RISK AND RELIABILITY ASSESSMENT OF HIGHWAY BRIDGES IN SEISMICALLY-ACTIVE FLOOD-PRONE REGIONS

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Abstract Flood-induced scour at pier foundations can alter the dynamic characteristics of a bridge, and may increase the vulnerability against earthquake excitations. This study aims to analyze the seismic risk and reliability of highway bridges located in flood-prone regions. For this purpose, real-life and characteristic river-crossing highway bridges are investigated under regional multi-hazard scenarios involving earthquakes and floods. For a number of flood cases with varied intensity levels, scour depths are calculated at bridge piers. To observe the combined effect of various frequency flood and seismic events on performance of these bridges, fragility curves are generated at component and system levels. Developed fragility curves are further used to generate seismic risk curves. An uncertainty analysis is simultaneously applied to quantify variations in bridge fragility curves and risk curves under the same multi-hazard scenario. The results of this study show that multi-hazard performance of bridges under earthquake and flood-induced scour may differ for different bridge types, especially for different types of foundations.

1. Introduction

The effect of multiple hazard (multi-hazard) conditions on structures has been increasingly recognized by the engineering society in recent years. Although design of structures is generally based on single dominant hazard, combined effect of two or more natural hazards on a structure can impose a higher risk endangering its safety and serviceability during normal lifespan. Thus, the concern on multi-hazard conditions can lead to improved design, planning, loss assessment, mitigation and maintenance of structures under such conditions.

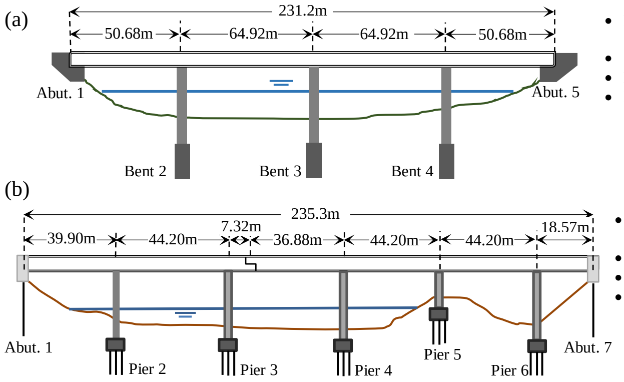
Occurrence of earthquakes in the presence of flood-induced scour is a possible multi-hazard scenario for highway bridges located in seismically-active flood-prone regions. Scour forming at bridge foundations during flood events can change the dynamic characteristics of a bridge and bridges may eventually become more flexible under lateral loading, such as earthquakes. Thus, the question of how much risk and reliability of bridges is affected by this multi-hazard condition has to be answered. The effect of flood-induced scour on seismic vulnerability of bridges was investigated in a number of past studies [1-8]. The findings of these studies have shown that seismic vulnerability of bridges can be affected positively or negatively depending on different bridge attributes and configurations.

The present article mainly presents the major findings of the research [1] that was carried out to assess the risk and reliability of highway bridges under the aforementioned multi-hazard condition. In the scope of this study, firstly multi-hazard performance of two real-life highway bridges are assessed for various levels of flood and earthquake hazards. Then, variation of the risk and vulnerability of bridges is investigated by considering one of these real-life bridges. Finally, characteristic highway bridges located in the West Coast of the U.S. are generated and vulnerability of these bridges are evaluated under no flood and flood conditions.

2. Multi-hazard Performance of Two Real-Life Bridges

This section summarizes the findings presented in [2] in which vulnerability and risk of two real-life bridges are investigated under the multi-hazard of flood-induced scour and earthquake. Both bridges (henceforth referred to as “Bridge-1” and “Bridge-2”) are located in California. Bridge-1 was built in 2010 and it is on State Highway 44 crossing the Sacramento River. Bridge-2 was built in 1972 and it is on Interstate 5 crossing San Joaquin River. The schematic drawings of Bridge-1 and Bridge-2 are presented in Fig. 1. The details on structural attributes of these bridges can be found in [1, 2].

