INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

IJIE

Vol. 17 No. 3 (2025) 116-126
https://publisher.uthm.edu.my/ojs/index.php/ijie

Effect of Scour and Seismicity on the Bridge's Response

Nordila Ahmad[1]*, Muhammad Amir Syauqi Mohd Shukri[1], Syuriya Mohamad[1], Mohd Zamri Ramli[2]

[1] *Civil Engineering Department, Faculty of Engineering,*
National Defence University of Malaysia, 57000 Sungai Besi, Kuala Lumpur, MALAYSIA
[2] *Civil Engineering Faculty,*
Universiti Teknologi Malaysia, 81310 Skudai, Johor, MALAYSIA

*Corresponding Author: nordila@upnm.edu.my
DOI: https://doi.org/10.30880/ijie.2025.17.03.013

Article Info

Received: 10 December 2024
Accepted: 4 June 2025
Available online: 29 August 2025

Keywords

Bridge, scour depth, displacement, peak ground acceleration, earthquake

Abstract

Bridges are critical points in rail and road networks, and their failure due to natural hazards like tsunamis, earthquakes, ground movements, or floods can cause significant losses. Identifying weaknesses and measuring bridge strength is crucial for disaster resilience. Current methods rely heavily on engineering judgment, lacking dependable quantitative evaluations. This framework offers a comprehensive approach to creating numerical simulations and assessing bridge resilience against multiple hazards. The project involves simulating a 130-metre pre-stressed concrete bridge exposed to seismic and scour depth hazards using the CSI Bridge software. The simulations consider three scour depth levels (1Df, 1.5Df, and 2Df), five earthquakes, and varying seismic intensities (0.25 to 1.5 Peak Ground Acceleration, PGA, with 0.125 increments). The foundation depth (Df) is 2.5 metres, and simulations are run under clay soil. Nonlinear Time History Analysis (NTHA) is employed for its suitability for inelastic beam-column elements under dynamic loading. Results indicate that increasing the scour depth from 1.5Df to 2Df increased pier displacement by 21.68% in clay.

1. Introduction

Bridges are vital components of highway and railway transportation networks, but they are highly vulnerable to natural and man-made catastrophes like earthquakes, floods, strong winds, explosions, and vehicle or vessel collisions. Such damage can disrupt transportation systems, causing substantial economic losses. Ensuring bridge safety and serviceability is a major focus in civil engineering. Notably, numerous highway bridges collapsed during the 1971 San Fernando, 1989 Loma Prieta, and 1994 Northridge earthquakes, severely impacting local transportation networks [1]. Fig. 1 shows the typical natural phenomena that always occurred that already affected the bridges.

Bridge scour is the meaning of removal of soil, sand and rocks from around a bridge's supports or piers, as shown in Fig. 2. The rapid flow of water against the pier generates turbulent currents, resulting in erosion near the base of the pier, which is directly impacted by these currents. A horseshoe-shaped vortex, formed due to water collection on the upstream side and increased flow velocity at the pier's tip, leads to erosion of the bed material around the base of the pier, resulting in the formation of a depression called a scour hole. The local scour around the bridge pier is caused by the increased bed shear stresses resulting from the flow acceleration near the pier, which is caused by the horseshoe vortex. With the increasing frequency of flooding, the scour hole intensifies and erodes the soil adjacent to the adjoining piles. As a result, the hole around the pile becomes wider and the depth of the hole grows as time passes [2]. Several bridges situated in areas prone to earthquakes also have significant foundation exposure because of riverbed scour. The lateral strength of a pile foundation can be greatly diminished by the loss of surrounding soil, which might lead to potential damage to the piles during an earthquake. Prior research has examined the evaluation of bridges' ability to withstand multiple hazards, specifically earthquakes combined with flood-induced scour. This combination is regarded as a significant multihazard scenario for bridges situated in flood-prone regions that are also prone to seismic activity [3].

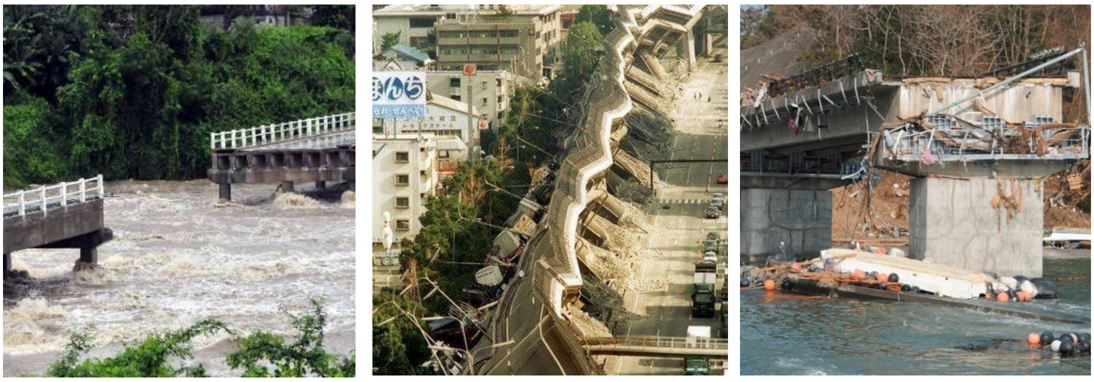

(a) (b) (c)

