Performance Assessment of Highway Bridges Under Earthquake and Scour Effects

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SUMMARY:
Bridge foundation scour is the most common cause for the failure of highway bridges in Unites States. To make sure that a highway bridge is capable of resisting structural degradation due to scour in addition to other natural hazards, development of a multi-hazard approach is necessary. Towards this goal, the current paper studies the combined effects of scouring and earthquake on the performance of RC bridges. The extent of scour represented by scour depth is estimated and its associated uncertainties are considered. Based on the probability distribution of scour depths obtained from Monte Carlo simulations, risk curves are developed to find the probability of occurrence of scour at the location of bridge. From the nonlinear time-history analysis of bridges, maximum structural responses and ductility ratios are calculated and bridge fragility parameters are estimated for a range of scour depths. The fragility curves developed based on the joint probabilities of scouring and earthquake clearly show that the lateral load bearing capacity of bridge decreases with the increase in the scour depth.

Keywords: seismic performance assessment, scour, failure probability, dynamic response, fragility analysis

1. INTRODUCTION

Bridge scour is the removal of soil around the foundation of bridge due to the flowing water. Bridge scour may happen around the foundation of bridge at pier or abutment and can be identified mainly in three forms: long-term aggradations and degradation which includes long-term changes in the streambed elevation of river caused by erosion and deposition of material, general scour which is due to the removal of material from bed and banks of the channel, and finally local scour which involves the removal of material from around piers and abutments. The current paper focuses on the local scour and studies the effects of that on the seismic performance of reinforced concrete (RC) highway bridges.

In flood situations, it is expected that the scour reaches large depths around the bridge foundation and leads to a dramatic reduction of foundation capacity. Because of significant changes that the bridge scour causes on the foundations of bridge, it is essential to evaluate the remained capacity of bridge after various scour scenarios. According to AASHTO LRFD (2007), scour is not considered as a load effect, but the changes that it may apply to the structural characteristics of bridge can result in a more vulnerable structure against the other extreme loads, such as earthquake. Hence, a multi-hazard approach is developed throughout this paper to consider the combined effects of scouring and earthquake on the structural capacity and performance of RC bridges by taking into account the uncertainties inherent in both events.

The extent of scouring effects on a bridge is usually characterized by the scour depth. There are many equations and models suggested so far to predict the scour depth for different bed conditions. Among all of them, two equations provided by the Federal Highway Administration (FHWA) Hydraulic Engineering Circular No.18 (HEC-18, 2001) are commonly used in the United States. The first equation is for sand and the second one is for clay bed streams and both are based on the model-scale experiments mainly conducted in Colorado State University and University of Texas A&M. Since sand is the most erodible soil type, this paper assumes that the bed stream is from sand and uses the first equation to predict the scour depth.

In order to obtain an accurate prediction of scour depth, it is necessary to consider the relevant uncertainties involved in the model and its parameters. Towards this goal, a probabilistic approach is proposed in the current study to calculate the scour depth through a risk curve. The risk curve here shows the probability of exceeding any specific level of scour depth at the bridge location. Since it has been proved that the deterministic equation of HEC-18 (2001) overestimates the scour depth (Johnson, 1998), the developed risk curve helps to estimate the scour depth more realistically considering most influential uncertainties.

A group of case-study bridges are then modelled and analysed to evaluate the structural response of RC bridges after degradation due to the scouring effects. These bridges are assumed to span a river located in Southern California. The seismic performance of case study bridges are evaluated at the next step using fragility parameters and the effects of local scouring on the response of RC bridges are studied during nonlinear time-history analysis. This provides a multi-hazard framework which can be used predict the probability of occurrence of different seismic damage states for a bridge under the scouring effects.

