

Selection of Performance Level

Recommended minimum performance levels are given in Table 2 according to the level of earthquake ground motion, bridge importance and service life category, as defined above. If retrofitting to these levels cannot be justified economically, the owner may choose a lower level. On the other hand, for certain classes of bridges, the owner may choose a higher level than that recommended here. An example of such a case is the bridges on STRAHNET, which are critically important to the operation of national or regional transportation routes. Suggested criteria for these special structures are given above, but it is also likely that these bridges are of sufficient importance to justify site-specific and structure-specific performance criteria. These bridges may fall outside the scope of this manual.

Retrofitting Process for Dual Level Ground Motions

Retrofitting is only one of several courses of action when faced with a bridge that is seismically vulnerable. Others include bridge closure, bridge replacement, and acceptance of the damage and its consequences. Bridge closure or replacement is usually not justified by seismic deficiency alone and will generally only be an option when other deficiencies exist. Therefore, for all practical purposes, a choice is made between strengthening and accepting the risk. This decision often depends on the importance of the bridge and on the cost and effectiveness of the proposed retrofit.

Budget constraints and limited resources prevent the simultaneous retrofit of all of the deficient bridges on the highway system, and the most critical bridges should be upgraded first. The selection and prioritizing of bridges for retrofitting requires an appreciation of not just the engineering issues but also the economic, social, and practical aspects of the situation.

Since it is recommended above that the seismic performance of a bridge be checked for two levels of earthquake ground motion (lower level and upper level) the overall retrofitting process has two distinct stages:

- Stage 1. Screening, evaluation and retrofitting for the lower level earthquake ground motion, and

- Stage 2. Screening, evaluation and retrofitting for the upper level earthquake ground motion.

It is not possible to combine these two stages into one, since the performance criteria for each is very different. For example, the criteria for the lower level ground motion includes no structural damage and no repair (i.e., elastic behavior is expected) whereas for the upper level ground motion, damage is acceptable provided collapse does not occur and, for some bridges, access for emergency vehicles is available (i.e., inelastic behavior is expected).

Table 2. Minimum performance levels for retrofitted bridges.

EARTHQUAKE GROUND MOTION	BRIDGE IMPORTANCE and SERVICE LIFE CATEGORY					
	Standard			**Essential**		
	ASL 1	**ASL 2**	**ASL 3**	**ASL 1**	**ASL 2**	**ASL 3**
Lower Level Ground Motion 50 percent probability of exceedance in 75 years; return period is about 100 years.	PL0[4]	PL3	PL3	PL0[4]	PL3	PL3
Upper Level Ground Motion 7 percent probability of exceedance in 75 years; return period is about 1,000 years.	PL0[4]	PL1	PL1	PL0[4]	PL1	PL2

Notes:

1. Anticipated Service Life categories are:
   - ASL 1: 0 – 15 years
   - ASL 2: 16 – 50 years
   - ASL 3: > 50 years
2. Performance Levels are:
   - **PL0**: **No minimum** level of performance is recommended.
   - **PL1: Life safety.** Significant damage is sustained and service is significantly disrupted, but life safety is preserved. The bridge may need to be replaced after a large earthquake.
   - **PL2: Operational.** Damage sustained is minimal and service for emergency vehicles should be available after inspection and clearance of debris. Bridge should be reparable with or without restrictions on traffic flow.
   - **PL3: Fully Operational**. No damage is sustained and full service is available for all vehicles immediately after the earthquake. No repairs are required.
3. Spectral ordinates and peak ground accelerations may be found for the Upper Level earthquake ground motion from http://eqhazmaps.usgs.gov. Ordinates and ground accelerations may be found for *both* the Upper and Lower Level ground motions from the CD-ROM: *Seismic Hazard Curves and Uniform Hazard Response Spectra for the United States*, (Frankel and Leyendecker, 2001)
4. Bridges assigned a Performance Level of PL0 have 15 years, or less, anticipated service life (ASL) and are candidates for replacement or rehabilitation. If the bridge is replaced or rehabilitated, the ASL category will change and so will the required Performance Level.

Each stage comprises three basic steps, i.e. screening, evaluation, and retrofitting for the relevant ground motion. The breakdown of each stage into these steps is illustrated in Figure 6.

Conclusions

The assumption is made in single-level design and retrofit, that if performance under the *design earthquake* is satisfactory, it will be satisfactory at all other levels of ground motion, both smaller and larger. Such an assumption is generally not true as seen in recent earthquakes in California, Costa Rica, Japan, Turkey and Taiwan. It would be true for a smaller event if elastic performance was required at the design ground motion, and it may also be true for a larger event, if it exceeded the design ground motion by only a small margin (i.e., less than 50 percent), and there was a sufficient reserve of strength in the bridge to accommodate this higher demand.

