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Impact spectrum of flood hazard on seismic vulnerability of bridges

Taner Yilmaz[1a] and Swagata Banerjee*[2]

[1]Department of Civil Engineering, Ozyegin University, Istanbul, Turkey
[2]Department of Civil Engineering, Indian Institute of Technology Bombay, Powai, Mumbai 400076, India

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Abstract. Multiple hazards (multihazard) conditions may cause significant risk to structures that are originally designed for individual hazard scenarios. Such a multihazard condition arises when an earthquake strikes to a bridge pre-exposed to scour at foundations due to flood events. This study estimates the impact spectrum of flood-induced scour on seismic vulnerability of bridges. Characteristic river-crossing highway bridges are formed based on the information obtained from bridge inventories. These bridges are analyzed under earthquake-only and the abovementioned multihazard conditions, and bridge fragility curves are developed at component and system levels. Research outcome shows that bridges having pile shafts as foundation elements are protected from any additional seismic vulnerability due to the presence of scour. However, occurrence of floods can increase seismic fragility of bridges at lower damage states due to the adverse impact of scour on bridge components at superstructure level. These findings facilitate bridge design under the stated multihazard condition.

Keywords: bridges; earthquake; flood; multihazard; fragility

1. Introduction

The growing recognition of multihazard threat to structures has led the civil engineering profession to explore the combined effect of two or more natural hazards on structures in order to facilitate structural design, analysis, planning, loss assessment, mitigation and maintenance under regional multihazard conditions. Although a single hazard may be significant for designing a structure, multihazard conditions may impose higher risk to structures endangering their safety and serviceability during normal lifespans. Hence, the profession is increasingly concerned about the inadequacy of individual hazard modeling, and interested in multihazard engineering. An example of such advancement is HAZUS-MH (FEMA 2004). Though originally developed for seismic risk assessment of structures, the current version of HAZUS includes guidelines to provide possible estimates of building and infrastructure losses due to earthquakes, floods, and hurricanes.

An ongoing research supported by the Federal Highway Administration (FHWA) in the U.S. envisions to set forth the AASHTO Load and Resistance Factor Design (LRFD) specifications for bridges to a multihazard framework (MH-LRFD) by incorporating fundamental principles and design guidelines for multihazard design of bridges. As part of this project, a nation-wide survey was conducted in the U.S. to identify important extreme load combinations for highway bridges resulting from multiple hazards (Lee *et al*. 2011). Result showed that a majority of state bridge engineers identified scour to be a must-consider condition for the design of US bridges. In fact, a number of recent past studies focusing on the multihazard performance assessment of bridges considered earthquake in the presence of flood-induced scour to be a critical multihazard scenario for bridges located in seismically-active flood-prone regions (Ghosn *et al*. 2003, Han *et al*. 2010, Decò and Frangopol 2011, Banerjee and Prasad 2011, Prasad and Banerjee 2013, Banerjee and Prasad 2013, Alipour *et al*. 2013, Dong *et al*. 2013, Wang *et al*. 2014, Chang *et al*. 2014, Yilmaz 2015, Wang *et al*. 2015, Chandrasekaran and Banerjee 2016, Yilmaz *et al*. 2016, Guo and Chen 2016, Guo *et al*. 2016). It is understood that scour holes may get replenished on their own in live river beds; however, the possibility of occurring an earthquake before the replenishment of scour holes cannot be ignored. Therefore, the question arises whether an extreme event earthquake to a non-scoured bridge or a less intensive earthquake to a bridge with scoured foundation is more critical for design purposes in high seismic regions. The question can be best answered only when the entire spectrum of possible influence of flood-induced scour on seismic vulnerability of bridges is known.

The key conclusion drawn from previous studies on this multihazard issue was that scour can have a variety of effects on seismic vulnerability of bridges depending on various bridge attributes and configurations. It was observed that large-diameter foundations (e.g., extended pile shafts with or without enlarged cross-sections) tend to reduce the impact of flood hazard on seismic vulnerability of bridges (Prasad and Banerjee 2013, Alipour *et al*. 2013, Wang *et al*. 2014, Yilmaz *et al*. 2016). This is because large-diameter foundations are greatly capable of resisting lateral forces such as the one from earthquakes. Depending on the

*Corresponding author, Associate Professor
E-mail: swagata@civil.iitb.ac.in
[a]Assistant Professor
E-mail: taner.yilmaz@ozyegin.edu.tr

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stiffness of such foundations, the loss of lateral support at around bridge piers due to scour has little to insignificant impact on the dynamic behavior of bridges. This conclusion is further supported by a field experiment performed on a real-life bridge with scoured caisson foundation (Chang *et al*. 2014). For bridges on pile foundations, scour may result in lower collapse risk for piers, but higher risk for piles (Wang *et al*. 2014). This is possibly due to the switch of bridge failure mode from pier to pile as scour depth increases. This phenomenon is also evident from an experimental study on seismic behavior of scoured bridge piers supported on pile foundations (Wang *et al*. 2015). Investigated results revealed that the bending moment demand of piles due to seismic activities increased with the depth of scour, whereas the same for piers decreased with scour depth. Yilmaz *et al*. (2016) found that bridge seismic vulnerability may worsen due to the presence of scour if bridges are not designed following appropriate seismic design provisions (i.e., ductile detailing in piers). That study also identified that bridge seismic vulnerability can increase if pile foundations are much below the ground level and scour only results in increased exposed height of piers (i.e., scour does not reach to pile cap, and foundations remain unexposed). On the other side, high-rise pile foundation with pile cap (river bed elevation is much lower than the pile cap level due to scour) is also observed to be detrimental (Han *et al*. 2010). It resulted in reduced overall resistance and higher seismic vulnerability of such foundations. For shallow foundations (modeled with beam-on nonlinear Winkler foundation), Guo and Chen (2016) observed the high potential of bridge scour to increase annual and cumulative probabilities of extensive damage (and collapse) of bridges. This literature, along with Dong *et al*. (2013) and Guo *et al*. (2016), investigated bridge performance at various phases of its lifespan under the same multihazard condition.

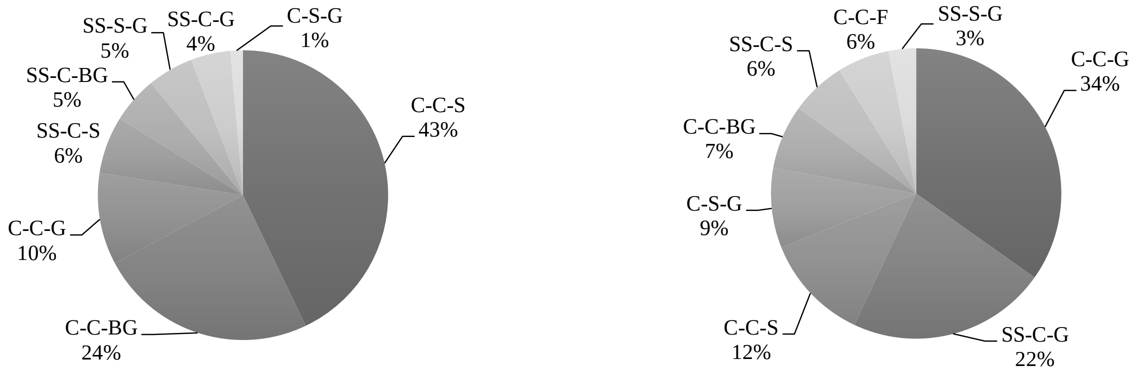
Observations from these previous studies helped in identifying some key bridge features which can control the degree of alteration of bridge dynamic behavior that a flood event may produce. However, none of these previous studies observed any beneficial impact of flood hazard on seismic performance of bridges. An earlier report by Ghosn *et al*. (2003) mentioned that the presence of scour may be beneficial and may improve the reliability of bridges. Hence, research is needed to enhance and expand the existing knowledge on this multihazard issue and to explore the possibility of having beneficial impact of scour on seismic vulnerability of bridges. Such findings will facilitate developing an impact spectrum of flood hazard on bridge seismic performance.

With this objective, the current study investigates the significance of essential bridge design attributes on multihazard performance of bridges. Newly constructed bridges (beyond 1990's) that are most common types in the West Coast of the U.S., particularly in California and Washington states, are considered. Moderate to high flood and seismic activities have been recorded in these two states over the years. A preceding study evaluated the multihazard performance of two real-life California bridges when regional earthquake and flood-induced scour form a multihazard condition (Yilmaz *et al*. 2016). Based on the knowledge gained from this case-specific study and from other previous studies relevant to this topic, the current research is focused on a higher population of bridges in order to capture general bridge design trends and strategies undertaken by bridge officials for specific regions. Through a systematic bridge inventory study for the states of California and Washington in the U.S., generic bridges are formed considering the most common bridge attributes and configurations for these two states. These attributes are in accordance with the current seismic design philosophy and practices, and are selected such that scour does not impose significant threats to seismic vulnerability of bridges. Such consideration helps to identify scenarios in which scour may result in improved seismic vulnerability of bridge components. Extended pile shafts are used for all generic bridges; these types of foundation are observed to perform better than traditional pile foundations for bridges under the stated multihazard condition. Pile shafts are increasingly being constructed in seismically active regions. Besides the high lateral capacity, advantage of using such foundations is due to the ease of construction in wet conditions, especially when there is space and time restrictions for bridge replacement projects. In addition to the investigation of collapse risk of bridges, the current research estimates damage probabilities of bridges at component and system levels for all seismic performance levels. This is indeed important to adequately address performance objectives with respect to multihazard bridge design at service, strength and extreme event limit states. The comprehensive discussion, as presented later in this article, on impact spectrum of flood hazard on seismic vulnerability of bridges provides a platform to make decisions on bridge design when the combined impact of two major natural threats, flood and earthquake, is of concern to the engineering community. This is a unique attribute of this article.

