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Risk-consistent calibration of load factors for the design of reinforced concrete bridges under the combined effects of earthquake and scour hazards

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Current bridge design specifications deal with various extreme hazards independently, which may lead to less economic design and construction practices, and may also underestimate failure probabilities. Therefore, a multi-hazard bridge design framework is required to guide the future design of new bridges or the retrofit of existing ones. This paper lays the foundation toward a risk-based design approach to combine earthquake and scour hazards. First, the development of a new multi-hazard probabilistic seismic demand model is proposed, which is the basis for calculating a combined fragility surface as a function of earthquake and scour hazards. Then, the joint failure probability of the bridge can be obtained by convolving the combined bridge fragility surface with the earthquake and scour hazard curves at a given site. Load combination factors for design are then determined by comparing the joint failure probability and the failure probability of the bridge for a certain scour depth. Results for the case studies considered suggest the use of a scour load factor equal to 0.59 to combine with the earthquake hazard. This risk-consistent multi-hazard bridge design framework provides a basis for exploring combinations of earthquake and scour loads for additional bridge types and geometries, while being consistent with the practical load and resistance factor design (LRFD) methodology.

1. Introduction

Although highway bridges play an important role in transportation networks, they are still vulnerable to extreme events, such as earthquakes, scour, hurricane, and vessel collision. The current AASHTO LRFD Bridge Design Specifications [1] deal with various extreme hazards independently and consider widely varying design level return period events for different hazards (e.g., 1000-year return period for earthquake and 100-year return period for scour). A reliability-based approach has been taken to derive load combination factors considered in bridge design only for the combination of dead load and vehicular load in the current AASHTO LRFD Bridge Design Specifications [1]. The other load combinations used for design are prescribed based on the experience of bridge engineers or the results of other codes, which is not consistent with the reliability-based methodology of the LRFD specifications [2]. Although extreme events have very low probabilities of occurrence, they may cause significant damage to highway bridges, loss of life, and huge economic loss. Among the various extreme events, scour and earthquakes are two of the most common causes of bridge collapses in the United States [3]. Therefore, a risk-based framework is required to bring consistency and establish multi-hazard design principles for bridges subjected to the combined effects of extreme events such as earthquake and scour.

Several researchers have studied the multi-hazard risk problem and the assessment of load combination factors for design, especially in the building community. Ellingwood and Rosowsky [4] used probabilistic load modeling techniques to evaluate appropriate snow load combination factors based on an ultimate strength limit state. They found that approximately 20% of the nominal snow load should be used in combination with the nominal earthquake load when considering ultimate strength and a 50-year reference period. Lee and Rosowsky [5] performed fragility analysis for a light-frame wood building subjected to combined snow and earthquake loads. The snow load factors are obtained by comparisons of the limit state probabilities obtained using the multi-hazard convolution procedure with those obtained using the seismic hazard convolution only. More recently, Yin and Li [6] proposed a framework for risk assessment of light-frame wood structures subjected to combined earthquake and snow hazards

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using a Filter Poisson Process model to consider the snow accumulation in heavy snow areas.

Although a great number of studies have focused on the performance assessment of highway bridges under seismic hazard [7–10], relatively limited research has been performed to investigate a risk-based design for highway bridges considering multi-hazard load effects, especially for the combination of earthquake and scour. Ghosn et al. [2] conducted a comprehensive study to derive load combination factors for highway bridges subjected to various extreme hazards (e.g., earthquake, wind, scour, and vessel collision) based on the Ferry-Borges model coupled with Monte Carlo simulations. However, they used a simplified bridge column bent model and a simple failure limit state equation (column over-tipping) for the combination of earthquake and scour hazards, which may not capture different aspects of current interest, such as the complex seismic behavior of bridge foundation systems. Sun et al. [11] proposed a probabilistic framework to combine the earthquake load and the heavy truck load based on the Ferry-Borges model. Banerjee and Ganesh Prasad [12] analyzed the risk of highway bridges subjected to the combined effects of earthquake and scour hazards through a fragility surface approach. Dong et al. [13] analyzed the influence of scour on the seismic fragility and the economic loss of a highway bridge with a deterministic scour depth. However, they did not discuss how to combine earthquake load and scour effects for the LRFD approach. Also, Alipour et al. [14] investigated load factors for the combination of scour and earthquake hazard for reinforced concrete bridges, and determined scour load factors by comparing the joint failure probability due to scour and earthquake with an acceptable failure probability. However, the fact that bridge failure can also be caused by the seismic hazard alone, and not just through the joint events, was neglected, which underestimates the failure probability of bridges under the combined effect of earthquake and scour hazards. This study addresses the current gap of an appropriate way to combine the earthquake and scour hazards by proposing a new risk-based bridge design approach to obtain the scour load factors without neglecting the contribution of the marginal events as done by others.

