Combined fragility surface analysis of earthquake and scour hazards for bridge

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ABSTRACT:
In recent years, bridge collapses due to earthquakes, flood and debris flows, as well as other extreme events have been a major concern of the bridge engineering research and professional community. These extreme events have underscored the need to develop solutions and approaches to reduce the damages/collapses of bridges with acceptable cost. As a result, the probability-based multi-hazard bridge design methodology is considered as one of the thrust research areas in the field of bridge engineering in recent years. This paper presents a combined fragility surface methodology based on system collapse criteria which is established first as the basis for further calculation of system collapse probability. Two code-conforming bridges are used to illustrate the method, where the synergistic responses of the bridge collapse due to combined earthquake and scour hazards are quantitatively analyzed. The preliminary fragility analysis results show that, although the pile foundation design of this bridge is capacity protected, with increasing scour depth, the pile has potential risk of the occurrence of plastic hinge due to the dynamic effect of the large pile cap mass. For these two different bridges, we also found the over-strength factor used to capacity protect of pile foundation had different inherent the inter-relationships of earthquake and scour hazards effect on the combined fragility surface of bridge.

Keywords: highway bridges, Earthquake, Scour

1. INTRODUCTIONS

Highway bridges are key components of transportation network. Past and recent extreme events have demonstrated the vulnerability of highway bridges to hazards such as earthquakes, hurricanes, fire, storm surge, impact load and blast load (Lee et al., 2008). These hazard events have underscored the need to develop solutions and approaches to reduce the damages/collapses of bridges with acceptable cost. Collapse risk evaluation should be considered from the viewpoint of system behavior of a bridge. It helps structural designer to identify continuous load path, critical members or hazards which have a substantial effect on structural reliability and to improve extreme event performance for bridges (Mohammed et al., 2005). For these reasons, the probability-based multi-hazard bridge design methodology is considered as one of the thrust research areas in the field of bridge engineering in recent years.

For most hazards (Earthquake, vessel collision, scour, storm surge etc.), the current some specifications intend to prevent collapse risk of bridges and provide the minimum criteria for protection of life safety. While bridge codes imply there to be a low chance of collapse, the specifications are generally silent on ways to evaluate the collapse risk. Moreover, the target reliability levels for different hazard may not be consistent (Ghosn et al., 2003). Each hazard has its own characteristics, such as probability and frequency of occurrence, and consequences. In addition, extreme hazard events have characteristics of very low-probability, large-uncertainty, and some with large consequences. Therefore, a general probability-based framework is required to explore and establish multi-hazard design principles for bridges. The major challenges are calculation of system collapse probability and a multi-hazard environment and system-level multi-hazard design considering the interrelationship (i.e., consistent and conflicting demands) between the manners that the bridge structural system responds to different hazards. Currently, the progress of establishing a probability-based design for highway bridges considering multi-hazard load effects has been relatively slow and is a complex and challenging task due to a number of reasons including a lack of sufficient information on the characteristics and occurrence of the extreme hazards and the corresponding performances of bridges.

This paper presents a combined fragility surface method based on system collapse criteria which is established first as the basis for further calculation of system collapse probability. Two code-conforming bridges are used to illustrate the method, where the synergistic responses of the bridge collapse due to combined earthquake and scour hazards are quantitatively analyzed. Several key parameters affecting the combined fragility surface of system collapse of bridges due to combined hazards of earthquake and scour are identified.

2. CALCULATE COMBINED FRAGILITY SURFACE OF EARTHQUAKE AND SCOUR

The combined effect of scour and earthquakes has been an important bridge failure mode. The designers are interested in desired life safety over the life-span of the bridge. Although methods for designing bridges to independently consider the earthquake load and scour effects have been established, procedures to account for the bridge system collapse possibility of the combination of these two hazard effects during life-span are not available (Ghosn et al., 2000).

To consider earthquake and scour hazards, we extend the method of system collapse probability for earthquake hazard alone (Luco, 2007, Liel, 2009). Important factors considered include uncertainty in combined hazard demand and structural capacity, nonlinear structural response behavior, redundancy etc. The methodology is for convolving the combined fragility surface of the bridge with the earthquake and scour hazards at a given site to obtain collapse probability. Equation (2.1) shows the coupling of probability distribution for collapse capacity with a corresponding combined (demand) hazard surface for the bridges.

$$\begin{aligned} P_f(Collapse) &= \int_0^\infty H\left[S_a > c, S_c > y\right] dP_f(c, y) \\ &= \int_0^\infty H\left[S_a > c, S_c > y\right] f_{Capacity}(c, y) d_c d_y \end{aligned} \tag{2.1}$$

Where, P_f(collapse) is the annual collapse probability, $H\left[S_a > c, S_c > y\right]$ is the combined earthquake and scour hazard surface, P_f(c,y) is the combined earthquake and scour fragility surface (conditional probability of collapse capacity), $f_{capacity}$(c,y) is the probability density function for collapse capacity, S_a is the PGA of earthquake, S_c is the scour depth.