2. Bridge models

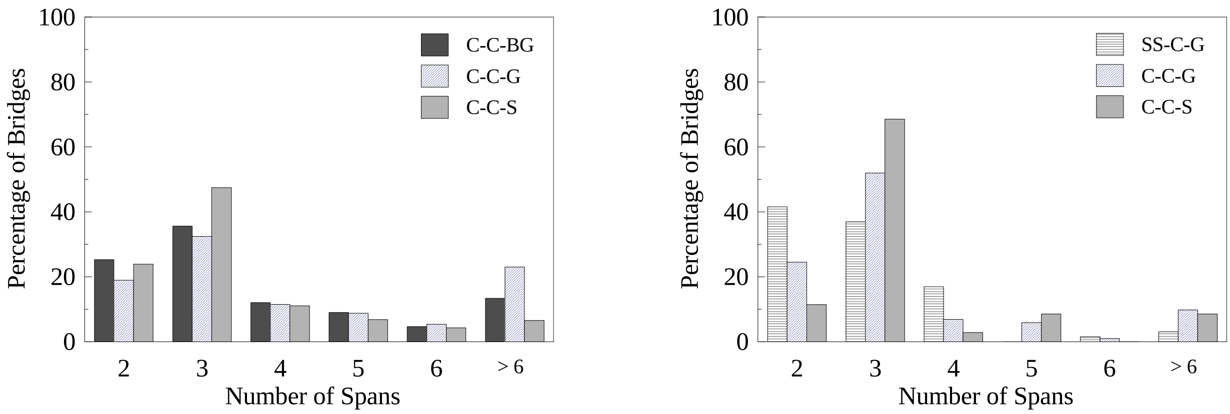
2.1 Bridge inventory in the west coast of the U.S.

The National Bridge Inventory (NBI) of U.S. (NBI 2014) is reviewed in detail to identify the general characteristics of river-crossing highway bridges in California and Washington states. The inventory data is filtered with respect to certain NBI information that are most relevant to the focus of this research. Bridges are considered if they are over waterways, serve for highway or highway-pedestrian and are either open without any traffic restriction or new structure not yet open to traffic and have multiple spans. Similarly, bridges are ignored if designated as tunnels or culverts, made of woods, masonry, aluminum, and other type of material, or have single spans. Following this, 7680 (among 29455 in total) bridges in California and 1765 (among 7902 in total) bridges in Washington state conformed to these selection criteria and are used in this study for further down selection. Ramanathan (2012) performed a general inventory study for California bridges, and generated bridge classes to investigate their seismic fragilities. Three bridge design eras were considered in that study - "Pre-1971", "1971-1990", and "Post-1990". Based



(a) California bridges (b) Washington bridges

Fig. 1 Bridge classes from bridge inventory
Abbreviations for the bridge types: the first letter is for superstructure - continuous (C) or simply-supported (SS), the second letter is for concrete (C) or steel (S) girder, and the third letter is for type of bridge girder - girder (G), slab (S), box-girder (BG), or frame (F)



(a) California bridges (b) Washington bridges

Fig. 2 Percentage of bridges with respect to the number of spans

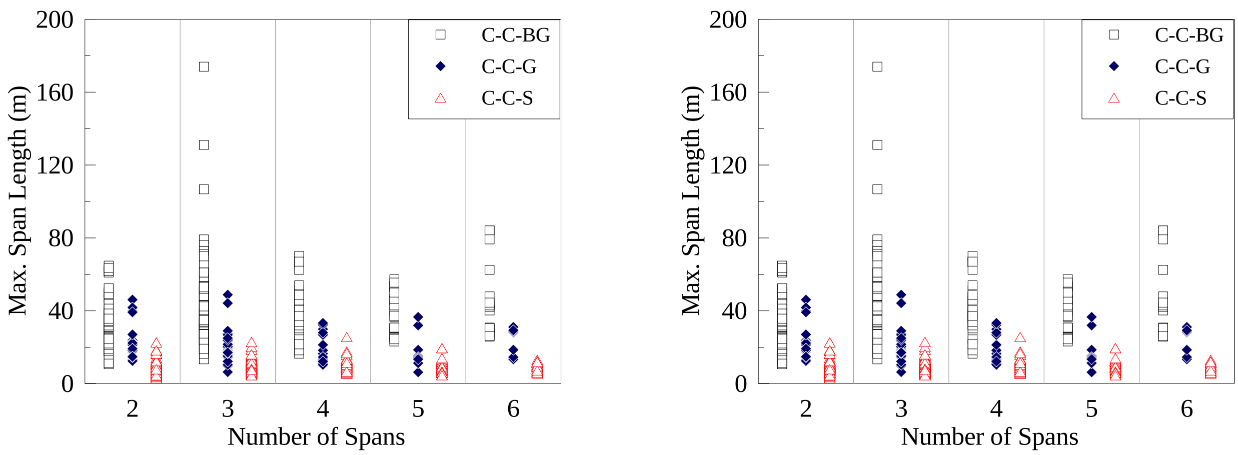
on this classification, "Post-1990" bridges that are designed following the recent developments in seismic design practice for highway bridges are examined in the current study. This down selection resulted in 1474 and 310 bridges under the category of "Post-1990" bridges for California and Washington, respectively. Further investigation shows that continuous concrete box-girder (C-C-BG), continuous concrete girder (C-C-G) and continuous concrete slab (C-C-S) are three most common types of river-crossing bridges in California. In Washington, continuous concrete girder (C-C-G), continuous concrete slab (C-C-S) and simply-supported concrete girder (SS-C-G) are most common types of bridges. Particular statistics are shown in Fig. 1. Note that the present article considered prestressed concrete and concrete bridges together within a common material group "concrete". With respect to the number of spans, Fig. 2 presents histograms of the most common bridge types in California and Washington. These histograms show that bridges having 3 spans are the most common type in the bridge inventories for all types of bridges.

Distribution of maximum span lengths of the three most common bridge types in California and Washington are shown in Fig. 3. As can be observed, slab type of superstructures (i.e., C-C-S bridges) are generally used in bridges with relatively short span lengths compared to other types of superstructures. In recent years, bridge engineering practice is moving away from this type of bridges due to the available practical and economic alternatives such as prestressed (including post-tensioned) girders. With prestressed girders, it is becoming possible to have fewer number of spans for the same overall length of bridges. Average maximum span lengths are found to be 38.2 m, 19.7 m, and 9.9 m, respectively, for C-C-BG, C-C-G, and C-C-S bridges in California. The same are 23.6 m, 34.4 m, and 12.3 m, respectively, for SS-C-G, C-C-G, and C-C-S bridges in Washington.

Fig. 4 shows the variation of deck widths for the most common bridge types in California and Washington. Average deck widths are found to be 18.7 m, 24.6 m, and 17.1 m, respectively, for C-C-BG, C-C-G, and C-C-S bridges in California. The same are 10.5 m, 12.9 m, and 17.2 m, respectively, for SS-C-G, C-C-G, and C-C-S bridges in Washington.

