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Applied methods for seismic assessment of scoured bridges: a review with case studies

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Abstract. Flooding induced scour has been long recognized as a major hazard to river-crossing bridges. Many studies in recent years have attempted to evaluate the effects of scour on the seismic performance of bridges, and probabilistic frameworks are usually adopted. However, direct and straightforward insight about how foundation scour affects bridges as a type of soil-foundation-structure system is usually understated. In this paper, we provide a comprehensive review of applied methods centering around seismic assessment of scoured bridges considering soil-foundation-structure interaction. When introducing these applied analysis and modeling methods, a simple bridge model is provided to demonstrate the use of these methods as a case study. Particularly, we propose the use of nonlinear modal pushover analysis as a rapid technique to model scoured bridge systems, and numerical validation and application of this procedure are given using the simple bridge model. All methods reviewed in this paper can serve as baseline components for performing probabilistic vulnerability or risk assessment for any river-crossing bridge system subject to flood-induced scour and earthquakes.

Keywords: bridge scour; multi-hazard analysis; soil-foundation-structure interaction; foundation impedance; seismic effects; nonlinear modal pushover analysis

1. Introduction

Flooding induced foundation scour has been recognized as a leading cause of bridge failure to river-crossing bridges in the United States (Dunker and Rabbat 1995, Hunt 2009, NCHRP 2016, USGS 2011); as such, latest literature also concern the monitoring of bridge scour as part of structural health monitoring practice (Deng and Cai 2010, Wu *et al*. 2017). Globally, another type of scour hazard that has drawn much attention recently is the observed foundation scour formed by tsunami waves (Boulanger 2011, Francis and Yeh 2006, Scawthorn *et al*. 2011). Regardless of the cause of scour (flood or tsunami), bridge scour modifies the geometric profiles of the near-field soil of foundations, hence the boundary condition and capacity of foundations, and ultimately impacts the performance of a bridge as a soil-foundation-structure (SFS) system.

Scour formation around a bridge foundation can cause a permanent modification to the bridge system unless countermeasures or retrofitting solutions are implemented. Therefore, it is intuitive to state that a potentially severe threat comes from the combined risk of permanent scour and other extreme hazards, such as earthquakes. This is particularly evidenced by the fact that many river-crossing bridges lie in seismically active regions (e.g., northern California and Washington States in the US). Globally in coastal regions with tsunami risks, tsunami-induced scour may coexist with strong aftershocks after the mainshock that triggers the tsunami (Mimura *et al*. 2011). This multi-hazard risk, although seemly secondary to the primary flooding, earthquake, or tsunami hazards alone at a regional level, may cripple some bridge systems when the scour becomes *critical*.

In the US, scour-critical bridges are nationally surveyed and the evaluation procedure is developed in the latest Hydraulic engineering circular report (HEC-18) of Federal Highway Administration (FHWA) (Arneson *et al*. 2012). However, the definition of 'scour critical' in this guideline is solely based on the risk of static stability; hence only very severe or extreme-level scour is considered 'critical', such as a scour that undermines a shallow foundation or reaches the bottom of a deep foundation. How to rigorously evaluate the critical levels of bridge scour in a multi-hazard context remains a challenging problem; and no general and practical procedure as those in HEC-18 exists to date.

In this paper, our objectives are twofold. First, by recognizing that the domain knowledge involved in seismic evaluation of scoured bridges spans hydraulic engineering, structural engineering, geotechnical engineering, and earthquake engineering, we provide a comprehensive review of the applied methods that come from these relatively independent arenas. Second, we propose a basic procedure for deterministically assessing the complex effects of foundation scour for bridges considering soil-foundation-structure interaction (SFSI) effects. Fig. 1 illustrates this procedure, which includes: (1) SFS bridge modeling, (2) scour estimation, (3) foundation analysis, (4) SFSI evaluation, and (5) seismic assessment through the proposed nonlinear modal pushover analysis (NL-MPA). It is noted that ground motion selection is not fully treated in

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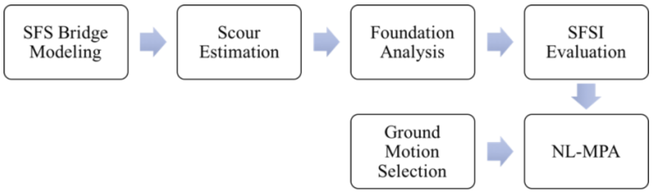


Fig. 1 Deterministic assessment of foundation scour and bridge performance (SFSI: soil-foundation-structure interaction; SFS: soil-foundation-structure)

this paper, since it is usually a separate procedure for probabilistic performance assessment including probabilistic seismic hazard analysis, and ground motion selection and scaling. Due to the fundamental differences in river flooding and coastal tsunamis, the emphasis of this paper is on assessing the performance and vulnerability of river-crossing bridges subject to riverine flood-induced scour and ordinary earthquakes, which are most commonly encountered in practice. Tsunami induced scour and earthquakes are not handled in this paper; and bridges subject to near-fault earthquakes are treated in our future efforts. Probabilistic and life-cycle analysis can be conducted, for which the basic techniques illustrated herein are essential and have been employed in our recent work (Guo and Chen 2015).

2. Literature review of design specification and recent advances

The current design codes for bridges in the United States primarily include the AASHTO's Load and Resistance Factor Design (LRFD) Specifications (AASHTO 2010). AASHTO requires that bridges be designed at both service and strength limit states and be checked at extreme-event limit states. At the strength and service limit states, the foundations should be designed with sufficient bearing capacity and lateral resistance considering an estimated scour depth (relative to the river bed depth). For the design check at extreme events, the LRFD specifications require that foundation stability should be ensured with scour depth estimated an extreme flood (e.g., a 500-year flood). This stability check only considers flood-induced scour, and does not consider the possibility of co-occurrence with other hazards.

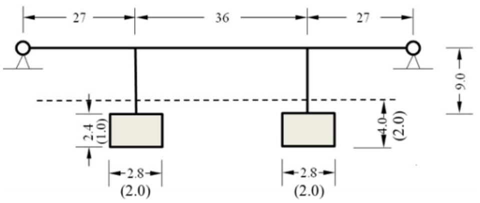
To consider multi-hazard extreme states, the National Cooperative Highway Research Program (NCHRP) Report-489 (Ghosn *et al*. 2004) proposed design load combinations for the joint occurrence of scour and other extreme hazards. For example, when earthquake loading is considered, NCHRP Report-489 recommends the load combination '1.25 DC+1.00 EQ; 0.25 SC', where DC is the dead load, EQ is the earthquake load, and 0.25 SC indicates that the analysis should assume a scour depth equal to 0.25 of the design scour depth (SC). When interpreting the small combination factor (0.25), the recommendation comments that "as long as a total washout of the foundation does not occur", scour-affected bridge foundations may introduce compliance therefore lower seismic force demands. Therefore, scour becomes a 'beneficial' factor; further more since scour estimation in practice is overly conservative, a much small factor (0.25) is used. With these insights, however, no quantitative calibration procedures are proposed in this report.