However, in many areas of the United States, these larger ground motions can be three or four times the design ground motions and may cause instability and collapse. Although such ground motions rarely happen, their occurrence should be explicitly considered in the design and retrofit process and a ‘multi-level’ rather ‘single-level’ design process should be used. In addition, performance requirements should be adjusted for ground motions of different sizes, with higher levels of performance being expected for smaller motions and lesser levels of performance for larger motions.

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In particular, a performance-based retrofit philosophy is introduced similar to that used for the performance-based design of new buildings and bridges. Performance criteria are given for two earthquake ground motions with different return periods, 100 and 1000 years. A higher level of performance is required for the event with the shorter return period (the lower level earthquake ground motion) than for the longer return period (the upper level earthquake ground motion). Criteria are recommended according to bridge importance and anticipated service life, with more rigorous performance being required for important, relatively new bridges, and a lesser level for standard bridges nearing the end of their useful life.

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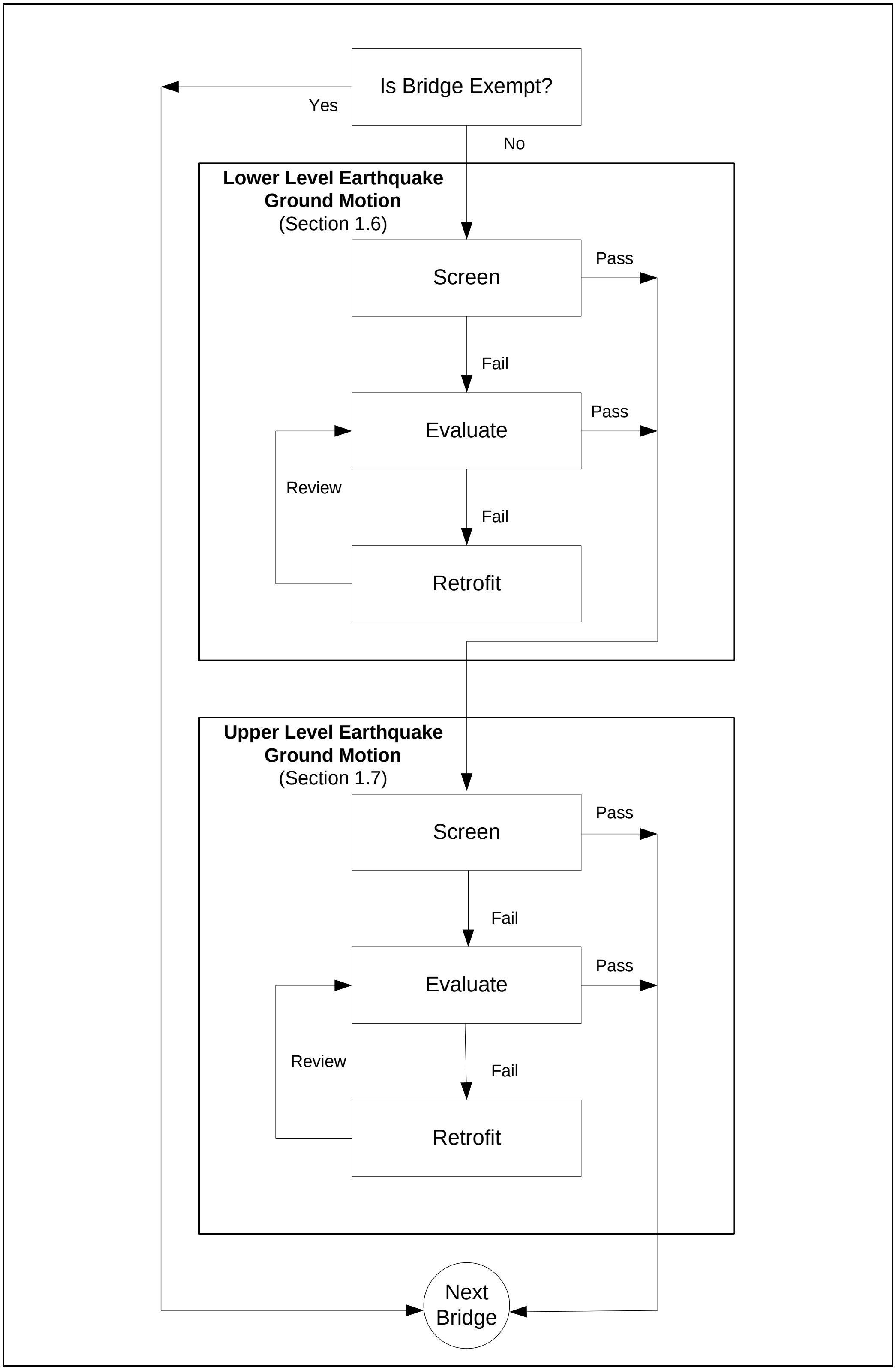

Figure 6. Retrofit process for dual level earthquake ground motions.

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