RISK-BASED SEISMIC DESIGN OF RC BRIDGE PIER TO MINIMIZE THE POST-DISASTER FUNCTIONALITY LOSS OF ROAD NETWORKS

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ABSTRACT

When designing bridges located in seismic hazard zones, the final design has to be determined by taking into consideration the functionality of the post-disaster road network. The effect of inelastic bridge behavior on the deterioration of the functionality of a road network after an earthquake needs to be incorporated in the seismic analysis. This paper deals with risk-based seismic design of RC bridges to ensure a specified post-disaster functionality of the road network. Computational results show that compared with bridges designed to minimize the seismic life-cycle cost, bridges designed taking into consideration the requirement of post-disaster traffic capacity of a road network need to have a higher seismic performance.

Keywords: bridge, seismic design, life-cycle cost, road network, traffic capacity

1. INTRODUCTION

Many destructive earthquakes inflicted various levels of damage on structures and infrastructures. The consideration of these negative consequences has motivated improvement in seismic design philosophy. However, the deterioration of functionality of post-disaster network due to the damages or failures of bridges has not been explicitly implemented in the seismic design of bridges. As observed in past earthquakes in Japan such as the 1995 Hanshin-Awaji (Kobe) Earthquake, the 2003 Sanriku-Minami Earthquake, the 2004 Niigata-Ken Chuetsu Earthquake, and the 2011 Great East Japan Earthquake, the transportation networks including bridges are one of the most critical civil infrastructure systems when a natural disaster occurs (Kawashima 2012, Akiyama & Frangopol 2012). Since the bridge transportation network plays a crucial role in the evacuation of affected people and the transportation of emergency goods and materials, the functionality of the network has to be recovered as soon as possible (Unjoh 2012, Decò & Frangopol 2011, 2013, Decò et al. 2013). A prompt restoration of the critical infrastructure facilities after an extreme event is

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always a goal of paramount importance (Bocchini & Frangopol 2012). Frangopol & Bocchini (2011) and Bocchini & Frangopol (2012) presented a methodology for the use of resilience as optimization criterion for the rehabilitation of bridges belonging to a transportation network subjected to earthquake. Their proposed approach could assist decision makers to enhance the disaster management and the recovery of the region.

When designing bridges located in seismic hazard zones, the final design has to be determined by taking into consideration the functionality of the post-disaster road network. However, generally, the limit state of bridge subjected to seismic design action is specified based on the damage of bridge components. For example, displacement ductility capacity of reinforced concrete (RC) bridge piers specified in the seismic design code is almost equal to that associated with the occurrence of buckling of rebars, because rebar buckling requires extensive repairs (Japan Road Association 2002, Akiyama et al. 2011, Berry & Eberhard 2005). The effect of inelastic bridge behavior on the deterioration of functionality after an earthquake needs to be incorporated in the seismic design.

This paper deals with risk-based seismic design of RC bridge piers to ensure the specified post-disaster functionality of road networks and to minimize the seismic life-cycle cost. Consequences associated with bridge failures are described in terms of monetary loss and loss of traffic capacity of a road network. The relationship between bridge damage and the resulting loss of functionality of the bridge is explicitly considered when assessing the impact of an earthquake event on the performance of the transportation network. In the proposed seismic design of RC bridge piers, the constraint on traffic capacity loss of the road network due to earthquake is considered. In an illustrative example, bridges are assumed as the only vulnerable components to earthquake in the road network. The seismic design methodology of RC bridge pier belonging to a road network is presented and discussed taking into consideration the post-disaster functionality of road network and life-cycle cost.

2. RISK-BASED SEISMIC DESIGN OF BRIDGE

Seismic design methodology of RC bridge piers as proposed herein requires integration of information regarding the seismic hazard, seismic fragility, costs associated with bridge damage, and functionality loss of a road network. Figure 1 shows the flowchart for the risk-based seismic design of four RC bridge piers belonging to network. This section outlines the proposed framework and its application.

