Earthquake Engineering for Transportation Network in Low to Moderate Seismicity Regions

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Abstract

Major seismic events during the past few decades have continued to demonstrate the destructive power of earthquakes, with failures to buildings, bridges, industrial and port facilities, as well as giving rise to great economic losses. However, in low to moderate seismicity regions, seismic resistant design is still considered complicated and expensive in terms of actual seismic risk. This is partly due to the fact that design codes do not have any special consideration for these regions; also, economic factors have not been integrated fully with the design principles.

Bridges are the most critical components of the transportation network, as failure of bridges can disrupt the total transportation system, and hence deserve proper consideration in terms of seismic risk. A systematic approach is proposed for evaluating the cost-effectiveness of existing bridge design codes from the perspective of lifecycle cost consideration. In the life-cycle cost formulation, cost of construction, damage cost, road-user cost, as well as discount cost over the design life of the bridge are considered. The optimal performance is selected on the basis of minimum life-cycle cost. It is demonstrated that life cycle cost should be considered in the design phase of a new/retrofitted structure, and the target performance significantly depends on the expected average daily traffic.

Keywords: low to moderate seismicity regions, bridges, cost-effective design, life cycle cost, optimal performance

1. INTRODUCTION

Increased knowledge about seismic hazard worldwide, associated with the lessons learned from the recent destructive earthquakes, have prompted low to moderate seismicity regions to pay attention to the design of structures with proper seismic consideration. However, most bridge design codes are based on the notion of life safety and do not account for the cost and benefits of proper seismic design. It is important to note that bridges are the most critical components of the transportation network of a country, as failure of bridges in the event of an earthquake can disrupt the total transportation system. In addition, economic loss from the failure of bridges often surpasses the actual construction costs by several times.

The objective of this paper is to propose expected life cycle cost oriented approach to ascertain optimal seismic design of bridges based on economic principles. It may be considered as a first attempt to define earthquake level for the design of bridges in low to moderate seismicity regions. This paper first presents an analytical approach for the estimation of the seismic performance of bridge piers. Performance limit states have also been correlated with the expected level of damage and repair. Second, economic impact on the seismic performance of bridges is incorporated in the life cycle cost (LCC) formulation. Finally, through the example of a two-span bridge, the estimation of optimal performance requirement is presented and the importance of user cost in such a calculation is highlighted.

2. SEISMIC PERFORMANCE ESTIMATION OF BRIDGE PIERS

Performance Limit States

Current seismic design codes define different levels of damage depending on the importance of the bridge and the return period of the earthquake event. The performance principles stated in the design codes are purely descriptive and have not been correlated with engineering parameters. Sheikh et al. (2007a) outlined four performance limit states in line with the recent development of performance based seismic assessment and are summarised in Table 1. Both qualitative and quantitative performance levels are described and are associated with engineering parameters. As well, level of necessary repairs is highlighted.

Analytical Modelling of Bridge Piers

An analytical model for seismic performance assessment of bridge pier has been developed in Sheikh et al., (2007b). The model forms an analytical tool that reproduces most of the important features of reinforced concrete bridge piers under the action of an earthquake event. The model can well predict the force displacement characteristics of bridge piers considering both flexural and shear behaviour. To evaluate the capability of the model, experimental results of a large number of solid piers and hollow core piers (Lehman et al, 2004; Mo and Nien, 2002; Pinto et al., 2002; and Calvi et al., 2005) tested under cyclic loading have been compared. Due to space restrictions, analytical predictions of piers 415 and 815 (Lehman et al., 2004) have been reported herein (Figure 1). It can be observed that the model not only predicts the overall behaviour very well, but all the limit states (LS) as well. Details of the analytical predictions for all the piers can be found in Guiziou et al. (2006).