2. SCOUR DEPTH ESTIMATION CONSIDERING UNCERTAINTIES

The design formula recommended by the Federal Highway Administration Hydraulic Engineering Circular No.18 (2001) is an empirical formula based on a set of experimental tests and evaluates the scour depth deterministically using a number of parameters, such as stream flow discharge rate, streambed condition, and shape of river. This equation can be expressed as below:

$$y_s = 2.0 y K_1 K_2 K_3 K_4 (D/y)^{0.65} F^{0.43} \tag{1}$$

where y_s = scour depth; y = flow depth at directly upstream of bridge pier, excluding local scour; D = bridge pier diameter; K_1 = correction factor for the nose shape of pier; K_2 = coefficient for the angle between the direction of flow and pier; K_3 = coefficient for the streambed condition; K_4 = coefficient for the streambed material size; and F = Froude number. The four correction factors mentioned in Eqn.1 can be obtained from the tables of HEC-18 (2001) and the flow depth and velocity can be calculated using the basic hydraulic equations, given the flow discharge rate, Q, and the shape of waterway at the location of pier. The velocity is defined as the total flow discharge rate divided by the cross-sectional area and the relationship between the velocity and flow depth is expressed by Eqn. 2: using the concept of hydraulic radius:

$$V = \frac{1}{n}\left(\frac{by}{b+2y}\right)^{2/3} S_0^{1/2} \tag{2}$$

where n = Manning roughness coefficient; b = width of waterway; and S_0 = energy slope. From Eqn. 2, the relationship between flow discharge rate and flow depth is given by:

$$Q = \frac{by}{n}\left(\frac{by}{b+2y}\right)^{2/3} S_0^{1/2} \tag{3}$$

For the estimation of bridge scour depth, there are some uncertainties associated with Eqn. 1 and its parameters. Eqn. 1 itself has been derived from a set of model-scale experiments in the sand streambed and cannot precisely represent the other streambed types. According to Johnson (1995), the average ratio of observed scour depth to calculated depth from Eqn.1 is 0.57 for selected ranges of flood depth to pier diameter, y/D. Hence, Eqn. 1 is modified by a model factor, λ_s, assumed to have a normal distribution with the mean of 0.57 and COV of 0.6. The scour depth equation can be updated as below:

$$y_{s,updated} = \lambda_s y_s \tag{4}$$

There are also some uncertainties associated with the parameters of Eqn. 1 that influence the scour depth estimation (NCHRP-450 2003 and Bolduc et al. 2008). For the reliability analysis of bridges under scouring effects, it is necessary to identify the variability of these parameters in terms of their probability distribution functions. As a case in point, the K_3 factor, which represents the effects of streambed condition, can be introduced as a normal distribution with the mean and COV of 1.1 and 0.05, respectively (Johnson, 1996). The Manning toughness coefficient can also be defined as a lognormal distribution with the mean of 0.025 and COV of 0.275 according to HEC-18 (1986).

The scour depth mainly depends on the discharge rate of river. While the other variables in Eqn. 1 are independent of time, the flow discharge rate is a time-dependent variable and it should be determined by the hydraulic engineer of project for the bridge site. The uncertainties associated with this parameter should also be taken into account for the scour depth estimation. As a case in point, the distribution of peak annual flow discharge rate of a river located in the Southern California has been extracted from the USGS website (Fig. 1). This river will be used as a case study throughout this paper.

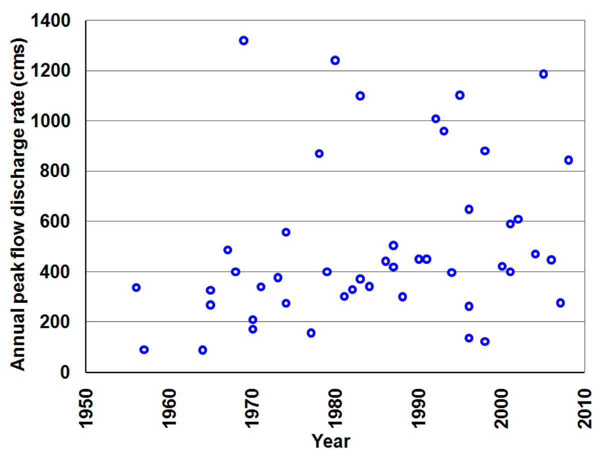


Figure 1. Annual peak flow discharge rate for a river located in the Southern California (from USGS)

In order to find the probability distribution function of the flow discharge rate, different distribution functions, such as normal, lognormal, and extreme event, are examined and their confidence intervals are calculated. The best fit for the available data is found to be the lognormal distribution.

The bed slope, S_0, of the river under study is 2 %. It is assumed here that two bridges with the total length equal to the minimum and maximum width of this river are joining two sides of the river. The bridges are two- and three-span with two circular columns at each bent. To account for the complexity of bridge columns located at the stream flow, the scour depth calculated for a bridge with one column at each bent (basic assumption in Eqn.1) should be multiplied by a factor of 1.2, following recommendations of HEC-18 (2001).

