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Probabilistic Assessment of Component-Specific Seismic Sensitivity in Railway Bridges under Local Scour

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Abstract
The structural integrity of railway bridges is frequently challenged by local scour and seismic excitations. This study investigates the combined effects of scour and seismic loading on the seismic fragility of a representative railway bridge and underscores the importance of including flood scour in seismic risk assessments. Accordingly, a probabilistic framework is developed to quantify the component-level fragility and associated uncertainty for bearings and piers under representative scour scenarios. The methodology integrates a three-dimensional finite element model with incremental dynamic analysis, employing a series of nonlinear time–history simulations extracted from ground motion data at varying scour depths to generate two-dimensional fragility curves and three-dimensional fragility surfaces. The numerical results indicate that while isolation bearings exhibit limited sensitivity to scour, the median peak ground acceleration (PGA) capacity of the piers decreases by approximately 6.7% under extreme conditions. This discrepancy causes a distinct shift in component sensitivity, in which the primary source of system vulnerability is transferred from the bearings to the piers under deep-scour conditions. Bootstrap resampling confirms that scour accumulation substantially amplifies the statistical uncertainty of the pier responses. These findings underscore the need to incorporate scour-dependent variables into fragility models. Ultimately, this study establishes a risk-informed prioritization framework for maintenance decisions, which posits that ensuring pier stability takes precedence over addressing bearing issues under deep-scour conditions.

Keywords: Seismic fragility, Local scour, Incremental dynamic analysis, Uncertainty, Nonlinear time history analysis, Coupled hazards.

1. Introduction

Transport infrastructure networks are essential for modern society and economic stability. Recent global risk analyses indicate that road and railway assets are increasingly exposed to natural hazards, such as floods and earthquakes (Koks et al. 2019). The disruption of these critical lifelines incurs substantial direct repair costs and indirect economic losses from traffic interruptions (Liu et al. 2022). When a scoured bridge is subjected to an earthquake, the altered boundary conditions significantly modify its dynamic characteristics and failure mechanisms. The formation of scour holes produces unsupported pile lengths, which can modify the fundamental period and ductility demand of the substructure elements (Klinga and Alipour 2015). Consequently, the engineering community emphasizes the necessity of rigorous multi-hazard design and assessment protocols to preserve structural safety under extreme environmental conditions (Ghosn 2014).

Extensive research has been conducted on the assessment of bridge fragility under single-hazard scenarios. Early studies by Choi et al. (2004) established probabilistic frameworks for evaluating the seismic fragility of moderate seismic zones. Similarly, Kang et al. (2017) investigated the seismic damage to high-speed railway bridge components under varying intensities. Regarding scouring hazards, Antonopoulos et al. (2025) and Lin et al. (2016) provided detailed insights into the dynamic behavior of scoured bridge piers. In light of the limitations of single-hazard approaches, recent studies have focused on multi-hazard risk assessments. Wang et al. (2014) pioneered the development of methodologies for calibrating load factors to incorporate the combined impacts of seismic events and scour. Kameshwar and Padgett (2014) extended this scope to include parameterized fragility curves for bridges exposed to hurricanes and seismic disturbances.

Despite these advancements, the existing literature exhibits notable limitations in terms of high-fidelity modeling of soil-structure interactions and quantification of failure mode shifts. Some studies have employed simplified lumped-spring models that fail to capture the complex distributed nonlinearity of pile foundations under deep-scour conditions (Davoodi et al. 2013). Other studies, such as those by He et al. (2020), utilized static pushover analyses, which may not fully represent the transient dynamic responses induced by near-fault ground motions. Although recent contributions by Fioklou and Alipour (2022) have incorporated scour uncertainty into fragility models, there is a scarcity of research that explicitly quantifies how vulnerability is transferred between isolation bearings and piers in railway bridges. Neglecting this component-level interaction can lead to non-conservative estimates of collapse risk (Annad et al. 2023).