Table 1: Performance limit states

Limit states (LS)	Operational performance level	Post earthquake serviceability	Qualitative performance description	Quantitative performance description	Repair
1A	Fully Operational	Full service	Onset of hairline cracks	Cracks barely visible	No repair
1B			Yielding of longitudinal reinforcement	Crack width <1 mm	Limited epoxy injection
2	Delayed Operational	Limited service	Initiation of inelastic deformation; onset of concrete spalling; development of longitudinal cracks	Crack width 1-2 mm ϵ_c=-0.004	Epoxy injection; concrete patching
3	Stability	Closed	Wide crack width/ spalling over full local mechanism regions; buckling of main reinforcement; fracture of transverse hoops; crushing of core concrete; strength degradation	Crack width>2 mm $\epsilon_c=\epsilon_{cc50}$ (initial core crushing) $\epsilon_c=\epsilon_{cu}$ (fracture of hoops) ϵ_s<0.06 (longitudinal reinforcement fracture)	Extensive repair / reconstruction
ε_c =axial strain of concrete; ε_{cc50}=post peak axial strain in concrete when capacity drops to 50% of confined strength; ε_{cu}= ultimate strain of concrete; ε_s=tensile strain at fracture					

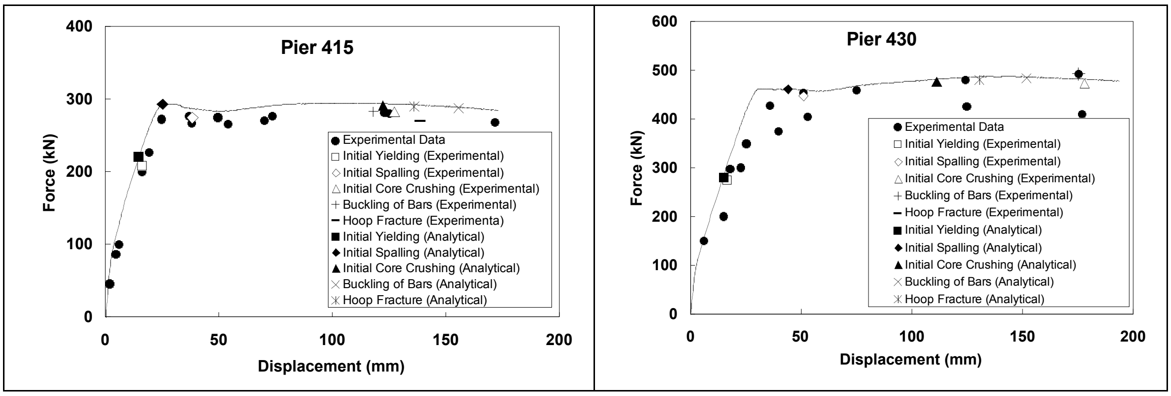

Figure 1: Experimental results compared with analytical predictions

3. LIFE CYCLE COST ANALYSIS FOR OPTIMAL PERFORMANCE

Life Cycle Cost formulation

In order to design the bridge economically, it is important to design it with due consideration to the total life cycle cost (LCC) for balancing initial construction cost and expected cost occurring within the design life of the bridge. LCC of a bridge consists of initial construction cost, maintenance cost, failure cost (repair cost, user cost, social and environmental cost, and so on), and the cost of loss of lives and injuries. Maintenance cost has been omitted as it is not directly related to earthquake design level. Moreover, data on cost of loss of lives and injuries are scarce and are not considered in this study. Hence, the LCC considering seismic risk can be calculated as:

$$\mathrm{LCC} = C_i + \sum_{n=1}^{n=N} \sum_{j=1}^{j=k} P_{nj} \times C_j \times e^{-\lambda t} \qquad (1)$$

where C_i is initial construction cost of new or retrofitted bridge; n is the severe loading occurrence number, N is the total number of severe loading occurrence; j is the number of limit state considered; k is the total number of limit states; P_{nj} is the probability of jth limit state being exceeded given the nth occurrence of earthquake; C_j is the cost of damage and user cost in present value due to jth limit state; $e^{-\lambda t}$ is the factor accounting for discount over time period t; and λ is the constant discount rate usually ranging from 2 to 5%.

Considering only four limit states (Table 1), and assuming that the limit state probability P_{nj} does not change with time (i.e. ignoring the deterioration capacity of the structure with time), LCC can be calculated as (Wen and Kang, 2001):

$$\mathrm{LCC} = C_i + (C_{1A}P_{1A} + C_{1B}P_{1B} + C_2P_2 + C_3P_3) \times (1 - e^{-\lambda t}) \qquad (2)$$

where C_j=limit state (1A, 1B, 2 and 3) failure cost and user cost; P_n is the annual probability of earthquake occurrence. Limit state failure cost includes repair cost of damage and user cost. User cost can be defined as the sum of time cost and energy consumption cost due to detouring or closure of the road.

