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Time-dependent seismic fragility analysis of bridge systems under scour hazard and earthquake loads

Xuan Guo [a], Yingkui Wu [b,d], Ya Guo [c,d,a,*]

[a] College of Agriculture, Food and Natural Resources, University of Missouri, United States
[b] Beijing Anke Technology Co., Ltd., China
[c] School of Aerospace Engineering, Xiamen University, China
[d] Beijing Vibrant Peak Technology Co. Ltd., China

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ABSTRACT

A scoured-bridge system has the potential to be subject to earthquake loads. In a bridge's service life, the depth of the scour hole may gradually increase with time due to future flood events. So, scour is a time-dependent hazard. Few efforts have been made to investigate the time-dependent scour hazard on bridge systems under seismic loads. In this work, time-dependent seismic fragility analysis is adopted to study scoured-bridge systems under earthquake loads across a bridge's whole service life. Through time-dependent fragility analysis, the annual fragility curves for different damage states of the bridge systems under combined hazards can be obtained efficiently, in which the uncertainty of materials, scour depth, and ground motions are considered with the Latin Hypercube Sampling method. Also, the fragility surfaces for different damage states can be obtained, which is conditional on both bridge service time and seismic intensity. By combining the fragility surface with earthquake hazards at a given site, the annual seismic risk or cost of scoured-bridge systems can be calculated. Two bridge models are used for the time-dependent fragility analysis. The results show that the probability of all the damage states increases with both time and seismic intensity; however, it does not increase linearly with time and seismic intensity. The nonlinearity depends on the severity of damage state. The damage probability is affected much less by time and seismic intensity if they are below certain thresholds. Then it quickly increases with both time and seismic intensity before another threshold is reached. The thresholds for both stages of time and seismic intensity become bigger when the severity of the damage state changes from slight damage to collapse.

1. Introduction

Bridge scour is defined as water-induced erosion of soil particles around bridge foundations [29]. Generally, there are three forms of scour: (1) long-term aggradation and degradation of the riverbed; (2) general scour due to contraction of the flow; and (3) local scour. Huizinga [19] conducted bathymetric surveys at highway bridges crossing the Missouri River in Kansas City, Missouri, using a multibeam echo sounder. The results show that scour holes exist around many bridge piers, and the scour holes are much deeper for some piers. According to Briaud et al. [9], the total number of failed bridges in the United States was about 1502 from 1966 to 2005. Among these bridge failures, around 58% of them were caused by foundation scour. This implies that flood-induced foundation scour is one of the major causes of bridge failures.

Once a scour hole is formed around a bridge pier, it may last in the bridge's remaining service life, and the scour hole may become deeper due to future flood events. The scoured bridge may be subject to other hazards, including earthquakes. Researchers have put some efforts into investigating the performance of pile-foundation-supported bridge systems under multiple scour and seismic hazards [18,2,21,15,34]. Chang et al. [11] investigated the performance of scoured caisson foundation under earthquake loads. Wang et al. [36] proposed a fragility surface method to investigate the effects of scour on the probability of pile-foundation-supported bridge performance. In the work, the fragility curves were calculated based on each scour depth, which may incur a large amount of calculation. Alipour et al. [3] calibrated the load and resistance factors for the design of reinforced concrete (RC) bridges under extreme events of scour and earthquake based on the reliability analysis.

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* Corresponding author at: School of Aerospace Engineering, Xiamen University, China.

E-mail address: guoy@xmu.edu.cn (Y. Guo).

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They suggested that the mean of scour-load modification factors is 1.42 and 1.12 for moderate and major damage, respectively. These values are larger than the scour load factor of 1.0 in AASHTO [1]. Wang et al. [35] proposed a risk-consistent method to calibrate load factors for the design of reinforced concrete bridges under the combined effects of scour and earthquake hazards. Dong et al. [13] examined the combined effect of seismicity and scour on bridge structures. However, they did not consider the effects of scour depth uncertainty around a bridge's service life. Banerjee and Ganesh Prasad [6] studied the seismic risk of reinforced concrete bridges in flood-prone zones based on different levels of flood events, which is very meaningful. However, the combinations of different flood events were not considered in the fragility and risk analysis. In Guo and Chen [17], annual probability of failure of a scoured shallow-foundation-supported bridge system under earthquake was simulated through the Monte Carlo method; however, the probability of failure conditional upon a specific ground intensity level and bridge service time was not calculated, which is considered in this work.

In this work, time-dependent seismic fragility analysis is used to study the performance of two scoured bridges under seismic loads over their service life while also considering the uncertainty of scour hazard and its dependency on time. The uncertainties of structure materials and soil properties are also considered with the Latin Hypercube Sample method. The focus of this research is to create time-dependent seismic fragility curves and surfaces to investigate the performance of soil–foundation–bridge systems under the combination of seismic and scour hazards across bridge's service life. For simplification, the effect of other hazards such as aging is not included.