This study addresses these shortcomings by establishing a comprehensive probabilistic framework to elucidate the mechanism by which scour depth alters the vulnerability levels of the components. Within this framework, incremental dynamic analysis (IDA), a widely adopted approach based on nonlinear time–history analysis under progressively scaled ground motions, is employed to capture the full range of structural response from elastic behavior to collapse (Vamvatsikos and Cornell 2002). To this end, a rigorous three-dimensional finite element model is developed using the OpenSees framework (McKenna 2011). The analysis incorporates fiber-section elements and dynamic p–y curves to effectively simulate the nonlinear characteristics of the pile–soil–structure system. IDA is performed using 640 nonlinear time–history simulations derived from 16 ground motions to generate fragility surfaces for both slight and severe damage states. The 16 ground motion datasets considered herein are obtained from the Pacific Earthquake Engineering Research Centre and are amplitude-matched. This study specifically highlights the trade-off between the displacement-sensitive response of bearings and the stability-sensitive response of piers under extreme-scour scenarios.

The remainder of this study systematically presents the methodology and findings. Section 2 presents the probabilistic models for flood scour and seismic hazard analyses. Section 3 outlines the derivation of the fragility curves and defines the structural performance criteria. In Section 4, the case study bridge and finite element modeling methods are described in detail. Section 5 presents the numerical results and discusses the implications of scour on pier and bearing reliability. Finally, Section 6 summarizes the principal conclusions and offers recommendations for risk management strategies.

2. Seismic and Scour Hazards Risk

2.1. Scour hazard risk analysis

Scour is defined as the erosion of soil surrounding infrastructure foundations owing to hydrodynamic action and represents a critical hazard to bridge integrity during floods (HEC-18). The assessment of this risk is based on scour depth, which is a key indicator of potential structural damage (Echogdali et al. 2022). As outlined in the HEC-18 guidelines, bridge structures are vulnerable to three distinct categories of scour: aggradation and degradation, general contraction, and local scour. Among these mechanisms, local scouring is widely recognized as the most significant threat to pier stability (Lin et al. 2016). The depth of local scour (y_s) can be defined as:

$$y_s = 2.0\gamma_s y_0 k_1 k_2 k_3 k_4 \left(\frac{a}{y_0}\right)^{0.65} Fr^{0.43} \quad (1)$$

where y_s, y_0, γ_s, and a are the calculated scour depth, the flow depth directly upstream, the scour depth correction factor, and the pier width, respectively. The terms k_1, k_2, k_3, and k_4 function as correction coefficients that account for specific environmental and geometric variables. These factors are adjusted for the pier nose shape, water flow angle, streambed condition, and soil particle size. The Froude number (Fr) is determined as follows:

$$Fr = v/(gy_0)^{0.5} \tag{2}$$

where v signifies the average velocity of flow, determined by the channel's cross-sectional dimensions and the discharge rate, and g is the gravitational acceleration constant of 9.81 m/s². The specific values for coefficients k_1 through k_4 and γ_s are determined in strict accordance with the HEC-18. For a specific flood event, the annual peak discharge (Q) is the primary input parameter.

2.2. Seismic hazard risk analysis

Bento et al. (2020) conducted prior research on the new Hintze Ribeiro Bridge in Portugal. Their study evaluated seismic occurrences across seven different return periods ranging from 5 to 1,000 years. Furthermore, these analyses revealed that the stochastic data followed a log-normal distribution, exhibiting asymptotic behaviors consistent with the Gumbel (extreme value type II) and Weibull functions (extreme value type III) (Bento et al. 2020). Given that the investigation emphasizes the structural performance under extreme loading conditions, the extreme value type III (ET-III) distribution is selected to model the probability density of the seismic intensity in this study. The adopted probabilistic model is in agreement with the seismic hazard analysis of the fault zone and adheres to the fundamental principles of the Chinese code for the seismic design of railway engineering (GB50111-2006) regarding the 50-year exceedance probability (Kang et al. 2017). The distribution function (Yang et al. 2016) is expressed as follows:

$$F_{IM}(im) = \exp\left[-\frac{t}{T}\left(\frac{\omega - im}{\omega - c}\right)^k\right] \tag{3}$$