Fig. 1 *(a) Flood phenomenon - bridge collapse after extensive scour and erosion during flood in Cuba [4]; (b) Earthquake event - extensive failure of the bridge after 1995 Kobe's earthquake, Japan [5]; and (c) Tsunami - severe damage of the Utatsu Bridge after 2011 Great East Japan [5]*

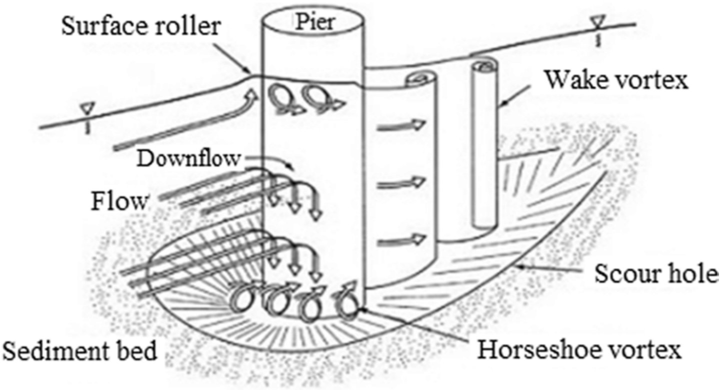


Fig. 2 *Scour mechanism around a single pier [2]*

Earthquakes and other geological hazards, including tectonic movements, landslides, and inundations, pose significant risks to infrastructure worldwide, leading to socioeconomic damage and loss of life. For instance, the 2008 Wenchuan earthquake in China caused over 15,000 landslides and over 20,000 deaths, isolating large regions due to highway destruction. The simultaneous occurrence of earthquakes and floods, causing erosion around bridge foundations (scour), further increases vulnerability to seismic activity. 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 [3]. Recent studies [6]-[11] highlight that bridges are susceptible to multiple hazards. In the U.S., around 70% of bridges spanning rivers are affected by flood-induced scour, destroying about 53% of these bridges. The increasing occurrence of multi-hazard events, such as combined scour and seismic activity, poses significant challenges for global bridge stability and safety [12]-[18]. These concurrent events heighten structural vulnerabilities, making bridges more prone to damage or failure. Current designs often overlook the simultaneous impact of scour and seismic events. Thus, extensive evaluation of bridge response to multiple hazards is deemed vital.

A recent study on bridge piles highlights the severe impact scour can have, especially when combined with other factors like soil-structure interaction [25]. Seismic forces introduce dynamic pressures that can significantly impact bridges, especially when the base material consists of stiff clay. Stiff clay can enhance seismic waves of specific frequencies, hence increasing the load on bridge foundations. Bridges with pile foundations in stiff soils have considerable seismic susceptibility, particularly in areas with high seismic activity [26]. Furthermore, seismic fragility analysis demonstrates that the reaction of bridges supported by stiff clay might vary significantly depending on how much of soil erosion is caused by scour [25]. Therefore, the investigation of the combined effect of seismic and scour in stiff clay is crucial.

Numerical modelling has become essential for exploring hazards from combined scour and seismic events on bridges. Advanced simulations, such as finite element analysis (FEA) and computational fluid dynamics (CFD), allow researchers to replicate real-world conditions and analyse the interplay between hydraulic pressures, soil erosion, and seismic vibrations. This research provides bridge engineers, policymakers, and disaster management agencies with valuable insights into vulnerabilities associated with scour and seismic events, guiding informed decisions on infrastructure design, construction, and emergency response protocols. Besides, numerical simulations are more reliable, it is also give significant results and are able to assess indirect losses for bridges subjected to multiple hazards. Thus, this study used numerical modelling to explore the bridge response and give a better understanding of how transport infrastructure works in the sense of combined multiple hazards. The objective of this study is to investigate the bridge's response under a combination of flood-induced scour and earthquake hazards.