After identifying the variability of parameters that influence the scour depth estimation, two sets of 10,000 Monte Carlo simulations are generated to find the probability of occurrence of different scour depths during a 100-year return period for the two- and three-span bridges. The frequency histograms of these two sets can be seen in Fig. 2. The obtained values from the Monte Carlo simulations for the bridge scour depth show that the 50 % probability of occurrence happens at the depth of 3.20 and 2.90 m for the two- and three-span bridge, respectively. It is evident that the mean value of scour depth for the two-span bridge is higher than the mean value for the three-span bridge. This is due to the fact that the river at the location of the two-span bridge is narrower and assuming a constant flow discharge rate, Q, a higher flow depth, y, is observed at the location of the two-span bridge.

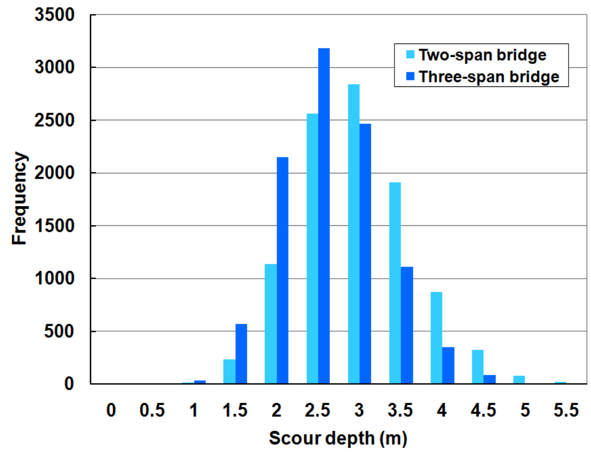


Figure 2. Distribution of scour depths obtained from Monte Carlo simulations

Based on the obtained probability distributions, risk curves are developed as a measure to find the probability of exceeding a specific scour depth level. This can be calculated using Eqn. 5:

$$P(Y \geq y_c) = P(y \geq \frac{y_c - \mu_y}{\sigma_y}) \tag{5}$$

where y_c = specific scour depth; z = standard normal variate; μ_y = mean scour depth; and σ_y = standard deviation of scour depth. The developed risk curves for the two- and three-span bridges are illustrated in Fig.3. As it can be seen from this figure, the probability of exceeding a specific scour depth is always higher for the two-span bridge comparing to the three-span bridge. For example, at a scour depth of 3.0 m, the probability of exceeding is equal to 0.429 for the three-span bridge while this probability increases to 0.624 for the two-span bridge.

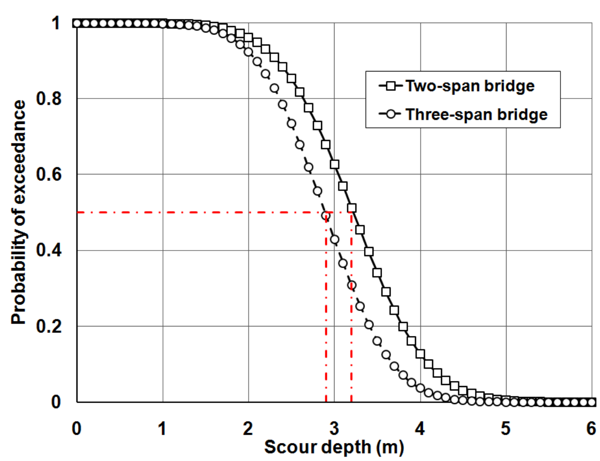


Figure 3. Developed risk curves for the two- and three-span bridges under different scour depths

3. CASE STUDY BRIDGES

Two case study bridges are considered in the current paper. The first bridge is a two-span bridge with the equal span lengths of 30 m. The second set of bridges is a three-span bridge with two spans of 30 m and one middle span of 36 m. The columns of both bridges are identical with the height of 10 m and section diameter of 1.7m. The deck width is 23 m and its cross-sectional area is equal to 12 m^2. The structural analysis of these two bridges has been carried out with the OpenSees software (2009). As an object-oriented finite element software, OpenSees is used here to assess the structural performance of RC bridges under various scour scenarios defined in the earlier sections of this paper. The developed bridge models consist of superstructure elements, columns, abutments, and pile shaft foundations.