Several quantitative efforts in recent years are found that concern the safety of scoured bridges subjected to earthquakes. Due to the epistemic and aleatory uncertainties involved in defining earthquakes, floods, flooding-induced scour, and materials subject to aging, all these endeavors adopted a probabilistic framework. Wang *et al*. investigated the vulnerability of scoured bridges through probabilistic fragility surface analysis (Wang *et al*. 2012) but using a deterministic scour depth input. Dong *et al*. (2013) used a multi-hazard assessment approach to studying bridge performance with time-varying structural deterioration, and scour uncertainty was not considered either (Dong *et al*. 2013). Prasad and Banerjee investigated the seismic risk of four example bridges considering scour variations (Banerjee and Prasad 2011, Prasad and Banerjee 2013). All these efforts largely concluded that foundation scour introduces detrimental effects (i.e., increased probability of exceedance of damage or collapse). Several recent efforts are found about the probabilistic calibration of load-resistance factors that are used to combine scour condition with seismic and other design forces (Alipour *et al*. 2012, Wang *et al*. 2014). However, it is noticed that no consensus was achieved on the load factors for scour (besides the factor of 0.25 was recommended in NCHRP Report 489).

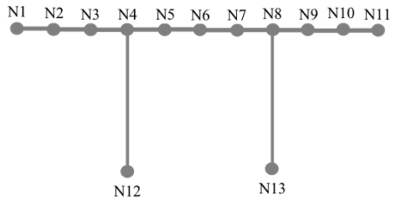
It is noted in those efforts that seismic fragility curves or surfaces were commonly used as the basic tool for vulnerability studies. In addition, system-level displacement-based demands (i.e., drift demand at the deck level) were commonly used to define damage states (DS). As will be elaborated in this paper, this treatment has limitations in reflecting the complex effects of flooding-induced scour. We argue that since design scour depth is usually excessively estimated (Bolduc *et al*. 2008), hence excessively designed foundation embedment, this indicates that foundation scour may more likely provide beneficial roles for most bridges in reducing force and local strain demands. Indeed, this beneficial role has been long recognized by the building design codes (e.g., ASCE's Minimum Design Loads for Buildings and Other Structures) (ASCE 2016) due to the consideration of foundation compliance and SFSI. We point out that the advantage of considering SFSI particularly the rocking behavior of foundation has been discussed in the latest literature (Deng *et al*. 2011, Hung *et al*. 2014). More comprehensively indicated by other researchers (e.g., in Mylonakis and Gazetas 2000), however, caution needs to be taken when quantifying the effects of SFSI since they are influenced by the configuration of structures, the site conditions, and the types of ground motions.

3. Simple bridge model

To illustrate the application of the techniques reviewed in this paper, a conceptual bridge model is designed in this



(a) Configuration (unit: m; the second foundation sizes are noted in parenthesis)



(b) Finite beam and column elements (abutment and foundation modeling are not included)

Fig. 2 Simple bridge model

paper, which has been similarly used the authors' previous effort (Guo and Chen 2015). The conceptual bridge is a three-span (27 m+36 m+27 m) continuous structure supported by two piers on two separate shallow foundations. The height of the circular piers is 9.0 m with a diameter of 1.4 m. The longitudinal reinforcement ratio in the column is about 1.3%. The foundation is constructed in hard clay with a density of 1700 kg/m^3 and with a small-strain shear wave velocity of 260 m/s. According to the practice, a conservative foundation design is initially considered. First, the foundation is set at 2.4 m thick with a transverse width of 2.8 m and a longitudinal length of 3.3 m, and a large embedment depth of 4.0 m. For an illustrative purpose of the proposed nonlinear modal pushover procedure, a relatively flexible foundation design with smaller foundation size (width×length×depth=2.0 m×2.0 m×1.0 m) and lower embedment depth (2.0 m) is conceptually used for in the incremental dynamic analysis in Section 5.

A three-dimensional finite-element model for the investigated bridge configuration is developed using the finite-element platform OpenSees (Mazzoni *et al*. 2005). For the superstructure modeling, a linear elastic beam-column element is used to simulate the beam, which consists of 10 elements with 11 nodes as shown in Fig. 2(b). The columns are modeled with a *DispBeamColumn* element with inelastic fiber sections. The first natural period of the resulting fixed-base superstructure is 0.96 sec, corresponding to an effective total weight of the superstructure of 11.9 MN and a transverse structural stiffness of 51.98 MN/m. The effects of the abutment on the seismic response are also considered. The stiffness of the abutment is calculated according to the Caltrans seismic design criteria (Caltrans 2004). Not shown in Fig. 2(b), elastic springs along longitude, transverse and vertical directions are used to connect with the bridge deck (at N1 and N11, respectively) to the ground. The boundary conditions at the nodes of N12 and N13 depend on the modeling of foundations, which can be simply fixed or modeled using nonlinear Winkler models (Section 4).

4. Scour estimation

Foundation scour is the result of erosive action of flowing water that excavates and carries away soils in the near field of a foundation. The physical process involved in foundation scour is incredibly complex including time-varying fluid-particle and fluid-structure interaction to account for the underlying sediment transport and hydrodynamic impact to structures. Therefore, the dynamic property of foundations is influenced at a similar level of complexity. Even within a linear-elastic range, if scour modifies the foundation soil, it potentially affects the boundary conditions of the bridge as a SFS system. Therefore, it is imperative to study scour effects on foundation impedance at the first place.

There are three types of scour including long-term degradation, contraction scour, and local scour to bridge foundations. In practice, the latter is the primary scour considered in bridge design (Arneson *et al*. 2012). To estimate local scour, the mostly used method was originally developed by Richardson *et al*. based on flume tests using sand beds in the laboratory (e.g., Richardson and Lagasse 1999). However, other researchers indicate that these equations were overly conservative especially for clay materials in river bed, and an improved method, the SRICOS-EFA method, was developed by Briaud *et al*. (e.g., Briaud *et al*. 2004), which can estimate the time-dependent foundation scour in both cohesive and cohesion-less soils. Both methods are included in the 2012 HEC-18. In the current paper, due to their emphasis in sand and clay, we will term them HEC-18 Sand and HEC-18 Clay methods, respectively.

Recent endeavors in the hydraulic/geotechnical engineering community also include the prediction of scour depth using sophisticated computational fluid dynamics (CFD) and fluid-structure interaction capable hydro-codes (Biswas 2010, Guo *et al*. 2009, Huang *et al*. 2009, Zhao and Fernando 2007). Those efforts mostly emphasized on predicting the complex geometric scour profiles around cylinder structures, which may satisfy the goal of predicting the complex geometric profiles of foundation scour (instead of a single depth estimate from the HEC-18 methods). However, it is not clear to date that any CFD-based procedures can accurately simulate realistic soil stress and strain distributions under high flow gradients as scour develops. Our impression is that realistic computational scour simulation is still considered a challenging task; therefore, traditional HEC-18 methods are still recommended in this paper.

4.1 The HEC-18 sand method

The HEC-18 Sand method is expressed as a deterministic equation that predicts the maximum scour depth around a bridge pier as follows

$$\hat{Z}_{\max} = 2.0\, K_1\, K_2\, K_3\, K_4 \left(\frac{\alpha}{y_1}\right)^{0.65} F_1^{0.43} \qquad (1)$$

where $\hat{Z}_{\max}$ is the maximum scour depth, K_1, K_2, K_3, and K_4 are correction factors for the pier shape, angle of the attack, bed configuration, and sediment gradation, respectively; α is the effective pier width, y_1 is upstream water depth, and $F_1 = \frac{V_1}{(g\, y_1)^{0.5}}$ is the Froude number where V_1 is mean upstream velocity and g is the gravity acceleration constant.

