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Multi-Hazard Assessment of Seismic and Scour Effects on Rural Bridges with Unknown Foundations

Xuan Guo, Zhaohua Dai and ZhiQiang Chen

Abstract

This chapter proposes a probabilistic framework for assessing seismic and scour effects on existing river-crossing bridge structures. The emphasis is on bridge structures in rural areas, for which it has been recognized that a large number of rural bridges have unknown foundation types and further are subject to both flooding-induced scour and seismic damage. With a review of the US-based rural bridges, this chapter presents a probabilistic framework for bridge performance assessment. Using a representative rural bridge model, the fragility results for the bridge reveal that scour tends to be beneficial in reducing structural damage at slight to moderate seismic intensities and to be detrimental in increasing collapse potential at high-level intensities. The demand hazard curves further quantify probabilistically the occurrence of local damage and global collapse, and systematically reveal the complex effects of scour as a hydraulic hazard on bridge structures.

Keywords: bridge, unknown foundation, flood-induced scour, multi-hazard, resilience

1. Introduction

There are over 484,500 highway bridges built over river channels in the U.S., among which over 20,904 are regarded scour-critical [1]. A distinct feature of flood-induced scour is that once it starts forming around a foundation, it may accumulate or vary over the bridge's service life. Hence it is intuitive that a potentially more severe risk is that scour is combined with other extreme hazards, such as earthquakes, which may threaten bridges serving in both earthquake and flooding active regions, such as Alaska, Oregon, and California in the U.S. On the other hand, it is recognized that a large number of bridges that are in service for tens of years have unknown foundation, in the meantime, been suffering from flooding induced scour.

In a recent National Cooperative Highway Research Program (NCHRP) report published in 2006 [2], it was identified that a very large proportion of the bridges built in 1950 and 1980 had unknown foundations, although it was surprising that even 69 bridges built during 2000–2005 were concluded with the label of bridges

with unknown foundation types. Based on this report, we further extract the proportion of bridge structures with unknown foundations in different function categories under two primary groups: rural and urban. Two characteristics are observed (**Figure 1**). First, the bridges with unknown foundations in rural areas outnumber significantly those in urban areas (50,743 vs. 8151). Second of all, among the bridges of different functions, the local bridges are the majority with unknown foundations. Particularly, in rural areas in the US, 34,478 bridges (out of 50,743 or about 68%) have unknown foundations; whereas in the urban areas, this number is 3948 (out of 8151 or about 48%). One significant feature of these local bridges is that they are usually structurally simple, short-span with one or two bents. When seismically active regions are concerned, in the aforementioned states of Oregon and California, 801 and 993 local rural bridges with unknown foundations are identified, respectively. Two arguments are raised herein. First, the seismic performance of these simple bridges imposes a great challenge to the stakeholders when duly considering the fact that these bridges have unknown foundation type, and in the meantime, they are subject to flooding induced scour. Second, a rapid and quantitative multi-hazard assessment methodology is demanded.

To evaluate the risk and to provide decision-making for managing these bridges, a methodological and practical procedure has been proposed in [2]; and **Figure 2** recreates part of the workflow. In this workflow, empirical methods are proposed to infer the foundation types and basic geometric parameters. If the foundation types can be determined, then a standard failure analysis is followed. Two additional steps are proposed if the foundation types are not inferable. If the bridge is of high priority, then field reconnaissance is needed to determine the foundation type and configuration. If not, simple risk calculation procedures are used to evaluate if the bridge's minimum performance levels are met (in terms of the annual probability of failure) are proposed. If further not, again the field reconnaissance is recommended to carry out followed by a rigorous and quantitative performance assessment procedure. With this state-of-the-practice methodological framework, however, two limitations are recognized. First, no quantitative procedure that considers the source of uncertainties (e.g., materials or scour) is found, which in nature demands a probabilistic procedure. Second, in light of the bridges that serve in seismically active areas, a multi-hazard approach is further necessary. These limitations imply the necessity of developing a quantitative and multi-hazard assessment procedure.

Besides the need for a quantitative multi-hazard framework, we further state that a rapid approach is favorable for the bridges with unknown foundations in
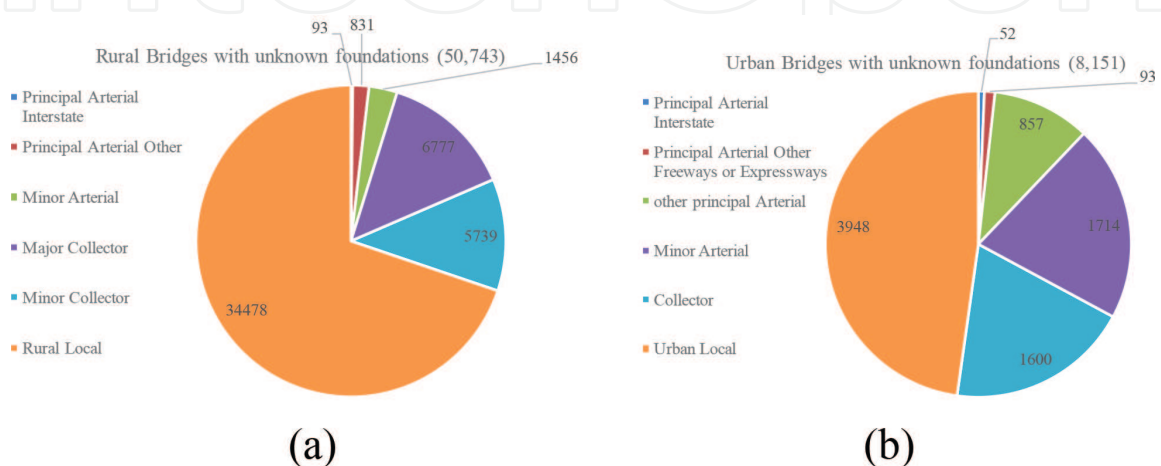

