Retrofitting Lifeline Corridor Bridges in Rural Montana: Combining Engineering, Economics and Emergency Response

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Abstract

The State of Montana lies within a zone of moderate seismicity and has experienced significant and damaging earthquakes in the 20th century. Ensuring operational performance of bridges along the vast and often rural portions of the National Highway System requires development of realistic goals using available but limited funds. The lifeline corridor approach used by Montana's Department of Transportation is a reasonable solution to providing safe transportation routes in rural areas of the state in a timely manner. It blends engineering, economics and emergency response into a systematic and thorough approach to seismic safety and recovery. This paper illustrates the procedure for evaluating a lifeline corridor through development of the Monida - Lima Retrofit Project in southwest Montana.

Introduction

The State of Montana faces many challenges regarding seismic performance of its transportation system. Despite the fact that Montana has one of the lowest population densities in the United States, it hosts 640 kilometers of Interstate 15 (running North-South), 890 kilometers of Interstate 90 (running East-West) and portions of other state primary routes within zones of high to moderate seismicity. These routes serve as important economic corridors both regionally and internationally, as well as life safety routes for local communities. Major structural damage combined with rugged terrain, severe weather conditions and lack of alternate routes could potentially isolate local communities from emergency services and necessitate multi-state detours for shipping.

Montana is one of the most seismically active states in the US. Small earthquakes are common in the region occurring at a rate of 7-10 per day. Most of the seismic activity is concentrated in the mountainous western portion of the state along the Intermountain Seismic Belt. Notable historic earthquakes in the 20th century include: June 1925 magnitude 6.75 in Gallatin County; October 1935 magnitude 6.25 in Helena; November 1957 magnitude 6.25 in Madison County; August 1959 magnitude 7.3 at Hebgen Lake near Yellowstone Park.

Despite these early warnings, little consideration was given to seismic forces in bridge design until the early 1990's. At that time, the Montana Department of Transportation (MDT) developed a methodology for evaluating seismic vulnerabilities of existing structures carrying or crossing important routes in high and moderate seismic zones. A retrofit program began to address several structures throughout the state identified as highly vulnerable. MDT's retrofit program continues to evolve with the

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development of new technologies, engineering philosophies and design standards. The Monida-Lima Seismic Retrofit project illustrates the performance based "lifeline corridor" approach to a retrofitting project in a rural area. This is a comprehensive method of determining the scope of a seismic retrofit project considering minimum acceptable performance, engineering needs, economic benefits and costs, and emergency response capabilities. The lifeline corridor approach was developed to provide reliable routes in a timely manner considering the vast need across the state and limited available funding.