In this context, ω represents the theoretical maximum limit of seismic intensity., which is set to 12. The characteristic parameter c assumes a value of 6.45, which corresponds to the intensity mode associated with a 63.2% probability of exceedance over a 50-year interval, as established by Yang et al. (2016). Furthermore, the shape parameter k is fixed at 6.88 to regulate the tail morphology of the distribution curve, while T denotes the design reference period of 50 years and t represents the specific time variable. Furthermore, it can be demonstrated that the probability density equation (Eq. 4) for seismic hazard can be obtained by differentiating Eq. 3.

$$f_{IM}(im) = \frac{k(\omega - im)^{k-1}}{(\omega - c)^k}\exp\left[-\frac{t}{T}\left(\frac{\omega - im}{\omega - c}\right)^k\right] \tag{4}$$

3. Structural Fragility Analysis

3.1. Fragility curves

In the context of the growing understanding of earthquake disasters and the heightened emphasis on bridge seismic resilience, seismic fragility analysis of bridge structures has emerged as a crucial method for evaluating seismic performance and post-earthquake damage (Wang et al. 2014). Seismic fragility curves represent the contingent probability that a structural component will reach or exceed a particular damage state under a specific level of seismic intensity (Argyroudis and Kaynia 2015). This study adopts peak ground acceleration (PGA) as the intensity measure and primary independent variable to facilitate its broad applicability.

The probabilistic parameters are derived using the IDA. This method involves subjecting the numerical model to a suite of ground motion records that are systematically scaled in fixed increments to cover a wide range of seismic intensities. By performing extensive nonlinear time-history simulations at different scour depths, this study captures the component-level responses of both the piers and bearings. The resulting data enable the generation of seismic fragility curves and three-dimensional fragility surfaces. The failure probability P_f is computed directly by quantifying the frequency of exceedance for specific damage thresholds at each intensity level, as expressed in Eq. 5.

$$P_f = P[DI \geq LS_i | IM] = \frac{n_i}{N} \tag{5}$$

where LS_i represents the *i-th* damage state, with the following values: $i = 1$ for slight damage, $i = 2$ for medium damage, $i = 3$ for serious damage, and $i = 4$ for complete destruction. The N denotes the number of seismic waves, while the n_i parameter represents the number of seismic waves that can cause the seismic response of the structure or component to exceed the specified damage limit state. Zhang and Huo (2009) pointed out that the vulnerability curve obtained by IDA analysis conforms to the cumulative normal distribution function.

3.2. Structural performance indexes

The execution of a component-level fragility analysis necessitates the precise definition of structural damage states and the subsequent quantification of their corresponding performance indices. The formulation of these limit states varies across different components based on factors, such as the structural criticality of the member, the impact on bridge serviceability, and the economic implications of post-event repairs (Orcesi et al. 2010).

The literature regarding components suggests various indices for assessing structural degradation, including curvature ductility and displacement ductility (Liu et al. 2022; Kang et al. 2017; Wang et al. 2014; Choi et al. 2004). In alignment with established engineering practices, this study employs relative displacement d_x to quantify the damage levels for the bearings, whereas curvature ductility β_φ serves as the primary performance index for the piers. Table 1 summarizes the specific quantitative thresholds adopted for the limit states (Liu et al. 2022; Choi et al. 2004).

Table 1. Standards for classifying the damage state of bridge components.