Life Cycle Cost of an Example Bridge

A simple two-span bridge in the region of Vancouver has been chosen to demonstrate calculation of LCC. Peak ground acceleration (PGA) for 475 year return period earthquake events is 0.3 g in Vancouver. The bridge is considered as an emergency-route bridge and the design life of the bridge is considered as 50 years. It has two spans of 20 m length. The bridge is supported by a single pier of 9 m high and the superstructure unit weight is 150 kN/m. A 11 km detour will be required for the 1 km of roadway in which the bridge is located. The existing facility is posted at 70 km/h and the average speed of the detour is 50 km/h. A constant discount rate of 2 percent is assumed.

The bridge is designed for different peak ground acceleration levels. Construction cost of the pier and foundation are calculated based on material cost and labour cost.

However, the construction cost of the superstructure is considered as a constant value of 400,000 Canadian Dollars (CAD). The assumption of constant cost for superstructure is reasonable as it does not vary significantly with the level of design earthquake ground motion. In fact, bridge piers are the sole structural elements that are designed to withstand earthquake induced ground displacement. The design ground motion has a significant impact on the size of the pier and its reinforcement ratios (longitudinal and transverse). Typically, the substructure cost of a bridge (pier and foundation) consists of around 30% of the total construction cost of the bridge.

Seismic damage cost of the bridge has been considered based on the recommendation of the HAZUS methodology (NIBS, 1999). Seismic damage cost ratio (damage cost/construction cost) is considered as 0.03 for very limited damage (LS-1A), 0.08 for limited damage (LS-1B), 0.25 for moderate damage (LS-2) and 1.0 for extensive damage (LS-3).

User cost can be defined as the sum of the time value cost and vehicle operating cost. Road user costs are calculated according to the procedure developed by New Jersey Department of Transportation (2001). The time value cost is considered as 12 CAD/vehicle-hr for car and 21 CAD/vehicle-hr for truck, and vehicle operating costs for car and truck are 0.25 CAD/vehicle-km and 0.45 CAD/vehicle-km, respectively. The restoration period are assumed as 2 days when the limit state 1A is exceeded, 2 weeks when limit state 1B is exceeded, 1 month when limit state 2 is exceeded, and 6 months when limit state 3 is exceeded.

Uniform hazard spectra have been developed by Geological Survey of Canada corresponding to four hazard levels: 40%, 10%, 5% and 2% probability of exceedance in 50 years. This represents annual exceedance frequency of 0.01, 0.0021, 0.001, and 0.0004, respectively. Seismic hazard (annual probability) for each damage state has been calculated by linear interpolation on the log-log scale between the two segments of the uniform hazard curve.

Three cases have been considered based on the average daily traffic using the road. First the bridge is considered to be in a busy roadway considering average daily traffic of 20,000; the second bridge is considered to be in a moderately busy roadway considering average daily traffic of 5,000, and the third bridge is considered to be in a small town with an average daily traffic of 500.

It is evident that for a bridge located in a busy roadway, life cycle cost decreases when the bridge pier is designed for a higher acceleration level (Figure 2a). For a moderately busy roadway, life cycle cost slightly decreases with the designed earthquake acceleration level and reach a minimum for return period of earthquake with PGA of around 0.4g (consistent with importance factor of 1.5) (Figure 2b). Whereas in a remote place, life cycle cost is minimum at around 0.3g, which corresponds to a 475-year return period earthquake event (Figure 2c). It is important to note that construction cost does not change significantly with the design earthquake acceleration level and that user cost is preponderant in the calculation (Figure 2). Hence it is prudent to design the bridge pier for higher earthquake acceleration level when the bridge is located in a busy roadway. In contrast, the bridge piers can be designed for design PGA level when it is located in places with limited traffic. This conclusion is based on the result of a simplified bridge model, although it is expected that similar findings may also be observed for real bridges.