Figure 1.
Bridges with unknown foundations in the US: (a) rural areas and (b) urban areas.
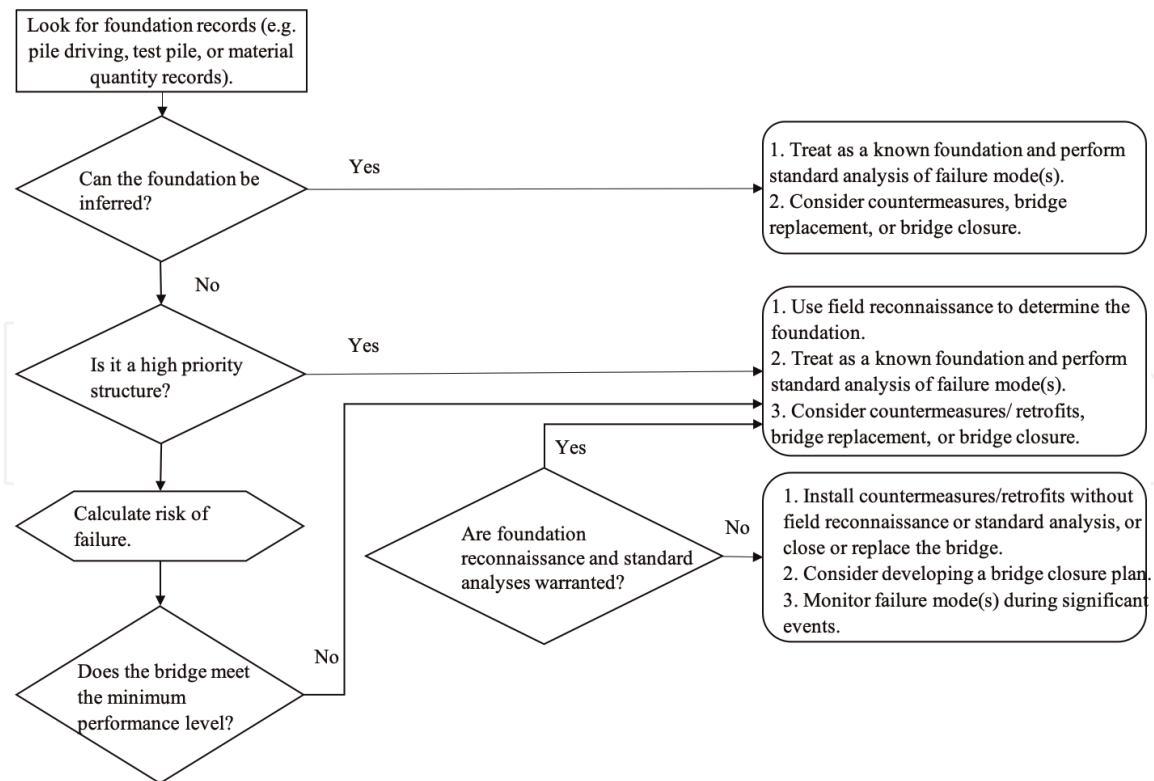
Figure 2.
Risk management workflow (part) proposed in [2].

rural and remote areas. This is a resourcefulness measure to increase the resilience of a bridge system [3, 4], and bridges are critical links with interdependence with other infrastructure systems. Indirectly, if a decision is made regarding that the scour countermeasure be added, this would build the structural redundancy to the bridge system hence reducing the possible bridge loss, increasing the robustness property of the bridge resilience against both the potential flooding, scour, and seismic hazards. Last and above all, rural areas lack technology resources when compared with urban areas; at least due to the geospatial remoteness, any technical measure when being deployed would take a longer time. Therefore, a rapid and quantitative assessment procedure is essentially necessary.

With this motivation, this book chapter is organized as follows. First, Section presents systematically the proposed methodology framework for multi-hazard seismic and scour assessment. Second, a numerical experiment is proposed with a known shallow foundation type. Last, this chapter concludes with a number of remarks for practical application and future research work.

2. Probabilistic methodology

2.1 Related work

Towards a multi-hazard approach to assessing the conjunct effects of earthquakes and flooding-induced scour on the vulnerability of bridges, a probabilistic approach to bridge scour analysis is required due to its inherent uncertainties in the first place. In two recent papers, a general approach to probabilistic scour hazard modeling was reported, which starts with the deterministic scour estimation equation then incorporates model bias and random errors [5]. Furthermore, Briaud et al. [6] concluded that for shallow foundations supporting bridge structures, the design scour depth needs to be 2.0–2.5 times of the HEC-18 estimates to ensure that the

probability of exceeding the estimated scour depth be less than 0.001, even that both HEC-18 (Sand and Clay) methods are considerably conservative compared with measured bridge scour data. Besides probabilistic scour assessment for bridge foundations, however, these two efforts did not address the multi-hazard effects on a bridge as a system if earthquakes are involved.

For a system-level multi-hazard assessment of seismic and scour effects (termed seismic-scour effects hereafter), a number of efforts are found. Wang et al. investigate the vulnerability of scoured pile-foundation supported bridges through probabilistic fragility surface analysis [7]. However, in their work, scour was treated deterministically. Dong et al. proposed a multi-hazard assessment approach to studying bridge performance considering time-variant structural deterioration; however, scour uncertainty was not considered either [8]. Prasad and Banerjee investigated the seismic risk of four example bridges considering scour variations [9, 10]. While studying the characteristics of seismic fragility curves, however, only system-level displacement-based demands (i.e., drift demands at the deck level) were used, which led to the conclusion that scour always increases seismic fragility. Several recent efforts are found on probabilistic calibration of load-resistance factors that are used to combine scour condition with seismic and other design forces [11–13]. No quantitative and probabilistic framework is found to date that is able to comprehensively assess the conjunct seismic-scour effects on river-crossing bridge's vulnerability. In the following, a probabilistic framework is proposed that aims to output seismic-scour integrated fragility and probabilistic demand hazard. The focus is then on the experimental results and observations based on a simple shallow-foundation supported bridge model, followed by the conclusions in the last section.