4.2 The HEC-18 Clay method

The HEC-18 Clay method, originally called the SRICOS-EFA method, can be applied to any soil types provided that a representative sample can be collected and tested in the erosion function apparatus (Briaud *et al*. 1999). As in the HEC-18 Sand method, this method can be used to predict the maximum scour depth according to the following equation

$$\hat{Z}_{\max} = 0.18\, R^{0.635} \tag{2}$$

In Eq. (2), $R=\upsilon\, D/\vartheta$ is the Reynolds number, where υ is the upstream velocity, D is the diameter of the pier, and ϑ is the water viscosity (10^{-6} s/m^2 at 20°C). Besides the maximum scour depth prediction, this method can estimate the time-dependent scour depth. The time dependency of scour estimation is introduced with a hyperbola that links the scour depth to the time over which a given velocity is applied

$$\hat{Z}_{final} = \frac{t}{\frac{1}{\dot{Z}_i} + \frac{t}{\hat{Z}_{\max}}} \tag{3}$$

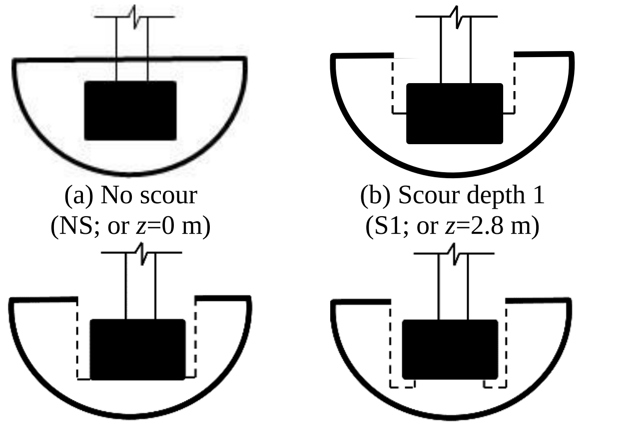
where $\hat{z}_{final}$ is the final scour depth at the time t over which a given flow velocity is applied, $\dot{z}_i$ is the initial rate of scour at the time, and $\hat{z}_{\max}$ is the maximum scour depth as given by Eq. (2).

In the latter efforts of Briaud *et al*., probabilistic treatment of the HEC-18 Clay method was further developed based on hydraulic flooding uncertainties. Therefore, scour as a hazard can be obtained in terms of a hazard curve model, which provides probabilistic exceedance of any scour depth at any service time (Bolduc *et al*. 2008, Briaud *et al*. 2007).

5. Foundation analysis

To illustrate the direct effects of scour on the simple bridge model (Fig. 2(a)), four representatives scour profiles are defined in Fig. 3 (NS, S1~S3). Among them, scour type NS indicates an intact or no-scour condition (z=0 m); S1 means the scour depth reaches to a half of the foundation depth (z=2.8 m); S2 implies a surface foundation when very severe scour reaches the bottom of the footing (z=4.0 m); and S3 means the most extreme scour condition where the scour depth is greater than the foundation embedment depth (z=4.2 m) or the foundation is undermined.

To put into some probabilistic context and using hydraulic uncertainties in Bolduc *et al*. (2008), the aforementioned scour depths of 2.8 m and 4.0 m, correspond to the probability of exceedance of about 0.15% and 0.02%, respectively, at the end of 50 years of service. These two profiles therefore represent the severe to very



(a) No scour (NS; or z=0 m)

(b) Scour depth 1 (S1; or z=2.8 m)

(c) Scour depth 2 (S2; or z=4.0 m)

(d) Scour depth 3 (S3 or z=4.2 m; with 0.3 m wide undermining at each side)

Fig. 3 Representative scour profiles

Table 1 Foundation stiffness at different scour conditions

Scour Case	Scour Depth (m)	K_v (MN/m)	K_h (MN/m)	K_r (MN×m)
NS	0.0	4081.9	4449.9	80989
*S*1	2.4	3274.5	3162.2	33945
*S*2	4.0	2527.9	1971.4	17742
*S*3	4.2	2194.8	1714.4	11405

severe level scour hazards. Note that in S3 (4.2 m), also calculated based on the Clay method, can be treated as a case where system instability has been reached, a 'Scour Critical' level defined in HEC-18.

5.1 Foundation impedance and capacity estimation

Foundation impedance estimation is a basic and useful step prior to assessing the system parameters and the SFSI effects of a SFS system. Commonly adopted Gazetas's equation tables can be used to compute impedance functions for shallow and simple deep foundations (Gazetas 1991). For bridge foundation, one should refer to the latest review article of Mylonakis *et al*. (2006). Briefly speaking, for an embedded foundation that is placed on a half-space or a soil stratum, one can calculate the foundation impedance based on the foundation's geometric and soil parameters. Among the geometric parameters for a shallow foundation, the key ones include the effective depth of foundation plate that contacts with the soil (d) and the total embedment depth (D) from the soil-surface to the bottom of the foundation. In theory, foundation impedance functions depend on the vibrating frequencies; therefore, dynamic impedance functions should be calculated. In practice, this dependence may be ignored in typical fundamental frequency ranges of structures, leading to the direct use of static impedance functions.

Foundation impedance parameters are calculated according to the scour profiles in Fig. 3. Table 1 lists the results of foundation stiffness values. Moreover, Table 1 indicates that with scour depth increasing, foundation stiffness along the three primary directions (where K_v is stiffness at the vertical direction, K_h at the sliding direction,

Table 2 Foundation capacities at different scour conditions

Scour Case	Scour Depth (m)	C_v (MN)	C_v/W_{sup}	C_h (MN)
NS	0.0	111.60	19.0	58.79
*S*1	2.4	71.107	12.0	57.72
*S*2	4.0	47.5	8.0	56.87
*S*3	4.2	34.58	6.0	42.05

and K_r at the rocking direction) decreases significantly. With these values, they clearly indicate that scour softens the bridge substructure hence the supported SFS system.

Another significant modification due to local scour on bridge foundations is the foundation capacities, including vertical bearing capacity (C_v) and the lateral passive capacity (C_h). The classical foundation bearing capacity and passive resistance equations can be used based on the Terzaghi's theory (Das 2015). Table 2 lists the changes of these capacity values, where W_{sup} denotes the total weight of the bridge.

Table 2 indicates that with scour depth increasing, foundation capacities along vertical and horizontal directions decrease as expected. Comparing the capacity of the NS foundation and the S3 foundation, the vertical bearing capacity of the S3 system is only 30.9% of the NS system. In addition, the horizontal capacity of the S3 system is 71.5% of the NS system. Therefore, scour has considerable influence on the bearing capacity of bridge foundations, hence the nonlinear inelastic behavior of the foundation when subject to cyclic loadings. On the other hand, from the vertical safety factors defined as the ratios of the variable bearing capacities (C_v) to the total weight of the bridge structure (W_{sup}), they imply that no direct bearing failure would occur under vertical loading only. On the other hand, cyclic loading may trigger bearing failure at severe scour due to reduced contact area in shaking. This is consistent with the fact that in reality even severe bridge scour occurs, bridges under normal service loads are likely safe. However, concern should be raised when dynamic transverse loads occur (e.g., boat impact or earthquakes).

5.2 Finite-element modeling of foundations

The foundation impedance and capacity estimation above clearly indicates the effects of scour on the dynamic properties of bridge foundation. In practice, these estimations (values in Tables 1 and 2) provide a basis for more realistically modeling the scoured foundations using finite-element (FE) methods. In a FE environment, foundation can be modeled to consider not only the elastic modification of foundation impedance but also more importantly the potential nonlinear inelastic and geometric relations. For the latter, this includes foundation sliding and foundation rocking that cause geometric nonlinearities at the interfaces of the foundation, the bottom soil, and the side soils, and further influence the system-level geometric nonlinearity (i.e., P-Δ effects).