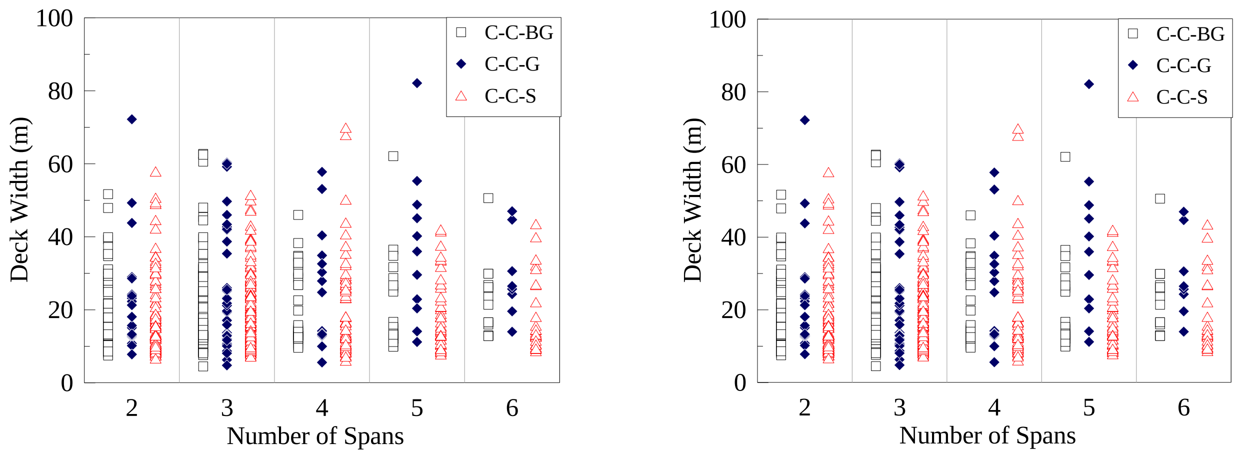
2.2 Characteristics bridges

Based on the knowledge gathered from bridge inventories, characteristics bridges are formed. Hence, these



(a) California bridges (b) Washington bridges

Fig. 3 Maximum span lengths of bridges



(a) California bridges (b) Washington bridges

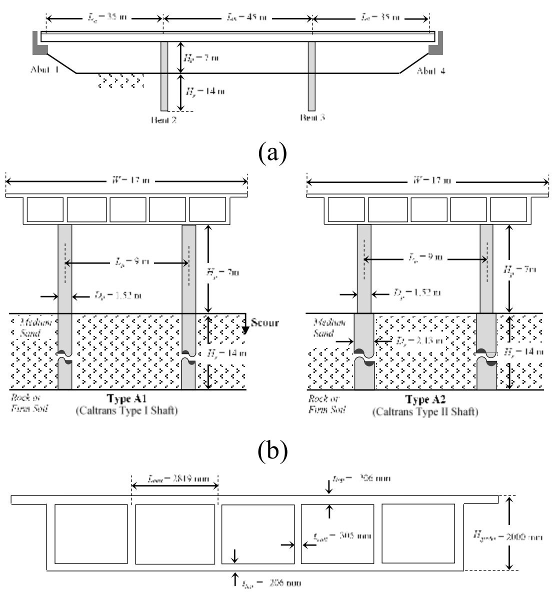
Fig. 4 Deck width of bridges

bridges reflect the state-of-the-art practice of bridge design and construction. Among the four major bridge classes (i.e., C-C-BG, C-C-G, C-C-S, and SS-C-G) observed for the two states, continuous concrete box-girder (C-C-BG) bridge and continuous concrete I-girder (C-C-G) bridge (henceforth referred to as Type A and Type B bridge, respectively) are considered to pursue this study. Continuous girders are given priorities over simply supported (SS) girders as continuous girders are economic and redundant. However, continuous concrete slab (C-C-S) bridges are not considered since these are generally constructed for short span bridges. As observed from Fig. 3, the upper limit of maximum span length for this bridge type is observed to be in the range of 20 m, which may not be an economic choice for highway bridges having multiple spans.

Characteristic bridges are considered to be straight and regular (no skewness, curves or other irregularities). Schematic drawings of these bridges are shown in Figs. 5 and 6. These three-span bridges (the most common span number of spans in the bridge inventories) have maximum span length of 45 m and 30 m at the middle for bridge Type A and B, respectively. The span lengths are also selected in accordance with the ranges observed from the bridge inventory study (Fig. 3). Length of exterior (or end) spans is decided such that adjacent interior span (i.e., the middle span) is approximately 1.3 times longer than exterior spans. This is a usual practice in order to avoid the uplift of exterior spans (in case of short span length) at the abutment locations.

Both bridges have a deck width of 17 m to accommodate three driving lanes. Dimensions of the box-girder for Type A bridges are decided following the findings of Ramanathan (2012) and the recommendations given by the California Department of Transportation (Caltrans 2008). The superstructure of Type B bridges is composed of 7 I-girders (Caltrans standard I-girders) with 2.586 m center-to-center spacing and a deck slab of thickness equal to 200 mm (based on Ramanathan 2012). All bridges have seat-type abutments with steel-reinforced elastomeric bearings. These seat-type abutments have 5 cm expansion gaps between the girder and abutment backwall at both ends of bridges. The cap beam connecting pier shafts of Type B bridges is assumed to have relatively high stiffness compared to piers so that the deformation due to the flexibility of the cap beam is neglected.

To capture the possible influence of large-diameter foundations on multihazard performance of bridges, Type A and B bridges are further divided in subcategories based on

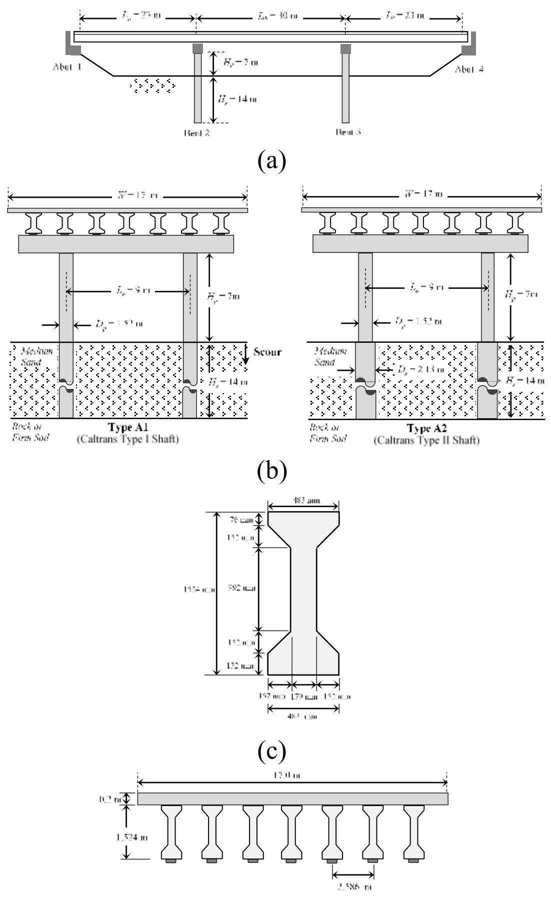


(a) (b) (c)

Fig. 5 Schematics of Type A1 and Type A2 bridges; (a) elevation, (b) substructures, and (c) cross-section of box-girder

two foundation alternatives; (i) A1 and B1 - extended pier-shaft with constant diameter (Type I shaft; Caltrans 2013) and (ii) A2 and B2 - extended pier-shaft with enlarged diameter (Type II shaft; Caltrans 2013). Diameters of Type I and Type II shafts are taken to be equal to 1.52 m and 2.13 m, respectively. These values are decided based on the dimensions of a real-life bridge in California (Yilmaz *et al*. 2016). For both foundation alternatives, the diameter of the piers (the sections above ground) is 1.52 m. All shafts are designed as ductile members according to Caltrans recommendations (Caltrans 2013). As per the performance-based seismic design philosophy, these members are designed to have inelastic deformation for several cycles without significant strength or stiffness degradation under design seismic loading. For Type II shafts, capacity design concept is adopted and necessary reinforcements are provided in the enlarged cross-sections of the piers. Expected compressive strength of concrete for substructure elements (pier-shafts), box-girder, I-girders, and deck slab of continuous concrete I-girder bridge is taken to be equal to, respectively, 32.5 MPa (design strength of 25 MPa), 40.3 MPa (design strength of 31 MPa), 53.8 MPa (design strength of 41 MPa), and 35.9 MPa (design strength of 27 MPa). Expected yield strength of reinforcing steel bars (Grade 60 reinforcement) is taken as 475 MPa. Longitudinal reinforcement ratios in pier-shafts with diameters equal to 1.52 m and 2.13 m are 2% and 1%, respectively. Pier-shafts are assumed to be well confined with transverse reinforcements to satisfy the minimum criterion for the plastic hinge regions of bridge piers.

A uniform soil profile of medium sand is assumed for all bridges down to a depth at which pile shafts are accepted to be fixed to a firm soil or rock socket. Typical peak friction angle of 35° and wet unit weight of soil of 1.9 t/m^3 are taken for medium sand.