2. Methodology

2.1 Numerical Modelling

The structure comprises two outside spans, each measuring 40 meters, and one internal span of 50 meters. The bridge is sustained by two piers that are securely embedded in the riverbed. The bridge has a length of 130 meters and a width of 13 meters. The structure comprises two traffic lanes, each measuring 3.5 meters, flanked by road shoulders of 3 meters on both sides. The bridge is sustained by cantilever beams positioned at the upstream section. The abutments are 18 meters in height, while the footing has a width of 1 metre and spans 5.5 meters in length. The piers have a circular shape with a diameter of 2.4 meters and a height of 20 meters. Fig. 3 and Fig. 4 show the front view of the bridge model and the cross section of the box girder. The material model of the bridge is characterised by linear elasticity. The bridge demonstrates non-porous characteristics. This study has used ground type B, which is classified as very stiff clay according to Eurocode 8–Part 1 [10]. These categorisations provide important information about the observed behaviours of bridge piers when subjected to seismic events and local scour. This is due to the fact that soil composed of stiff clay might exhibit a distinct behaviour when subjected to seismic loads compared to other types of soil, such as loose sand or soft clay. It is possible that it will magnify particular frequencies of seismic waves, which will ultimately have an effect on how the bridge reacts to scour effects and earthquakes. With a Poisson's ratio of 0.40 for unsaturated conditions and 0.30 for saturated conditions, the unit weight of the unsaturated and saturated states is γ = 18 kN/m^3 and γ_{sat} = 20 kN/m^3, respectively. Additionally, the angle of friction φ' is equal to 30°, and the dilation φ is equal to 5°. Due to the fact that homogeneous circumstances reduce complexity [26], the simulation has only utilised a single type of soil. The bridge model depicted in Fig. 5 was developed utilising the CSI Bridge software. The bridge is made of reinforced concrete and has a Poisson's ratio of 0.2 and a Young's modulus of 3×10^7 kN/m^2. The bridge components were constructed using C30/37 concrete, while the unit weight was determined to be γ = 25 kN/m^3 and the elastic modulus was measured as $E = 3.5\times10^6$ kN/m^2.

The p-y link element is a commonly utilised component in geotechnical engineering and finite element analysis software for modelling soil structure interaction (SSI). The lateral soil-structure interaction in the analysis of deep foundation systems, such as piles, is accurately modelled using this technique [15]. This study simulates the interaction between the soil and foundation by assigning nonlinear p-y springs to the nodes throughout the whole length of the equivalent pile at intervals of 0.5 m. The spacing for the lateral springs in the simulation of the foundation was determined from the findings of a prior parametric analysis. This study showed that the hydrodynamic behaviour of the sample bridges remained unchanged when the lateral springs were placed at intervals of 0.5 m. Scour occurs when a section of the bridge foundation, or the corresponding pile, experiences a loss of sideways support from the surrounding soil. In order to simulate the decrease in lateral support, the p-y springs are eliminated until the depth of scour is attained, which is evaluated from the top of the corresponding pile or ground level. The chosen spacing between two adjacent soil springs, measuring 0.5 meters, is a common variable for the depths of erosion under investigation in this study. Therefore, three soil springs, namely those with values of 5, 7.5, and 10, are extracted from the highest point of the pile to imitate scour depths of 2.5 m, 3.75 m, and 5.0 m, respectively. According to Priestley et al. [19], hinge supports are placed at the ends of the comparable piles. Fig. 6 illustrates the piles that have been assigned the p-y link.

The flood impact is measured by the maximum scour depth (Sc) in the intensity measures (IM). The analysis focuses on the increasing maximum scour depth at pier 2, specifically at distances of 1.0 times the foundation depth (Df), 1.5 times Df, and 2 times Df. The foundation depth, denoted as Df, is equal to 2.5 meters. Scouring is assumed to happen when the floodwater reaches a level 1.0 metres above the ground level (G.L), resulting in a flooded channel with a cross-sectional area of approximately 80m^2 and a wetted boundary of 100m. In order to turn the local scour action into a plane strain problem, the geometry of the scour hole is simplified [20].

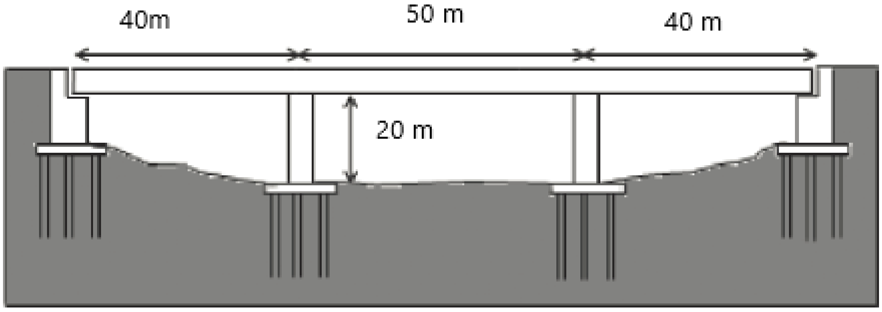


Fig. 3 *Front view of bridge model*

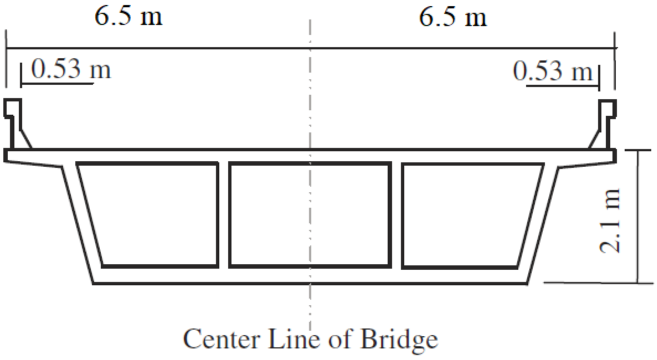
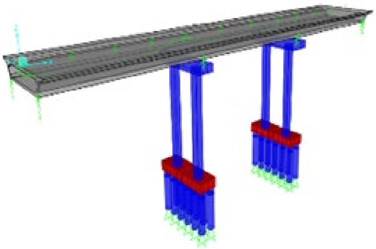