For assessing performance and vulnerability of structures considering seismic hazards, two probabilistic analysis tools are usually employed, which are probabilistic seismic fragility analysis (PSFA) and probabilistic seismic demand analysis (PSDA). PSFA can be applied to identify the probability of a defined limit-state (e.g., structural damage or collapse) conditional on one or multiple measures of seismic intensity [14–17]. PSDA is used to assess structural vulnerability by estimating the annual probability of a structural demand exceeding a varying demand parameter without conditioning on the input hazard [18, 19]. The output of the PSDA model is a demand hazard curve that is analogous to a seismic hazard curve (from probabilistic seismic hazard analysis, PSHA). Since the demand hazard curve is an essential component of the probabilistic performance-based seismic design framework [20], PSDA has been frequently used for assessing building structures [21, 22] and bridge structures [23, 24].

Different from general multi-hazard analysis wherein two or more hazards appear as a joint occurrence of two independent events that may be generalized as external forces applied to structures (but independent to structures), earthquake and scour should be treated distinctly. Different from loading-based hazards, scour primarily leads to modification of the geometric boundary condition of the soil-foundation-structure (SFS) bridge system. This boundary modification further results in reduction in foundation stiffness, and nonlinear foundation bearing and lateral capacities as demonstrated previously. To account for such changes, a system-level modeling approach needs to be adopted considering SFSI subjected to dynamic loadings (e.g., earthquakes). This in turn leads to an unfavorable situation, wherein the SFS bridge system is not invariant; rather, it is subject to significant modification in terms of foundation impedance and nonlinear capacities due to the varying scour (treated as a hazard).

2.2 Mean-scour seismic fragility modeling

The seismic fragility or the probability of structural damage given a seismic *IM* can be modeled as a conditional probability, $P(Z > z^* | IM)$, where z^* is a specifically defined value of the demand variable. The expression $Z > z^*$ defines a limit state that indicates occurrence of a certain level of damage or even collapse. For measuring the seismic intensity, a sufficient *IM* should be chosen. Peak ground acceleration (PGA) is often used as an objective scalar measure of seismic intensity. When a structure is considered, the spectral displacement (Sd) and spectral acceleration (Sa) defined at the structure's modal period (Tn) are two commonly used measures. In this chapter, Sa is adopted; particularly, Sa measured at the fixed-base first-mode period of the bridge model is used When the sample values of *IM* and *Z* are available, a fitting function in terms of *IM = x* is usually used to fit the conditional probability $P(Z > z^* | IM)$, denoted by $\Psi(x)$. The most popular approach is to enforce a monotonically increasing function bounded by [0, 1], such as the Lognormal cumulative distribution function $\Psi(x)$ [15], to fit the data set of $\{(Z > z^*)_i, IM_i \,|\, i = 1 \ldots N\}$:

$$\Psi(x) = P(Z > z^* | IM = x) \approx \Phi\left(\frac{\ln x - \mu}{\beta}\right) \qquad (1)$$

where μ and β are the mean and standard deviation parameters of the Lognormal cumulative function, respectively. Based on the sample data, a general approach to parameter estimation is the maximum likelihood estimation (MLE) method [25]. This method is adopted in this chapter and formulation details are found in [25].

When scour depth (SD) is considered in seismic fragility analysis, an easy treatment is to compute seismic demands using the SFS bridge model that incorporates a designated scour condition in terms of a deterministic *SD* value, y^*:

$$\Psi(x) = P(Z > z^* | IM = x, SD = y^*) \approx \Phi_{y^*}\left(\frac{\ln x - \mu}{\beta}\right) \qquad (2)$$

The expression in Eq. 2 represents the seismic fragility considering a deterministic scour depth, wherein the uncertainties come from external seismic inputs and possibly from structural materials.

If one considers scour as a type of hazard and then treats scour depth as a random variable, a bivariate fragility model becomes of interest:

$$\Psi(x, y) = P(Z > z^* | IM = x, SD = y) \qquad (3)$$

If the conditional probability model in Eq. 3 is fitted by a bivariate Lognormal function, a fragility surface model is achieved. A fragility surface model has its merit in expressing the true fragility of a structure when multiple hazards are affecting the structure [26] or multiple parameters are used to describe one hazardous effect [27]. As implied in Eq. 6, one may consider fitting the conditional probability by a bivariate function in terms of both seismic intensity and scour depth as independent variables and then study the resulting seismic-scour fragility surface. However, a significant difference of scour effects from seismic effects as illustrated previously is that scour may cause beneficial effects (i.e., reduction of force demands). This implies that the fragility when partially conditional on scour may decrease as the scour depth increases. With the fragility partially depending on seismic measure *IM* (which often designates a monotonic increasing relation), the resulting fragility surface from Eq. 3 may be nonmonotonic, which causes difficulty

in interpreting such a surface. To retain the traditional simplicity in a fragility curve, it is more straightforward to marginalize out the scour depth as a random variable. Based on the law of total probability, one has

$$
\begin{aligned}
P(Z > z^* | IM = x) &= \\
&= \int P(Z > z^* | IM = x, SD = y) f_{SD}(y) \mathrm{d}y \\
&= E_{SD}[\Psi(x, y)]
\end{aligned}
\tag{4}
$$

$$
P(Z > z^* | IM = x) \approx \Phi_{MS}\left(\frac{\ln x - \mu}{\beta}\right)
\tag{5}
$$

where $f_{SD}(y)$ is the probability density function for the scour depth as a random variable and $E[]$ defines the mathematical expectation operator. In Eq. 4, the seismic fragility is defined by integrating out scour depth as a random variable, which is equivalent to the mathematical mean of the bivariate fragility upon the scour depth distribution. Due to this analytical meaning, a notion of *mean-scour* (MS) fragility is proposed in this chapter. In the meantime, the analytical expression of the mean-scour fragility $P(Z > z^* | IM = x)$ means that the fragility model can be directly estimated by fitting the simulated data set using the Lognormal model in Eq. 5.