(1) Superstructure:
The superstructure is modeled using linear-elastic elements. In the ordinary RC bridges, the columns and abutments are usually expected to experience the inelastic behavior. As a result, the superstructure remains in the elastic range and no nonlinearity is needed to be assigned to superstructure elements. Furthermore, since the concrete superstructure always experiences some cracks due to the loading conditions, the cracked section properties should be calculated. According to the Caltrans seismic design criteria (SDC 2006), the flexural stiffness of concrete box girder superstructures can be modified by a factor of 0.50 to 0.75 in order to reflect the effects of this type of cracking.

(2) Column:
Columns are modeled using inelastic beam-column elements. In these elements, the plasticity has been concentrated over a specified length of element ends and it is used to model the plastic hinge zone of the columns (OpenSees 2009). The column cross section is modeled here using the fiber section module available in OpenSees, while the reinforcing bars of concrete section are modeled in two layers considering the expected steel properties. The stress-strain relationship of confined concrete is developed by using Mander's model to capture the capacity and behavior of bridge columns accurately.

(3) Abutment:
The model for abutment consists of a rigid element with a length equal to the superstructure width, connected to the superstructure centerline through a rigid joint. At the both ends of rigid element, there are three spring components that carry the nonlinear response of the abutment in longitudinal, transverse and vertical directions. In each direction, a zero-length element is assigned with a nonlinear stiffness which is dependent upon the material properties of the abutment backfill. The stiffness and strength of these springs are determined from section 7.8.1 of Caltrans SDC (2006). It should be mentioned that a gap element has also been added to the abutment model in the longitudinal direction, which represents the 5 cm expansion joint in bridges under study.

(4) Foundation:
The foundation system in this study is assumed to be the drilled pile shaft in sand. When scouring happens, the soil around the pile shaft is washed, which results in a significant change in the performance of the bridges under seismic loads. The soil-structure interaction has been modeled here by bi-linear (p-y) springs along the length of shaft, which represent the nonlinear force-deformation relationship of the shaft and soil (Fenves and Ellery 1998). Since the soil at the bridge location is sand, the p-y spring properties given in recommendations of American Petroleum Institute (API 1993) are used here. The p-y relationship can be expressed as Eqn. 6:

$$p(y) = Ap_u \tanh\left[\frac{kx}{Ap_u} y\right] \tag{6}$$

where A = modification factor to account for static and cyclic loading (= 0.9); y = lateral deflection; x = pile depth; k = initial modulus of sub-grade reaction, which is a function of angle of internal friction,

φ', and can be calculated based on the graphs given by API (1993); and p_u = ultimate bearing capacity at depth x, which can be found from Eqn. 7:

$$p_u = \min\left\{\begin{aligned} p_{us} &= (C_1 H + C_2 D_{pile})\gamma x \\ p_{ud} &= C_3 D_{pile}\gamma x \end{aligned}\right\} \tag{7}$$

where C_1, C_2, and C_3 are coefficients determined from the charts given by API (1993); γ = effective soil weight; and D = diameter of the pile. To account for the effects of scouring on the structural performance of bridge, it is assumed that for each case of scouring, the p-y springs located in the range of scour depth are removed from the bridge model and the length of columns increases instead. This can provide a more realistic model of the bridge after scouring and will be used as the upgraded model for seismic analysis.

4. PROBABILISTIC SEISMIC PERFORMANCE ASSESSMENT

In order to assess the seismic performance of RC bridges subjected to the scouring effects, fragility curves are developed in this section by employing the methodology proposed by Shinozuka et al. (2000 and 2003). The fragility curve is defined in the current study as a relationship between ground motion intensity measure (e.g. PGA) and probability of exceeding a specified damage state. The assumed damage states include the state of (at least) slight, E_1, (at least) moderate, E_2, and (at least) extensive damage, E_3, while E_4 represents complete collapse. By indicating the probability that the bridge is in the damage state of E_k when it is subjected to the ground motion intensity of PGA = a_i, the fragility curve can be developed by estimating the probability distribution parameters of Eqn. 8:

$$F_j(a_j; c_j, \zeta_j) = \Phi\left(\frac{\ln(a_j/c_j)}{\zeta_j}\right) \tag{8}$$