In theory, a foundation subsystem can be modeled within a large soil subdomain. However, this will bring in significant and even prohibitive computational cost. To practically model the nonlinear response of the foundation subsystem, nonlinear Winkler-spring based foundation modeling has been widely studied, which can account for both inelastic and nonlinear geometric properties of the foundations with a much reduced computational cost for bridge structures (Cremer *et al*. 2002, Gajan *et al*. 2008) and building structures (Lee *et al*. 2015). For isolated footings used in bridges or buildings, the Beam-on-nonlinear-Winkler-foundation (BNWF) model has been developed and validated by a number of researchers in the community, which are collectively found in the PEER report (Gajan *et al*. 2008). Due to its simplicity, it has been used as a reasonable tool for accounting for the inertial effects in a SFS system. In a BNWF model, distributed spring elements that combine nonlinear springs, gap elements, and dashpots are formulated. Such nonlinear 'zero-length' elements have been implemented in the OpenSees framework. In this paper, the *PySimple2*, *QzSimple2*, and *TzSimple2* are integrated for the foundation modeling. Details for these elements and experimental validation are summarized in (Raychowdhury 2009, Raychowdhury and Hutchinson 2009).

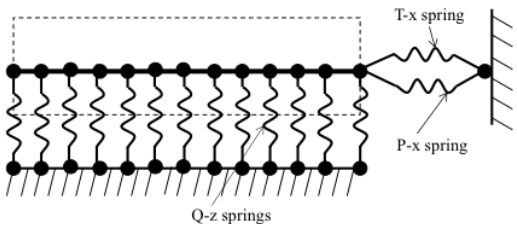


Fig. 4 A finite element discretization scheme for the shallow footing.

Fig. 4 illustrates the FE discretization scheme for the bridge's shallow footing. To define the zero-length *P-x*, *Q-z* and *T-x* springs used within the BNWF model, the bearing capacity, lateral passive capacity, lateral frictional capacity, and the linear elastic foundation stiffness and damping must be computed based on the aforementioned impedance and capacity estimation methods, then they are distributed to these spring elements. The practical distribution scheme can be found in the PEER report (Gajan *et al*. 2008).

6. Preliminary SSI analysis

The direct effects of scour on bridge system parameters are two-fold. As introduced earlier, first, foundation scour modifies the elastic impedance at small soil strains and the capacities at extreme loading with plastic deformation. Second, since scour modifies foundation impedance and capacities, the intrinsic SSI parameters at a system level are altered. Starting from linear-elastic analysis, these parameters are reviewed as follows, which provides preliminary understanding to the degree of SSI for the bridge.

Fig. 5 illustrates an idealized soil-foundation-structure oscillator as similarly used in the classical SSI literature (Jennings and Bielak 1973, Veletsos and Meek 1974). This model consists of a single centered mass (m) at the top with

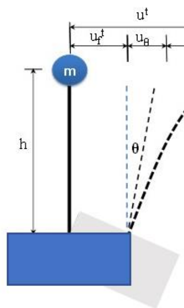


Fig. 5 Soil-foundation-structure oscillator model

a superstructure height h, a linear superstructure with a bending stiffness of K_1, and with a rigid foundation resting on a half-space (one can assume that the square foundation is B wide, a fully embedded foundation depth D, and a mass of m_f). The basic input is denoted by (u_g), which is typically the free-field ground motion. The foundation and superstructure responses include the total lateral displacement of the superstructure (u_t), the total lateral foundation displacement (u_f^t), the foundation rocking (θ), and the elastic displacement due to structural bending (u). If the four displacement variables (u_g, u_f^t, u_t and θ) are small, two linear equations $u_f^t=u_g+u_f$ and $u^t=u_g+u_f+u_\theta+u$ can be used to linearly correlate the primary lateral displacements in the system. In the nonlinear range (then individual displacement response components, u, u_f, and u_θ, are generally large), this linear combination is not valid. However, it holds true that the total displacement u^t has contributions from all the individual components. This simple displacement decomposition essentially indicates that although the total displacement can be used as a proxy to define damage state especially collapse, it is not directly related to local structural damage. It is the structural displacement (u) that defines the collective structural deformation; therefore, either u or the local structural deformation (e.g., the strain at the base, ϵ) is a better measure for defining structural damage (e.g., through normalizing with the yielding displacement or strain, u/u_y or ϵ/ϵ_y, where the subscript 'y' indicates yielding).

With these displacement parameters, one can construct the dynamic equilibrium equations, which can be found in Jennings and Bielak (1973). One essential result from the governing equations is the formulation of the fundamental period considering SSI (T_{SSI}). Denote the fundamental period at the fixed-base boundary condition, T_{fixed}, the ratio of the two periods is the so-called period lengthening ratio (PLR = T_{SSI} / T_{fixed}), which is expressed as

$$PLR = \sqrt{1 + \frac{K_1}{K_h} + \frac{K_\theta\, h^2}{K_h}} \tag{4}$$

where K_1 denotes the lateral bending stiffness of the fixed-base superstructure system, h is the height of bridge column, K_h and K_θ are defined in Table 1.

In addition to the analytical PLRs based on the conceptual linear oscillator model in Fig. 5, at this point the 3D soil-foundation-structure bridge model in OpenSees can be utilized, through which the eigenvalue analysis can be performed. By switching between the fixed-base and the variable boundary conditions modeled for the scoured foundations (at S0, S1, S2, and S3), more realistic PLR results can be produced. Table 3 reports the full results.

Table 3 Soil-foundation-structure system periods at different scour conditions

Scour Case	Scour Depth (m)	K_1/K_h	$K_1\times h^2/K_r$	T_{ssi} (sec)/T_{fixed} (Eq. (4))	T_{ssi} (sec)/T_{fixed} (OpenSees)
NS	0.0	0.006	0.0268	1.02	1.12
*S*1	2.4	0.0085	0.0639	1.04	1.14
*S*2	4.0	0.0136	0.1223	1.07	1.21
*S*3	4.2	0.0156	0.1903	1.10	1.29

Table 3 indicates that with scour depth increasing, the fundamental period (T_{ssi}) of the scoured bridge system increases. This further implies that scour softens the bridge as a SFS system. In addition, comparing the rocking stiffness between the systems with scour depth increasing from the NS to the S3 condition, the rocking stiffness at S3 is only 14% of the stiffness in the NS condition. Using the numerical OpenSees FE simulation results, the softened foundation modified the system period. In the NS case, the PLR is about 1.12, indicating potentially moderate SSI effects; whereas in the S3 case, the PLR increases up to 1.29, implying much significant SSI effects. Last, the analytical results based on the estimates of foundation stiffness, the relative values of lateral foundation stiffness to the fixed-base superstructure's transverse stiffness (K_1/K_h), and the rocking stiffness of $K_1\times h^2/K_r$ give another important insight. Accordingly, by comparing the two sets of normalized values, clearly one may expect that the bridge is rocking dominated as a SFS system, since the values of $K_1\times h^2/K_r$ are much greater than the K_1/K_h values.