2.3 Seismic-scour integrated demand modeling

Traditional PSDA assesses the performance of a structure by probabilistically predicting the seismic response in terms of the probability of exceedance for a limit state defined by $Z > z$, where z is a varying demand value. The resulting function, $H_z(z) = P(Z > z)$, is termed probabilistic demand hazard model. In the original efforts [e.g., [18]], a probabilistic demand hazard model (or strictly speaking the mean annual frequency of the exceedance event for a response demand) is evaluated based on the summation over seismic sources described by magnitudes and site distance. In more recent literature, a probabilistic demand hazard model for evaluating the seismic performance of a structure has been defined in a continuous form [19]:

$$
H_Z(z) = \int P(Z > z | IM = x) |\mathrm{d}H_{IM}(x)|
\tag{6}
$$

where $P(Z > z | IM = x)$ defines the likelihood that the structural demand Z exceeds a post-elastic demand value z, and $\mathrm{d}H_{IM}(x)$ defines the derivative of the seismic hazard model (the absolute sign is necessary since the derivative is negative).

It is noted that Eq. 6 considers one (seismic) hazard. If flooding-induced scour as a hazardous condition is considered, the integrated seismic-scour demand hazard, denoted by $H_{SS}(z)$, is proposed, which is based on a simple extension of Eq. 6:

$$
H_{SS}(z) = \iint P(Z > z | IM = x, SD = y) \mathrm{d}H_{IM}(x) \mathrm{d}H_{SD}(y)
\tag{7}
$$

where $H_{IM}(x)$ and $H_{SD}(y)$ are the probabilistic seismic hazard and scour hazard models, respectively. The demand hazard model in Eq. 7 involves probabilistic models of seismic and scour hazards. The two hazard models are introduced below.

2.4 Probabilistic seismic hazard analysis

The probabilistic seismic hazard analysis (PSHA) attempts to define the probability of exceedance (POE) for an IM variable x that is exceeded annually, denoted by $H_{IM}(x)$. In practice, PSHA can be analytically conducted for a given site [28].

In addition, seismic hazard models can be obtained from the web portal of the United States Geological Survey (USGS) for a given site in the United States [29]. One key step in PSHA is to select an appropriate seismic *IM* type. Traditionally, peak ground acceleration (PGA) and spectral acceleration (Sa) at a certain natural period (T_n) are commonly used [30]. In this chapter, the USGS' seismic hazard model in terms of SAs is adopted.

2.5 Probabilistic scour hazard analysis

For local bridge scour (scour around bridge foundation), two primary estimation methods exist as described in Hydraulic Engineering Circular No. 18 [31], which is termed the HEC-18 Sand and HEC-18 Clay. The HEC-18 Clay method was developed at the Texas A&M University, which was designed to predict scour depths in cohesive fine-grained soils (e.g., clay) and was once termed the SRICOS-EFA method [32]. Using the HEC-18 Clay method, the scour depth is the function of time over the period of the hydrograph. First, this method predicts the maximum scour $\hat{y}_{max}$ as:

$$\hat{y}_{max} = 0.18R^{0.635} \tag{8}$$

where R is Reynolds number equal to $\nu D_p/v$, v is the upstream velocity, D_p is the diameter of the pier, and v is the water viscosity (10^{-6} s/m^2 at 20°C). The time-dependent scour depth, denoted by $\hat{y}_t$, is defined by linking the maximum scour depth in Eq. 1, the time at which a given velocity is applied, and the initial rate of scour:

$$\hat{y}_t = \frac{t}{\frac{1}{\hat{y}_i} + \frac{t}{\hat{y}_{max}}} \tag{9}$$

where t with a unit of year is the time over which a given velocity is applied and $\dot{y}_i$ denotes the initial rate of scour.

Based on the deterministic estimation described in Eqs. 8 and 9, multiplicative correction factors are considered to account for the bias and random errors inherent in the deterministic models, which leads to the probabilistic scour modeling [5] and is termed probabilistic scour hazard analysis in this chapter (PScHA to be different from PSHA).

In Bolduc et al. [5], by adopting a Lognormal distribution for scour depth, the probabilistic scour depth is formulated in a Logarithm expression:

$$Log[y_t] = Log[\theta_y] + Log[\hat{y}_t] + \sigma_y \mathbf{N}(0;1) \tag{10}$$

where θ_y is a parameter accounting for the model bias; $\hat{y}_t$ is the deterministic and time-dependent scour estimation from Eq. 9; $\mathbf{N}(0;1)$ represents a Normal random variable with zero mean and unit variance; σ_y is therefore the standard deviation of the Lognormal variable y_t. This implies that when these deterministic parameters, θ_y, $\hat{y}_t$ and σ_y are available, a probability density function for the distribution of the scour depth can be defined using a Lognormal distribution, denoted by $f_{SD}(y_t)$ in this chapter. Given $f_{SD}(y)$, the scour hazard can be analytically expressed as $H_{SD}(y_t) = 1 - \int_0^{y_t} f_{SD}(y)dy$. Similar to the seismic hazard curve, this model when depicted as a curve quantifies the probability of exceeding a scour-depth value at a bridge site; the only distinction is that different from the annual POEs as used in a seismic hazard model, a scour hazard model defined above is calculated at a certain year of service.

3. Experimental results

3.1 Simple bridge model

The bridge chosen in this chapter has a shallow foundation system with a full embedment depth that is constructed in a hard-soil (e.g., cohesive clay) river bed. The bridge has three spans of concrete decks supported by two concrete columns. Such a bridge is commonly used in practice for short-span river passing when the foundation soil is relatively hard (e.g., clay) [33]. In addition, by analyzing a shallow foundation-supported bridge model, the probabilistic assessment can be readily conducted. It is noted, nevertheless, the framework developed and demonstrated in this chapter can be easily adapted for assessing existing bridges with deep foundation systems (e.g., piles) in soft-soil river bed provided a finite-element (FE) based SFS model is provided. **Figure 3** illustrates a simple bridge model, which is considered as a representative rural local river-crossing bridge. The bridge is a three-span (27 m + 36 m + 27 m) continuous structure supported by two piers on two separate shallow foundations. This bridge model was used in the author's previous work [34].