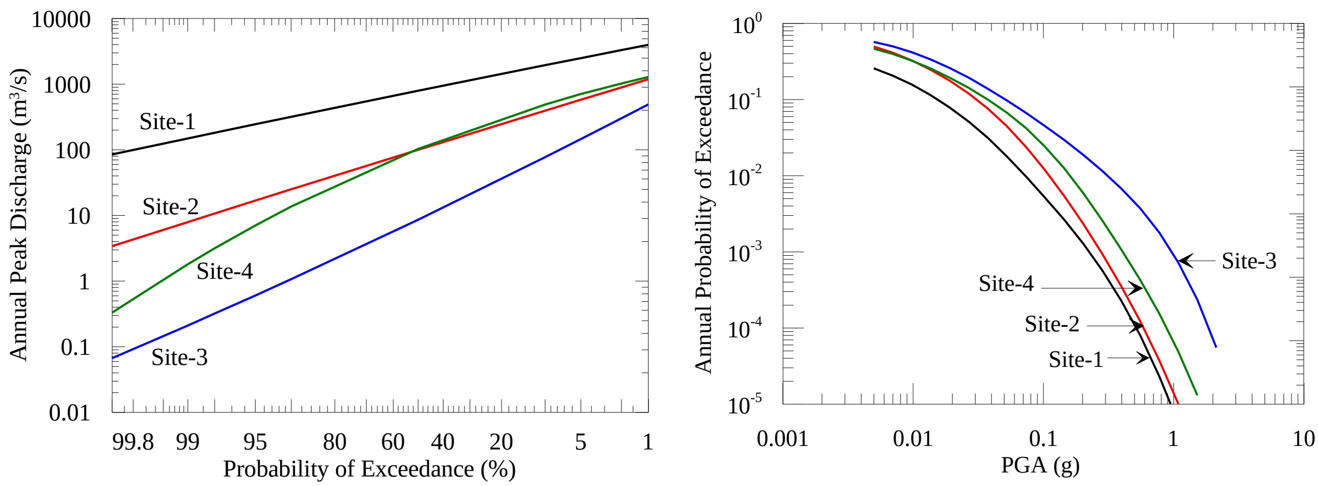


(a) (b) (c) (d)

Fig. 6 Schematics of Type B1 and Type B2 bridges; (a) elevation, (b) substructures, (c) cross-section of I-girder, and (d) superstructure

3. Hazard matrix

The bridges are considered to be located at four different sites. Seismic and flood hazards of these locations are listed in Table 1 and mean hazard curves are shown in Fig. 7. Flood-frequency analysis is performed using the streamflow data from USGS (2015) to develop mean flood hazard curves at bridge sites. Readers are referred to Yilmaz (2015) and Yilmaz *et al*. (2016) for further details on the development of mean flood hazard curves. Mean seismic hazard curves for the same sites are obtained from USGS (USGS 2008). Peak discharge of a 100-year flood and PGA (peak ground acceleration) of a 1000-year earthquake are listed in Table 1 to show the comparison of hazard intensities at different sites. These intensities are combined such that chosen bridge sites statistically represent moderate to high seismic and flood hazard levels of seismically-active, flood-prone regions. For an instance, the peak-discharge of a 100-year flood is the highest at Site 1, whereas the seismic hazard of this site is equivalent to that of Site 2. Similarly, Site 3 is the highest seismically active region among all four sites, though in seismically-active, flood-prone regions. Hence, the discussion on whether any real-life bridge exists at these locations is not directly applicable to the current research.



(a) Mean flood hazard curves (b) Mean seismic hazard curves

Fig. 7 Hazard curves at study locations

Table 1 Hazard intensities at bridge sites

Site	100-year flood discharge (m^3/s)	1000-year earthquake PGA (g)
Site-1	3949	0.24
Site-2	1181	0.28
Site-3	491	1.01
Site-4	1272	0.42

Table 2 Mean scour depths (in m) under 100-year flood event

Bridge type	Site-1	Site-2	Site-3	Site-4
Type A	4.29	3.18	2.56	3.24
Type B	4.71	3.51	2.83	3.58

Mean scour depths at the foundation of Type A and Type B bridges are estimated for flood event with 1% annual exceedance probabilities (corresponding to 100-year flood) and given in Table 2. The Federal Highway Administration (FHWA) specifies this flood event to be the design flood for bridges, unless the region is flood-critical for which higher intensity flood events such as 200-year flood should be considered. The scour depths are estimated following HEC-18 (Arneson *et al*. 2012) with a consideration of mean scour modeling factor of 0.93 (Johnson and Dock 1998). River bed slope and Manning's coefficient are assumed to be 0.0015 and 0.025, respectively. For the chosen bridges, no variation in river bed elevation and flow is considered at bridge pier locations; hence, equal scour depths at piers are considered.

For each site, separate sets of ground motion records are acquired for seismic fragility analysis of the generic bridges. For this purpose, corrected and filtered historic ground motion time histories recorded in close proximity to the study sites are obtained from the Next Generation Attenuation (NGA) database of the Pacific Earthquake Engineering Research Center (PEER 2015). Final datasets of ground motions for Site-1, Site-2, Site-3, and Site-4 are composed of 99, 101, 108, and 96 earthquake records, respectively.

4. Seismic vulnerability analysis

4.1 Bridge modeling

Three dimensional finite element (FE) models of the characteristic bridges are developed and analyzed in FE analysis platform OpenSees (McKenna and Fenves 2012). The impact of flood hazard on bridge seismic vulnerability is assessed by comparing seismic performance of bridges at no scour (i.e., only seismic) and scoured (i.e., multihazard with 100-year flood) conditions. Based on the authors experience and observations from previous studies, bridge seismic performance for a more-frequent flood event (with return period < 100 year) remains within the envelope of that obtained for no flood and 100-year flood conditions.

The box girder in Type A bridges and the composite superstructure (I-girders and concrete deck) in Type B bridges are expected to stay elastic during earthquakes. Thus, the superstructures of these bridges are modeled with linear elastic beam-column elements that have the lumped equivalent mass and stiffness properties of superstructures. Displacement-based fiber elements are utilized to model the piers (including extended shafts), which are expected to response in inelastic range. In OpenSees, uniaxial material models Concrete07 and Steel02 are considered for concrete and longitudinal reinforcing bars, respectively. Mander's concrete model (Mander *et al.* 1988) is applied for the stress-strain relations of both unconfined and confined concrete in pier cross-sections. Modeling of fiber elements is validated through the comparison of numerical and experimental responses of same test columns as detailed in Yilmaz (2015). The uniaxial material pySimple1 in OpenSees is utilized for the p-y springs. Properties of these springs are calculated following the guidelines of the American Petroleum Institute (API 2003). At shaft bottoms, full fixity condition is considered as pile shafts are expected to be fixed at their bottoms to a firm soil.

Modeling of seat-type abutments includes abutment response in the longitudinal and transverse directions, response of elastomeric bearings and exterior shear keys. During seismic excitations, passive resistance at abutment

Table 3 Modal periods (in sec) of Type A bridges

Flood condition	Study site	Max. pier scour	Bridge A1			Bridge A2		
			Long.	Trans.	Tor.	Long.	Trans.	Tor.
No flood	all	-	0.774	0.539	0.344	0.657	0.484	0.337
100-year flood	Site-1	4.29 m	1.054	0.639	0.356	0.873	0.582	0.351
	Site-2	3.18 m	0.983	0.617	0.354	0.821	0.561	0.348
	Site-3	2.56 m	0.942	0.604	0.352	0.790	0.548	0.346
	Site-4	3.24 m	0.987	0.619	0.354	0.824	0.562	0.348

Table 4 Modal periods (in sec) of Type B bridges

Flood condition	Study site	Max. pier scour	Bridge B1			Bridge B2		
			Long.	Trans.	Tor.	Long.	Trans.	Tor.
No flood	all	-	0.925	0.422	0.285	0.852	0.397	0.281
100-year flood	Site-1	4.71 m	1.018	0.481	0.294	0.920	0.450	0.290
	Site-2	3.51 m	0.997	0.467	0.292	0.904	0.438	0.288
	Site-3	2.83 m	0.985	0.459	0.291	0.894	0.430	0.287
	Site-4	3.58 m	0.997	0.468	0.292	0.905	0.438	0.288

Longitudinal Transverse Torsional Longitudinal Transverse Torsional

(a) Type A bridges (b) Type B bridges

Fig. 8 Fundamental mode shapes of bridges at no flood condition

backwall mobilizes in the longitudinal direction when the gap between bridge superstructure and backwall is closed. This response is modeled with elastoplastic elements having a gap property. The backbone curve of the passive resistance is derived based on Caltrans (2013) recommendations. In the transverse direction, abutment response is represented with elastoplastic elements (Aviram *et al*. 2008). Lateral seismic response of elastomeric bearings is modeled with nonlinear elements assigned in two horizontal directions. These elements have elastic-perfectly plastic hysteretic backbone curves characterized with initial stiffness equal to the shear stiffness of elastomer and yield force equal to the frictional resistance developed between concrete surface and elastomer. Shear modulus of elastomer and interface friction between concrete and elastomer coefficient are taken as G = 107.8 MPa (Caltrans 2000) and μ = 0.40 (Caltrans 2013), respectively. Vertical deformation and rotation of bridge girders about the global transverse axis of bridges are modeled with linear elements.

During earthquakes, displacement of bridge girders in the transverse direction is restricted with exterior shear keys. Abutment shear keys are characterized with nonlinear force-deformation relation on the basis of hysteretic model proposed by Megally *et al*. (2002). The post-yield stiffness value of the utilized backbone curve of these elements is assumed to be 2.5% of the initial stiffness (Aviram *et al*. 2008). The yield capacity of abutment shear keys is accepted to be α times the superstructure weight, where α varies between 0.5 and 1.0 (Caltrans 2013). α is taken to be equal to 0.5 and 1.0 for Type A and Type B bridges, respectively. Further details on the modeling of bridge components and model validation can be found in Yilmaz *et al*. (2016).