Classification standards for the damage status		
Damage stage	Displacement d_x (mm)	Curvature Ductility Coefficient β_φ
None	d_x<100	β_φ<1
Slight	100≤d_x<150	1≤β_φ<2
Medium	150≤d_x<200	2≤β_φ<4
Serious	200≤d_x<250	4≤β_φ<7
Complete	d_x≥250	β_φ≥7

4. Case Study

4.1. Railway bridge description

To demonstrate the applicability of the proposed probabilistic framework, a typical three-span continuous bridge located in a high-seismic zone is selected as a case study. The superstructure is characterized by a single-cell box girder cross-section supported by uniform hollow circular piers. The piers measure 28 m in height, 4.0 m in outer diameter, and 0.4 m in wall thickness. The foundation system consists of a pile group configuration of nine reinforced concrete piles, each extending 45 m in length and 2.2 m in diameter. According to the material specifications, the piers utilize C50 concrete to ensure a high load-bearing capacity, whereas the unconfined concrete regions employ C40 concrete. Fig. 1 illustrates the general arrangement of the bridge and provides a comparative visualization between the condition with no scour and the scour scenario characterized by a depth of 6.26 m.

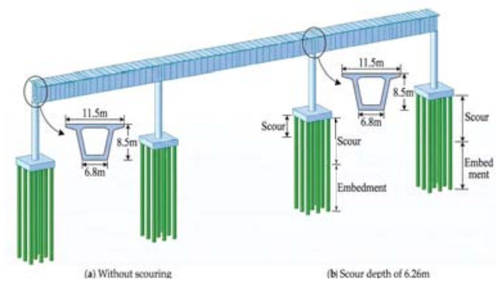

Fig. 1. Overall layout of the bridge: (a) without scour and (b) with a scour depth of 6.26 m.

4.2. Finite element modeling

The open-source framework OpenSees is employed to perform numerical simulations of bridge responses under the coupled influence of scour and seismic excitations.

The main girders of the superstructure are represented by elastic beam elements, whereas the piers are modeled using nonlinear elements. This model captures the stress-strain history of the steel reinforcement and concrete core, thus characterizing the cross-sectional behavior with high fidelity. Regarding the substructure, a refined mesh size of 1.0 m per pile segment is adopted to enable a rigorous characterization of the complex soil-structure interaction.

Standard constitutive models available in the OpenSees libraries are applied to the material behavior. Both unconfined and confined concrete are modeled using the Concrete02 formulation. The constitutive behavior of the confined concrete is predicted using the Mander model (Mander et al. 1988). The reinforcement behavior is characterized using Steel02 material with a yield strength of 335 MPa. The lateral soil resistance is represented by distributed springs governed by the p-y curves. In addition to this lateral mechanism, independent spring elements are employed to simulate both the vertical skin friction and pile tip bearing capacity. For the scour depth, this study uses a 100-year return period flood discharge of 4200 m³/s for the case study. To evaluate the structural performance under varying scour depths, the analysis explicitly considers three distinct scour conditions corresponding to depths of 0.0, 2.0, and 4.0 m.

5. Results of Components

5.1. Piers

The structural effects of scour on bridge piers are notably sensitive under seismic loading. Figs. 2 and 3 present the two-dimensional fragility curves and three-dimensional surfaces corresponding to the slight and medium damage states, respectively. As shown in Fig. 2(b), under medium damage conditions, the fragility curve shifts markedly to the left as the scour depth increases. This indicates that an increase in the scour depth degrades the seismic performance of the piers. The numerical outcomes substantiate this interpretation, with the median PGA declining from 0.60 g in the absence of scour to 0.56 g at a scour depth of 6.26 m. This reduction of approximately 6.7% highlights the destabilizing effect of scouring on structural performance.

Additionally, the three-dimensional fragility surfaces in Fig. 3 reinforce this finding, as the failure probability surface exhibits pronounced warping along the scour depth axis, particularly at higher damage levels. Collectively, these findings indicate that scouring substantially enhances the vulnerability of bridge piers to seismic responses. Consequently, this effect should be explicitly considered in seismic performance assessments and designs.

