Estimating Benefits for Bridge Protection Improvements

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Estimating Benefits for Bridge Protection Improvements

Introduction

Benefit-cost analysis for bridge preservation, rehabilitation, repair, and protection projects often requires a different approach than that used for other operational improvements. Other operational improvements typically do not affect the day-to-day experience of users of the facility. Rather, the improvements are aimed at reducing ongoing maintenance needs and ensuring the continued serviceability of the structure. As a result, their estimated benefits are realized from the reduction in the likelihood that local or global structural failure will result in extended reduction, or loss, of service or loss of the structure. Reducing the risk of incurring the resulting capital, user, and operating costs produces a benefit that can be assigned a monetary value. This document describes a possible approach that can be implemented to make that evaluation, aimed specifically at seismic retrofit improvements intended to improve the resilience of the structure.

Methodology

To derive benefits from a reduction in anticipated losses, the value and likelihood of the loss must be estimated for both the base (no-build) and build scenarios. From this, a stream of Estimated Annual Loss (EAL) values can be determined for both scenarios, which can then be differenced and discounted to produce an estimated present value for the expected benefits. Project benefits from addressing different hazards can be evaluated separately and superimposed. Similarly, if recurrence intervals can be established for different levels of performance (for example, continued operation and collapse prevention), benefits derived from improvements in both would be additive.

Rehabilitation and retrofitting projects are typically designed by determining where the capacity (C) of the structure is exceeded by the demand (D) resulting from the target design-level hazard and assembling a cost-effective suite of retrofitting measures to address those deficiencies (to ensure that $C > D$). A key difference between design- and benefit-cost analysis is the need to also determine the likelihood (in terms of an annual rate or recurrence interval) that, without retrofit or rehabilitation, the structure will experience damage that will result in economic losses (the no-build scenario).

In both analyses, demand would be based on deterministic or probabilistic hazard analysis and presented in terms of a force, imposed displacement, or other intensity measure, at different recurrence rates. For the no-build scenario, capacity represents the damage (such as inelastic behavior or instability) expected to result from the demand that would, in turn, result in operational impacts, and other indirect costs, from structural damage or collapse. For the build scenario, capacity represents the improved ability of the repaired or retrofitted structure to resist the demand in a manner consistent with the target level of performance, resulting in reduced likelihood of damage and associated loss of service.

Available approaches to determining C and D will vary depending on the hazard being addressed and may be based on probabilistic hazard analysis, deterministic hazard analysis, or structural reliability (i.e. fragility). Some available resources presenting approaches to hazard determination:

- FHWA, “Seismic Retrofitting Manual for Highway Structures: Part 1 – Bridges,” January 2006. Publication FHWA-HRT-06-032.

- FHWA, “Hydraulic Engineering Circular No. 18, Evaluating Scour at Bridges, Fifth Edition,” April 2012. Publication FHWA-HIF-12-003.
- AASHTO, “The Manual for Bridge Evaluation, 3rd Edition,” 2018, with 2019 and 2020 interim revisions (23 CFR 650.317(a)(1) to (3)).

In the example presented below, the estimated loss values are assumed to be constant over time. However, the same approach would be applicable where expected losses are time-dependent (such as due to future traffic growth in the corridor).

Analysis Values

The analysis uses the following values:

λ_{Base} - For the base scenario, the annual rate of exceedance for a given consequence-based limit state

λ_{Build}- For the build scenario, an annual rate of exceedance for the target performance-based limit state

L_{Base} - Estimated loss from exceeding consequence-based limit state in the base scenario (reconstruction, traffic delay, etc. - $)

L_{Build} – Estimated loss from exceeding the performance-based limit state in the build scenario (if different from L_{Base})

P - Project cost ($)

D - Discount rate (%)

n - Number of analysis cycles corresponding to the discount rate

Base (No Build) Scenario Analysis

Project Cost: $0

Estimated Annual Loss, $EAL_{Base} = L_{Base} \cdot \lambda_{Base}$

Total present value of base scenario EAL:

$$PV_{Base} = EAL_{Base} \cdot \frac{1 - \left(\frac{1}{(1+D)^n}\right)}{D}$$

Build Scenario Analysis:

Project Cost: P

Estimated Annual Loss, $EAL_{Build} = L_{Build} \cdot \lambda_{Build}$

Total present value of build scenario EAL:

$$PV_{Build} = EAL_{Build} \cdot \frac{1 - \left(\frac{1}{(1+D)^n}\right)}{D}$$

Project Benefit

Realized benefit from the project is the reduction in the present value of the estimated annual loss:

$$B = PV_{Base} - PV_{Build}$$

Project Benefit Cost Ratio

$$BCR = \frac{B}{P}$$

Example Calculation

Introduction

In this example, a seismic protection project under consideration will retrofit a bridge to reduce the likelihood of damage from future seismic events. The three-span steel girder bridge, built in 1953, carries an Interstate route over a river, with an average daily vehicle count of 100,000, 10% of which is commercial trucks. Detouring around the bridge in the event of a closure would add 12 miles to a typical trip. The cost to replace the bridge in the event of collapse would be $25 million. The proposed project, estimated to cost $1.8 million, would replace the existing bearings with seismic isolation bearings that will improve the bridge's seismic performance.

Estimated Annual Loss

Estimated annual losses for the no-build and build scenarios will be calculated using the Expected Damage Method presented in the FHWA seismic retrofitting manual (FHWA, 2006). For this analysis, demand is represented by hazard curves relating maximum structural (spectral) accelerations to annual rate of exceedance at the bridge site (Figure 1):

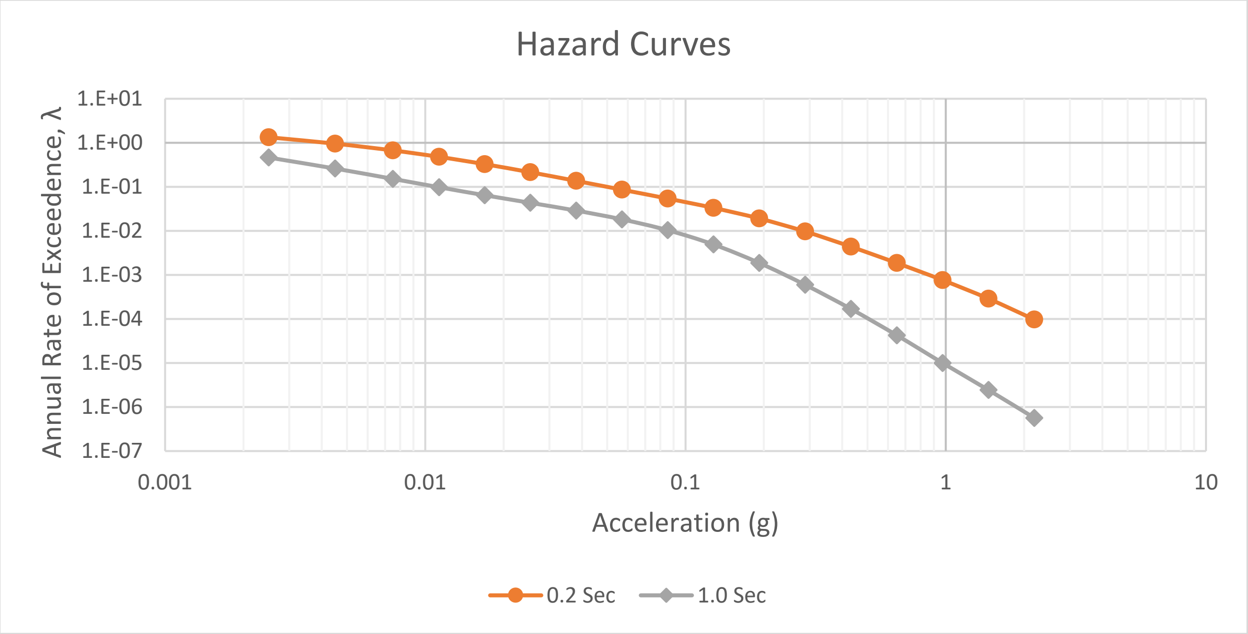

Figure 1: Seismic hazard curves for the bridge site, for both 0.2 sec and 1.0 sec structural period