Multi-hazard performance of the bridges is assessed by fragility curves which are developed using the results of a large number of earthquake simulations. Three dimensional models of the bridges are constructed in the finite element analysis platform Opensees [9] and nonlinear time-history analyses are carried out for no flood (no scour) and various levels of flood (scour) cases. For multi-hazard performance assessment, flood event is accepted to occur prior to a seismic event. Flow discharges at various flood levels are obtained from regional flood hazard curves and accordingly scour depths at the bridge foundations are estimated as recommended by [10]. Ground motion data sets for each bridge locations are gathered from PEER NGA database [11]. Damage state of each critical bridge component resulting from time-history analysis is assessed by comparison of the analysis results with the threshold limits (as obtained from literature) defined at each damage level (i.e. minor damage, moderate damage, major damage, and collapse).



- Prestressed concrete box-girder type superstructure
- Seat-type abutments
- Bents composed of two circular piers
- Extended pier shafts with enlarged cross-section below a certain depth

- Reinforced concrete box-girder type superstructure
- Integral abutments
- Wall-type piers
- Pile foundation with a pile cap

Fig. 1. Schematic views of (a) Bridge-1 (b) Bridge-2

Seismic fragility curve can be defined with a two-parameter log-normal distribution:

$$F\left(x_j;c_k,\zeta_k\right)=\Phi\left[\frac{\ln\left(x_j/c_k\right)}{\zeta_k}\right] \tag{1}$$

where the fragility function *F*() represents the failure probability of a bridge component (or at system-level) at damage state *k* (such as minor, moderate, major and collapse) under a ground motion *j* with PGA x_j. Fragility parameters, c_k and ζ_k, refer to median and log-normal standard deviation at damage state *k*, respectively. In the current study, fragility parameters are estimated by using the method of maximum likelihood. The log-normal standard deviation indicates the scatterness (or dispersion) of data. A single dispersion value of $\zeta_k = 0.6$ is adopted from HAZUS [12] for all damage states in order to prevent the intersection of any two fragility curves. Hence, it is possible to compare fragility curves in terms of their median values. A higher median value indicates a stronger fragility curve (i.e. failure probability is lower). System-level fragility curve is computed by using the governing damage state of the entire bridge.

Median values of the fragility curves of the most critical bridge components and for system-level are presented in Table 1 and 2 for Bridge-1 and Bridge-2, respectively. As can be observed from these tables, both component- and system-level fragilities of Bridge-1 are not considerably affected by regional flood hazard (except minor damage state). This is because the seismic design philosophy adopted for this bridge helped in minimizing the impact of scour on seismic vulnerability of the bridge. Meanwhile, for Bridge-2 the estimated scour depths for various flood levels never reach to the pile cap, thus the bridge becomes more seismically vulnerable as the exposed height of bridge piers increases with the increasing level of flood hazard.

Table 1. Median Values (units in *g*) of Fragility Curves of Bridge-1

Damage Level	Bridge Component	No fl.	1-yr fl.	2-yr fl.	10-yr fl.	≥ 20-yr fl.
Minor Damage	Piers	0.409	0.364	0.364	0.364	0.364
	Bearings	0.451	0.423	0.395	0.384	0.384
	System	0.409	0.364	0.354	0.345	0.345
Moderate Damage	Piers	0.688	0.688	0.688	0.688	0.688
	Abutments	0.894	0.894	0.894	0.894	0.894
	System	0.688	0.688	0.688	0.688	0.688
Major Damage and Collapse	Piers	0.815	0.815	0.815	0.815	0.815
	System	0.815	0.815	0.815	0.815	0.815