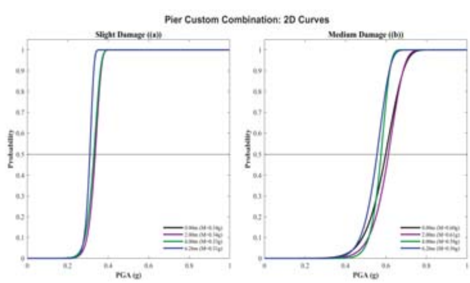

Fig. 2. Fragility curves of the piers under (a) slight and (b) medium damage conditions.

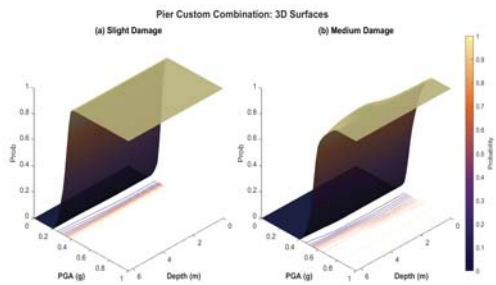

Fig. 3. Fragility surfaces of the piers under (a) slight and (b) medium damage conditions.

5.2. Bearings

In contrast to piers, bridge bearings exhibit limited sensitivity in their response to scour. As demonstrated in Figs. 4 and 5, the development and presentation of fragility curves and surfaces corresponding to both slight and severe damage states are the subjects of this study. The outcomes are presented across a range of PGA from 0.1 to 1.0 g. Furthermore, Fig. 6 presents the fragility surfaces for scour depths of 2.0 and 6.26 m on the left and right sides, respectively. These fragility surfaces reveal the combined influence of PGA and scouring on the damage probability curves. The relationship between the damage state and the two loading variables is evident, with the failure probability rising along pronounced gradients as the PGA increases, and substantial scouring further complicates this pattern.

The analysis of the two-dimensional projection in Fig. 4(a) reveals that the median PGA for the slight damage state shifts marginally from 0.20 g at zero scour to 0.21 g at a scour depth of 6.26 m. The proximity of these values suggests that seismic intensity plays a more critical role than scour depth in initiating the loss of the bearing functionality of the bridge.

Regarding the serious damage state presented in Fig. 4(b), the fragility curves show a modest divergence as the scour depth increases. The median PGA decreases from 0.44 g under no-scour conditions to 0.42 g at a scour depth of 6.26 m. This trend suggests a slight increase in the structural vulnerability associated with deeper-scour environments. The fragility surfaces of the support shown in Fig. 5 also demonstrate the distinction between the slight and serious damage states.

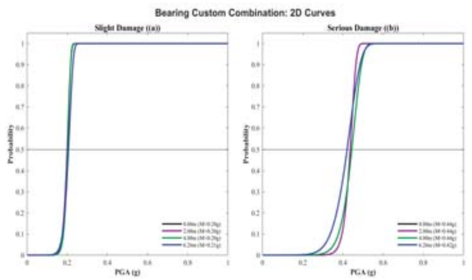

Fig. 4. Fragility curves of the bearings under (a) slight damage and (b) serious damage conditions.

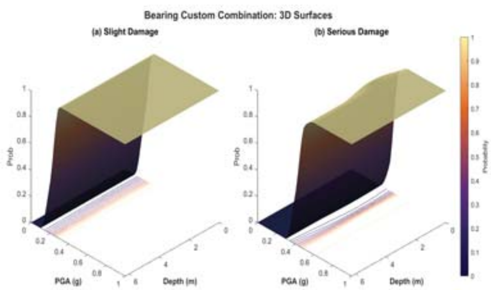

Fig. 5. Fragility surfaces of the bearings under (a) slight and (b) severe damage conditions.

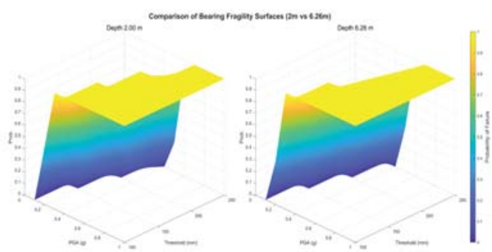

Fig. 6. Fragility surfaces for scour depths of (left) 2.0 m and (right) 6.26 m.