A combined fragility surface of earthquake and scour depth is a conditional probabilistic statement describing the likelihood that a bridge will meet or exceed a specified level of damage for a given combined hazard intensity measure or combined hazard loading. It represents the ability of a bridge to withstand a combined earthquake and scour depth event. For collapse limit sate of bridge, this conditional probability is given in the following equation.

$$P_f(c, y) = P\left[collapse \mid IM = c, y\right] \tag{2.2}$$

Where, P_f(c,y) is the combined earthquake and scour fragility surface (conditional probability of collapse capacity), *c* and *y* are intensity value of earthquake and scour hazards.

The combined fragility surface can depict the overall bridge vulnerability and relative impact of combined hazards of earthquake and scour on the performance of the bridge system. In this paper, we adopted and extended the system collapse fragility analysis approach which was recently developed for seismic collapse of building structures [ATC 63, 2009, Nielson 2007, and Pan, 2006] to calculate the combined fragility surface of earthquake and scour depth for a bridge at a specific site. A systematic analysis approach of the combined collapse fragility surface (P_f) to integrate relationship

between members, connections and system performance is outlined and shown in the followings:
Step 1: Choose ground motions;
Step 2: Establish the finite element model within the given scour depth;
Step 3: Perform nonlinear dynamic time history analyses;
Step 4: Choose appropriate engineering demand parameters (seismic response);
Step 5: Repeat step 4 with increment in the scale of PGA and build the IDA curve;
Step 6: Repeat step 2 to 5 with different scour depth.
Step 7: Establish the combined fragility surface (P_f) for earthquake and scour depth.

This analysis approach will include the effect of backbone strength deterioration, and cyclic deterioration effects on the global collapse of bridge structural systems. The combined fragility surface indicates the influence of key parameters that related to the system-level performance: minimum seat width and overstrength factors for capacity protection design of foundation etc. on the probability of collapse level. We chose two code-conforming bridges as case study example and compare these results to identify how each parameter and different hazard affects collapse risk.

3. CASE STUDY

3.1 Bridge description

The case study bridges used in this study are two three-span continuous bridge models. One example bridge is a three span continuous concrete box-girder bridge, the schematics of this bridge is shown in figure 3.1. The bridge has two 36.8 m-long exterior spans and one 58 m-long interior spans. The other example bridge used for the case study is a three span continuous steel-girder with concrete-deck, the configuration of bridge consists of a three spans 36-64-36m having the profile shown in figure 3.2.

For demonstration purposes, the bridge is assumed to span over a river that may produce scour around the bridge columns (the analysis only focus on local scour of the pier due to flood). Each bent has two concrete columns. Foundations are concrete friction piles. In the following analysis, pile foundation failure is focused on bending. The pile foundation is assumed not to overtip. Further, the foundation fails by exceeding the bearing capacity is not considered. The bridge is modeled in the Sap2000 utilizing fiber hinge for the columns and performs collapse simulation. To model the soil – foundation interaction, soil springs are assigned to the nodes along the entire length of the pile. The finite element model in the analysis was shown in figure 3.3.