7. Nonlinear modal pushover analysis

Besides structural damage as inelastic deformation in bridge structures, extensive case histories in geotechnical and structural earthquake engineering have revealed that building and bridge systems subject to strong ground motion can manifest inelastic soil deformation and complex nonlinear soil-foundation interface behavior (foundation sliding, uplifting, and rocking). Therefore, the most comprehensive seismic assessment is based on the time-history analysis (THA) given the ground motions as input to a properly modeled SFS system. In practice, when nonlinearity is involved, this process is very computationally expensive. As a matter of fact, the computational cost related to THA has been a major challenge in performance-based seismic assessment wherein a large number of FE-based THA runs are the baseline for probabilistic assessment.

When scour is considered as another hazard, it becomes another dimension in probabilistic fragility and demand analysis. Moreover, each change of scour depth will lead to the change of the finite element models. The computational cost is then further scaled up as the number of scour depths increases. In the following, nonlinear modal pushover analysis is proposed as a reduced-order replacement to the traditional nonlinear THA.

7.1 Nonlinear modal pushover for soil-foundation-structure bridge systems

Nonlinear modal pushover analysis (NL-MPA) has been used to estimate the seismic response of buildings (Chopra and Goel 2003, Nezhad and Poursha 2015, Reyes and Chopra 2011) and bridges (Kappos *et al*. 2005, Muljati and Warnitchai 2004, Paraskeva *et al*. 2006). NL-MPA provides a cost-effective approach when computational cost is a concern compared with the regular THA procedures. However, this procedure has not been utilized for scoured bridge assessment except for the author's previous effort performing life-cycle probabilistic analysis (Guo and Chen 2015). In this paper, a full description of this procedure is provided with numerical validation. The following steps are summarized:

1) Compute natural frequency ω_n and modal shape vector ϕ_n for the SFS bridge system. Different from most NL-MPA applications for buildings or bridge structures without considering SFSI, both foundation sliding and rocking at the base of the bridge columns are considered for increasing modeling accuracy.

2) Calculate the pushover force using the above vibration modes according to the following equation

$$S_n^* = M\,\phi_n \tag{5}$$

where *M* is the mass matrix with the size consistent with the modal shape vector. With the obtained pushover force vector applied to the nodes of the structure at the designated nth mode and recording the base shear and drift demands, the pushover curve corresponding to the mode can be obtained.

3) Idealize the pushover curve, the post-yielding strain-harden ratio yield α_n, yielding displacement U_{rny}, and base-shear force V_{bny} can be estimated as shown in Fig. 6(a).

4) Calculate the properties of the nth-mode inelastic single-degree-of-freedom (SDOF) system as shown in Fig. 6(b), which can be obtained from the above idealized pushover curve using the following equations

$$F_{sny} = \frac{V_{bny}}{\Gamma_n}$$
$$D_{ny} = \frac{U_{rny}}{\Gamma_n\,\phi_{rn}} \tag{6}$$

where $\Gamma_n = \dfrac{\phi_n^T M\, l}{\phi_n^T M\, \phi_n}$ and *l* is a unit vector of the same size of ϕ_n.

5) Compute the peak deformation (D_n) of the n^{th}-mode inelastic SDOF system.

6) Calculate the peak displacement u_{rno} of the target structure associated with the n^{th} mode SDOF system using the following equation

$$u_{rno} = \Gamma_n\,\phi_{rn}\,D_n \tag{8}$$

where ϕ_{rn} is n^{th} modal shape vector of the target node, and D_n is the peak displacement calculated from step 4.

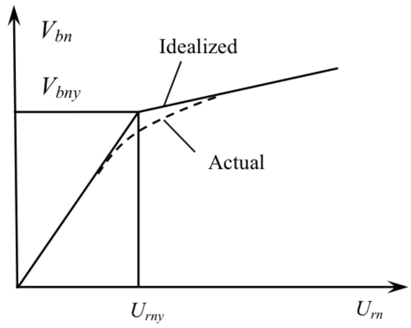
7) At u_{rno}, extract from the pushover database values other expected response, such as the drift of the bridge deck, the sliding/rocking at the foundation, and the local strain demands at the base of the bridge pier.

8) Repeat the above procedure for more modes to ensure the required accuracy and combine the peak modal response by the Square-Root-of-Sum-of-Squares (SRSS) combination rule using

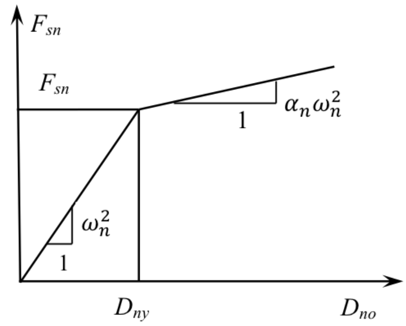
$$r_o \approx \left(\sum_{n=1}^{N} r_{no}^2\right)^{1/2} \tag{9}$$

where r_o is a structural demand parameter and r_{no} is a structural demand parameter at the nth mode.

The first-three vibration modes of the bridge system are considered in this paper for the scoured bridge system with different scour depths. According to Eq. (5), the pushover forces applied at each node and at each mode can be obtained. Table 4 shows the force distributions at the first three modes that are applied to the nodes of the bridge deck considering the non-scoured bridge. By plotting force values at the different modes, the resulting modal shapes will be shown clearly. The force distributions along the



(a) Actual and idealized system pushover over curve



(b) Normalized modal pushover curve for the n^{th}-mode SDOF

Fig. 6 Modal pushover formulation

Table 4. Modal force distribution along foundation sliding and rocking.

Mode	F1 (MN)	F2 (MN)	F3 (MN)	F4 (MN)	F5 (MN)	F[*]6 (MN)
1	0.16	45.76	85.98	119.61	145.69	155.77
2	10.29	353.90	384.20	119.61	-229.26	-387.10
3	-12.32	-126.60	18.22	119.61	-5.46	-119.03

[*]The bridge model hence the modal force distributions are symmetric about the sixth node; therefore, only the forces applied to the first six nodes are listed in this table.

Table 5 Modal force distribution along the foundation sliding and rocking directions

Mode	Sliding force (KN)	Moment (KN×m)
1	752.0	-1690.9
2	759.7	-1690.8
3	814.4	-1690.0

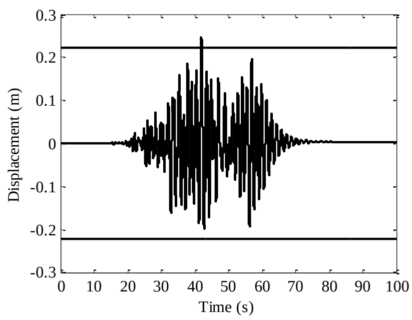
foundation's sliding and rocking directions are listed in Table 5.

Table 5 indicates that the force along the sliding direction increases as the vibration mode increases. Nonetheless, the absolute values of the moment along rocking approximately keep constant as the vibration mode increases. Our numerical simulations indicate that the incorporation of the modal pushover forces at the foundation levels increases the overall accuracy of seismic demands estimation.

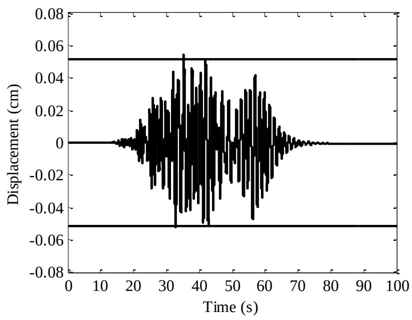
Under the pushover forces listed in Tables 4 and 5, the resulting modal pushover curves are obtained through nonlinear modal pushover analysis. According to the yielding properties shown in the modal pushover curves (Fig. 6), the properties of the SDOF systems can be calculated using Eqs. (6)-(7). The seismic demand parameters, such as drift, base shear force, strain and stress at the base can then be obtained through the Eq. (9).