2.1. Seismic failure probability

The annual probability of exceeding different levels of damage is

$$p_{fa} = \int_0^{\infty} -\frac{dp_0(\gamma)}{d\gamma} \cdot P\left[D_e \geq C_a \middle| \Gamma = \gamma\right] d\gamma \tag{1}$$

where p_0 (γ) = annual probability that the seismic intensity, Γ, at a specific site would exceed a value γ; and $P[D_e \geq C_a \mid \Gamma = \gamma]$ = fragility which describes the probability that the seismic demand D_e

exceeds the seismic capacity C_a when structure is subjected to the seismic intensity γ. In this paper, three damage states are considered; slight, moderate and complete damage states. The seismic fragility curves are estimated as a lognormal distribution, indicating the probability of meeting or exceeding different level of damage conditioned up-on the seismic intensity.

$$P\left[D_e \geq C_a \middle| \Gamma = \gamma\right] = \Phi\left[\frac{\ln\left(\gamma/\lambda\right)}{\zeta}\right] \tag{2}$$

where λ and ζ = median and log-standard deviation of the fragility curve, respectively; and $\Phi[\cdot]$ = standard-normal distribution function. The parameters used to determine the lognormal distribution (median λ and log-standard deviation ζ) are estimated by the method of maximum likelihood.

Peak ground acceleration is used as the intensity measure for conditioning the fragility curves in this paper. Fragility curves are developed using non-linear time history analysis for probabilistic seismic demand modeling. This study uses the artificial ground motions presented by Akiyama et al. (2012). These ground motions could simulate the maximum acceleration, velocity and displacement of previously observed ground motions. Uncertainties in the ground motion, material properties, bridge pier modeling, demand and capacity are considered in the fragility analysis.

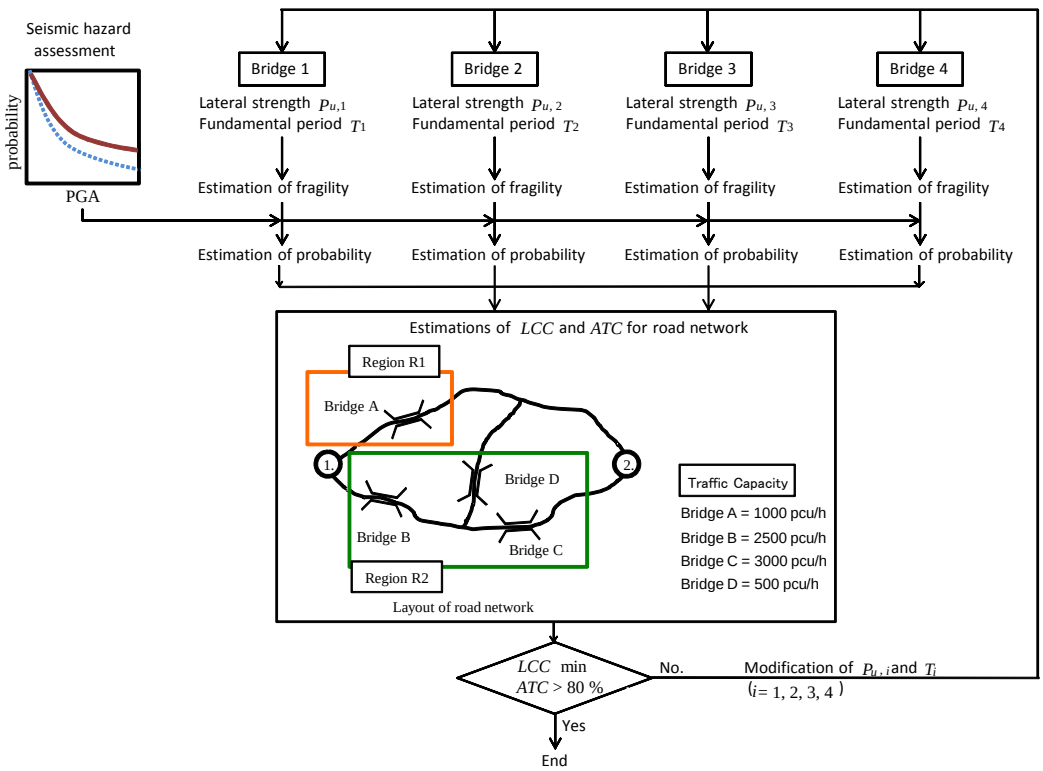


Figure1: Flowchart for the risk-based seismic design of four bridges to ensure the post-disaster functionality of road network in where *LCC* = seismic life-cycle cost, and *ATC* = allowable post-disaster traffic capacity.

2.2. Seismic life-cycle cost

As illustrated in previous studies (e.g., Padgett et al. 2010), earthquake occurrence is assumed to follow a Poisson process. There have been studies on hazard estimates based on non-Poissonian seismicity (Bommer 2002). The Poisson assumption is adopted herein. The expected life-cycle costs due to seismic damage can be expressed as

$$LCC = C_I + \sum_{i=1}^{3} Pf_{Ti} C_i \tag{3}$$

where C_I = initial construction cost; Pf_{Ti} = probability of exceeding damage state i during T years; and C_i = repair cost associated with damage state i. In this study, T is assumed 50 years. Pf_{Ti} is estimated using Equation 1 under the assumption of Poison process. Discount ratio of money is not considered in this study.