Bridge-specific fragility curves, which relate spectral acceleration for a 1.0-second structural period to the probability of exceeding each of 5 possible damage states (none, slight, moderate, extensive, and collapse) for both the non-retrofitted (No-Build) and retrofitted (Build) cases, can be constructed using reference fragility curves (from FEMA, 2020) and data from the National Bridge Inventory (Figures 2 and 3):

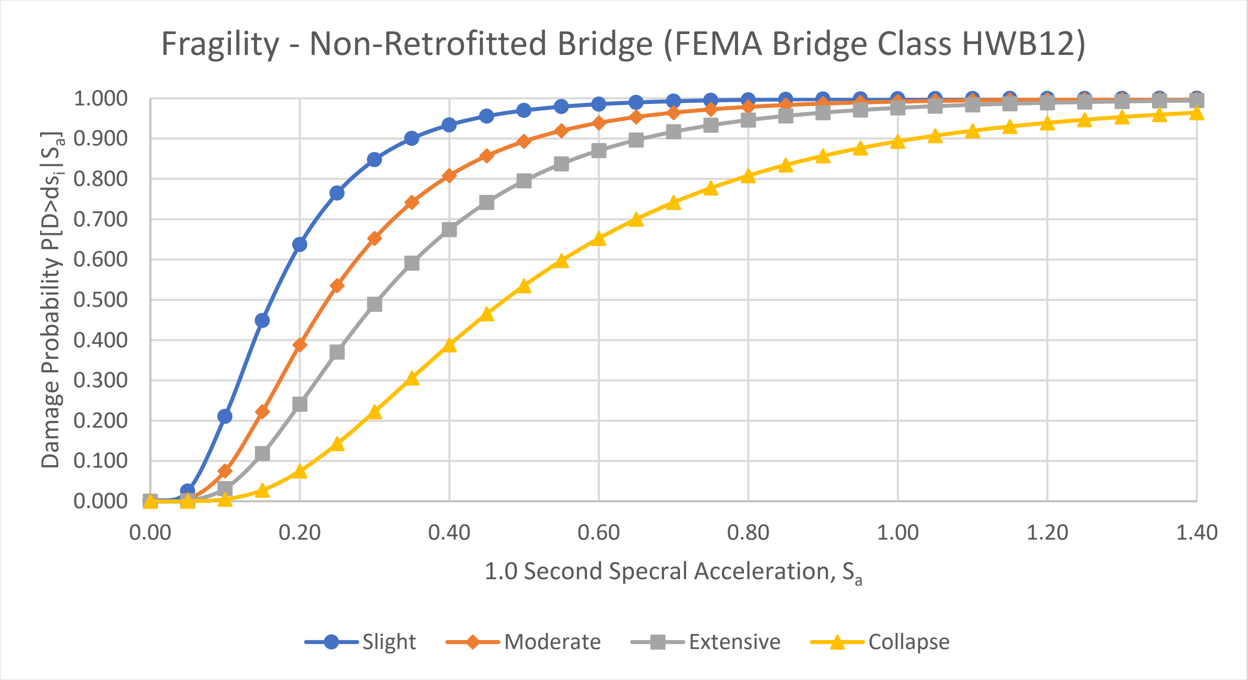

Figure 2: Bridge Specific Fragility, non-retrofitted bridge (from FEMA, 2020, Tables 7-6 and 7-7)