The height of the circular piers is 9.0 m with a diameter of 1.4 m. The steel ratio of the column is about 1.3%. The foundation is constructed on hard clay with a density of 1700 kg/m^3 and with a small-strain shear wave velocity of 260 m/s. The thickness of the foundation is 2.4 m, with the transverse width being 2.8 m and the longitudinal length being 3.3 m, respectively. In this experiment, the embedment depth of foundations is 4.0 m. For bridges with unknown foundation, such full embedment depth can be determined through field inspection methods (for example, for shallow foundations, one can use a drilling device to drill through the footing to determine the elevation of the footing bottom). The simplified configuration of the bridge is shown in **Figure 3**. A three-dimensional finite-element (FE) model for the bridge is developed to simulate the bridge using the OpenSees framework [35]. The FE modeling and the details about beam-column elements, footing elements, material uncertainties, sampling scheme, and the nonlinear time-history analysis details are found in this work as well. Particularly, we consider a target service period of 50 years among its 75-year design life. The purpose is to mimic the situation of an existing bridge that is subject to progressive scour after 50 years of service.

3.2 Demand variables

A variety of response demand parameters can be extracted. In this chapter two demand variables are considered in the following fragility and demand modeling.
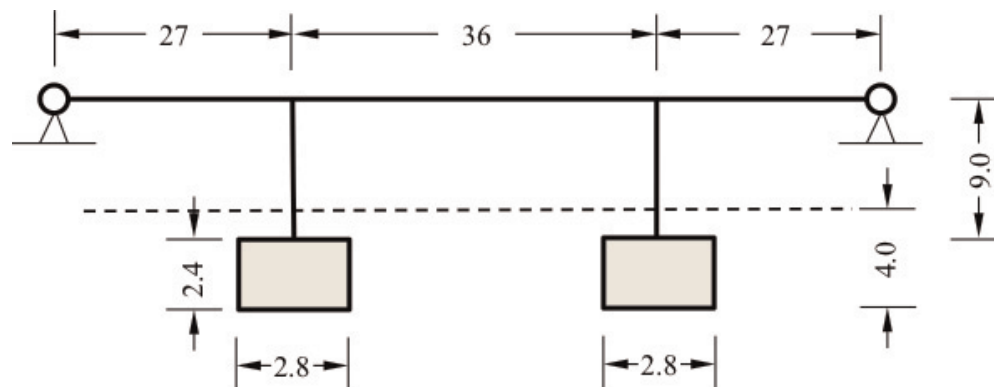

Figure 3.
Bridge configuration (unit: m).

1. Local strain ductility: defined as the ratio of the strain demand ($|\epsilon_{max}|$) at the base of the concrete pier to the compressive yielding strain (ϵ_y) of the concrete, $\mu_s = |\epsilon_{max}|/\epsilon_y$. Since the local strain at the surface is proportional to the curvature, $\epsilon = \rho\,r$, where r is the diameter of the circular column, one can define an equivalent local curvature ductility demand. Hereinafter, local strain ductility demand (μ_s) is used.

2. System drift ductility: defined as the ratio of the transverse system drift demand at the mid-span of the bridge deck ($|u_{max}|$) to the bridge's yielding drift (u_y) at the fixed-end boundary condition, $\mu_d = |u_{max}|/u_y$. For the bridge model considered herein, the yielding drift is about 6.1 cm.

The local strain ductility demand μ_s reflects the degree of local inelasticity occurred to the bridge's concrete piers. For bridge structures, the ranges for using local strain ductility demand to characterize different damage levels are well defined (e.g., [36]). In general, when given a limit state of $\mu_s > 1$, it implies the onset of local damage or indication of slight damage. A larger threshold may be used to define higher-level structural damage, such as $2 < \mu_s < 4$ for moderate damage or $\mu_s > 4$ for extensive damage. Fragility models resulting from these higher-level damage limit-states are not reported in this chapter. The system drift ductility demand indicates the degree of global displacement, which in general consists of structural deformation and foundation-induced rigid-body motion (e.g., sliding and rocking) as a SFS system. In this chapter, if μ_d is larger than seven ($\mu_d > 7$), the onset of system collapse limit-state is defined (usually a drift ductility of 5–10 is used to define bridge collapse in the literature; herein a median value of 7 is used) [37, 38]. We particularly note that for a scoured SFS bridge, it may be biased to define a limit-state using the system-level ductility demand to indicate structural damage in local members. Especially when considering an extreme scour, a limit-state in the range of $2 < \mu_d < 3$ may be dominated by the rigid-body displacement from the substructure with linear-elastic or insignificant inelastic structural deformation; in this case, structural damage may not reach to the expected level (e.g., $\mu_s < 1$).

3.3 Fragility analysis results

Based on the limit states defined previously, **Figure 4(a)** shows the probability of local damage defined by $\mu_s > 1$ considering four designated scour-depth values (No scour; Scour S1 with $z = 2.8$ m; S2 with $z = 4.0$ m; S3 with $z = 4.2$ m). In addition, the mean-scour (MS) fragility curve according to Eq. 5 is shown as well. **Figure 4(b)** uses the same configuration for plotting the fragility curves in terms of the defined collapse limit-state ($\mu_d > 7$). It is noted that material uncertainties are not considered in the two fragility illustrations in **Figure 4**.