Table 2. Median Values (units in *g*) of Fragility Curves of Bridge-2

Damage Level	Bridge Component	No fl.	1-yr fl.	2-yr fl.	10-yr fl.	20-yr fl.	50-yr fl.	100-yr fl.
Minor Damage	Piers	0.230	0.224	0.224	0.222	0.222	0.222	0.222
	Abutments	0.204	0.204	0.202	0.197	0.192	0.192	0.192
	System	0.204	0.204	0.202	0.197	0.192	0.192	0.192
Moderate Damage	Piers	0.407	0.407	0.407	0.359	0.359	0.359	0.354
	Abutments	1.081	1.081	1.081	1.081	0.980	0.980	0.980
	System	0.407	0.407	0.407	0.359	0.359	0.359	0.354
Major Damage	Piers	0.684	0.659	0.659	0.599	0.566	0.566	0.525
	System	0.684	0.659	0.659	0.599	0.566	0.566	0.525
Collapse	Piers	0.842	0.748	0.720	0.689	0.689	0.634	0.634
	System	0.842	0.748	0.720	0.689	0.689	0.634	0.634

Within the context of the risk-based framework utilized in this research, the expected risk of bridges due to the regional multi-hazard conditions is expressed in the form of risk curves. A risk curve demonstrates the annual exceedance probabilities of various levels of performance degradation after the occurrence of multi-hazard event. Post-event bridge restoration cost is considered herein for the performance degradation since it is the direct consequence from bridge damage due to a regional multi-hazard condition.

Bridge restoration cost C_{Rm} for a multi-hazard scenario m (including no flood condition) can be estimated as [13]:

$$C_{R_m} = \sum_{k=1}^{4} p_m\left(DS = k \mid a_m\right) C_n r_k \tag{2}$$

where $p_m(DS = k|a_m)$ is the probability that the bridge can sustain the damage state k under a ground motion with PGA = a_m. This probability information can be attained from the fragility curves of bridges. C_n and r_k represent bridge replacement cost and damage ratio corresponding to the damage state k, respectively. The details on calculation of bridge restoration cost are given in [2].

Risk curves (presented with respect to the ratio of restoration cost to replacement cost) of Bridge-1 and Bridge-2 under regional multi-hazard scenarios are presented in Fig. 2. Seismic hazard curves at the bridge sites obtained from USGS [14] are employed for the annual exceedance probabilities of a range of seismic events. As can be observed from Fig. 2, risk of Bridge-1 does not increase with the increasing level of flood hazard. This is consistent with the seismic fragility characteristics which are observed to be insensitive to flood hazard. However, the increase in flood hazard level has a negative impact on the risk of Bridge-2. Such an increase is a natural outcome due to the increased seismic vulnerability of Bridge-2 in the presence of flood-induced scour, particularly at higher damage levels.

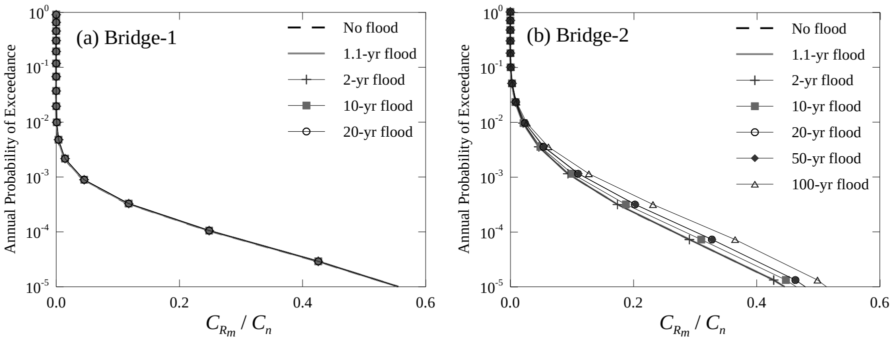


Fig. 2. Risk Curves for (a) Bridge-1 and (b) Bridge-2

3. Uncertainty Study

An uncertainty analysis study is performed in order to obtain the variability in risk of bridges under the investigated multi-hazard condition. The abovementioned Bridge-1 is considered for this study. The applied analysis focuses on the uncertainties in input parameters related to bridge and soil parameters. The possible variations in key input parameters taken into consideration are compressive strength of concrete, yield strength of reinforcing steel, mass of the bridge, shear modulus of elastomer and friction coefficient at the PTFE-stainless steel interface in the bridge bearings, initial abutments stiffness, unit weight of soil and peak friction angle for the underlying soil.