Unlike other natural hazards, scour is not treated as a load effect on bridge structures in the current AASHTO LRFD Bridge Design specifications [1], but scour can change the condition of the bridge so that the effect of other natural hazards may be altered. The flood-induced scouring effect on a bridge structure is usually characterized by the scour depth. Scour is defined as the water-induced erosion of soil around the foundation of the bridge and can be identified mainly in three forms: (1) long-term aggradation and degradation, (2) contraction scour, and (3) local scour [15]. Aggradation and degradation are long-term elevation changes in the streambed of the river while contraction scour and local scour result from the existence of the bridge structures. Contraction scour results from a contraction of the flow area at the bridge site which causes an increase in velocity and shear stress on the bed at the bridge. Local scour is caused by an acceleration of flow and resulting vortices induced by the obstruction of the foundation, which usually forms a scour hole. Both local scour and contraction scour can be characterized as either clear water or live bed. Live bed scour means that there is a transport of bed materials while there is no transport of bed materials for clear water scour. Live bed local scour is cyclic because it allows the scour hole that develops during the rising stage of the water flow to refill during the falling stage [1]. This paper focuses on live bed local scour around the bridge column due to its cyclical and unpredictable nature [1].

This paper investigates an appropriate way to probabilistically combine earthquakes and scour considering the simultaneous occurrence of these two extreme hazards. The objective of this study is to lay the foundation toward a risk-based design approach to address scour and earthquake demands together and use it to develop appropriate scour load factors that can be used in the practical load and resistance factor design (LRFD) methodology for a broad range of bridges. First, a multi-hazard probabilistic seismic demand model is proposed, which is the basis for calculating a combined fragility surface as a function of earthquake and scour hazards. The joint failure probability of the bridge is then obtained by the multi-hazard convolution of the fragility surface with the seismic hazard curve and the scour hazard curve. Then, the scour load factors are identified by comparing the joint scour-earthquake failure probability and the seismic failure probability of the bridge for a certain scour depth. The proposed method for deriving scour load factors is illustrated in detail using two code-conforming concrete box-girder bridges crossing over two rivers with low and medium flow discharge rates. The sensitivity of the scour load factors for different bridge geometries is also explored by testing eight additional case studies.

The following sections illustrate the risk-consistent methodology for bridge design under multiple extreme events. Section 2 proposes a multi-hazard probabilistic seismic demand model and the associated fragility surface model. Section 3 introduces the calculation of mean annual failure probability (*MAFP*) based on the multi-hazard convolution procedure. Then, the seismic and scour hazards are derived from the USGS natural hazards database as described in Section 4. Next, Section 5 uses two code-conforming concrete box-girder bridges to obtain the scour load factors based on the method discussed above as well as eight additional case studies to test the sensitivity of the scour load factors for different bridge geometries. The article ends with conclusions and suggestions for future research to advance the design of bridges under the combined effects of earthquake and scour hazards.

2. Multi-hazard probabilistic seismic demand model and fragility surface

2.1. Multi-hazard probabilistic seismic demand model

Methods for predicting the response of the bridges under seismic hazard alone have been well established through the development of probabilistic seismic demand models (PSDM). These models offer a relationship between peak demands (S_D) on a structure and the ground motion intensity measure (*IM*) as shown in Eq. (1), where a and b are regression coefficients. Furthermore, the logarithmic standard deviation of the demand β_D can be obtained by Eq. (2), where D_i is the ith realization of the demands from non-linear time history analyses and N is the number of simulations. However, PSDMs under the combined effects of seismic and scour hazards have not been explored yet. Previous studies assume a small scour depth first, then do the seismic analysis with the given scour depth and use Eq. (1) to calculate the seismic demand. Then these studies increase the scour depth and do the seismic analysis again. However, this simulation process can become very computationally intensive considering that not only a series of small to large earthquake ground motions are needed for seismic risk analysis but that the scour depth should be treated as a random variable too. Therefore, a predictive model known as a multi-hazard probabilistic seismic demand model (MH-PSDM) is needed to reduce the computational effort by estimating seismic demands based on the intensity of the earthquakes and the scour depth.

$$S_D = aIM^b \tag{1}$$

$$\beta_{D|\mathrm{IM}} = \sqrt{\frac{\sum\left[\ln(D_i) - \ln(aIM^b)\right]^2}{N-2}}. \tag{2}$$

To consider the combined effects of earthquake and scour hazards, the traditional PSDMs are extended here to include additional