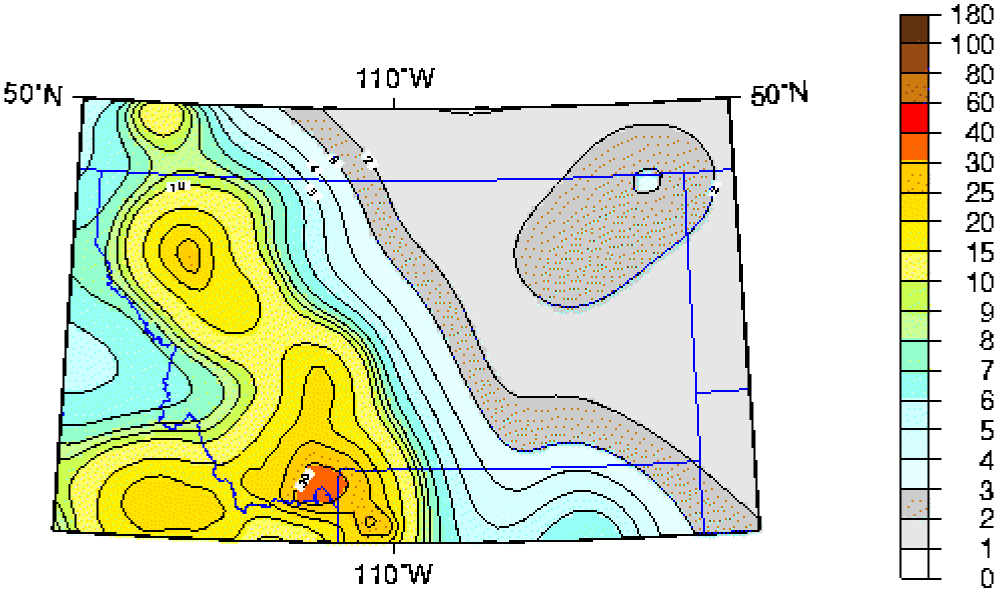

Figure 1- Peak Ground Accelerations for 10% Probability of Exceedance in 50 Years (% g)

Minimum Performance Levels and Emergency Response Capabilities

A lifeline corridor has a minimum performance goal of at least 50% operational lanes following a seismic event with a 10% probability of exceedance in 50 years (approximately 500-year return period). Expected peak ground accelerations for this return period are 0.2g to 0.4g [AASHTO, 2002]. A lifeline corridor must have access from either end to a population center with civil defense and public health agencies, or an emergency response team such as a trained highway maintenance section. This will allow post earthquake access to the segment, allowing adequate traffic control to be placed to direct traffic to those structures whose performance has been enhanced with seismic retrofit measures. A performance based evaluation will identify viable alternatives for seismic performance, including retrofit and replacement.

Project Description

The corridor segment chosen for study was 24-kilometers of Interstate 15 in southwest Montana from the Idaho border to the rural community of Lima. There are nine structures within this segment, all designed and built prior to the adoption of modern seismic design standards. The Interstate in this region consists of 2 lanes in each direction. This corridor lies between two mountain ranges with no alternate routes available for detours. Lima houses MDT's nearest maintenance section which will be responsible for emergency response, primary structure evaluation, and traffic control following a major seismic event. A magnitude 5.6 earthquake occurred in the area July 2005, and another of magnitude 4.6 was recorded in February 2006. Slight damage to bridges and highways was observed after these minor earthquakes, but they indicate the potential for a larger event.

An $8-million funding limitation was chosen by the administration based on estimated costs extrapolated from previous retrofit projects. Seismic vulnerability assessments, preliminary seismic analysis and retrofit proposals, along with Cost-Benefit calculations were completed to determine a realistic scope of work that could be delivered in a timely manner.

Seismic Vulnerability Assessment

To quantify the seismic vulnerability of an individual bridge, consideration is given to the site *seismicity*, structural *vulnerability* of the certain bridge elements, and the bridges *importance* as a vital transportation link. This is accomplished by a combination of qualitative assessments and associated quantitative ratings in each of these three areas. The ratings are then added to arrive at an overall Seismic Vulnerability Index (SVI) according to the following procedure:

$$\text{SVI} = 1.11*(\text{structural vulnerability}) + 51.6*(\text{seismicity}) + 8.03*(\text{importance})$$

The constants in this equation were derived to give equal weight to the three primary areas of concern. SVI values may range from 7 (low vulnerability) to 100 (high vulnerability). SVI of 50 or higher indicates a need for retrofit at a minimum.

The structural vulnerability rating is based on qualitative assessments of four individual components: the superstructure; substructure; abutments; and soils (liquefaction).

$$\text{Structure Vulnerability} = \text{superstructure} + \text{substructure} + \tfrac{1}{2}\ \text{abutment} + \tfrac{1}{2}\ \text{liquefaction}$$

Superstructure and substructure vulnerability are based on susceptible structural details, and are given the highest quantitative rating weight due to their potential for causing catastrophic failure and loss of service. Attention is given to critical details of the superstructure such as seat lengths, bearing types, continuity, skew, and redundancy. Locations of column reinforcing splices, shear confinement, anchorage and development lengths into footings and caps is identified and rated for the substructure. Abutment vulnerabilities generally will cause serviceability failures, such as settlement, and therefore have a lower weight in the rating than the structure itself. Areas with liquefaction potential are also weighted in the rating system.