Fig. 4 *Cross section of the box girder*



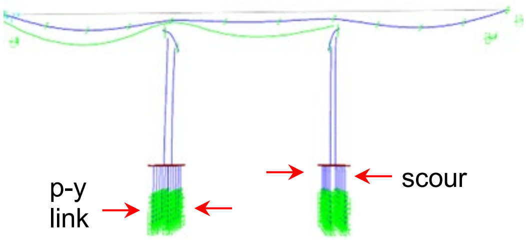


Fig. 5 *Bridge model in CSI Bridge*

Fig. 6 *Scour depth and P-y spring assigned*

As outcrop motion for the analysis, five acceleration time histories reported on rock or very stiff soil were chosen for the earthquake hazard. The minimum quantity of ground motions required for dynamic analysis is thought to be these five: Gubbio-Piana, Italy (1997), Hector Mine, USA (1999), Friuli, Italy (1976), Kocaeli, Turkey (1999), and Duzce, Turkey (1999). Using the Peak Ground Acceleration (PGA) as an indication, the earthquake dangers were evaluated. The time histories in the dynamic studies had their scale altered so that, with a 0.125 g increment, their Peak Ground Accelerations (PGAs) increase from 0.25 to 1.50 g. To model the two dangers occurring one after the other, these PGAs are applied independently for each scour depth, i.e., 2DF, 1.5DF, 1DF, and 0DF. Thus, a total of 220 analyses were examined, which included 4 distinct scour depth levels, 5 seismic events, and 11 PGA levels. Eurocode 8 (EC8) - Part 1 classifies the foundation soil, which is an extremely rigid clay, as ground type B. With increasing depth, its mechanical qualities become more pronounced. The material weighs 19.5 kN/m^3 and has a Poisson's ratio of 0.35. The backfill material has a friction angle of $\varphi = 42°$ and is composed of well-compacted sand. A saturated unit weight of $\gamma = 20$kN/m^3 and an unsaturated unit weight of $\gamma =$ 18.5kN/m^3. For unsaturated circumstances, 0.40 is chosen as the Poisson's ratio, whereas for saturated circumstances, it is 0.35. Argyroudis et al. [3] explain how the features of the saturated soil layers are changed to account for the effects of floods on the soil. Discrete phases are used to simulate the scour effect, representing varying scour depths where the soil around the pier foundation is removed.

2.2 Fragility Assessment

In the context of bedrock settings, fragility equations are mathematical models that evaluate the likelihood of exceeding certain threshold conditions based on a particular measure of earthquake strength called the Peak Ground Acceleration (PGA). Eq. (1), which represents a lognormal probability distribution function, is commonly used to define fragility curves [3],[21]. Two parameters are determined as part of the development procedure: βtot, which represents the overall lognormal standard deviation, and IMmi, which stands for the median threshold value of IM required to create the ith damage state.

$$P(IM) = \Phi\left[\ln\left(\frac{IM}{IM_{mi}}\right) \Big/ \beta_{tot}\right] \tag{1}$$

The relationship between the engineering demand parameters (EDP) and the intensity measure (IM), specifically peak ground acceleration (PGA) for earthquakes, was utilised to create fragility functions for each bridge component. The latter was ascertained using computer simulations that took demand uncertainty and seismic hazard actions into account. Both the maximum vertical displacement of the pier and the maximum bending moment (BM) along the deck were taken into account in the models. Very stiff clay soil was one kind of soil that was taken into account. Changes in danger intensities and the associated ground motions lead to different estimated EDPs. The proper threshold values were established by Argyroudis & Mitoulis [2], and a best-fit regression was used to calculate the median threshold intensity measure (IMmi) for each damage state of every bridge component [22]. The reason for choosing the maximum bending moment (Mmax) as the engineering design parameter (EDP) for the principal deck components is to signify structural failure. Three uncertainty variables are included while determining the overall variability (β_{tot}), which is calculated using Eq. (2). Yuan et al. [23] indicate that the expert opinions establish the uncertainty associated with capacity (β_C) at 0.3 and the uncertainty associated with the definition of damage states (β_{ds}) at 0.4. The standard deviation of the residuals between the computed EDP and the best fit regression is utilised to evaluate the level of uncertainty in response to hazard actions (BD).

$$\beta_{tot}^{\ 2} = \beta_C^{\ 2} + \beta_D^{\ 2} + \beta_{ds}^{\ 2} \tag{2}$$

The existence of steel buckling and concrete cracking indicates the bridge deck's modest damage status. The quantity of moderate damage incurred by the deck is shown by the yielding bending moment (My). In contrast, a bending moment of 1.5My defines the conditions for the state of significant damage to the deck. The equivalent dynamic properties (EDP) of the pier are thought to be replaced by the drift ratio, and Jain et al. [13] have applied the damage criterion established by Kim & Shinozuka [24].