As the first step, a sensitivity study is carried out utilizing Tornado Diagram and Advanced First Order Second Moment Reliability Analyses and the most significant uncertain parameters to which bridge seismic response is remarkably sensitive are screened. The sensitivity study showed that bridge seismic response is most affected by compressive strength of concrete, yield strength of reinforcing steel, mass of the bridge, abutment stiffness and peak friction angle of subsurface soil. The uncertainties involved in other parameters are ignored for the rest of the analysis.

Secondly, Latin Hypercube Sampling technique is used to generate random combinations of the identified key uncertain parameters. For each of these random combinations, seismic fragility curves at each flood hazard level are developed. These fragility curves (not presented here due to lack of space) show the variation of vulnerability of the bridge due to inherent uncertainty of input parameters and statistical uncertainty in estimation of fragility parameters.

As the last step, confidence intervals (90%) of fragility curves are obtained through random sampling of uncertain parameters and Monte Carlo simulations. These fragility curves are further utilized to find the 90% confidence intervals of risk curves. Fig. 3 shows the 90% confidence intervals of the system-level fragility curves and risk curves of Bridge-1 for the 10-year flood condition as an example. Fragility and risk curves pertaining to other flood conditions and more details on this study could be found in [1]. The scatter observed in the estimated multi-hazard risk of the study bridge suggests that the variation in risk due to uncertain parameter cannot be ignored to assure bridge safety under the stated multi-hazard condition.

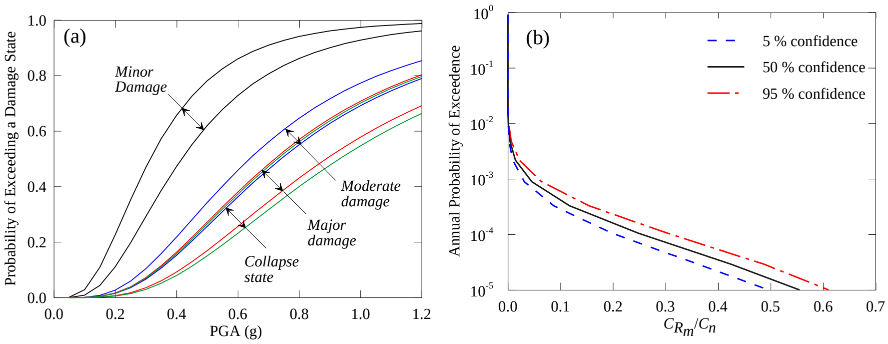


Fig. 3. 90% confidence intervals of (a) system-level fragility curves and (b) multi-hazard risk of the bridge under 10-year flood condition

4. Fragility Analysis of Characteristic Bridges

To improve design procedures for bridges located in seismically-active flood-prone regions, multi-hazard performance of highway bridges with different bridge design attributes is investigated. For this purpose, a detailed inventory study is performed for the bridges in California and Washington states which can be regarded as critical regions with moderate to high potential of exposure to earthquake and flood events. Based on this inventory study, characteristic bridges are formed in accordance with the current seismic design philosophy and practice. In this study, two bridge types are investigated: continuous concrete box-girder bridge (Type A) and continuous concrete I-girder bridge (Type B). These bridges are accepted to have seat-type abutments. Two foundation alternatives are considered to capture the effect of large-diameter foundations on bridge performances: Caltrans Type I shaft (bridges A1 and B1), and Caltrans Type II shaft (bridges A2 and B2). The schematic drawings of the investigated bridge types are presented in Fig. 4 and Fig. 5 for Type A and Type B bridges, respectively.