Figure 4(a) indicates that the probability of damage is insignificant (less than 10%) if Sa (T1) < 0.33 g (equivalently corresponding to an annual POE of 9.2×10^{-3}, which is the Expected Earthquake design level). In addition, at the NS (i.e., $z = 0$ m) and the S1 level of scour depth (i.e., $z = 2.8$ m), the probability of damage quickly approaches to a high probability (>50%) when the spectral acceleration becomes larger than 0.5 g (or an equivalent 0.38% annual POE). The general trend is that if the scour depth increases when the *IM* is greater than 0.33 g, the probability of damage decreases significantly. Especially, when the scour reaches the full-depth of the foundation (S2), the probability of damage dramatically reduces; for example, at Sa (T1) $= 1.19$ g (about 4.1×10^{-4} annual POE or subject to the MCE-level earthquake), the probability of damage is around 5%, whereas it is 95% compared with the N1 case ($z = 2.8$ m). This observation is consistent with the
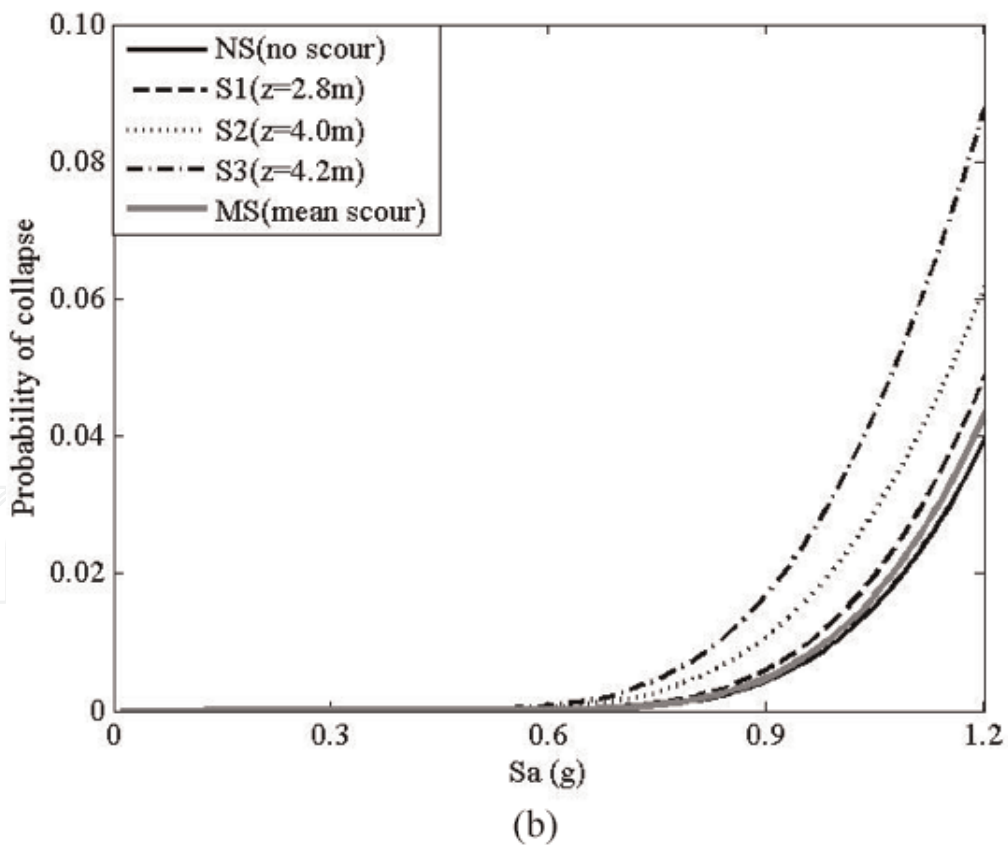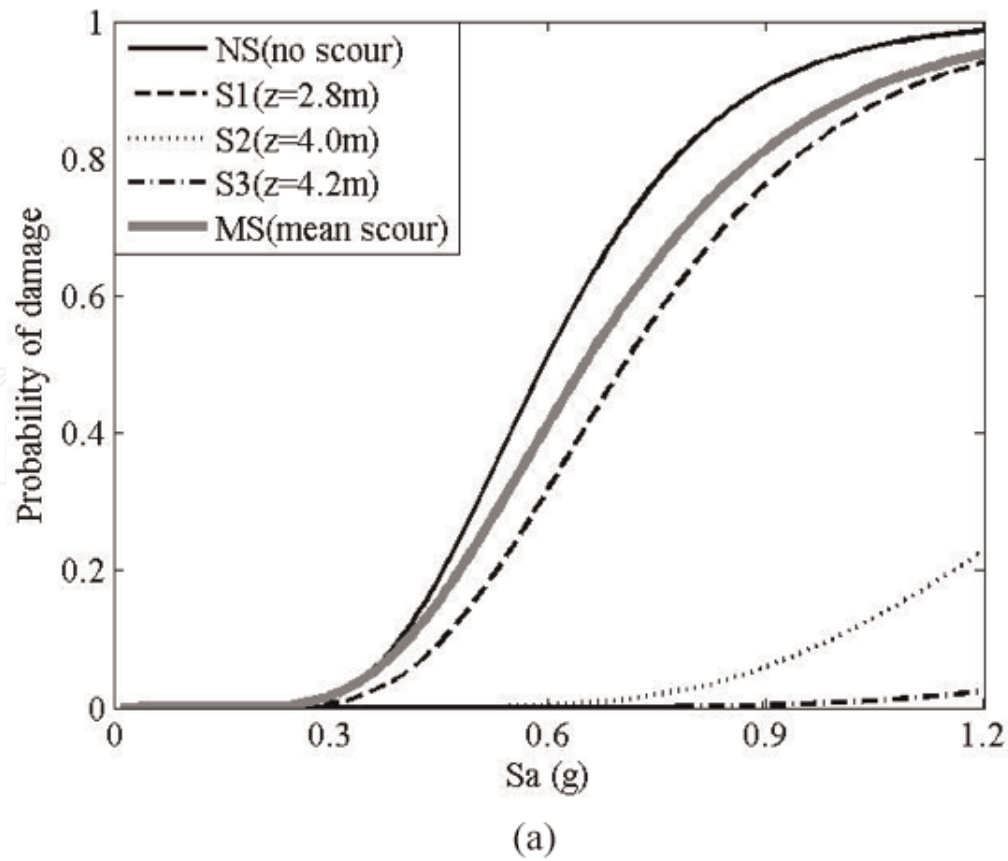
Figure 4.
Fragility model at different scour depths without considering material uncertainties: (a) probability of structural damage at the column base and (b) probability of system collapse.

aforementioned literature that softened foundations in the context of seismic soil-structure interaction tend to lead to less structural damage or smaller base-shear force demands [11]. However, it should be pointed out that when the bridge is

subjected to high-intensity earthquakes and greater scout depths, the potential threat is system collapse. Therefore, it is rational to state that increasing scour depth is only beneficial when subjected to weak to moderate-intensity earthquakes (e.g., in the case of the bridge model herein, Sa(T1) < 0.8 g).