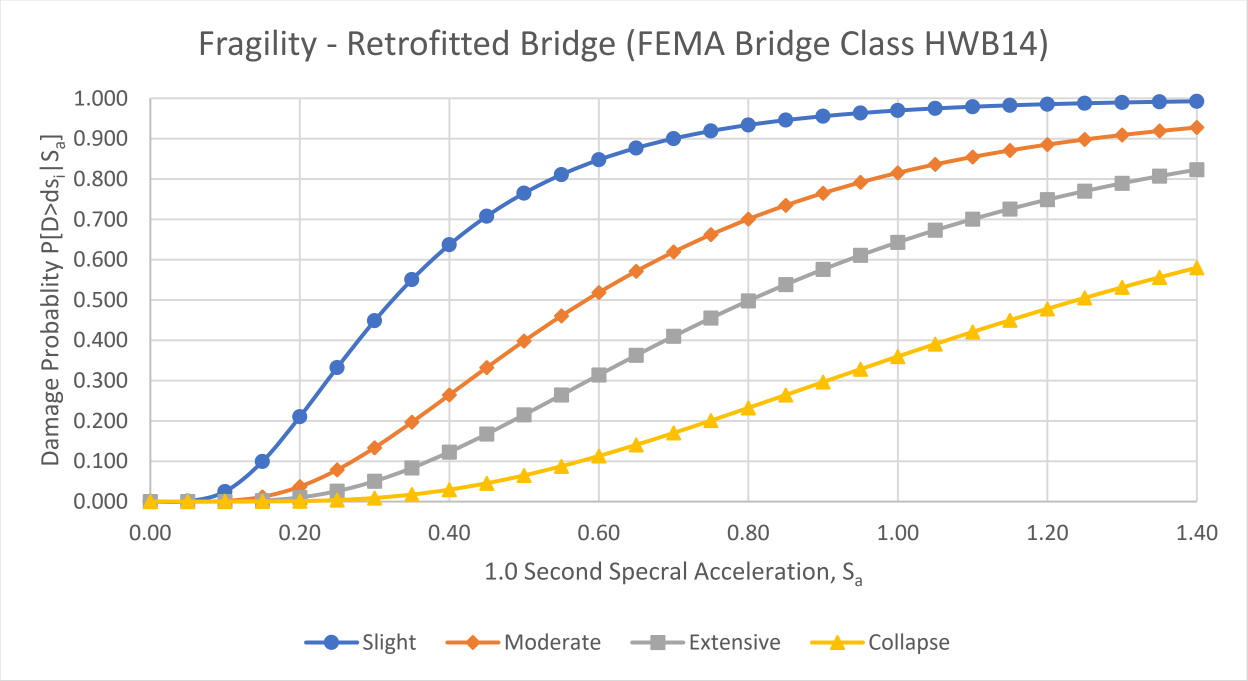

Figure 3: Bridge Specific Fragility, retrofitted bridge (from FEMA, 2020, Tables 7-6 and 7-7)

From the FHWA Seismic Retrofitting Manual, each damage state can be associated with a Repair Cost Ratio (RCR), which expresses repair losses as a proportion of bridge replacement costs (Table 1):

Damage State	RCR
Slight	2%
Moderate	8%
Extensive	25%
Collapse	$1/n_s$ = 67%

Table 1: Mean Repair Cost Ratios (from FHWA, 2006, Table 4-7), where n_s *is the number of spans.*

This analysis assumes that median recovery times from the Hazus earthquake loss estimation methodology (FEMA, 2020) will represent the number of days the bridge would be closed due to slight, moderate, extensive, or collapse-level damage (Table 2):

Damage State	Days Closed
Slight	0.6
Moderate	2.5
Extensive	75
Collapse	230

Table 2: Average restoration times (from FEMA, 2020, Table 7-3)

This analysis also assumes that operating costs due to closure are in accordance with DOT's BCA guidance (Table 3):

Vehicle Type	Value per Mile
Light Duty	\$0.45
Commercial Trucks	\$0.94

Table 3: Vehicle operating costs (from DOT, 2022, Table A-4)

From this, for each damage state, operating losses can be calculated as:

$$Loss_{Operating} = ADT \cdot (\%\ light\ vehicles \cdot \$0.45/mile + \%\ commercial\ trucks \cdot \$0.94/mile) \cdot Detour\ length \cdot Number\ of\ days\ closed$$

Lastly, casualties in the event of reaching the collapse-level damage state are estimated from Hazus casualty severity rates for continuous bridges (Table 4):

	Casualty Severity Level			
Structure Type	**Severity 1**	**Severity 2**	**Severity 3**	**Severity 4**
Major Bridge	17%	20%	37%	7%
Continuous Bridge	17%	20%	37%	7%
Simply Supported Bridge	5%	25%	20%	5%

Table 4: Casualty Severity Levels (from FEMA, 2020, table 12-7)

To apply these rates, the analysis must estimate the average number of people on the bridge at a given point in time, taken as:

$$P = R_{pt} \cdot t_c$$

Where,

P = Average number of people on the bridge
R_{pt} = Person trips per minute, calculated as,

$$\frac{ADT \cdot O_{ave}}{1{,}440 \ {}^{minutes}/_{day}}$$

Where,

ADT = Average daily traffic
O_{ave} = Average vehicle occupancy rate, taken as 1.67 (from DOT, 2022, Table A-4)