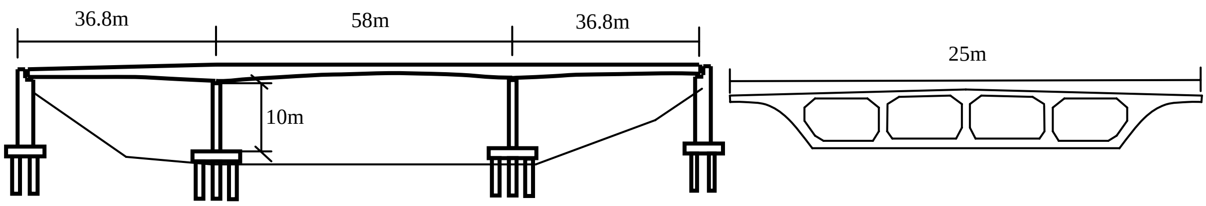


Figure 3.1 Schematic of three span continuous concrete box-girder bridge

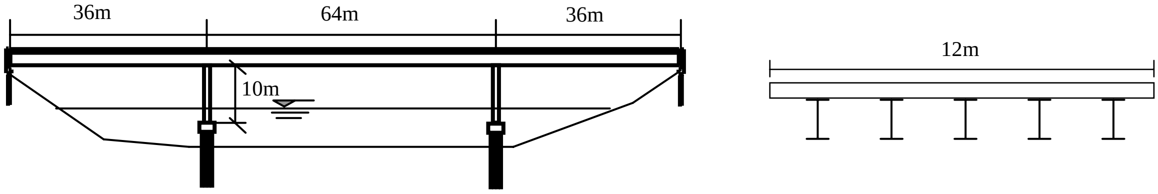


Figure 3.2 Schematic of three span continuous steel-girder with concrete-deck bridge

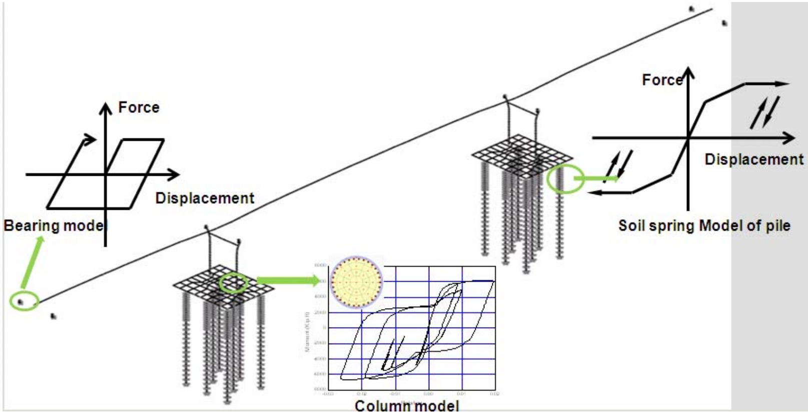


Figure 3.3 The analytical model

3.2 Combined fragility surface of earthquake and scour

The above presenting analysis procedure of the system collapse fragility of combined earthquake and scour hazards can be performed via nonlinear dynamic time-history analyses. The combined fragility surface for the three-span concrete box-girder example bridges at the complete collapse states are illustrated respectively in figures 3.4. The figure 3.4 (a) (b) and (c) show bridge pier fragility surface, pile fragility surface, and bridge system fragility surface under earthquake and scour.

These figures show that, although the pile foundation design of the bridge is capacity protected, when there is no scour, the bridge collapse modes are controlled by ductility failures of the column. With increasing scour depth, the pile also has potential risk of failure due to the dynamic effect of the large pile cap. This means that when the scouring action is combined with earthquake ground motions, the response of the bridge is a synergistic action.

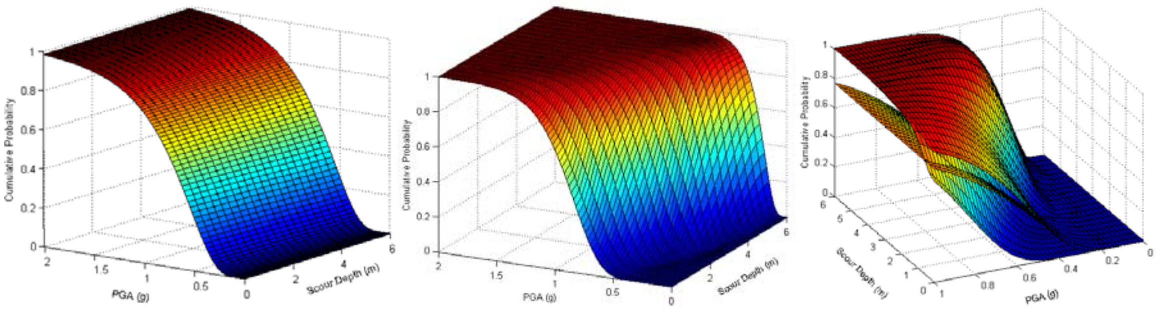


Figure 3.4 Combined fragility surface of continuous concrete box-girder bridge under earthquake and scour

3.3. Effects of design parameters on collapse risk

We found that many of design parameters or requirements can cause significant change in collapse behavior of bridge system, especially with other hazard loads that many inherent the inter-relationships of concurrent hazards effect on collapse behavior for bridge (It should point, the concurrent hazards not only point to presume that a number of hazards will act upon an infrastructure system simultaneously, but also point to the structure that have sustained damage from one event must resist additional loads inflicted by a subsequent event prior to an agency being able to make repairs to the initial damage sustained.).