3. Results and Analysis

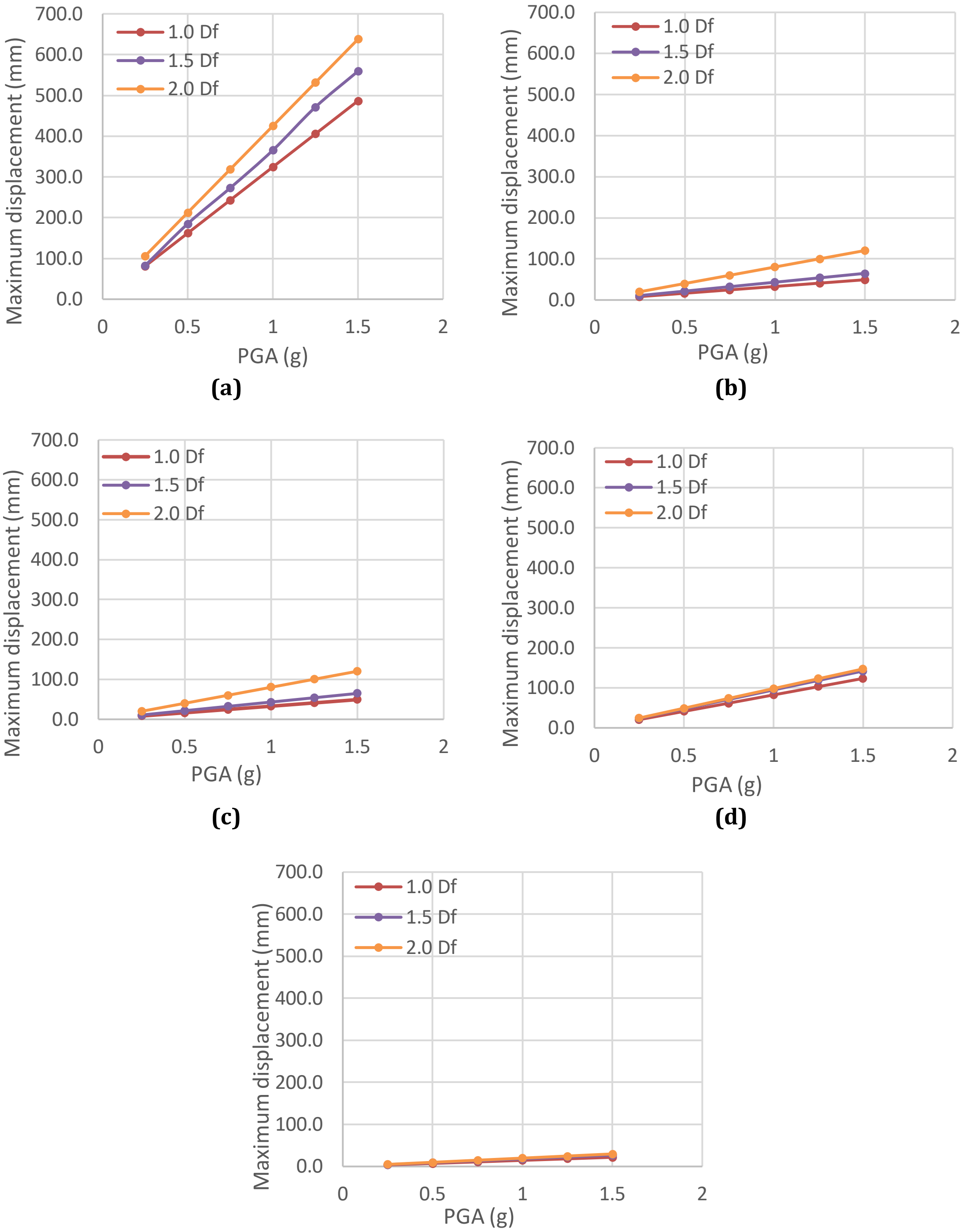
3.1 Effect of Different Scour Depths on Pier Displacement

This study investigates the impact of varying scour depths on pier displacement, specifically analysing depths of 2Df, 1.5Df and 1Df, with Df representing the foundation depth of 2.5 meters. The findings reveal a direct correlation between increased scour depth and greater pier displacement. As depicted in Fig. 7, at a scour depth of 1Df (2.5 meters), the pier exhibits moderate displacement across all five simulated earthquake events, establishing a baseline level of stability. When the scour depth increases to 1.5Df (3.75 meters), there is a marked rise in displacement, indicating that the reduction in effective foundation depth substantially impairs the pier's resistance to lateral forces. At the maximum scour depth of 2Df (5.0 meters), the displacement becomes significantly pronounced, underscoring a critical decline in structural stability. These results emphasise the necessity of considering potential scour effects in bridge design and maintenance, as deeper scour depths can severely compromise foundation integrity and heighten vulnerability under dynamic loading conditions. Understanding these impacts enables engineers to devise effective countermeasures to mitigate scour-related risks.