where $\Phi(.)$ = standard-normal distribution function; and c_j and ζ_j = median and log-standard deviation of the fragility curves for the damage states of (at least) slight, (at least) moderate, (at least) extensive, and complete collapse, identified by j = 1, 2, 3, and 4, respectively. For the nonlinear dynamic time-history analysis of bridges under study, a suite of 60 ground motion time histories recorded in the Los Angeles area, originally generated for the FEMA/SAC project, are used here. This suite consists of three sets of actual records corresponding to earthquakes with the exceedance probability of 2, 10, and 50 % in 50 years. Using the suite of 60 ground motions, the seismic responses of the bridges under study are evaluated. In order to consider the effects of scouring on the structural performance of bridge, it is assumed that the length of column increases due to the washout of the soil surrounding the columns. This causes the bridge to become more ductile and as a result, larger deformations are expected during an earthquake. In the current study, the seismic responses of the two- and three-span bridges have been obtained for ten scour scenarios ranging from a scour depth of 0.5 to 5.0 m. Fig. 4 shows the time-history of deck drift ratio for the two-span bridge at the first and last scour scenarios. As it can be seen from this figure, the maximum of absolute drift ratios increases from 0.011 to 0.021 when the scour depth changes from 0.5 to 5.0 m.

After finding the maximum drift ratios for all scour scenarios, the corresponding ductility values, μ, are calculated. Now for each ground motion, the probable damage state that the bridge may suffer from is identified by comparing the bridge ductility with ductility limit states. These ductility limit states are defined here as: $1 < \mu < 2$ for (at least) slight damage state, $2 < \mu < 4$ for (at least) moderate damage state, $4 < \mu < 7$ for (at least) extensive damage state, and $\mu > 7$ for complete collapse damage state. A bridge sustains failure in a specific damage state if its ductility becomes larger than the given ductility corresponding to that damage state.

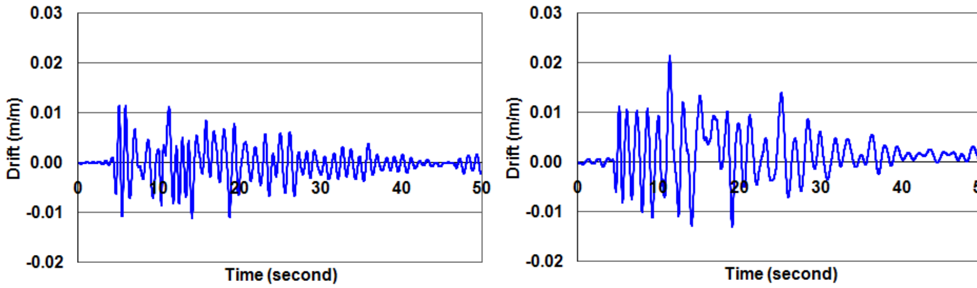
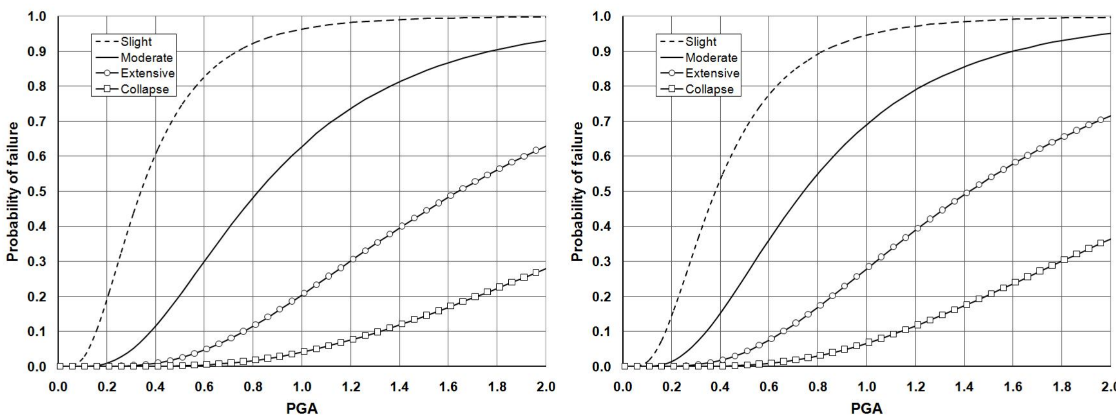