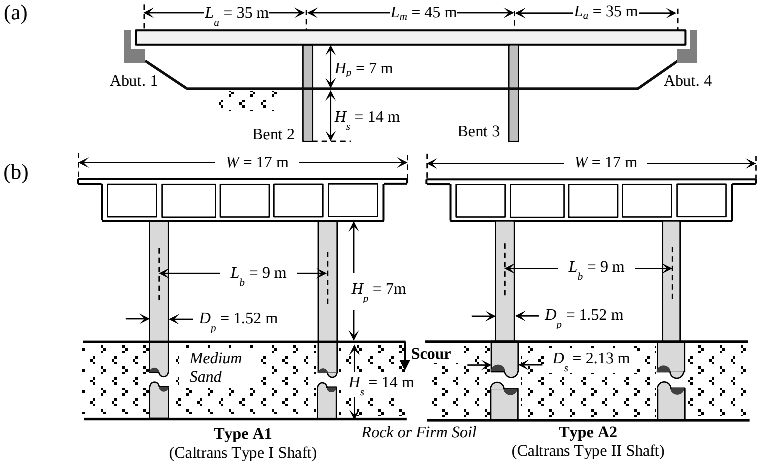


Fig. 4. Schematic views of Type A bridges; (a) elevation view, (b) substructures

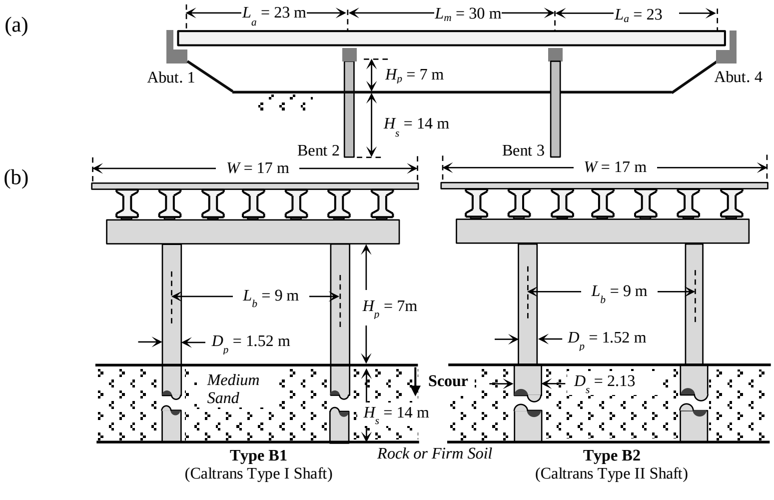


Fig. 5. Schematic views of Type B bridges; (a) elevation view, (b) substructures

The impact of flood hazard on bridge seismic vulnerability is assessed by comparing seismic performance of bridges at no scour (i.e., only seismic) and scoured (i.e., multi-hazard with 100-year flood) conditions. In both cases (with and without scour) nonlinear time-history analyses of the bridges are performed at four different locations with varied patterns of hazard intensities under the selected sets of ground motions for each site. Bridge models are generated similar to the ones developed for real-life bridges mentioned previously. Modal analysis results (not presented here due to lack of space) showed that modal periods for both Type A and Type B bridges increase in the presence of scour. However, no distinct change was observed in their mode shapes.