4.2 Modal analysis

Fundamental modal periods and mode shapes of the bridges are obtained from modal analysis. Tables 3 and 4 list three fundamental modal periods of Type A and Type B bridges, respectively, under no scour and scoured (100-year flood) conditions. These mode shapes are shown in Fig. 8. Bridges with Type II foundations are stiffer than the bridges with Type I foundations because of the increased diameter of pile shafts, and hence observed to have lower time periods. Note that the modal periods of a bridge at scoured condition changes between sites because of the change in flood discharge at different sites. As expected, modal periods, especially in the longitudinal and transverse directions, are observed to increase in the presence of scour for both Type A and Type B bridges. However, no distinct change is observed in their mode shapes. The three fundamental mode shapes of Type A and Type B bridges remain almost unaltered with the change in shaft type (I and II) and flood condition (no and 100-year floods).

Table 5 Threshold limits of critical bridge components

Damage states / Components		Minor	Moderate	Major	Collapse	Reference
Piers and shafts (flexural damage)		$1.0 \le \mu_\varphi < 4.0$	$4.0 \le \mu_\varphi < 8.0$	$8.0 \le \mu_\varphi < 12.0$	$12.0 \le \mu_\varphi$	Ramanathan (2012)
Abutment (long. def. in passive dir., mm)	Type A bridges	$35 \le \Delta_{long,p} < 104$	$104 \le \Delta_{long,p}$	-	-	Shamsabadi *et al.* (2007), Aviram *et al*. (2008), Caltrans (2013)
	Type B bridges	$29 \le \Delta_{long,p} < 88$	$88 \le \Delta_{long,p}$	-	-	
Abutment (trans. def. in mm)		$50 \le \Delta_{trans} < 150$	$150 \le \Delta_{trans}$	-	-	
Shear key (trans. def. in mm)		$15 \le \Delta_{sk} < 150$	$150 \le \Delta_{sk}$	-	-	Megally *et al*. (2002)
Bearings (long. def. in mm)		$40 \le \Delta_{b,long} < 86$	$86 \le \Delta_{b,long} < 310$	$310 \le \Delta_{b,long} < 533$	$533 \le \Delta_{b,long}$	**
Bearings (trans. def. in mm)		$40 \le \Delta_{b,trans} < 86$	$86 \le \Delta_{b,trans}$	-	-	

** Threshold limit for minor damage is based on engineering judgment. Collapse state is assumed as the deformation at which bridge deck falls off from the bearing. The minimum abutment seat width recommended in Caltrans (2013) is considered.

4.3 Fragility curves

Seismic fragility analyses are carried out considering the existence of scour at bridge foundations. In both scour conditions (with and without scour) nonlinear time history analyses of the characteristic bridges are performed at each study location under the selected sets of ground motions for each site. Hence, fragility analysis is performed for a total of 32 combinations including 4 bridges, 4 sites and 2 scour cases. In general, fragility curves are developed for four damage levels, namely minor, moderate, major damage and collapse state. Based on the observations from Yilmaz *et al.* (2016), the focused failure modes of the bridges are due to the flexural damage of pier-shaft, bearing damage (including abutment seat width failure), abutment damage, and shear key damage. Accordingly, curvature ductility of pier-shaft (μ_φ), bearing deformation in the longitudinal and transverse directions ($\Delta_{b,long}$ and $\Delta_{b,trans}$), abutment passive deformation in the longitudinal direction ($\Delta_{long,p}$) and in the transverse direction (Δ_{trans}), and the transverse deformation of shear keys (Δ_{sk}) are taken to be the engineering demand parameters (EDPs) for the performance assessment of critical bridge components with the aforementioned failure modes. Damage states of these components are determined by comparing their numerical response with pre-defined threshold limits corresponding to each seismic damage state. These threshold limits for each failure mode of critical bridge components are set according to the recommendations from Caltrans and/or previous studies (see Table 5).

For a bridge component, the mathematical expression of a fragility curve is given as

$$F(a_j, c_k, \zeta_k) = \Phi\left[\frac{\ln(a_j/c_k)}{\zeta_k}\right] \tag{1}$$

where a_j is the PGA of j^{th} ground motion and k represents damage states of the bridge component. The fragility function F() expresses the failure probability of the component at damage state k and c_k and ζ_k are corresponding fragility parameters, which refer to the median and log-normal standard deviation, respectively. The maximum likelihood method is performed to estimate fragility parameters. The likelihood function is given by

$$L = \prod_j \left[F(a_j, c_k, \zeta_k)\right]^{r_j} \left[1 - F(a_j, c_k, \zeta_k)\right]^{(1-r_j)} \tag{2}$$

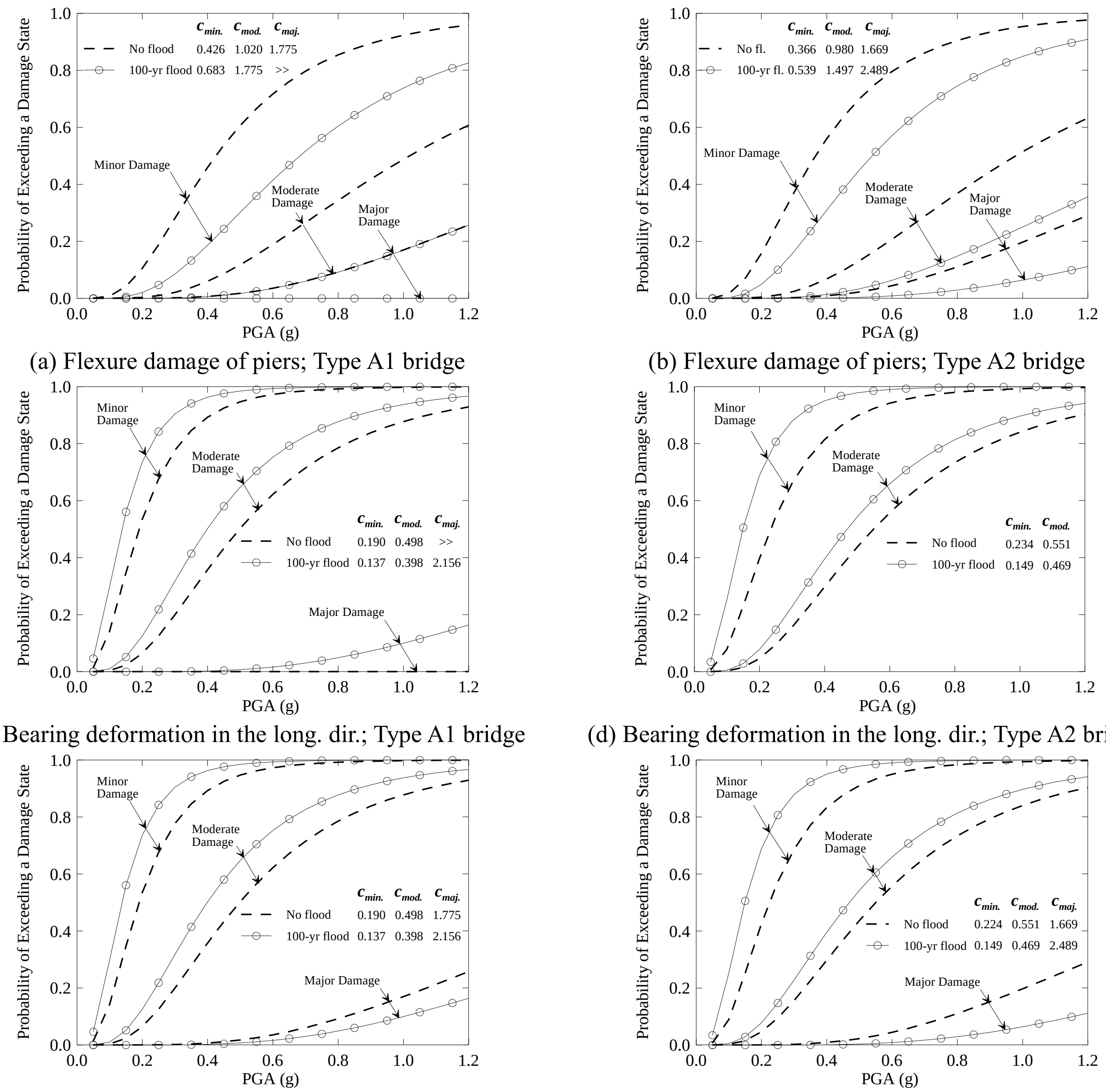
where r_j =1 or 0 depending on whether or not component damage state k is exceeded under a_j. A dispersion value of ζ_k = 0.6 is adopted from HAZUS (FEMA 2013) for all damage states, so that fragility curves do not intersect each other. This also makes it possible to compare fragility curves in terms of their median values. Higher the median value, stronger is the fragility curve (or, failure probability is lower).

This procedure is followed to develop fragility curves for all damage states of critical bridge components. These component-level fragility curves are used to generate system-level fragility curves. Figs. 9 and 10 show fragility curves of Type A and Type B bridges, respectively, at component and system levels for Site-1. Similar curves are generated for other three sites. Median values of these curves are plotted in Figs. 11-14. In these figures, open and solid symbols signify no scour and 100-year scour conditions, respectively.