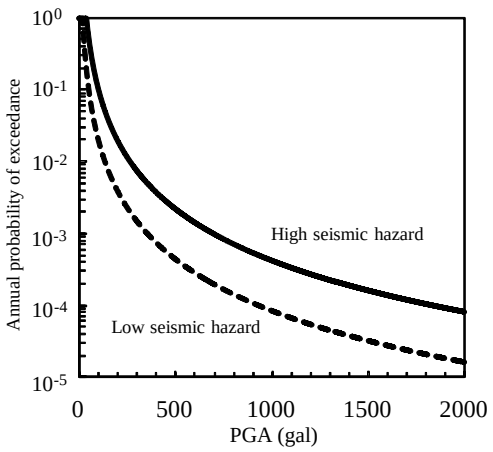
2.3. Traffic capacity loss

The general procedure for assessing the consequences of a seismic event includes defining the system and region of interest, evaluating the seismic hazard, assessing the performance of individual components (bridges), assigning associated levels of functionality to the bridges and roads, performing a network analysis and simulated traffic flow, and assessing the losses (Padgett & DesRoches 2007). Decò et al. (2013) proposed a methodology to evaluate the probabilistic seismic resilience of bridges and assess the impact in terms of direct and indirect costs which can be used for decisions concerning proactive maintenance, retrofit, or life-cycle management for key components of the infrastructure system. In their method, the relationship between functionality and time from extreme event depending on the recovering patterns associated with different types of dam-age and recovery options are considered.

In this study, since it is difficult to design the bridge belonging to the road network taking into consideration the effect of bridge damage on the seismic resilience and recovery patterns, the loss of traffic carrying capacity depending on the seismic damage is implemented. Expected loss of traffic capacity of bridge j (j=1,2,3...n) is

$$E[LCT_j] = \sum_{i=1}^{3} X_{OC,j} \cdot Pf_{Ti} \cdot C_{a,l,i} \tag{4}$$

where $X_{OC,j}$ = traffic capacity of intact bridge j; and $C_{a,l,i}$= traffic capacity loss ratio associated with the bridge damage i. Resulting traffic capacity loss of a road network including n bridges is estimated performing a network analysis and using Equation 4.



Figue2: Seismic hazard curves

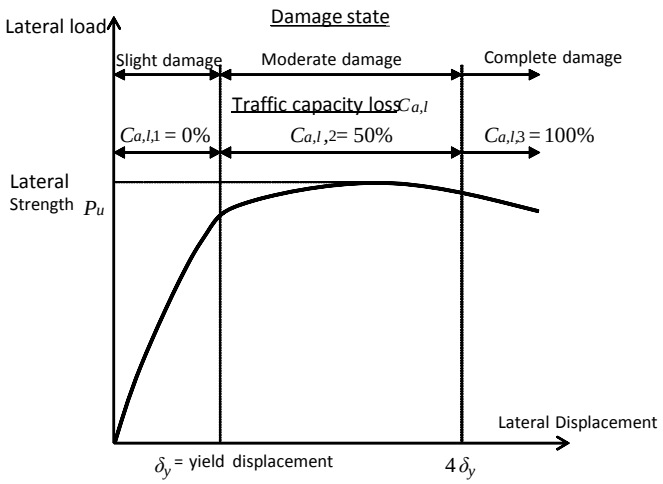


Figure 3: Relationship between lateral load, lateral displacement, and traffic capacity loss of a bridge pier

Table 1: Layout of the road network

Road network A				
	Region R1	Region R2		
Seismic hazard	high	high		
Notion of Bridge	Bridge A	Bridge B	Bridge C	Bridge D
Traffic Capacity (pcu/h)	1000	2500	3000	500

Table 2: Layout of the road network

Road network B				
	Region R1	Region R2		
Seismic hazard	high	high		
Notion of Bridge	Bridge A	Bridge B	Bridge C	Bridge D
Traffic Capacity (pcu/h)	1000	2500	3000	500