3.2 Bridge System Fragility at Pier

The bridge system fragility curves presented in Fig. 8 depict the probability of the bridge reaching three defined damage states-minor, moderate, and extensive-based on time history analysis using peak ground acceleration (PGA) as the intensity measure (IM). These fragility curves are generated for very stiff clay, considering four distinct scour depth scenarios. The bridge's highest probabilities of reaching minor, moderate, and extensive damage states on stiff clay soil are 0.9996, 0.9770, and 0.8549, respectively, all of which are associated with the

2Df scour depth scenario. The analysis reveals that scour depth has a significant impact on the probability of exceeding all damage states. As scour depth increases, the likelihood of the bridge sustaining damage under seismic loading escalates. The very stiff clay foundations indicate that bridges exhibit higher probabilities of damage. Thus, it suggests that bridges founded on stiff clay are susceptible to seismic damage.

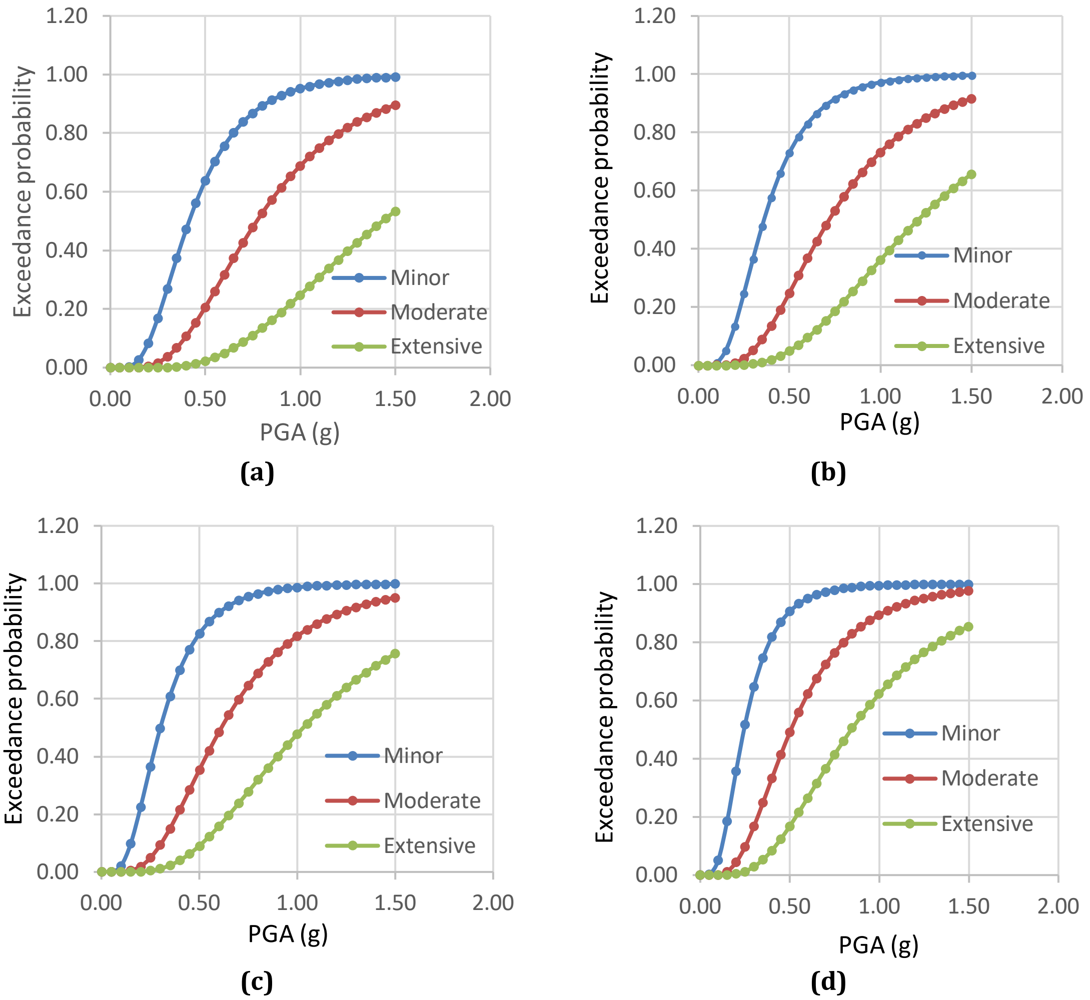


(a) **(b)** **(c)** **(d)** **(e)**

Fig. 7 *The effect of different scour depth on pier's displacement for all earthquake's events: (a) Duzce; (b) Kocaeli; (c) Gubbio-Piana; (d) Hector Mine; and (e) Friuli*

3.3 Combine the Effect of Seismic and Flood-Induced Scour

This analysis investigates the combined effects of seismic activity and flood-induced scour on bridge stability using advanced simulations. The 3D graphs have been generated to illustrate the probability of the bridge reaching minor, moderate, and extensive failure modes. The study has been implemented in very stiff clay and evaluates three scour depths: 1Df, 1.5Df, and 2Df, where Df denotes the foundation depth of 2.5 meters. By integrating these variables, the research aims to provide a comprehensive understanding of the impact of concurrent seismic and scour events on bridge performance. The 3D visualisations offer a detailed comparison, highlighting the varying degrees of vulnerability under different conditions.