Following the Section 1, the second section presents a probabilistic method for scour depth prediction. In the third section, time-dependent fragility analysis is introduced. The fourth section introduces two bridge models and the finite element models. The fifth section presents the numerical experiments. The sixth section introduces the discussions. The conclusion of this work is presented in the final section.

2. Probabilistic scour depth prediction

The SRICOS-EFA method can be used to calculate the maximum scour depth as well as the time dependency scour depth [10]. For the maximum scour depth, the equation is written as

$$\hat{z}_{\max} = 0.18(VD/\upsilon)^{0.635} \tag{1}$$

where V (m/s) is the mean flow water, D (m) is the pier diameter, and υ (m^2/s) is the viscosity of water (10^{-6} m^2/s at 20 °C). The time dependency of the scour depth evolution is introduced through a hyperbola that links the scour depth to the amount of time that a given velocity has been applied. The deterministic time dependency scour depth takes the form [10]

$$z = \frac{t}{\frac{1}{\dot{z}_i} + \frac{t}{\hat{z}_{\max}}} \tag{2}$$

where z (mm) is the final scour depth, t (h) is the time over which a given velocity is applied, $\dot{z}_i$ (mm/h) is the initial scour rate related to soil material, and $\hat{z}_{\max}$ (mm) is the maximum scour depth.

Based on the deterministic method, a probabilistic scour depth prediction method adopted in this research has been developed by Briaud et al. [7,8] using the future flood risk. For a given site, uncertainty of future scour risk is predicted through past recorded peak discharges. Then the predicted future scour risk is used to predict the probabilistic scour depth around a bridge pier. Fig. 1 shows the history of discharge at Sonoma County, California (data from U.S. Geology Survey [33]), which is used in this work to predict future flood risk. Based on the data, the discharges of 100-year and 500-year flood events can be predicted according to the procedure proposed by Chow et al. [12], in which a linear regression is performed over the past years of data. Briaud et al. [7] also adopt the procedures proposed by Chow to calculate the discharge of 100-year and 500-year flood events at a given site.

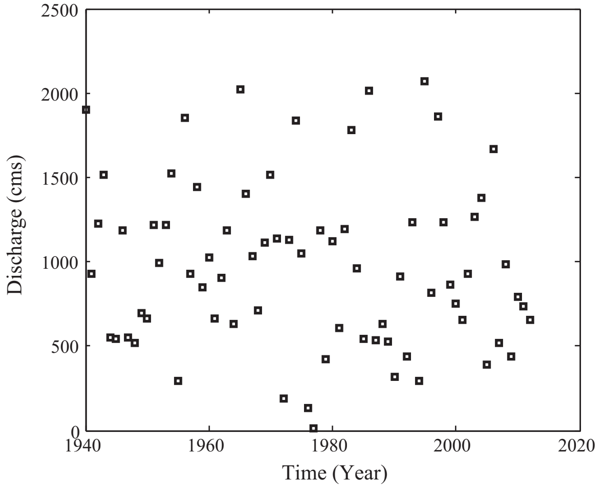

Fig. 1. Distribution of the peak annual flow discharge rate.

After the discharges of 100-year (Q100) and 500-year (Q500) flood events are obtained, the scour depth induced by flood risk can be estimated according to the steps listed in Briaud et al. [7,8] and Guo and Chen [17]. For readers' convenience, some major equations and steps from Briaud et al. [7,8] and Guo and Chen [17] are summarized and presented in this work.

(1) Calculate the parameters of the lognormal distribution (log-normal mean μ_y and standard deviation σ_y) according to Eqs. (3) and (4) [8]. The solutions of Eqs. (3) and (4) are conditional on $P[Q > Q_{100}] = 0.01$ (per year) and $P[Q > Q_{500}] = 0.002$ (per year);

$$P(Q > Q_{100}) = 1 - \frac{1}{\sigma\sqrt{2\pi}} \int_0^{Q_{100}} \frac{1}{Q} e^{\frac{-(\ln Q-\mu_y)^2}{2\sigma_y^2}} dQ \tag{3}$$

$$P(Q > Q_{500}) = 1 - \frac{1}{\sigma\sqrt{2\pi}} \int_0^{Q_{500}} \frac{1}{Q} e^{\frac{-(\ln Q-\mu_y)^2}{2\sigma_y^2}} dQ \tag{4}$$

(2) Future stream flow can be computed as an exponential function of a normally distributed random variable [8]:

$$Q_f = \exp(\mu_y + x\sigma_y) \tag{5}$$

where x is the standard normal random variable;

(3) The relationship between discharge and water velocity and the relationship between discharge and water depth can be computed according to the discharge Q_f, and determine scour rate for each velocity;

(4) Scour depth can be predicted according to Eq. (2) and the previous steps.

Repeating the above steps, the probability of exceeding a specific scour depth can be obtained. According to the above procedures and the details in Briaud et al. [8], the probability of exceeding a specific scour depth around the bridge pier can be calculated for any year. Fig. 2 shows the probability of exceeding a specific scour depth at the 20th, 40th, 60th, and 75th year for the bridge model in