5. Discussion of results

5.1 Type A1 and A2 bridges

Results from fragility analysis reveal that components of Type A bridges at the superstructure level, such as abutments and bearings, get adversely affected due to scour at bridge foundations. Low median values obtained for bearing deformation in the longitudinal direction (Figs. 9, 11-14) prove that abutment bearings are the most vulnerable bridge components at minor and moderate damage states. These failure modes control the performance of Type A bridges at system level at these low damage states. Some damage at major damage state is also observed in the bearings (due to longitudinal deformation); however, this



(a) Flexure damage of piers; Type A1 bridge
(b) Flexure damage of piers; Type A2 bridge
(c) Bearing deformation in the long. dir.; Type A1 bridge
(d) Bearing deformation in the long. dir.; Type A2 bridge
(e) At system level; Type A1 bridge
(f) At system level; Type A2 bridge

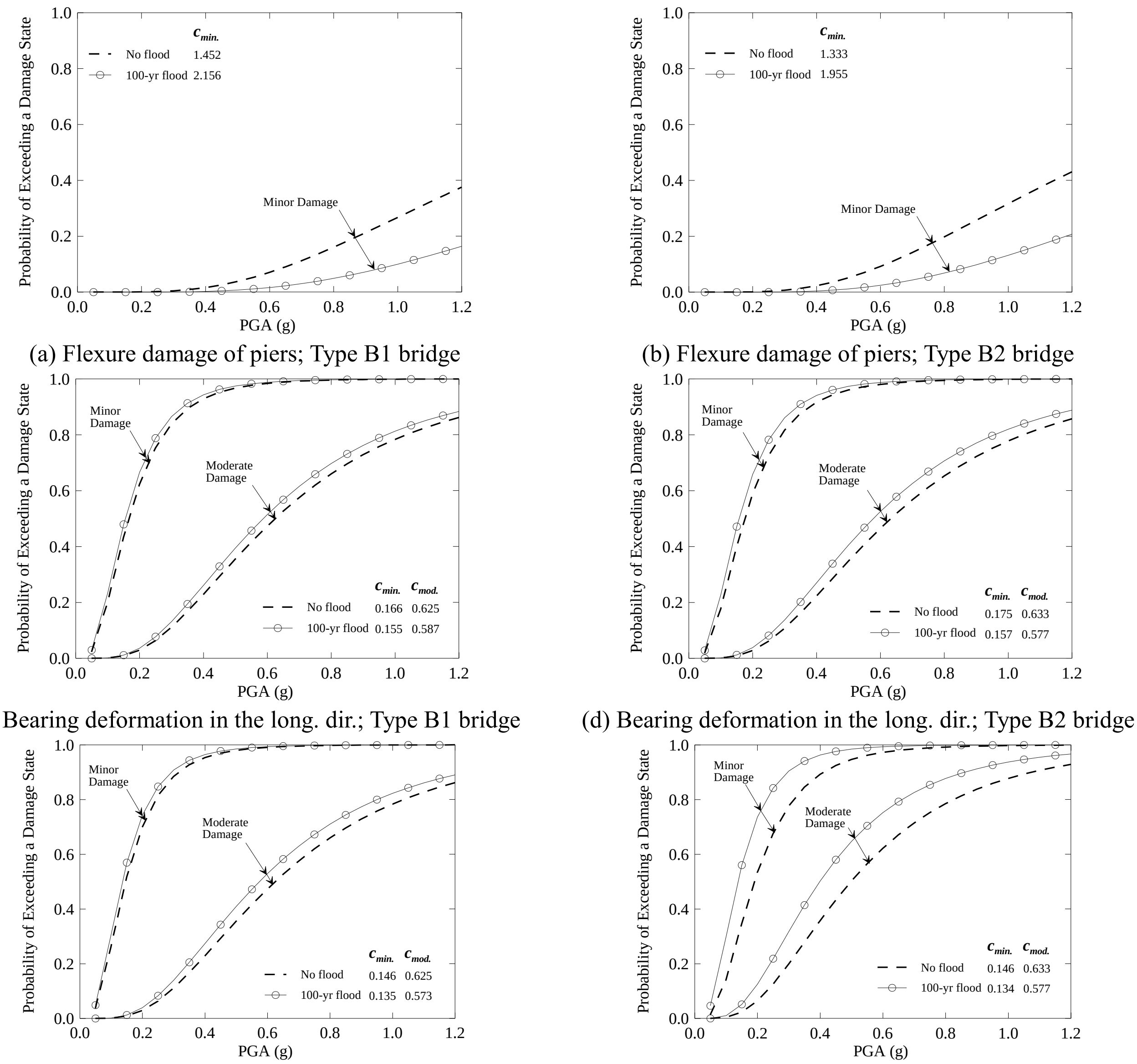
Fig. 9 Fragility curves of Type A bridges at Site-1

damage is too little to control the global damageability of the bridge at major damage state. Note that no damage at collapse state is observed for any of the Type A bridges. This is because none of the selected ground motions could produce collapse damage of any critical bridge component. Also, no damage (at any damage state) is observed at shear keys and bearings from the transverse deformation of Type A bridges.

Seismic vulnerability of piers for Type A bridges is observed to get improved with scour. As Figs. 9(a) and 11-14 indicate, median values of pier fragility curves increase with scour at all observed damage states. This is because the added flexibility at the foundation level due to the occurrence of scour protects piers from getting additional curvature deformation, and hence it facilitates in reducing pier flexural damage. This type of behaviour is observed for both Type A1 and A2 bridges. Other than little stronger fragility curves for bridge components at the superstructure level, enlarged foundation in Type A2 bridge does not provide any significant advantage over Type A1 bridge. Though flexural damage (at minor damage state) is observed in shafts of Type A2 bridge, performance of this bridge component remains almost unaltered with the occurrence of flood.

5.2 Type B1 and B2 bridges

The effect of flood hazard on seismic vulnerability of Type B bridges is similar to that of Type A bridges. Occurrence of scour at bridge foundations leads to higher seismic failure probabilities of bridge components at superstructure level. For both Type B1 and B2 bridges, abutment bearings are found to be the most vulnerable components at lower damage states (i.e., minor and moderate damage). Hence, these components govern the global failure of the bridge at these low damage levels. Note



(a) Flexure damage of piers; Type B1 bridge

(b) Flexure damage of piers; Type B2 bridge

(c) Bearing deformation in the long. dir.; Type B1 bridge

(d) Bearing deformation in the long. dir.; Type B2 bridge

(e) At system level; Type B1 bridge

(f) At system level; Type B2 bridge

Fig. 10 Fragility curves of Type B bridges at Site-1

that all bridge components of Type B bridges survived from major damage and collapse states under the applied ground motion data sets. Therefore, it can be stated that Type B bridges have low seismic vulnerability than Type A bridges. In addition, no damage is observed in Type B bridges for the transverse deformation of abutments.

Alike Type A bridges, added flexibility at the foundation level due to scour protects piers of Type B bridges, and hence fragility curves of piers become stronger with scour (Figs. 10(a), 11-14). This trend remains the same for both Type I and Type II foundations. As observed earlier, the enlarged shaft diameter of Type B2 bridge does not provide any notable advantage over Type B1 bridge. Seismic fragility of shaft of Type B2 bridge does not get affected with the presence of flood at the foundation level.

6. Impact spectrum of flood hazard on seismic vulnerability of bridges

Both real-life and representative bridges have been investigated by the author's research group to acquire a comprehensive knowledge on the impact of flood hazard on seismic vulnerability of bridges. Various foundation types such as extended pile shafts (with and without enlarged section) and pile group with pile cap are studied. Based on the observations, an impact spectrum is constructed as shown in Table 6. Nature of this spectrum is discussed in following sections. In an overall sense it can be stated that bridge foundations have a crucial role when scoured bridges are subjected to seismic ground motions. Hence, the impact spectrum in Table 6 is primarily constructed on the basis of bridge foundation types. Note that the developed spectrum is applicable only to non-cohesive soils.