The seismicity rating is the peak ground acceleration at the site for a 10% probability of exceedance in 50-years multiplied by the site coefficient S, which approximates the effects of soil conditions on ground motions. These values are based on information originally published in AASHTO Division IA [AASHTO, 2002] and in current editions of AASHTO Bridge Design Specifications [AASHTO, 2004].

$$\text{Seismicity} = S*a$$

The importance rating is based on a mathematical model developed by MDT. Information from the National Bridge Inventory (NBI) database is used for the elemental factors. The importance rating model considers both the route carried (subscript c) and the route crossed (subscript x).

$$\text{Importance}=1.0*[RT_c* DL_c* N_c]+0.67*[RT_x*DL_x*N_x]+0.25* [(ADT /6000)*L]^{0.25}+RV$$

RT is a factor representing the economic and life safety importance of the route with Interstates, primary highways and railroads having the highest importance values. DL is a factor representing the estimated detour length and N the impact of traffic congestion on the detour routes. ADT is the measured average daily traffic of the route under consideration. RV is a factor representing a river crossing and is a function of the length of the crossing structure. Guidance on rating is provided to the engineer in MDT's Bridge Design Standards document.

Review of the structures along the Monida-Lima corridor result in the vulnerability ratings and SVI in Table 2. Two structures within the segment have been identified as requiring retrofit, at a minimum. These structures at reference post 12.7 have an SVI exceeding 50, with the highest superstructure vulnerability rating of 10, and a high importance factor relating to their function on the interstate and crossing the Union Pacific railroad shipping line.

Bridge Characteristics

Three sets of structures within the corridor were chosen for the initial seismic retrofit assessment based upon the calculated SVI and the presence of higher elemental vulnerability ratings. They include the pair at reference point (RP) 0.5, the pair at RP 1.56, and the pair at RP 12.7 described in Table 3. A notable feature on three of the structures is the transverse girder supporting the superstructure crossing the railroad tracks. This method of construction was used extensively in Montana to extend the span length over a railroad while minimizing superstructure depth. The transverse girder is typically a welded plate girder with two webs, supported on slender columns, and connected to columns with bearings that allow rotation in the horizontal plane.

Longitudinal girders framing into it are connected by a pin, or two pins with a link acting as a hinge, to allow expansion and contraction due to temperature fluctuations. The columns supporting the transverse girder are all within the crash zone for railroad derailment, the closet measuring 3.65-m from the centerline of the tracks at RP 12.7 Southbound. The potential for failure of the superstructure resulting from earthquake or train derailment is very high.

Table 2 - Seismic Vulnerability Indices for Corridor Bridges

Seismic Vulnerability Index								
Bridge Reference Points	Importance	Acceleration	Soil Type	Superstructure	Substructure	Liquefaction	Abutment	SVI
RP 0.5 NB	1.48	**.27**	1	0	**8**	0	5	37
RP 0.5 SB	1.48	**.27**	1	0	2.8	0	0	29
RP 1.56 NB	2.14	.26	1	5	7	0	5	**47**
RP 3.2 NB	1.47	.25	1.2	0	5.6	10	0	39
RP 9.5 NB	1.38	.25	1.2	0	5.6	0	0	33
RP 12.7 NB	**2.26**	.24	1	**10**	8	0	5	**53**
RP 12.7 SB	**2.24**	.24	1	**10**	6.3	0	5	**51**
RP 15.2 NB	1.5	.21	1	5	6.3	0	0	35
RP 15.2 SB	1.5	.21	1	3	5.6	0	0	32
Note: NB for Northbound structures, SB for Southbound structures on Interstate 15.								

Preliminary Seismic Analysis

The intent of preliminary seismic analysis was to specifically identify vulnerabilities in the structure and develop viable retrofit strategies to prevent collapse during a design level seismic event. A multi-mode response spectrum analysis was performed on three representative structures with the intent of extrapolating the results for the remaining structures for this preliminary study. Based on results, seismic demand was compared to elastic capacities of various structure components to identify the most vulnerable elements.