7.2 Verification of NL-MPA against Time-History Analysis (THA)

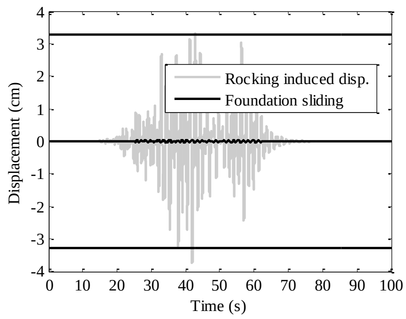
To check the accuracy of the NL-MPA, key seismic demands extracted from the NL-MPA procedure are compared with those obtained from the traditional time-history analysis (THA). Herein the results using the ground acceleration record, NGA_1258, from the HWA005 station during the 1999 Chi-Chi Taiwan event are studied. In the calculation, the ground motion was scaled to 1.0 g at the fundamental period (0.96 sec) of the fixed-base bridge, which is sufficiently large to incur nonlinear SFS responses (corresponding to a 6% probability of exceedance in 75 years at this bridge site). Subject to this ground acceleration record, the results under the two methods (THA and NL-MPA) are obtained and compared in Fig. 7. Fig. 7(a) shows the transverse mid-span displacements of the bridge deck, in which the displacements obtained from NL-MPA is only 9% less than the absolute maximum values from the THA. Fig. 7(b) illustrates the displacement of the footing, in which the displacement obtained from NL-MPA is almost the same as the absolute maximum values from the THA. In addition, Fig. 7(c) shows the foundation displacements at both the sliding and the rocking modes, which confirms that the foundation motion is dominated by the rocking behavior. Moreover, the extracted foundation rocking demand from NL-MPA is about 12% less than the peak value from the THA. Fig. 7(d) shows the extracted base shear demands from the NL-MPA, which is almost identical to the peak force from the THA results. Fig. 7(e) illustrates the strain at the bottom of the columns. Accordingly, the strain demands are almost the same under the two kinds of calculation methods. It is noted that the discrepancies values reported above are in the expected range when using the NL-MPA procedure as reported in the literature (Chopra and Goel 2003). Therefore, we state that NL-MPA can be



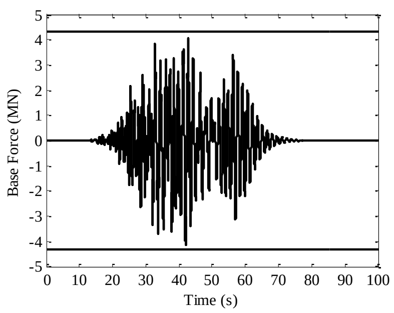
(a) Transverse bridge deck displacements



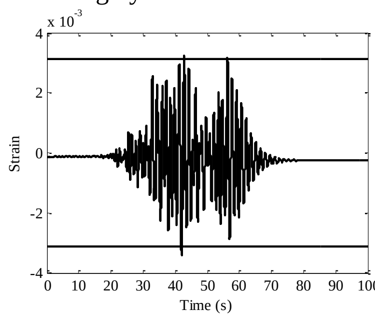
(b) Foundation displacement



(c) Foundation sliding and rocking induced displacements and overlaid with the transverse bridge deck displacements leading by foundation rotation

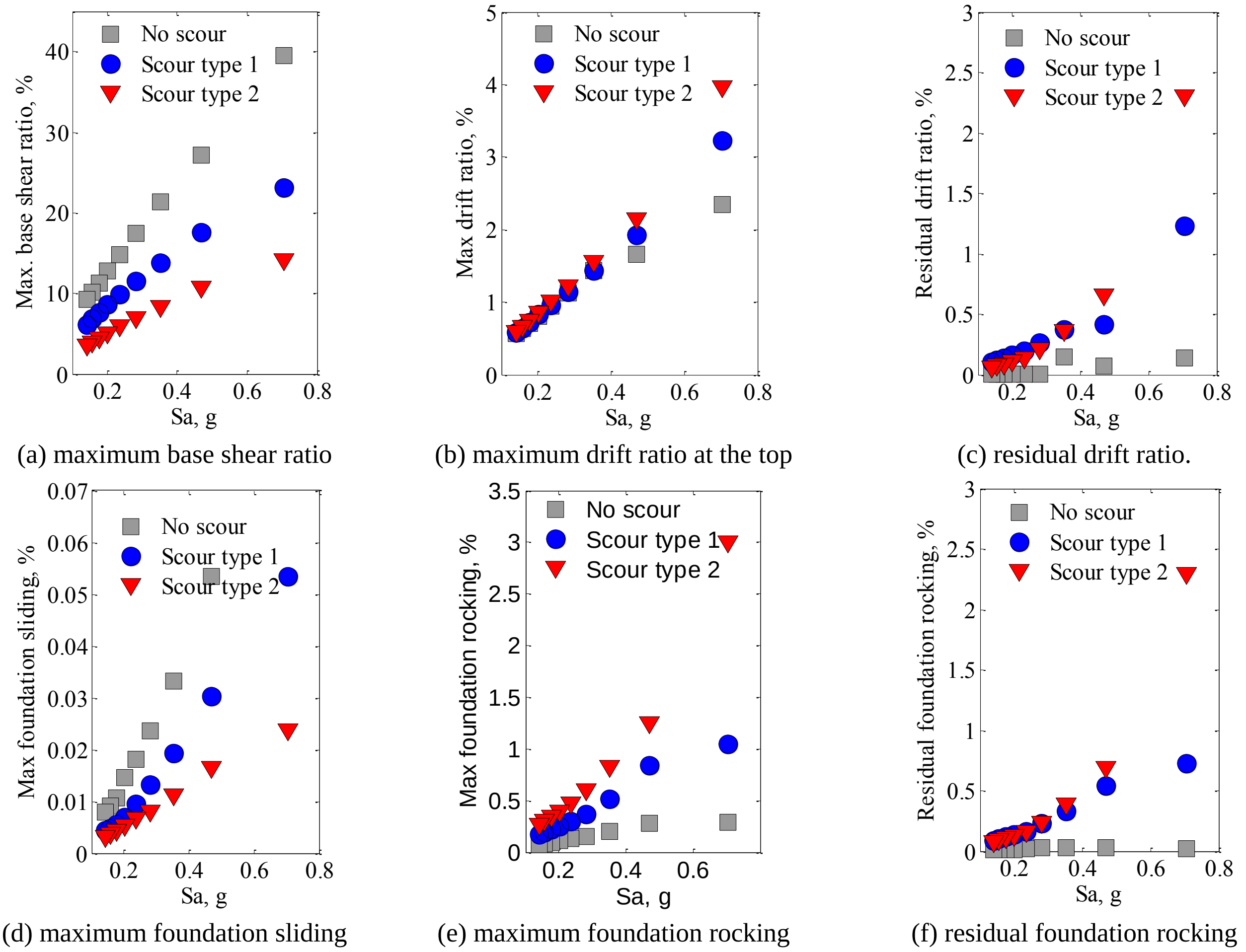


(d) Base shear forces



(e) Strain at the bottom of bridge column

Fig. 7 Comparative NL-MPA and THA analysis results (the horizontal solid lines indicate the NL-MPA based demand values)



(a) maximum base shear ratio (b) maximum drift ratio at the top (c) residual drift ratio.