Uncertainty evaluation is not included within the scope of the current study. This is primarily because of the availability of a number of past studies focusing on that topic. In a concurrent study by the authors (Yilmaz *et al.*

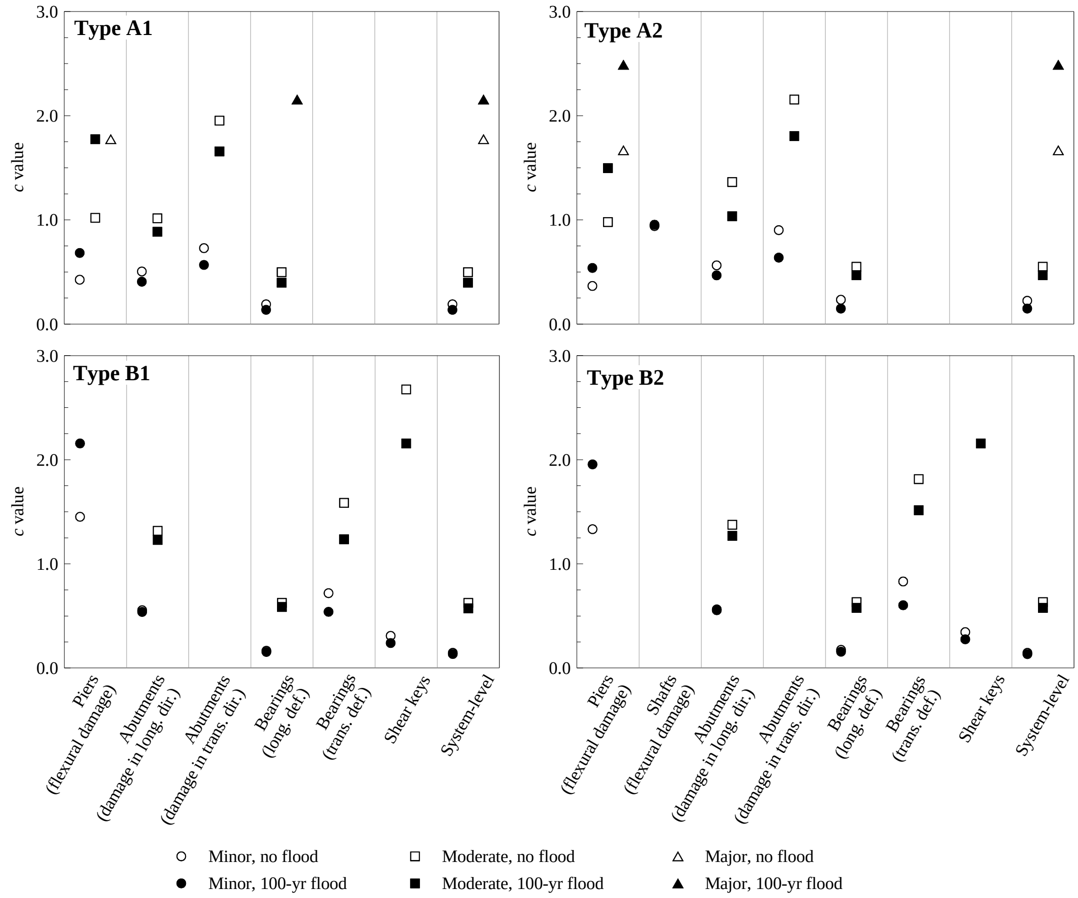


Fig. 11 Median values of fragility curves of characteristic bridges for Site-1

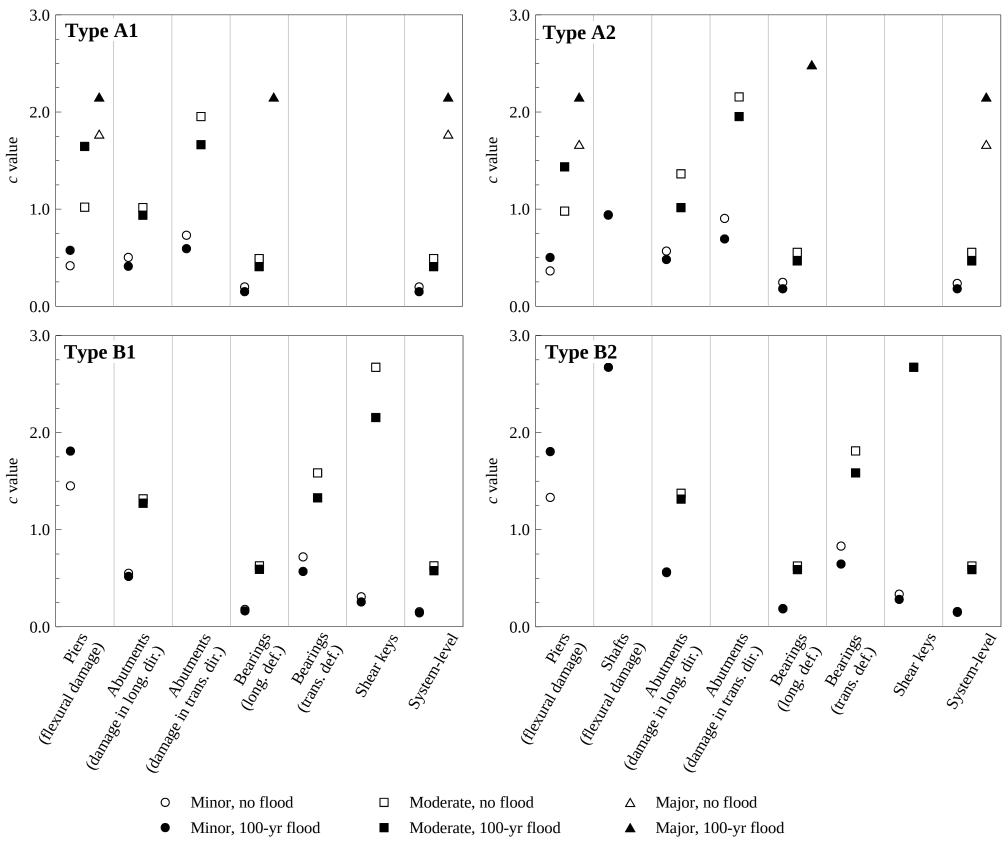


Fig. 12 Median values of fragility curves of characteristic bridges for Site-2

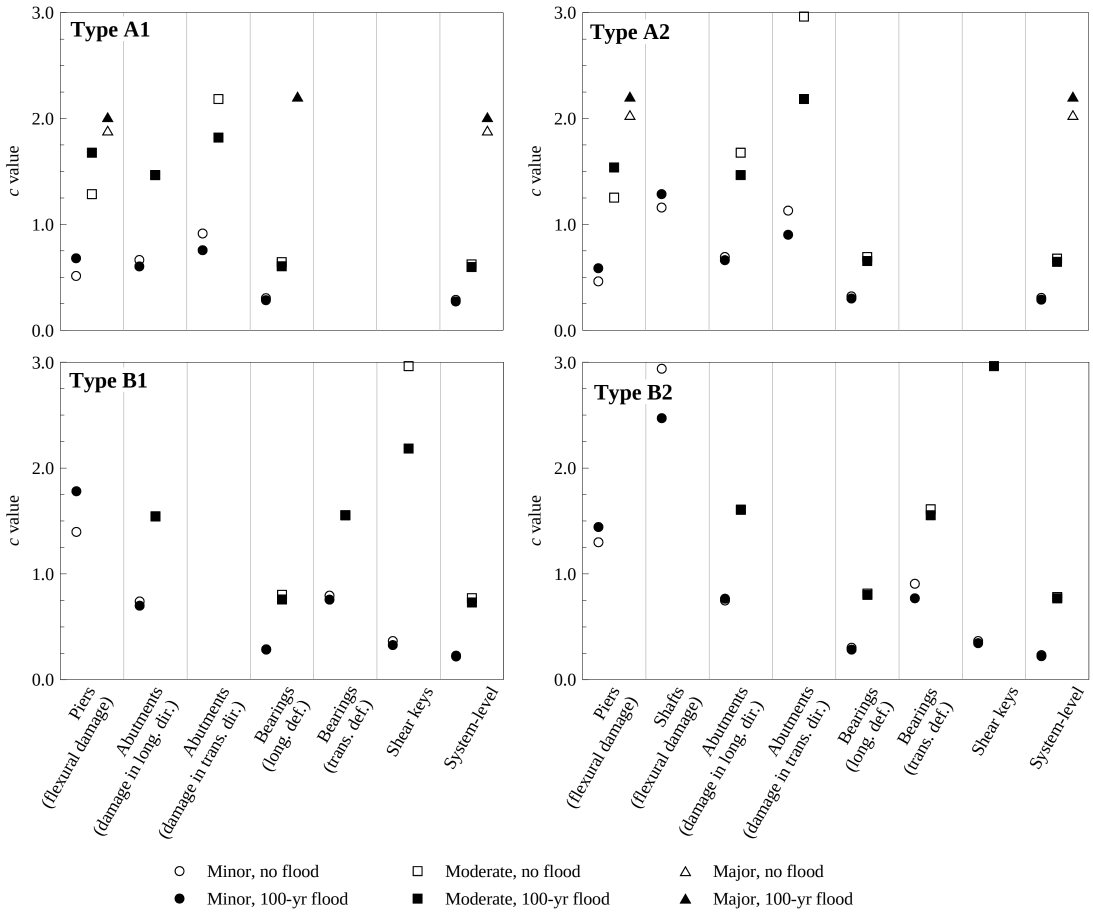


Fig. 13 Median values of fragility curves of characteristic bridges for Site-3

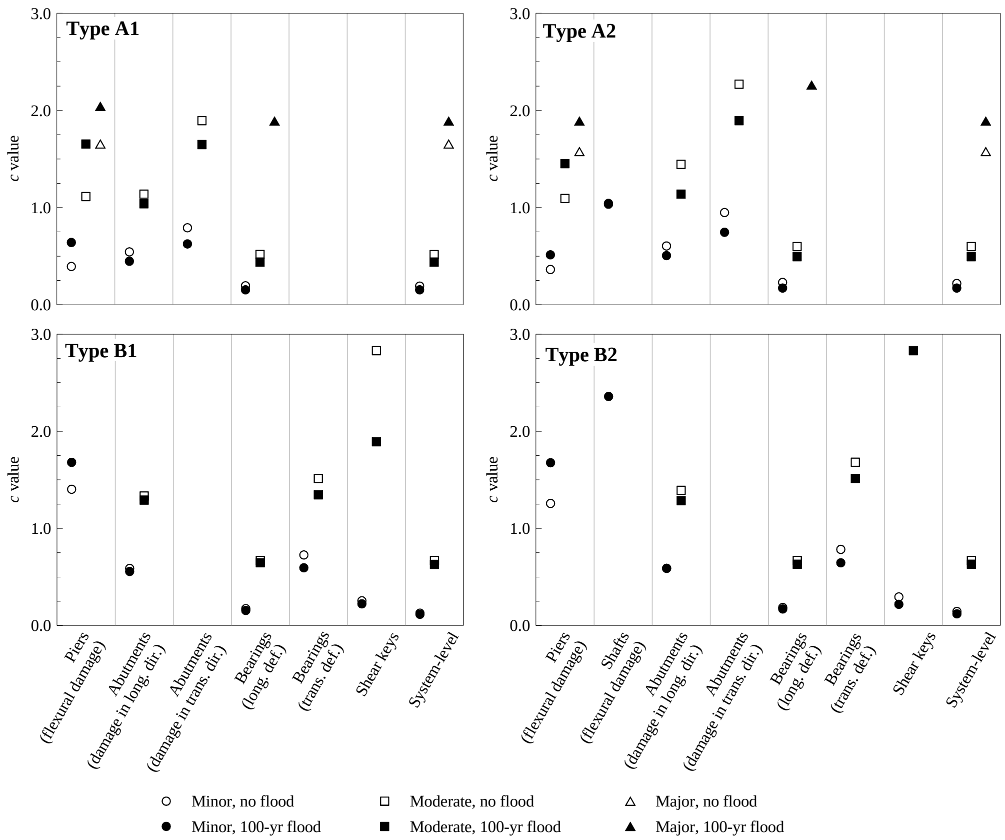
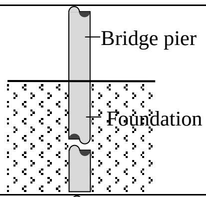
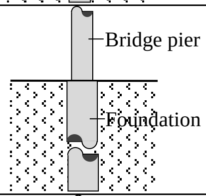
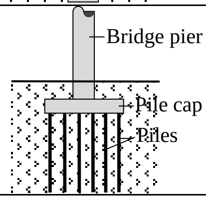


Fig. 14 Median values of fragility curves of characteristic bridges for Site-4

Table 6 Impact spectrum of flood hazard on seismic vulnerability of bridges

Bridge foundation type		Detrimental impact	Low-detrimental to no impact	No to beneficial impact
Extended shafts (Banerjee and Prasad 2013, Prasad and Banerjee 2013, Yilmaz *et al.* 2016, current study)		Not observed	Superstructure components at lower damage states	Piers at all damage states
Enlarged shaft (Banerjee and Prasad 2013, Prasad and Banerjee 2013, current study)		Not observed	Superstructure components and foundation shafts at lower damage states	Piers at all damage states
Pile group with pile cap (Yilmaz *et al.* 2016)		Piers at higher damage states	Superstructure components at lower damage states	Not observed

2017), uncertainties associated with different structural and geotechnical parameters are investigated to identify the possible variation of the impact of a flood event on bridge seismic vulnerability. It is observed that the compressive strength of concrete, yield strength of reinforcing steel, mass of the bridge, abutment stiffness and peak friction angle of subsurface soil are the five most significant parameters that have major influences on seismic performance of bridges. Previous research also calculated possible variation in the depth of scour due to variations in annual peak discharge, diameter of bridge piers, pier height, number of bridge spans, and span length, and thus estimated of scoured bridges (Banerjee and Prasad 2013, Prasad and Banerjee 2013, Alipour *et al*. 2013, Wang *et al*. 2014, Yilmaz 2015). Yilmaz (2015) found that scour depth may vary within 10% of its mean value due to uncertainty in annual peak discharge, Manning's roughness coefficient and other parameters related to scour calculation. Similar variation in scour depth is obtained for different cases with varied frequency flood events. This much variation of scour depth, though, is not observed to produce any notable variation of seismic vulnerability and risk of bridges. Hence, scour is considered to be a deterministic parameter in estimating uncertainty in fragility curves under this multihazard effect (Yilmaz *et al*. 2017). Effect of uncertain deck width on bridge seismic fragility is studied in Padgett and DesRoches (2007). Readers are referred to these literatures for more information on uncertainty. In addition, it is worthy to mention in this regard that more than a precise estimation, a well-rounded impact evaluation covering all possible ranges (positive and negative) is of prime interest of the current research. The nature of the spectrum (Table 6) is not expected to change if uncertainty analysis is performed.

6.1 Significance of bridge foundations

The current study and previous studies by the authors identified that pier damage governs bridge fragilities at higher damage states and extended shaft foundations take a major role to minimize the impact of scour on bridge seismic vulnerability. Pile shafts are extremely capable of carrying lateral forces induced by earthquake shaking. Thus, this type of foundation generally results in lower seismic vulnerability of bridges than that pertinent to the pile foundations. Because of the extension of piers below ground level (as extended pile-shafts), the lateral deformation at the deck and foundation levels of piers changes simultaneously during seismic shaking in the presence of scour. This results in a very little to no change in relative deformation between the two ends of bridge piers. Hence, extended shaft foundations save bridge piers from any additional seismic vulnerability in the presence of flood-induced scour (Banerjee and Prasad 2013, Prasad and Banerjee 2013, Yilmaz *et al*. 