Common characteristics and deficiencies were found in the representative structures. Intermediate bents are comprised of multiple reinforced concrete columns on relatively small spread footing foundations. In all cases, the columns lack adequate flexural reinforcement to resist the design seismic loading elastically, and they do not have adequate confinement reinforcement to provide ductility. The footings lack top reinforcing, sufficient depth for shear resistance, and in some instances do not have sufficient bearing area to prevent soil failure and overturning.

Table 3 - Characteristics of Corridor Bridges

Structure Reference Point	Crossing	Length (M)	Superstructure	Substructure and Abutment
RP 0.5 NB	S 509	36	3-Spans Prestressed Concrete Girders	Multiple Column Bents on Spread Footings, Stub Abutment on Piles
RP 0.5 SB	S 509	36	3-Spans Prestressed Concrete Girders	Multiple Column Bents on Spread Footings all Locations
RP 1.56 NB	UPRR	85.5	6-Spans of Prestressed Concrete Girders, Rolled Steel Girders, and Pinned Transverse Girder	Multiple Column Bents on Spread Footings all Locations
RP 1.56 SB	UPRR	77	3-Spans Prestressed Concrete Girders	Multiple Column Bents on Spread Footings, Stub Abutment on Piles
RP 12.7 NB	UPRR	147	7-Spans of Prestressed Concrete Girders, Welded Steel Plate Girders, and Pinned Transverse Girder	Multiple Column Bents on Spread Footings, Stub Abutment on Piles
RP 12.7 SB	UPRR	137	8-Spans of Prestressed Concrete Girders, Welded Steel Plate Girders, and Pinned Transverse Girder	Multiple Column Bents on Spread Footings all Locations

The bridge abutments at all locations are relatively stiff in the longitudinal direction compared to the rest of the structure and attract significant force, most of the resistance to loads in the longitudinal direction is provided by the interaction of soil and abutment wall. In the transverse direction, seismic design forces exceed the capacity of anchor bolt connections between the abutment wall and cap. At abutments with piles, pile to cap connections are insufficient to transfer the force to the piles. Intermediate bents lack sufficient ductility to resist the transverse loads.

Demand Capacity ratios for the critical bent supporting the transverse girder over the railroad in a post-retrofit condition are shown in Table 4 for illustration [Hirose, 2005]. The retrofit measures were intended to prevent collapse and maintain operational or life safety performance, but with repairs necessary to bring them to full service after a design level earthquake. The resulting D/C ratios indicate some significant vulnerabilities exist, particularly at the connection of the transverse girder to column. Allowing this connection to fail (fuse) would reduce the demand on the column and footing, but it would also mean potential loss of seat support for the transverse girder resulting in hinging of the superstructure and likely catastrophic failure. Additional seat length would encroach on railroad clearance zones.

Table 4 - Demand to Capacity Ratios for Vulnerable Pier

Structural Element	D/C	Comments
Anchor Bolt Shear	**5.08**	Per bearing of Transverse Girder with all bolts effective (4 total).
Transverse Beam(Connection to Girders)	0.68	Shear on pins controls
Transverse Beam (Bending/Shear/Torsion)	0.44	
Column Flexure	**2.12**	
Column Shear	0.88	
Column to Footing Anchorage	0.78	
Column Vertical Bar Splice	0.89	Requires confinement for functionality.
Footing Flexure (Long Direction)	**2.68**	Soil Bearing failure.
Footing Flexure (Trans Direction)	**4.14**	Footing shear failure.

Cost-Benefit Studies

With viable retrofit strategies outlined, the associated costs and benefits of the work were then determined. A simple Benefit-Cost ratio model is used for comparison of alternate proposals [FHWA, 1995].