Figure 4. Time-history of deck drift ratio for the two-span bridge at the scour depth of 0.5m (left) and 5.0m (right)

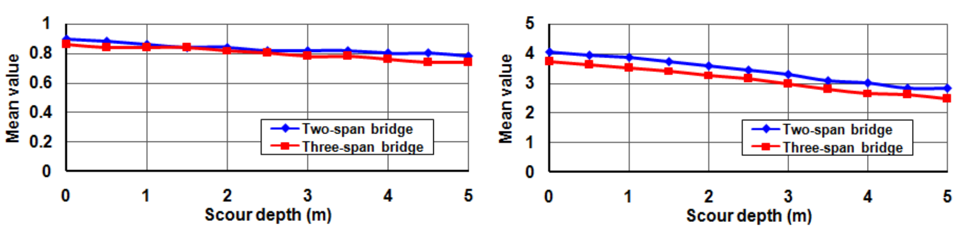
Based on the number of cases in each damage state, the fragility parameters of Eqn. 8 can be estimated in a way that the likelihood function is maximized. From the obtained parameters, the fragility curves can be drawn using the standard normal distribution function of Eqn. 8. As an initial condition, the fragility curves of the two- and three-span bridges without any scouring effects are shown in Fig. 5.



(a) two-span bridge (b) three-span bridge

Figure 5. Developed fragility curves for the case study bridges without any scouring effects

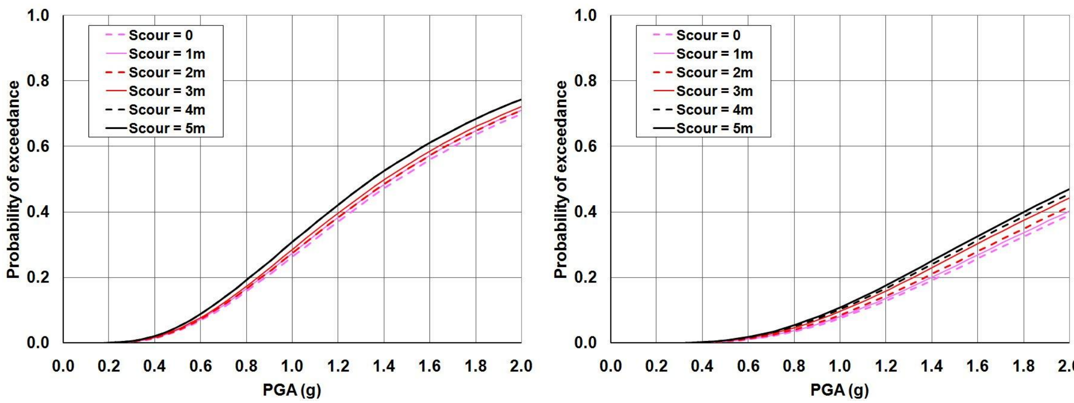
To study the effects of scour depth on the seismic performance of bridges, the two- and three-span bridge models are analyzed assuming different scour depths. Based on the maximum structural responses and ductility ratios, the bridge fragility parameters are estimated for a range of scour depths. The obtained mean values for the fragility curves are shown in Fig. 6 for two damage states. As it can be understood from this figure, there is a decreasing trend for the mean value as the scour depth increases. This trend is especially more evident for the more significant damage states.



(a) at least moderate damage state (b) complete collapse damage state

Figure 6. Change in the mean values of seismic fragility curves by scour depth

It is worth to mention that when scour happens at the pier of a bridge, the effective length of column increases. In other words, the bridge becomes more flexible and less demand is applied to that. This may result in some improvement of seismic response. But on the other hand, the occurrence of scour leads to the removal of the soil around the column and pile shaft. This phenomenon can be taken into account by the removal of p-y springs from the mathematical model of bridge and causes a significant loss in the lateral load bearing capacity of pier. This leads to the overall decrement of the mean value of fragility curves and eventually increases the probability of failure. For further illustration, changes in fragility curves due to the scouring effects are shown in Fig. 7 for the three-span bridge. As this figure shows, when the scour depth increases, the probability of exceeding a specific damage state increases accordingly and the bridge becomes more vulnerable to future seismic events.