And,

t_c = Crossing time, calculated as,

$$\frac{L_B/5{,}280}{s} * 60$$

Where,

L_B = Bridge length, feet
s = Travel speed, mph

From these rates, for the collapse damage state, losses related to casualties can be calculated using Hazus-equivalent maximum abbreviated injury scale (MAIS) levels and value of a statistical life (VSL) fractions (Table 5):

Hazus Severity Level	MAIS Level	Fraction of VSL
Severity 1	1 – Minor	0.003
Severity 2	3 – Serious	0.105
Severity 3	5 - Critical	0.593
Severity 4	6 – Unsurvivable	1.000

Table 5: Hazus Casualty Severity Level (from FEMA, 2020, Table 12-1) equivalencies with MAIS levels and VSL fractions (from DOT, 2021, Table 2)

With this information, for a given rate of exceedance, a spectral acceleration can be identified and related to probability of exceeding a damage state which can, in turn, be related to expected repair, operating, and casualty losses. The following is an example of this calculation for an annual rate of exceedance of 0.001 (the 1000-year event, $S_{a\ 1.0\ sec} = 0.258g$) for the no-build scenario (Table 6):

Damage State	$P[D > d_{si}\|S_a]$	$P[DS_i\|S_a]$	Repair Loss	Operating Loss	Casualty Loss	Total Loss	Total Loss $\cdot P[DS_i\|S_a]$
1 - None	1.000	0.220	$0	$0.00	$0	$0	$0
2 - Slight	0.780	0.225	$500,000	$431,136	$0	$931,136	$208,562
3 - Moderate	0.555	0.165	$2,000,000	$1,796,400	$0	$3,796,400	$624,841
4 - Extensive	0.389	0.235	$6,250,000	$53,892,000	$0	$60,142,000	$14,104,280
5 - Collapse	0.154	0.154	$16,666,667	$165,268,800	$71,296,665	$253,232,131	$39,074,827

Estimated Loss $42,985,404

Table 6: Example loss calculations for a 1000-year seismic hazard, un-retrofitted bridge

Repeating this calculation for a range of exceedance rates using both the non-retrofitted and retrofitted fragility curves results in a range of possible losses for each scenario (Figure 4):

Figure 4: Estimated loss vs. Rate of Exceedance

Calculating the area under these curves represents the estimated annual loss ($EAL = L \cdot \lambda$) for both the base and build scenarios, yielding:

$$EAL_{Base} = \$256{,}660$$

$$EAL_{Build} = \$13{,}432$$

Benefit-Cost Analysis Values

$D = 7\%$

$n = 30\ years$

Base (No Build) Scenario Analysis

Project Cost: $0

Estimated Annual Loss, $EAL_B = \$256{,}660$

Total present value of base scenario EAL:

$$PV_{Base} = EAL \cdot \frac{1 - \left(\frac{1}{(1+D)^n}\right)}{D} = \$256{,}660 \cdot \frac{1 - \left(\frac{1}{(1+0.07)^{30}}\right)}{0.07} = \$3{,}184{,}909$$

Build Scenario Analysis:

Project Cost: $P = \$1{,}800{,}000$

Total present value of build scenario EAL:

$$PV_{Build} = EAL_T \cdot \frac{1 - \left(\frac{1}{(1+D)^n}\right)}{D} = \$13{,}432 \cdot \frac{1 - \left(\frac{1}{(1+0.07)^{30}}\right)}{0.07} = \$166{,}678$$

Project Benefit

Realized benefit from the project is the reduction in the present value of the estimated annual loss:

$$B = PV_{Base} - PV_{Build} = \$3{,}018{,}231$$

Project Benefit Cost Ratio

$$BCR = \frac{B}{P} = \frac{\$3{,}018{,}231}{\$1{,}800{,}000} = 1.68$$

References

Federal Highway Administration (FHWA), 2006, *Seismic Retrofitting Manual for Highway Bridges: Part I – Bridges*, FHWA-HRT-06-032, Washington DC.

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