In seismic design philosophy, ductile detailing is utilized for piers to enhance response, and pile foundation are designed to be capacity protected through the requirement of overstrength factor, i.e. the resistance of a pile foundation in some codes is not less than 1.2 times the maximum force effect imposed on the pile foundation by the inelastic action of the adjacent piers. The figure 3.5 shows the changes of the pile fragility for different overstength factors under combined earthquake and scour hazards.

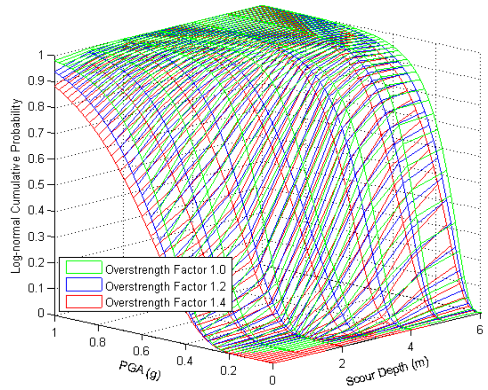
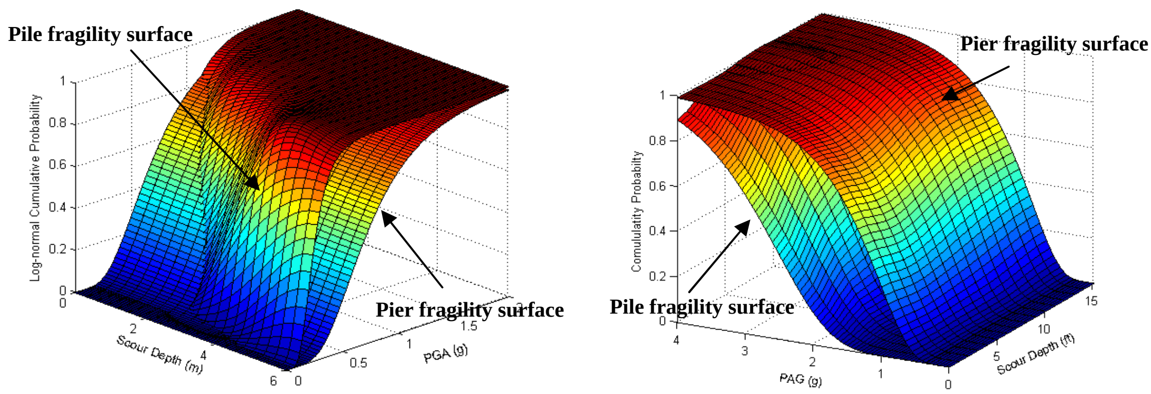


Figure 3.5 Combined fragility surface for different overstrength factors under earthquake and scour hazards

With increasing overstrength factor, pile foundation has lower damage risk, and with different scour depth, this collapse risk is also chaanged.

Look at how different bridge types affect collapse performance. Figure 3.6 (a) and (b) show the combined fragility surfaces of two example bridges respectively under earthquake and scour. For concrete box-girder bridge, when no scour, the bridge collapse modes are controlled by ductility failures of the column. With increasing scour depth, collapse mode changed to controlled by pile. For steel –girder with concrete deck bridges, the bridge collapse modes are controlled mainly by pier.



(a) The concrete box-girder bridge

(b) The steel-girder with concrete-deck bridge

Figure 3.6 Combined fragility surface for different bridges under earthquake and scour hazards

It has been illustrated that various design provisions affect the seismic response and demand of the bridge. Moreover, some factors under different hazards may have either a positive or negative impact on fragility surface of system collapse of bridge. Here, with bridge example, we will identify the effects of capacity protect of foundation factor and different bridge type on collapse risk.

4. CONCLUSIONS

This paper has presented a methodology to developing combined fragility surface for bridge. Two case study bridges, under earthquake and scour hazards were used to exemplify the methodology and recommended implementation details.

The preliminary combined fragility surface analysis result shows that, although the pile foundation design of the bridge is capacity protected, when there is no scour, the bridge collapse modes are controlled by ductility failures of the column. With increasing scour depth, the pile also has potential risk of failure due to the dynamic effect of the large pile cap. With increasing overstrength factor, pile foundation has lower damage risk, and for different scour depth, this collapse risk is also different. To different bridge type, these effects also were changed. This means that when a bridge faces the potential of both scour and earthquake hazards, the design of foundation should account for scour effects.

From the preliminary analysis, the combined fragility surface can be used to identify the some design parameters of interrelationship between the manners that the system responds to concurrent hazards. By identifying different ways/issues the hazards affect the bridge with combined fragility surface, optimizing those issues can result in achieving to improved safety and economic goals.

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