(d) maximum foundation sliding (e) maximum foundation rocking (f) residual foundation rocking

Fig. 8 Incremental dynamic analysis results at different scour types (No scour; Scour type 1; and Scour type 2)

adopted as an effective approach to seismic demand estimation, especially when a rapid assessment approach is needed to assess the performance of the scoured bridge systems in terms of extracting system-level seismic demands.

In terms of time cost given the ground motion, the THA method spent 149 seconds to finish in a 64-bit/dual-core/48GB-ROM workstation, whereas the NL-MPA takes 58 secs to complete the nonlinear modal pushover at three modes, and about 7 secs to complete the SDOF-based time-history simulations. The time cost reduction is much more significant when performing the latter analysis in the context of statistical sampling based performance analysis (including the IDA method below). Once a bridge model with a selected scour depth is formulated in OpenSees, the one-time modal pushover analysis will provide the baseline nonlinear static response data, which can be used to extract the response demands subject to many ground motions. Suppose that 100 ground motions are used to perform statistical simulation, and using the above numbers as average time cost to estimate the time cost approximately, the THA cost will be 149×100=14,900 secs while the NL-MPA be 58+7×100=758 secs. Therefore, the computational cost using the proposed NL-MPA analysis dramatically improves the computational efficiency of the proposed framework.

7.3 Application of NL-MPA: incremental dynamic analysis

To expose the scour effects on modifying primary seismic response demands and to illustrate the use of NL-MPA presented above, we employed incremental dynamic analysis (IDA) to observe the overall trends influenced by scour. IDA is one of the widely-used approach for assessing the performance of structures, preparing response data for probabilistic fragility analysis, and for investigating the effects of physical parameters. The detailed procedure and formulation is are provided in (Vamvatsikos and Cornell 2002). To explore the effects of foundation-scour on bridges considering SSI more significantly, a less conservative foundation design is considered. With the same soil and the same superstructure, a foundation size of 2 m×2 m×1 m with the originally embedment depth of 2 m is considered. Such configuration, the foundations become more flexible and vulnerable to scour impact.

Further, we define a new set of foundation depth value, in which Scour type 1 has D=1 m, and Scour type 2 has D=0.2 m. The adopted depth values can be viewed as the result of scour depth estimation as shown previously (Section 3). To conduct the NL-MPA simulation, a typical ground motion found in the PEER ground motion database is selected to assess the seismic performance of the parametric foundation-structure system as a function of scour severity. In this study, the ground motion recorded during the Imperial Valley, 1976 (Ms=6.53) earthquake (Station: El Centro Array #5) is used. The spectral acceleration at the fundamental period of the fixed-base system (T1=0.96 sec) is used as the incremental seismic intensity measure (IM), denoted as Sa in the plots. Figs. 7(a)-(f) aggregates the results of this analysis.

The plot of the base shear ratio demands in Fig. 7(a) indicates that when greater scour depth is considered at all scour depth, the force demands are reduced due to stronger SSI effects. However, very high drift ratio demands are observed at large IM values (Fig. 7(b) and (c)). From observing Figs. 7(b) and 6(e), it can be inferred that as scour becomes more severe, excessive foundation rocking demands tend to dominate the total drift demands at the top of the structure. These trends imply that at small to moderate level earthquakes, the presence of foundation scour can reduce the possibility of structural damage. However, as ground motions get more intensive, it is probable that foundation may be much mobilized leading to large peak demands and foundation residual deformation, which may be expensive to be retrofitted. At even more intensive ground motions, the severe foundation scour will contribute to the system collapse, even statically the bridge likely remains stable subject to vertical gravity loads. To explore the effects of scour and earthquakes, fully probabilistic or statistical methods are needed; and the IDA results herein can provide the basis data, such as for conducting fragility analysis. Nonetheless, the deterministic results herein reveal important insights of how foundation scour affects the simple bridge's seismic behavior.

8. Conclusions

In this paper, we provide a comprehensive review of applied techniques used for sourced bridge assessment considering seismic hazards. These techniques include scour estimation, foundation impedance and capacity analysis, foundation modeling, soil-foundation-structure interaction parameter estimation, and more importantly the application of nonlinear modal pushover procedure to a bridge system with scour under seismic attacks. These methods span the knowledge domain of hydraulic engineering, structural engineering, geotechnical and earthquake engineering. In the meantime, it is stated that the proposed methods can serve to construct the basic analysis components to perform probabilistic vulnerability or risk-based analysis for scoured bridge systems. Particularly, the nonlinear modal pushover procedure can be used as a proxy to extract system-level seismic demands (e.g. not only system displacement or structural deformation but also foundation level demands) to realize computationally efficient and comprehensive performance assessment. Last, we expect that this review can facilitate the research community conduct rapid assessment of foundation scour for river-crossing bridges if seismic hazards need to be considered jointly.

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References

AASHTO (2010), AASHTO LRFD Bridge Design Specifications, American Association of State Highway and Transportation Officials.

Alipour, A., Shafei, B. and Shinozuka, M. (2012), "Reliability-based calibration of load and resistance factors for design of RC bridges under multiple extreme events: Scour and earthquake", *J. Bridge Eng.*, **18**(5), 362-371.

Arneson, L.A., Zevenbergen, L.W., Lagasse, P.F. and Clopper, P.E. (2012), *Evaluating Scour at Bridges*, Federal Highway Administration.

ASCE (2016), ASCE/SEI 7 Minimum Design Loads for Buildings and Other Structures, Amer Society of Civil Engineers.

Banerjee, S. and Prasad, G.G. (2011), "Analysis of bridge performance under the combined effect of earthquake and flood-induced scour", *First International Symposium on Uncertainty Modeling and Analysis and Management (ICVRAM 2011); and Fifth International Symposium on Uncertainty Modeling and Anaylsis (ISUMA)*, 889-896.

Biswas, D. (2010), "Development of an iterative scouring procedure for implementation in CFD code for open channel flow under different bridge flooding conditions", Northern Illinois University.

Bolduc, L.C., Gardoni, P. and Briaud, J.L. (2008), "Probability of exceedance estimates for scour depth around bridge piers", *J. Geotech. Geoenviron. Eng.*, **134**(2), 175-184.

Boulanger, R.W. (2011), "Geotechnical effects of the Mw 9.0 Tohoku, Japan, earthquake of March 11, 2011", EERI Special Earthquake Report, September.

Briaud, J.L., Ting, F.C., Chen, H., Gudavalli, R., Perugu, S. and Wei, G. (1999), "SRICOS: Prediction of scour rate in cohesive soils at bridge piers", *J. Geotech. Geoenviron. Eng.*, **125**(4), 237-246.

Briaud, J.L., Brandimarte, L., Wang, J. and D'Odorico, P. (2007), "Probability of scour depth exceedance owing to hydrologic uncertainty", *Georisk*, **1**(2), 77-88.

Briaud, J.L., Chen, H.C., Li, Y. and Nurtjahyo, P. (2004), "SRICOS-EFA method for complex piers in fine-grained soils", *J. Geotech. Geoenviron. Eng.*, **130**, 1180-1191.

Caltrans, S. (2004), "Caltrans seismic design criteria version 1.3.", California Department of Transportation, Sacramento, California.

Chopra, A.K. and Goel, R.K. (2002), "A modal pushover analysis procedure to estimate seismic demands for buildings: Summary and Evaluation", *Proceedings of the Fifth National Conference on Earthquake Engineering*, 26-30.

Cremer, C., Pecker, A. and Davenne, L. (2002), "Modelling of nonlinear dynamic behaviour of a shallow strip foundation with macro-element", *J. Earthq. Eng.*, **6**(2), 175-211.