(a) **(b)**

(c) **(d)**

Fig. 8 *Bridge system fragility at pier: (a) No scour; (b) 1Df; (c) 1.5Df; and (d) 2Df*

Referring to Fig. 9, a comparison of the three failure modes (minor, moderate, and extensive) reveals that clayey soil exhibits a higher probability of reaching each failure mode. This suggests that bridges built on clay are more susceptible to both seismic and scour-induced damage. It also exhibits that clay provides initial stability; its cohesive nature may lead to larger displacements and higher failure probabilities under combined dynamic loading and scour conditions. These findings show how important it is to use custom engineering solutions to make bridges more durable, especially ones with clayey foundations that are vulnerable to both scour and earthquakes [9].

Additionally, the findings indicate that the likelihood of a bridge experiencing minor damage is significantly higher than that of sustaining moderate or extensive damage. This is due to the relative ease with which a bridge can incur minor damage rather than a complete pier collapse when subjected to combined scour and earthquake hazards. These results align with the study by Argyroudis & Mitoulis [2], which also demonstrated a similar pattern when comparing these hazards. While minor damage may be frequent and less costly to repair, the cumulative effect over time can weaken the bridge's structural integrity, emphasising the need for regular maintenance and early intervention strategies. Furthermore, the higher probability of minor damage highlights Next, empirical data indicate that for all earthquake events, clayey soil experiences a significantly greater increase in displacement with increasing scour depth. Specifically, during the Gubbio-Piana event, clayey soil recorded an 83.3% increment in displacement from the no scour case to the 2Df scour case. Clayey soil is very easily damaged because its particles are smaller, and it is more flexible. This means that it holds more water and is easier to compress, which makes it more likely to deform during earthquakes. The presence of scour exacerbates this vulnerability, resulting in significantly higher displacements in clayey soils, which are more stable and less affected by changes in scour depth. The importance of implementing robust design and construction practices to enhance the resilience of bridges against multiple hazards.

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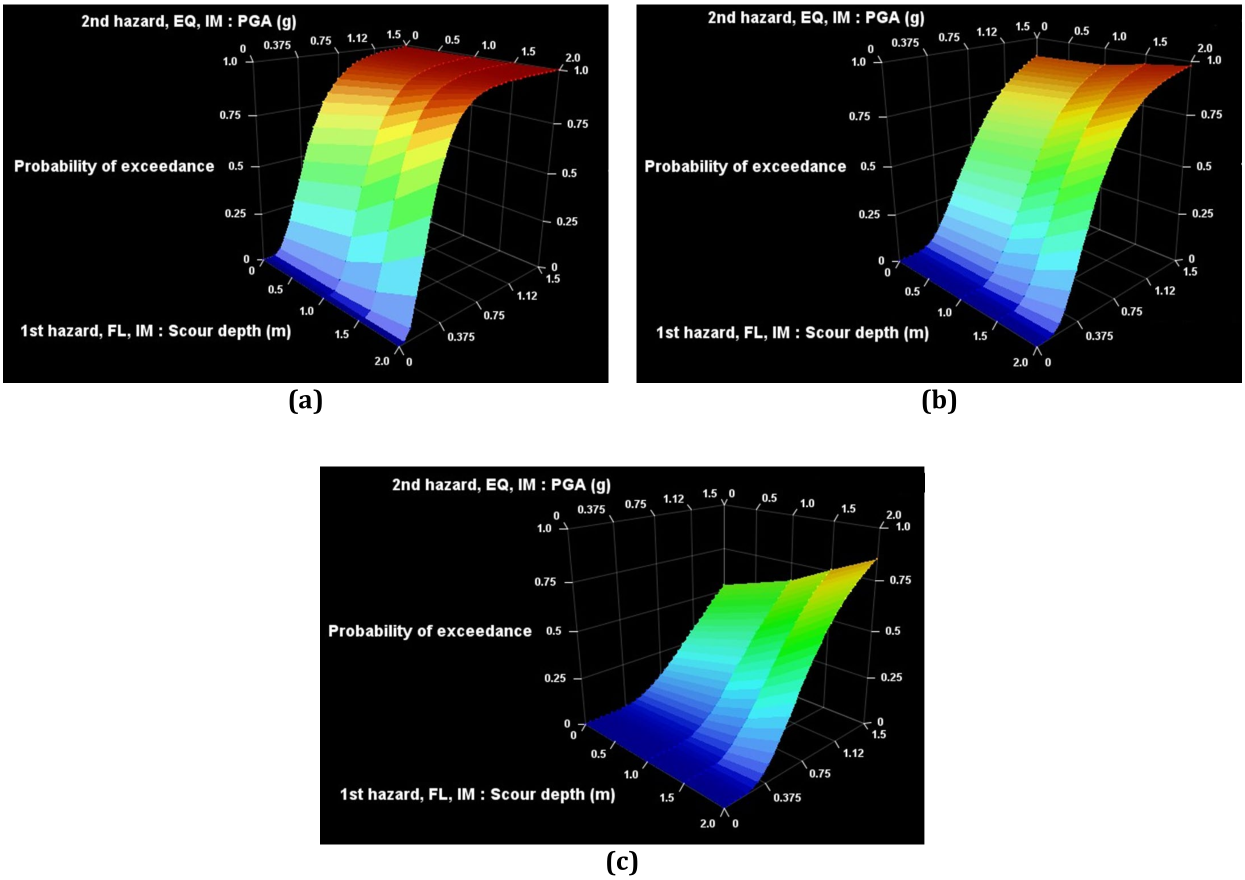