(a) at least minor damage state (b) at least moderate damage state

Figure 7. Developed fragility curves for the three-span bridge with different scour depths

5. JOINT PROBABILITY OF FAILURE

In order to ensure the safety of bridges, it is imperative to consider the combined effects of all possible natural hazards. Since the main focus of current study is to evaluate and minimize the seismic risk of scoured bridges, the cascading nature of scour and earthquake should be taken into account. This nature is due to the fact that a bridge substructure which has sustained specific damage from a scour (caused by either flooding or storm) must resist additional loads inflicted by the subsequent earthquake, prior to the bridge authorities being able to make repairs to the initial sustained damage. Hence, the failure risk of a bridge under multi-hazard conditions should be carefully quantified during design procedure to prevent catastrophic life and monetary losses during future extreme events (Alipour et al. 2011). The probability of exceeding the damage state of k, DS_k, for a bridge under the earthquake demand of EQ_j and the scour event of SC_i can be calculated as:

$$(P_f)_{ijk} = P(Failure \mid DS_k, EQ_j, SC_i) \tag{9}$$

During the design life, a bridge may be subjected to a number of extreme events. But it should be noted that since the occurrence probabilities of scour and earthquake events are statistically independent, Eqn. 10 can be formulated as:

$$(P_f)_{ijk} = P(Failure \mid DS_k, EQ_j) P(SC_i) \tag{10}$$

where $P(SC_i)$ is the probability of experiencing the i-th scour scenario which is represented by its scour depth. This probability can be obtained from the scour risk curves developed in Section 2 of this paper. By reviewing a scour risk curve, it can be found that the frequency of occurrence of a specific scour depth has been estimated through the statistical analysis of collected real data from past years. Furthermore, the expected intensity of scour events at the bridge site and its associated uncertainties have been considered in the development procedure of risk curves.

Further to potential scour hazard, the effects of seismic hazard on the scoured bridges should be taken into account. For this purpose, Eqn. 10 can be expressed as:

$$(P_f)_{ijk} = P(Failure \mid DS_k)P(EQ_j)P(SC_i) \tag{11}$$

where $P(EQ_j)$ indicates the probability of occurrence of the j-th earthquake scenario which is defined by an intensity measure, such as peak ground acceleration (PGA). This probability can be estimated from a seismic hazard curve.

The other term in Eqn. 11 is the probability of failure under a specific damage state, DS_k. This probability can be estimated from the seismic fragility curves of the scoured bridges. As it was discussed in Section 4, the fragility curve considers the uncertainties associated with the response of a structural system and provides here the probability of exceeding any defined damage state for a specific bridge under given earthquake and scour demands. Assuming any tolerable state of damage, the fragility curves can be used towards the adjustment of demand on a structural system for design purposes.

During the design life of a bridge, there is only a low probability that several extreme events occur simultaneously and even when the simultaneous events do occur, the chance that all the events are at their highest intensities is very small. To address this fact and evaluate the occurrence probabilities of the scour and earthquake events with different intensities, a matrix of joint probabilities of the two events is developed for a range of intensities. For development of this matrix, the scour risk curves generated in Section 2 have been used. On the other hand, the seismic hazard curve has been obtained from the USGS website for a high seismic region. This hazard depicts the probabilities of exceeding a range of PGA values at the specified region for duration of 75 years. This duration is equal to the expected design life of bridges in the AASHTO LRFD Bridge Design Specifications (2007). Based on the selected combination of scour and earthquake scenarios (i and j, respectively), the associated probability of exceeding the damage state k is extracted from the developed fragility curves. This procedure is repeated for all the hazard scenarios and all the bridge cases. Fig. 8 shows the joint probability of failure of two-span bridges at the moderate and major damage states. The comparison between the obtained probabilities of failure and the code-specified acceptable values can be used towards the estimation of the load modification factors.