2016). It may as well happen that this relative displacement reduces due to the presence of scour. In such a case, pier seismic vulnerability improves with scour as observed in the current study (Figs. 9(a), 10(a), 11-14). Nevertheless, the impact, either beneficial or detrimental, of flood-induced scour on seismic vulnerability of bridge piers is minimal in case of extended shaft foundations. It is also found that enlarged cross-sections of extended shafts do not have any notable advantage over the same-diameter shafts when scour is considered. However, a big difference between shaft and pier diameters may result in a higher change in bridge seismic behaviour than that is observed for Type A2 and B2 bridges. Even in that case, no adverse impact of flood hazard is expected on pier seismic vulnerability.

For pile groups with pile caps, Yilmaz *et al*. (2016) found that a bridge can get higher seismic vulnerability in the presence of scour if scour does not reach the bottom of the pile cap. No beneficial impact of scour on seismic vulnerability of any bridge component is observed for this foundation type. Similar observations are made from other relevant literatures.

6.2 Significance of bridge superstructure

Bridge components at superstructure level primarily govern the global performance of bridges at lower damage states (i.e., minor damage) (Yilmaz *et al*. 2016 and the current study). Seismic vulnerability of critical superstructure components such as bearings and abutments increase due to the presence of scour. This is because the enhanced flexibility of bridges due to scour at foundations results in increased displacements at the superstructure level. This outcome is observed irrespective of bridge foundation type (Type I or Type II shafts). Since bridge service limit states are associated with bridge condition at lower damage states, the negative impact of the multihazard condition at lower damage states should not be ignored for bridge design under the same multihazard scenario. Results from the current study revealed that the type of bridge girder has no noticeable role to play in deciding the impact of flood hazard on bridge seismic performance.

7. Conclusions

The paper presents an impact spectrum of flood-induced scour on seismic vulnerability of bridges. This spectrum is constructed based on the observations made from multihazard analyses of a variety of bridges having different attributes and configurations. Results from author's past research on this topic and other relevant studied showed either detrimental or no insignificant impact of scour on bridge seismic performance. The current study explored the possibility of obtaining beneficial impact of scour on bridge seismic vulnerability. Characteristics bridges are chosen such that the stated objective is met. These bridges are selected based on a detailed inventory study of bridges in California and Washington states in the US. Only extended pile shafts (with and without enlarged cross-section) are used as foundation elements. Conventional pile foundations (pile group with a pile cap) are not considered as this type of foundation has shown to worsen bridge seismic performance in the presence of scour.

For analysis, a varied combination of flood and seismic hazard intensities are considered in order to represent their activities in moderate to high seismically-active flood-prone regions. Developed impact spectrum demonstrates the significance of bridge foundation type when bridges are subjected to a multihazard effects of earthquake and flood-induced scour. As the observed results suggest, extended shaft foundations can be selected for bridge design under the stated multihazard condition as this type of foundation protects bridges from getting additional seismic vulnerability in the presence of flood-induced scour. It is also observed that extended shaft may provide beneficial impact when scoured bridges are subjected to earthquakes. Bridge components at superstructure level should get proper attention in order to satisfy performance objectives at bridge service limit states under the same multihazard condition.

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