Figure 4(b) shows the probability of collapse defined based on the drift ductility demand at the bridge deck. This figure indicates that the probability of collapse increases as the scour depth and the seismic intensity levels increase. Specifically, the conditional probability of collapse is close to zero when Sa (T1) < 0.7 g. Nonetheless, the probability of collapse rises for each scour condition when Sa (T1) > 0.7 g. For a NS system, the probability of collapse is 4% if Sa (T1) = 1.19 g or considering a MCE level earthquake. By contrast, the corresponding probability for a scour system with the scour depth of 4.2 m is about 9%, which is about 2.25 times of that for the NS system. Accordingly, scour is detrimental by increasing the probability of collapse at all levels of ground motions, but much significantly when the seismic intensity approaches to the MCE level.

The above fragility curves are constructed at designated scour conditions (NS, S1, S2, and S3). However, for an in-service bridge, its scour depth may be completely unknown; therefore, one may not be able to designate a scour depth. Based on Eq. 5, **Figure 4(a)** and **(b)** also report the resulting MS fragility curves. First, one can observe that the MS fragility curve at either of the limit states lies between the fragility curve at the S1 condition (z = 2.8 m) and the one at the NS condition (no scour or z = 0 m), although it is worthy to mention that this observation depends on the probabilistic scour hazard modeling at a specific site.

Second, similar observations in the trend of the MS curves as *IM* increases are still seen compared with the curves at the designated scour depths. Considering the smaller difference of the MS fragility curves from the curves at the S1 condition yet significant difference from the curves at the S2 and S3 conditions, one may assert that scour survey is critical in terms of the potential high risk resulting from a possibly greater scour depth. Nonetheless, if an accurate scour depth is not available, the proposed probabilistic MS fragility modeling becomes instrumental to quantitatively assess the seismic-scour effects.

3.4 Demand analysis results

The seismic-scour integrated demand hazard curves can be approximated as expressed in Eq. 7. With the two ductility demand measures, **Figure 5** reports the demand hazard curves, wherein the vertical axis indicates the probability of exceeding a demand variable that is marked in the horizontal axis (which is either μ_s or μ_d). The two illustrations in **Figure 5** provide a comparison between the cases of considering scour vs. not considering scour (in both cases, material uncertainties, denoted by "mu," are considered). Among them, **Figure 5(a)** illustrates the demand hazard curves in terms of the local strain ductility variable; whereas **Figure 5(b)** presents the system drift-ductility hazard curves.

First of all, the demand hazard curves in **Figure 5** reveal the effects of scour as a source of hazard on the bridge structure. In terms of the local strain ductility μ_s in **Figure 5(a)**, the POEs in the range of μ_s < 2.1 indicates that scour lowers the probability of structural damage in bridge piers, which is consistent with the previous fragility study. However, in the range of 2.1 < μ_s < 4.1, scour increases the probability of damage, which is not revealed in the fragility study since such limit-state of 2 < μ_s < 4 is not defined. It is noted that in both ranges, scour effect is insignificant due to the fact that scour-depth (*SD*) as a random variable has been integrated out numerically; therefore, it should be roughly regarded as a "mean"
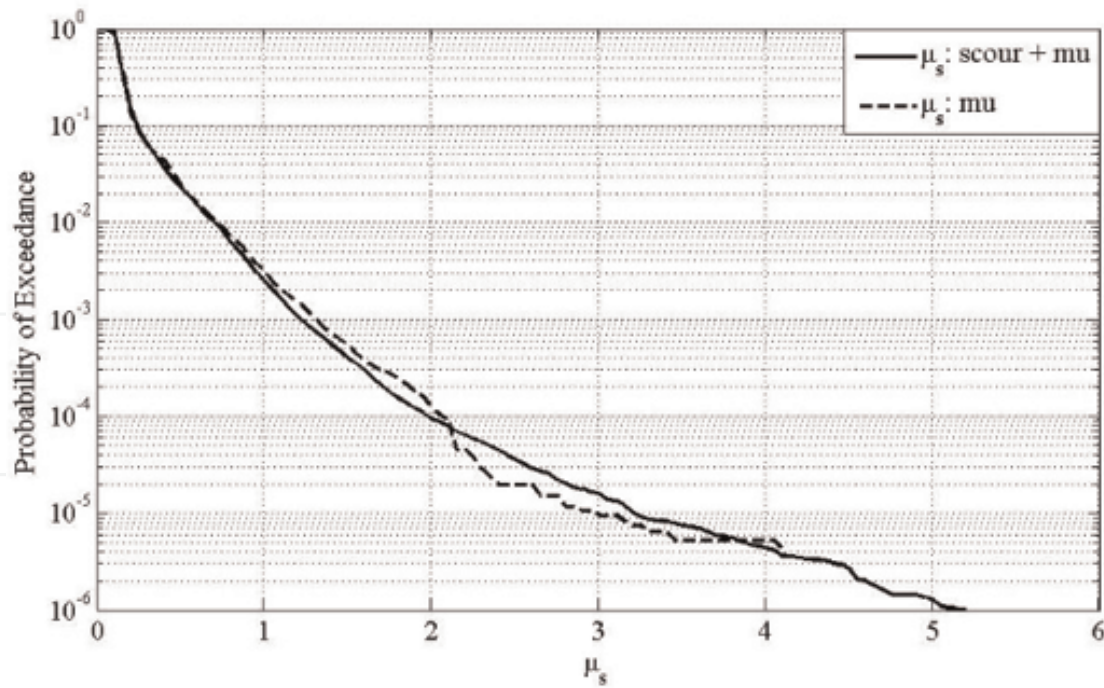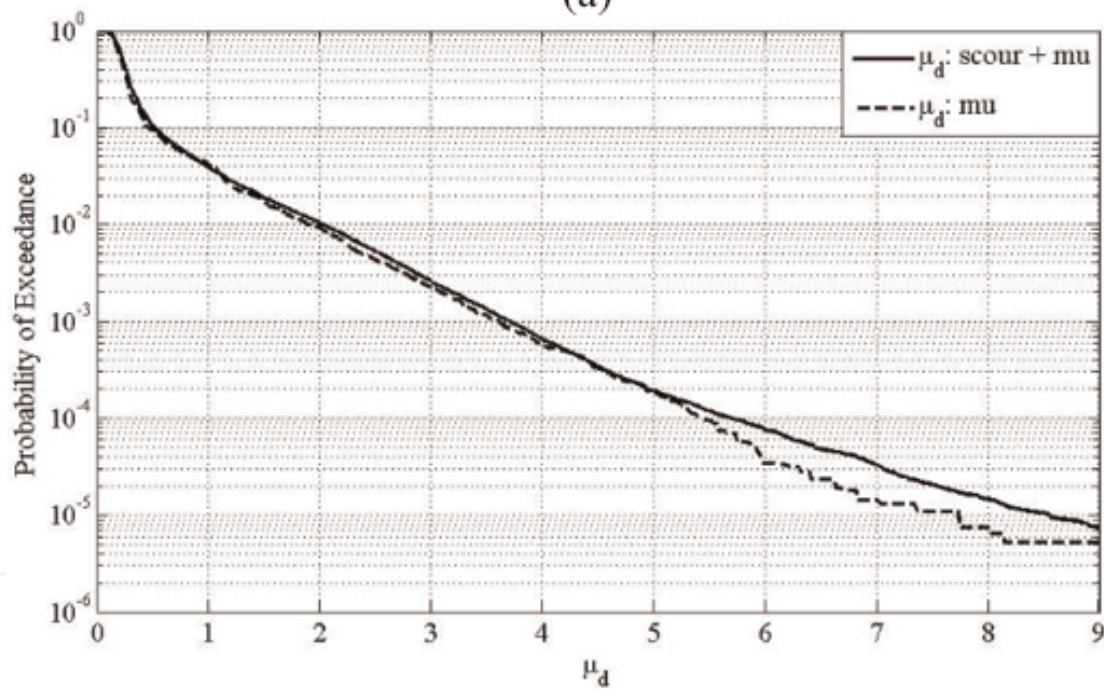
Figure 5.
Probabilistic demand hazard curves considering scour and material uncertainties (denoted by "mu") vs. considering "mu" only: (a) strain ductility demand hazard curves and (b) drift ductility demand hazard curves.