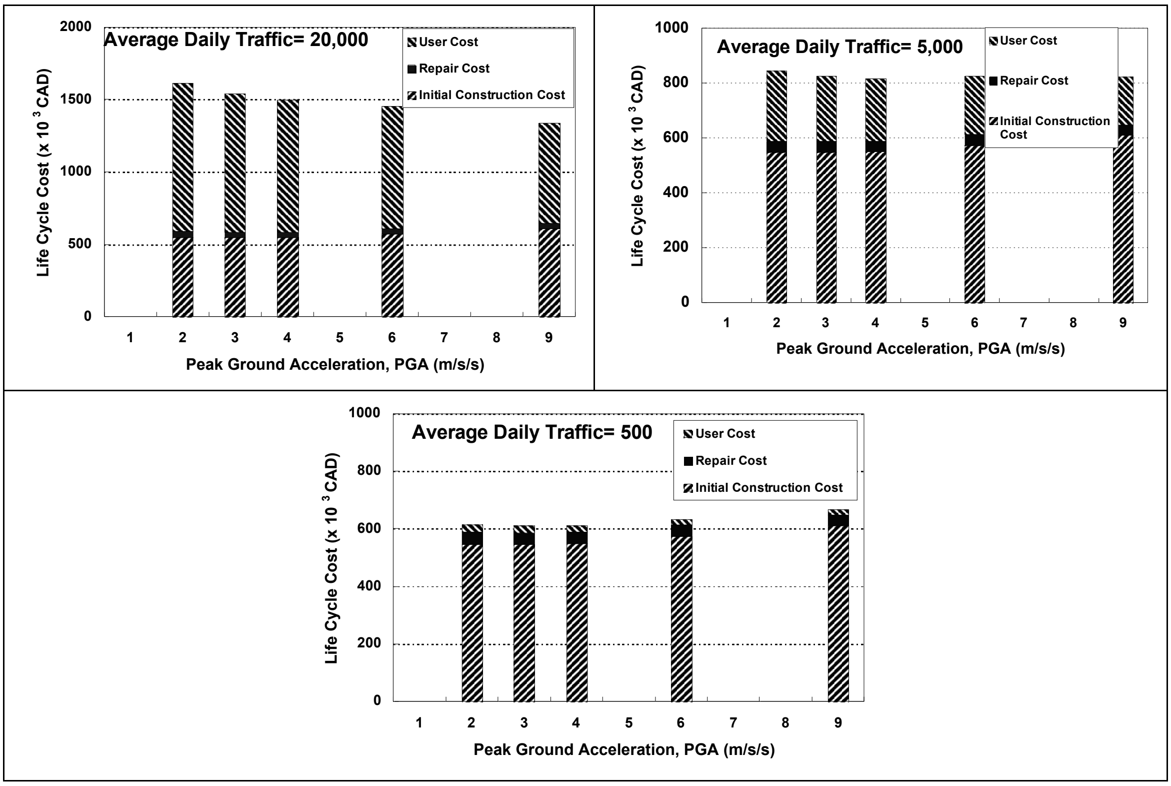

Figure 2. Life-cycle cost analysis of a two-span bridge

4. CONCLUSIONS

A systematic approach is proposed for the optimal seismic design of bridges considering life cycle cost, based on performance limit states that can be related directly to the functionality and repair cost. The methodology could be used for the design of a new bridge or retrofitting of an existing one. However, in the methodology, cost of death and injury is not included as such data is scarce. Maintenance cost is also not included as the design earthquake event has an insignificant influence on maintenance cost. The proposed methodology should be seen as a first attempt to define the earthquake level for the design of bridges in low to moderate seismicity regions based on economic considerations only. The methodology may need to be integrated properly with life safety issue and is a part of an ongoing collaborative research of the authors.

The proposed methodology for life cycle cost estimation has been applied to a simple two span bridge supported by a single pier. It has been observed that life cycle cost of a bridge depends largely on the user cost. If the bridge is located in a busy roadway, it is economical to design the bridge for a higher level of earthquake ground motion.

This study should be extended and results could help bridge owners to decide rationally the level of earthquake for which their structures should be designed.

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