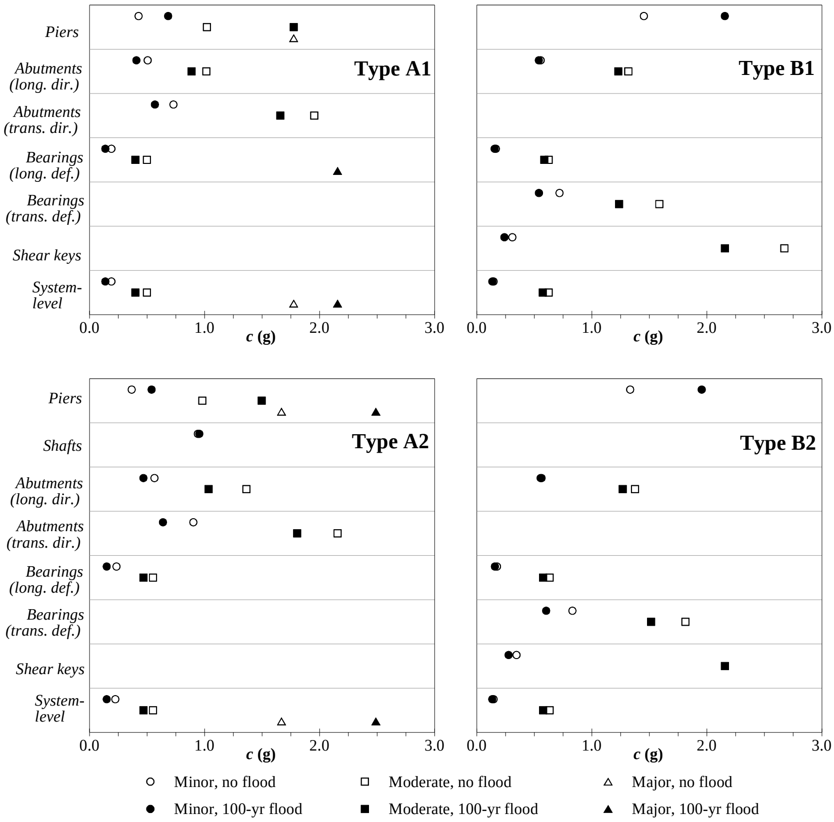


Fig. 6. Median (c) values of the fragility curves of the characteristic bridges at Site-1

Fragility curves of the bridges are developed at component and system levels for each study location. The median values of all component- and system-level fragility curves (with an identical dispersion value of 0.6) of all bridge types at one of the investigated sites (called as Site-1) are presented in Fig. 6. Similar results are obtained for other three study locations. As can be observed from Fig. 6, abutment bearings are the most vulnerable components at low (i.e. minor and moderate) damage states. Bridges become more seismically fragile at low damage states with the occurrence of flood, as the increased displacements at bridge deck level have a detrimental effect on the related bridge components (e.g. bearings and abutments). Although high damage levels at piers are not observed except Type A bridges, system-level bridge fragility curves at higher (i.e. major damage and collapse) damage states are mostly governed by piers. Scour is found to have a beneficial effect on bridge piers in terms of seismic vulnerability because of the increased displacements at both foundation and deck level. The use of enlarged shaft diameter in Type A2 and B2 bridges is observed to not provide any considerable advantage over the bridges having constant diameter shafts. High fragility median values of shafts of these type of bridges indicate that shafts with enlarged cross-section are almost undamaged.

5. Conclusions

The findings of this research evoke a number of major conclusions that may be significant for future design, maintenance and risk mitigation strategies of the bridges located in seismically-active flood-prone regions. The outcomes obtained from the investigation of both real-life and characteristic bridges conclude that bridge fragilities are generally governed by bridge components at superstructure level (e.g. bearings) at low damage states while piers are the governing bridge components at higher damage states. Flood-induced scour has a more dominant impact on bridge fragilities at low damage states, since occurrence of scour at bridge foundations leads to unfavorable impact on bridge components at superstructure level (such as bearings and abutments) under a multi-hazard condition. Nevertheless, at higher damage states multi-hazard performance of bridges may vary for different types of foundations. When the foundation flexibility is not directly affected from scour, bridge fragilities get enhanced with the increase in exposed height of piers. On the other side, particularly for bridges having extended pier shaft type foundations, scour has an insignificant impact on bridge fragilities. This is because the added flexibility at the foundation level due to scour protects piers by reduced seismic fragilities of piers.

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