5.3. Confidence intervals and uncertainties

To rigorously evaluate the reliability of the fragility estimates derived from the 16 ground motion records, this study utilizes a bootstrap resampling procedure with 1,000 iterations to generate 95% confidence intervals (CIs). Fig. 7(a) and (b) show the resulting uncertainty bands for the bearings and piers, respectively, at a scour depth of 6.26 m. A consistent pattern emerges across all cases, with both figures showing a non-uniform distribution that is constricted in the central region but divergent at the extremities. Specifically, the uncertainty minimizes within the central probability range of 20% to 80% and expands significantly in the lower and upper tails, defined by probability ranges of 0% to 20% and 80% to 100%, respectively. This phenomenon is attributed to the statistical constraints of the log-normal fitting algorithm near the asymptotic failure probability boundary.

As illustrated in Fig. 7(a), the uncertainty profile of the bearings demonstrates a specific dependency on both the damage state and scour depth. The dispersion bands widen notably as the damage state transitions from slight to severe. In contrast, Fig. 7(b) shows that the confidence intervals for the piers are wider than those for the bearings. This increased variance reflects the complex coupled nonlinearity inherent in the pile–soil–pier system.

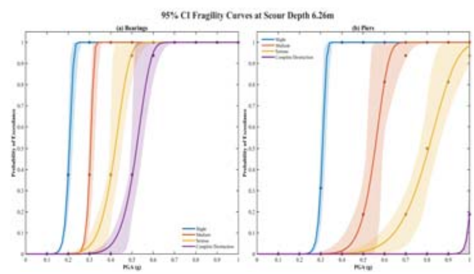

Fig. 7. 95% confidence intervals for (a) bearings and (b) piers at a scour depth of 6.26 m.

6. Conclusions

In this study, a probabilistic framework is developed to evaluate the seismic fragility of a railway bridge subjected to varying scour depths using a three-dimensional finite element model and incremental dynamic analysis. The probabilistic seismic demand assessment is based on 640 nonlinear time history simulations generated from 16 selected ground motions, covering a peak ground acceleration (PGA) range of 0.1 g to 1.0 g and four scour depths (0.0, 2.0, 4.0, and 6.26 m). The examination of the component-level responses and their associated uncertainties yield the following principal conclusions.

The numerical results demonstrate that scour and seismic intensity jointly govern the fragility of the bridge system, although their relative influence varies by component. A clear division of the response mechanisms emerges from the results. Although bearing functionality primarily depends on ground motion intensity, piers exhibit a significant reduction in seismic capacity under extreme scour conditions. This increased fragility significantly reduces the lateral stiffness of the piers. This trend is particularly pronounced for high-intensity motions with a PGA greater than 0.6 g. Additionally, a median PGA capacity reduction of approximately 6.7% at an extreme scour depth of 6.26 m illustrates how increased scour diminishes effective lateral stiffness and amplifies curvature demand. This process results in systematic leftward shifts in the fragility curves and demonstrates that scour effectively transfers systemic vulnerability from displacement-sensitive bearings to stability-sensitive piers.

An uncertainty analysis based on bootstrap resampling shows that the confidence intervals widen toward the distribution tails and remain consistently broader for piers than for bearings. At the ultimate limit states associated with severe damage, scour further amplifies the dispersion in the fragility estimates. These findings support the adoption of probabilistic safety margins in risk assessment rather than reliance on deterministic safety factors, as neglecting uncertainty effects may lead to non-conservative estimates of pier collapse risk.

From a risk management perspective, monitoring strategies can be differentiated based on structural components. Although PGA-based monitoring is adequate for the routine identification of slight bearing damage, pier-focused inspection protocols and conservative intervention thresholds should be prioritized in scoured environments to prevent catastrophic failure. Future research should extend the present framework through sensitivity analyses of ground motion selection and scaling, as well as variations in bearing and pier configurations, to enhance the generality of the proposed analytical relationships.

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