effect of the scour. In terms of the system drift ductility μ_d in **Figure 4(b)**, the overall trend is that the probability of exceeding any specified μ_d increases due to the consideration of scour. This is especially evident when μ_d is greater than 5. This implies that at larger drift ductility levels, wherein the likelihood of system collapse is defined, scour tends to increase the probability of system collapse. Due to these observations, we state that the probabilistic demand hazard modeling provides a more comprehensive approach to evaluating the effects of scour on the seismic response and the vulnerability of bridge structures.

4. Conclusions

This chapter begins with a review of studying bridges with unknown foundations, which can be impacted by both flooding induced scour and earthquakes. Using the data from the United States (US), it is recognized that a large number of bridges have foundation types not identified in the database; in the meantime, many of these bridges serve in rural areas. With this fact, this chapter states that is essential to develop a probabilistic and multi-hazard framework to assess these bridges, although they are often simple in configuration. Such methodological framework can be treated as a resourcefulness measure to improve the resilience of rural bridges, hence local civil infrastructure systems in general (as bridges are interconnected with the functions of other infrastructure systems), and communities. With this motivation, this chapter presents a comprehensive probabilistic framework for assessing the effects of scour on the seismic response of existing bridge structures. Through a case-based assessment using a representative bridge model, several important observations are quantitatively revealed. These include:

- The fragility curves at designated scour depths or the proposed mean-scour seismic fragility curves indicate that scour tends to be beneficial in reducing structural damage at slight to moderate seismic intensities. However, the concern should be raised at strong seismic intensities, wherein even with a lowered probability of structural damage, the collapse potential is significantly increased due to scour.

- The demand hazard curves systematically reveal the complex effects of seismic attacks and scour conditions on exceeding any local structural deformation or system drift demands. These effects include that scour can lower the probability of exceeding a local strain ductility demand at small values compared to the case where scour is not considered; nonetheless, scour can increase the probability of exceedance at larger demand values. In the meantime, scour systematically increases the probability of exceedance at any system drift ductility level, and more significantly at a larger demand level; or equivalently, scour in general increases the likelihood of system collapse when compared with the case of no consideration of bridge scour.

  - Material uncertainties can be ignored if solely for evaluating the effects of scour. If ignored, the proposed framework provides a computationally efficient approach to performing an integrated seismic-scour assessment for bridge structures. However, if material uncertainties considered, the computational cost is much increased since more parametric finite-element models are included, which results in excessive nonlinear static pushover analysis in the framework. To mitigate this, one may choose a small and unique set of ground motions (e.g., only one motion is used in this chapter) at different seismic intensity levels.

To this end, we envision that the proposed probabilistic framework and the associated numerical implementation in this chapter may provide a rapid means for assessing the conjunct seismic and scour effects on existing river-crossing bridges, particularly the simple bridges in the rural areas. We further note that the proposed probabilistic framework can be adapted when it is used to assess the effects of flood-induced scour on other bridge types (e.g., deep-foundation supported bridges in soft soils), provided that a finite-element based nonlinear model for the bridge is available.

Acknowledgements

Author details

Xuan Guo[1], Zhaohua Dai[2] and ZhiQiang Chen[3]*

1 College of Civil Science and Engineering, Yangzhou University, Yangzhou, Jiangsu, China

2 School of Civil Engineering, Nanjing Forestry University, Nanjing, China

3 School of Computing and Engineering, University of Missouri, Kansas City, USA

*Address all correspondence to: chenzhiq@umkc.edu

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