Das, B.M. (2015), *Principles of Foundation Engineering*, Cengage Learning.

Deng, L. and Cai, C. (2010), "Bridge scour: Prediction, modeling, monitoring, and countermeasures-Review", *Prac. Period. Struct. Des. Constr.*, **15**, 125-134.

Deng, L., Kutter, B. and Kunnath, S. (2011), "Centrifuge modeling of

bridge systems designed for rocking foundations", *J. Geotech. Geoenviron. Eng.*, **1**, 363.
Dong, Y., Frangopol, D.M. and Saydam, D. (2013), "Time-variant sustainability assessment of seismically vulnerable bridges subjected to multiple hazards", *Earthq. Eng. Struct. Dyn.*, **42**(10), 1451-1467.
Dunker, K.F. and Rabbat, B.G. (1995), "Assessing infrastructure deficiencies: the case of highway bridges", *J. Infrastr. Syst.*, **1**(2), 100-119.
Francis, M.J. and Yeh, H. (2006), "Tsunami inundation scour of roadways, bridges and foundations-observations and technical guidance from the Great Sumatra Andaman Tsunami", 2006 EERI / FEMA NEHRP Professional Fellowship Report.
Gajan, S., Hutchinson, T.C., Kutter, B.L., Raychowdhury, P., Ugalde, J.A. and Stewart, J.P. (2008), "Numerical models for analysis and performance-based design of shallow foundations subjected to seismic loading", Pacific Earthquake Engineering Research Center Berkeley, CA.
Gazetas, G. (1991), "Formulas and charts for impedances of surface and embedded foundations", *J. Geotech. Eng.*, **117**(9), 1363-1381.
Ghosn, M., Moses, F. and Wang, J. (2004), "NCHRP report 489: design of highway bridges for extreme events", Transportation Research Board, Washington, DC.
Guo, J., Kerenyi, K. and Pagan-Ortiz, J.E. (2009), "Bridge pressure flow scour for clear water conditions", No. FHWA-HRT-09-041.
Guo, X. and Chen, Z. (2015), "Lifecycle multihazard framework for assessing flood scour and earthquake effects on bridge failure", *ASCE-ASME J. Risk Uncertain. Eng. Syst. Part A: Civil Eng.*, **2**(2), C4015004.
Huang, W., Yang, Q. and Xiao, H. (2009), "CFD modeling of scale effects on turbulence flow and scour around bridge piers", *Comput. Fluid.*, **38**(5), 1050-1058.
Hung, H.H., Liu, K.Y. and Chang, K.C. (2014), "Rocking behavior of bridge piers with spread footings under cyclic loading and earthquake excitation", *Earthq. Struct.*, **7**(6), 1001-1024.
Hunt, B.E. (2009), "Monitoring scour critical bridges", Transportation Research Board.
Jennings, P.C. and Bielak, J. (1973), "Dynamics of building-soil interaction", *Earthq. Eng. Struct. Dyn.*, **63**, 9-48.
Kappos, A., Paraskeva, T. and Sextos, A. (2005), "Modal pushover analysis as a means for the seismic assessment of bridge structures", *Proceedings of the 4th European Workshop the Seismic Behaviour of Irregular and Complex Structures*.
Lee, J., Jeong, S. and Lee, J.K. (2015), "3D analytical method for mat foundations considering coupled soil springs", *Geomech. Eng.*, **8**(6), 845-857.
Mazzoni, S., McKenna, F., Scott, M.H. and Fenves, G.L. (2005), "OpenSees command language manual", Pacific Earthquake Engineering Research (PEER) Center.
Mimura, N., Yasuhara, K., Kawagoe, S., Yokoki, H. and Kazama, S. (2011), "Damage from the Great East Japan Earthquake and Tsunami-a quick report", *Mitig. Adapt. Strateg. Glob. Change*, **16**(7), 803-818.
Muljati, I. and Warnitchai, P. (2004), "A modal pushover analysis on multispan concrete bridges to estimate inelastic seismic responses", *Civil Eng. Dimens.*, **9**(1), 33.
Mylonakis, G. and Gazetas, G. (2000), "Seismic soil-structure interaction: beneficial or detrimental?", *J. Earthq. Eng.*, **4**(3), 277-301.
NCHRP (2016), "Assessing, coding, and marking of highway structures in emergency situations (NCHRP RESEARCH REPORT 833)", National Cooperative Highway Research Program, Washington, DC.
Nezhad, M.E. and Poursha, M. (2015), "Seismic evaluation of vertically irregular building frames with stiffness, strength, combined-stiffness-and-strength and mass irregularities", *Earthq. Struct.*, **9**(2), 353-373.
Paraskeva, T., Kappos, A. and Sextos, A. (2006), "Extension of modal pushover analysis to seismic assessment of bridges", *Earthq. Eng. Struct. Dyn.*, **35**(10), 1269-1293.
Prasad, G.G. and Banerjee, S. (2013), "The impact of flood-induced scour on seismic fragility characteristics of bridges", *J. Earthq. Eng.*, **17**(6), 803-828.
Raychowdhury, P. (2009), "Effect of soil parameter uncertainty on seismic demand of low-rise steel buildings on dense silty sand", *Soil Dyn. Earthq. Eng.*, **29**(10), 1367-1378.
Raychowdhury, P. and Hutchinson, T.C. (2009), "Performance evaluation of a nonlinear Winkler-based shallow foundation model using centrifuge test results", *Earthq. Eng. Struct. Dyn.*, **38**(5), 679-698.
Reyes, J.C. and Chopra, A.K. (2011), "Three-dimensional modal pushover analysis of buildings subjected to two components of ground motion, including its evaluation for tall buildings", *Earthq. Eng. Struct. Dyn.*, **40**(7), 789-806.
Richardson, E.V. and Lagasse, P.F. (1999), *Stream Stability and Scour at Highway Vridges*, ASCE Publications.
Scawthorn, C., Porter, K.A. and Risk, S. (2011), "Aspects of the 11 March 2011 Eastern Japan Earthquake and Tsunami", Reconnaissance Report.
USGS (2011), "National bridge scour database", U.S. Geological Survey.
Vamvatsikos, D. and Cornell, C.A. (2002), "Incremental dynamic analysis", *Earthq. Eng. Struct. Dyn.*, **31**(3), 491-514.
Veletsos, A.S. and Meek, J.W. (1974), "Dynamic behavior of building-foundation systems", *Earthq. Eng. Struct. Dyn.*, **3**(2), 121-138.
Wang, Z., Padgett, J.E. and Dueñas-Osorio, L. (2014), "Risk-consistent calibration of load factors for the design of reinforced concrete bridges under the combined effects of earthquake and scour hazards", *Eng. Struct.*, **79**, 86-95.
Wang, Z., Song, W. and Li, T. (2012), "Combined fragility surface analysis of earthquake and scour hazards for bridge", *Proceedings of 15th World Conference on Earthquake Engineering*, September.
Wu, W.H., Chen, C.C., Shi, W.S. and Huang, C.M. (2017), "Assessment of environmental effects in scour monitoring of a cable-stayed bridge simply based on pier vibration measurements", *Smart Struct. Syst.*, **20**(2), 231-246.
Zhao, Z. and Fernando, H.J.S. (2007), "Numerical simulation of scour around pipelines using an Euler-Euler coupled two-phase model", *Environ. Fluid Mech.*, **7**(2), 121-142.

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