3. ILLUSTRATIVE EXAMPLE

3.1. Description of bridge and road network

In an illustrative example, two simple road networks as shown in Table 1 and 2 are analyzed. Each road network has four bridges. The difference between the road networks shown in Table 1 and 2 is the hazard intensity in Region R2. The origin and destination nodes have been fixed. Each RC bridge pier is modeled as single degree of freedom (SDOF). Figure 3 also shows the assumed relationship between bridge demand and traffic capacity loss $C_{a,l,i}$. Although recent studies have tried to provide general approaches for the determination of such relationship (Padgett et al. 2007), further investigation is needed to relate the effects of bridge component damage to the functionality of the bridge, expressed as traffic capacity. Two seismic hazard curves are used in this case study as shown in Figure 5. Sakai et al. (2012) reported the initial construction cost and repair costs associated with damage state *i* in Japanese Yen:

$$C_I = \left(44929 \times K^2 + 16843 \times K + 5319\right) \times T_{eq}^{\frac{1}{1.5}}$$

$$\times \left(1 + \frac{(\delta_u / \delta_y) - 2.5}{2.5} \times 0.12\right) \times 1000 \tag{5}$$

$$C_1 = 0$$

$$C_2 = (2024 \times K^2 + 509 \times K + 167) \times 1000 \tag{7}$$

$$C_3 = 10 C_I \tag{8}$$

$$K = P_u / W_u \tag{9}$$

where K = normalized lateral strength; Wu = weight supported by the bridge pier; Teq = equivalent fundamental period of bridge; and δ_u= displacement ductility capacity. In this illustrative example, δ_u is assumed to $4\delta_y$.

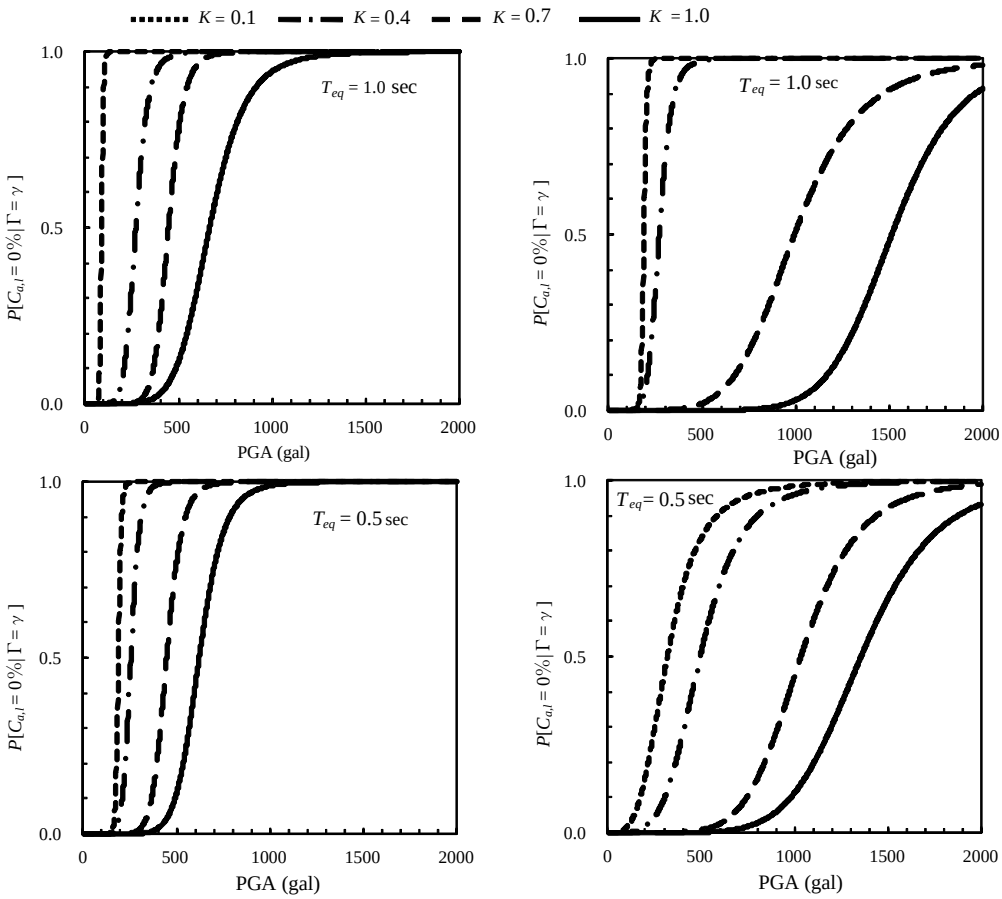


Figure 4: Fragility curves associated with the traffic capacity loss due to the seismic damage to bridge pier