B/C = [(cost of loss before retrofit) – (cost of losses after retrofit)] / (cost of retrofit)

The possible retrofit scenarios assume that some damage is expected at the design level earthquake. Loss scenarios were assumed as part of the Benefit-Cost analysis. For some structures, damage may be repairable, and the same methods of construction and material types will be used to repair the damage as were used to retrofit the structure. For instance, columns may require removal and replacement of damaged concrete and replacement of steel jacketing, and bearings may require replacement. A partial replacement loss scenario assumes that a portion of the superstructure may also require major rehabilitation or replacement, particularly in the case of spans supported by the transverse girders and slender columns.

Cost of loss before retrofit includes demolition of existing structures, replacement of the structure in kind, approach roadway reconstruction and traffic control. It does not include “intangible” costs due to emergency mobilization, road user and railroad user costs resulting from loss of service or detours, or liability to adjacent property owners. Resulting B/C ratios for the structures are shown in Table 5.

Lifeline Corridor Performance

The benefit cost ratios pinpoint needs for structures on both the northbound and southbound routes, however, a cursory review of the construction costs indicate that working on all of the structures would exceed the budget. With that in mind, the minimum lifeline corridor performance was proposed. A 50% reduction in service would leave two operational lanes through the segment. Benefit-Cost ratios for the structures on the northbound route were compared to those for the structures on the southbound route. The results show that the southbound route has the greatest need and offers the highest potential for operational performance or better after retrofitting. The decision to replace the structure at RP 12.7 rather than attempt retrofitting was based on many factors: the high B/C ratio; functionally obsolete deck width geometry; maintenance problems with deck, joints and guardrail system; operational safety; and the vulnerability of the transverse girder. Total project costs estimated for replacement, retrofit, and associated roadwork and miscellaneous construction for the lifeline corridor option is approximately \$5.7 million, which is much less than the budgeted amount of \$8.0 million, leaving us with the opportunity to apply the balance towards other segments of the corridor.

Table 5- Economic Loss Scenarios and Benefit Cost Ratios for Corridor Bridges

Feature Crossed	Seismic Retrofit Estimate	Cost of Losses After Retrofit	Cost of Losses Before Retrofit	BCR
RP 0.5 NB	\$210,000	\$500,000	\$680,000	0.9
RP 0.5 SB	\$210,000	\$500,000	\$680,000	0.9
RP 1.56 NB	\$720,000	\$1,400,000	\$2,100,000	1.0
RP 1.56 SB	\$550,000	\$770,000	\$1,900,000	2.0
RP 12.7 NB	\$950,000	\$2,100,000	\$2,900,000	0.9
RP 12.7 SB	\$720,000	\$1,200,000	\$2,800,000	2.2

Non-Engineering Factors for Lifeline Corridor Performance

The lifeline corridor approach was well received by MDT administrators and was seen as prudent use of limited funds. This study and proposal was a means to develop confidence that our goals are realistic, attainable and important. However, the task is not complete. Engineering must be partnered with emergency response for this approach to succeed. Lifeline corridors engineered for operation level of service will sustain damage after a seismic event. Structures on the Northbound route that have not been retrofitted may be lost. It is critical that an emergency response plan be in place to redirect traffic to the lifeline structures following an earthquake.

MDT is currently developing a comprehensive emergency response plan which identifies first responders to an earthquake: our maintenance personnel. Training is essential to help develop the skills necessary for them to quickly evaluate structural damage expected from seismic forces, and inform them of the routes designated as lifeline corridors so they can quickly redirect traffic to safe operational structures.

Conclusions

The lifeline corridor philosophy is a reasonable solution to providing safe bridges in Montana's highest seismic regions, particularly through sparsely populated areas or mountainous terrain. It blends engineering, economics and emergency response into a systematic and thorough approach to seismic safety and recovery.

Acknowledgments

The success of MDT's seismic engineering program is a result of many years of development by David F. Johnson, Bridge Design Engineer and Bryan Miller, Bridge Area Engineer and the continued support of MDT's administrators and directorship. Additionally, the efforts of Jim Hyatt, MDT Emergency Response coordinator towards the development of an emergency response plan and David Crumley, Bridge Maintenance Engineer for his commitment to develop training procedures for first responder bridge inspection is recognized.

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