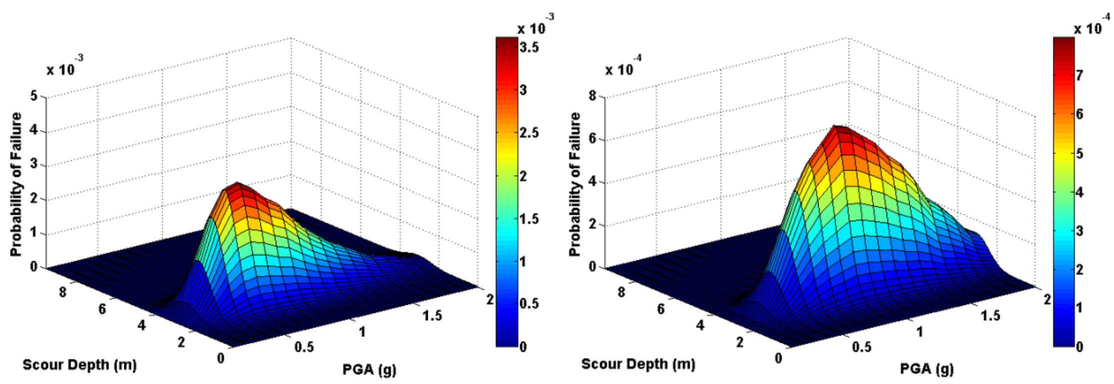


Figure 8. Joint probability of failure of two-span bridges at moderate damage state (left) and major damage state (right)

6. CONCLUSIONS

This paper studies the seismic performance of RC bridges subjected to scouring effects. Towards this goal, the common procedure for the estimation of scour depth is first reviewed and the uncertainties associated with the model and its parameters are discussed. The risk curves are then developed to consider the probability of occurrence of different scour depths at the location of bridge. The effects of scour on the structural performance of RC bridges are studied by selecting two case study bridges with two and three spans. A detailed structural model of these bridges is generated and the seismic response of each has been obtained for a range of probable scour depths. Developed fragility curves for these bridges clearly show that the lateral load bearing capacity decreases with the increase in the scour depth. This makes the bridge more vulnerable to the probable earthquake events and increases the probability of exceeding any specified damage state.

REFERENCES

AASHTO LRFD (2007). Bridge Design Specifications, American Association of State Highway and Transportation Officials, Washington, DC.

Alipour, A., Shafei, B., and Shinozuka, M. (2011). Reliability-based calibration of load factors for LRF Design of reinforced concrete bridges under multiple extreme events: scour and earthquake, *ASCE Journal of Bridge Engineering*, **DOI:** http://dx.doi.org/10.1061/(ASCE)BE.1943-5592.0000369.

API (1993). Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms, 20th Edition, Report No. RP 2A-WSD, American Petroleum Institute, Washington, DC.

Bolduc, L.C., Gardoni, P., and Briaud, J. (2008). Probability of exceedance estimates for scour depth around bridge piers, *ASCE Journal of Geotechnical and Geo-environmental Engineering*, **134: 2**, 175-1184.

FHWA (1995). Evaluating scour at bridges, 4th Edition, Federal Highway Administration (FHWA), Hydraulic Engineering Circular No. 18, U.S. Department of Transportation, Washington, DC.

Fenves, G. L., and Ellery, M. (1998). Behavior and Failure Analysis of a Multiple-Frame Highway Bridge in the 1994 Northridge Earthquake, Report No. PEER98/08, Pacific Earthquake Engineering Research Center (PEER), University of California, Berkeley, CA.

Johnson, P. (1995). Comparison of pier-scour equations using field data, *Journal of Hydraulic Engineering*, **121: 8**, 626-629.

Johnson, P. (1996). Uncertainty of hydraulic parameters, *Journal of Hydraulic Engineering*, **122: 2**, 112-114.

Johnson, P. (1998). Probabilistic bridge scour estimates, *Journal of Hydraulic Engineering*, **124: 7**, 626-629.

NCHRP (2003). Design of Highway Bridges for Extreme Events, Report No. 450, National Corporate Highway Research program, Transportation Research Board, Washington, DC.

Shinozuka, M., Feng, M.Q., Kim, H.K., and Kim, S.H. (2000a). Nonlinear static procedure for fragility curve development, *Journal of Engineering Mechanics*, **126: 12**, 1287-1296.

Shinozuka, M., Feng, M.Q., Lee, J., and Naganuma, T. (2000b). Statistical analysis of fragility curves, *Journal of Engineering Mechanics*, **126: 12**, 1224-1231.

Shinozuka, M., Feng, M.Q., Kim, H., Uzawa, T., and Ueda, T. (2003). Statistical Analysis of Fragility Curves, Report No. MCEER-03-0002, Multidisciplinary Center for Earthquake Engineering Research (MCEER), Buffalo, NY.