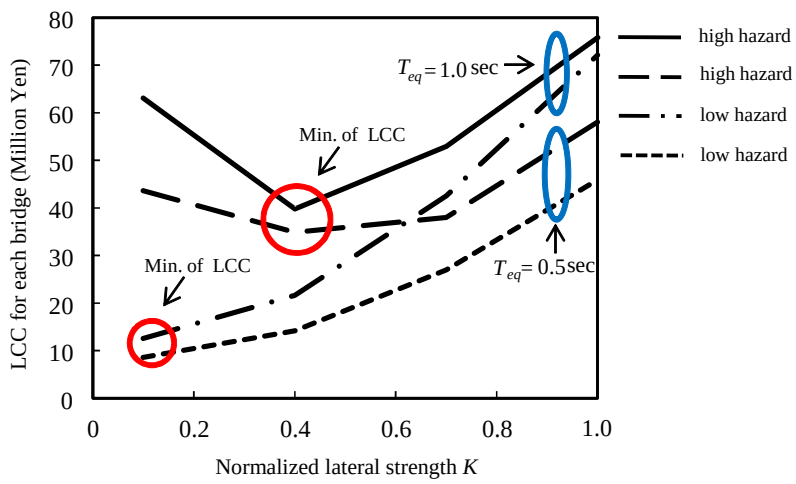


Figure 5: Comparison of total cost of bridge under high seismic hazard with that under low seismic hazard

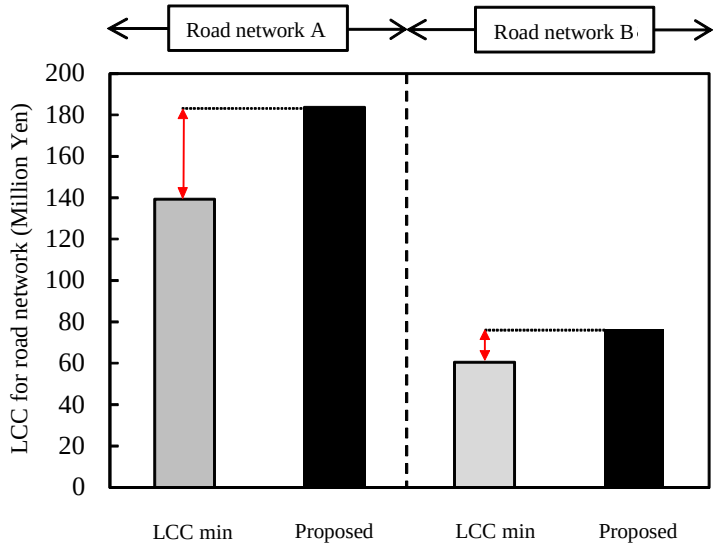


Figure 6: Comparison of total cost of road network to minimize LCC with that to minimize LCC and ensure the specified post-disaster functionality

3.2. Seismic design of bridge pier taking into consideration the traffic capacity loss

Figure 4 shows the examples of fragility curves of bridge pier with K = 0.1, 0.4, 0.7 and 1.0, and T_{eq} = 0.5 sec and 1.0 sec. Figure 5 shows the relationship between seismic life-cycle cost for each bridge and normalized lateral strength K. It should be noted that traffic capacity loss of the road network due to earthquake is not considered in this figure. As shown in Figure 5, seismic life-cycle cost of bridge pier under low seismic hazard monotonically increases with normalized lateral strength; this is due to the fact that C_1 is larger compared to $Pf_{Ti}C_i$ in Equation 3. Meanwhile, K = 0.4 is optimal to minimize the seismic life-cycle cost when bridge pier is located in the high seismic hazard region. The minimum allowable post-disaster traffic capacity from the origin to destination nodes is set to 80% of the traffic capacity of intact road networks. Figure 6 shows the total cost for road networks A and B. As shown in this figure, compared with bridges designed only to minimize

the seismic life-cycle cost, bridges designed taking into consideration the requirement of post-disaster traffic capacity of a road network need to have a higher seismic performance.

4. CONCLUSIONS

This paper deals with risk-based seismic design of RC bridges to ensure the specified post-disaster functionality of road networks and to minimize the seismic life-cycle cost. Consequences associated with the bridge failures are described in terms of monetary loss and loss of traffic capacity of a road network. When bridges are designed to satisfy the specified post-disaster traffic capacity of a road network, they need to have a higher seismic performance than those designed without considering functionality of the road network.

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