(a) (b)

(c)

Fig. 9 *3D fragility curve for all damage states (minor, moderate and extensive): (a) Clay (moderate) with a highest failure probability of 0.976960; (b) Clay (moderate) with the highest failure probability of 0.976960; and (c) Clay (extensive) with the highest failure probability of 0.854853*

As the scour depth increases, the percentage increment in pier displacement becomes markedly higher. For example, in the Duzce scenario, there was a modest 3.44% increase in pier displacement from no scour to 1Df scour depth. However, a substantial increase of 21.68% was observed when the scour depth increased from 1.5Df to 2Df. This pattern suggests that deeper erosion, which exposes more of the foundation, progressively weakens the structural integrity of the pier. The fact that the observed increase in displacement happened when scour conditions got worse shows how important it is to take scour depth into account when designing and testing the seismic performance of bridge piers, especially in places where the soil is clayey and easily deformed. Implementing scour protection and soil stabilisation measures is essential to mitigate the risks of deep scour and to maintain structural integrity during seismic events.

The variations in displacement are primarily attributed to the distinct dynamic loading characteristics of each earthquake, including differences in velocity and acceleration spectra. These factors influence the interaction between seismic waves, soil, and structures, thereby affecting the displacement experienced by bridges founded on clayey soils during seismic events [2].

4. Conclusions

This study underscores the critical impact of soil-structure interaction on bridge stability under seismic and scour conditions, particularly highlighting the vulnerability of bridges founded on clayey soils. The study shows that when scour depths get deeper, there are big changes in the structure and different ways it could fail. This shows how important it is to take these things into account when designing and maintaining bridges. The findings offer valuable insights for policymakers, engineers, and the Public Works Department, advocating for the incorporation of enhanced multi-hazard resilience in infrastructure projects.

A major contribution of this research is the development of new fragility models for combined hazards, specifically addressing flood-induced scour and seismic events. These models, represented as curves or surfaces, introduce a novel methodology for predicting the resilience of bridges under multiple hazards. This study improves the dependability of fragility functions by analysing various realistic scour hole geometries and standard intensity metrics, including scour depths reaching twice the foundation depth and peak ground accelerations of up to 1.5 g. This advancement in fragility modelling provides a more accurate framework for assessing and mitigating risks, ultimately contributing to safer and more resilient bridge infrastructure.

As a conclusion, this research holds significant practical implications, enabling realistic risk evaluations for network owners and operators. It facilitates an accurate estimation of performance and anticipated losses from single or multiple bridge failures. The insights gained from this analysis benefit designers and assessors by providing a comprehensive evaluation of transportation assets throughout their life cycle, which is crucial for informed decision-making and proactive hazard mitigation strategies. These evaluations help infrastructure owners in predicting anticipated damage, financial losses, and declines in asset performance across diverse danger scenarios. In conclusion, this study contributes to the projection of the impacts of hazards on local networks and the quantification of resilience to natural and climatic stressors at both the regional and national levels.

Acknowledgement

The study was funded by a grant from the Ministry of Higher Education of Malaysia (FRGS Grant: R0149 - FRGS/1/2022/TK06/UPNM/02/3).

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***Study conception and design:*** *Nordila Ahmad;* ***Data collection:*** *Syuriya Mohamad, Muhammad Amir Syauqi Mohd Syukri;* ***Analysis and interpretation of results:*** *Nordila Ahmad, Syuriya Muhammad, Muhammad Amir Syauqi Mohd Syukri;* ***Draft manuscript preparation:*** *Syuriya Mohamad, Nordila Ahmad;* ***Critical review of the hydrodynamic forces and sediment transport:*** *Zuliziana Suif;* ***Critical reviewing of the soil properties and soil interactions:*** *Jestin Jelani; and* ***Critical reviewing of numerical modelling:*** *Mohd Zamri Ramli. All authors reviewed the results and approved the final version of the manuscript.*

References

[1] Anisha, A., Jacob, A., Davis, R., & Mangalathu, S. (2022). Fragility functions for highway RC bridge under various flood scenarios. Engineering Structures, 260, 114244. https://doi.org/10.1016/j.engstruct.2022.114244

[2] Argyroudis, S. A., & Mitoulis, S. A. (2021). Vulnerability of bridges to individual and multiple hazards- floods and earthquakes. Reliability Engineering and System Safety, 210, 107564. https://doi.org/10.1016/j.ress.2021.107564

[3] Argyroudis, S., Mitoulis, S., Kaynia, A. M., & Winter, M. G. (2018). Fragility assessment of transportation infrastructure systems subjected to earthquakes. Geotechnical Earthquake Engineering and Soil Dynamics, V, 174–183. https://doi.org/10.1061/9780784481479.018

[4] Thestructuralengineer.info (2018). Bridge collapse due to heavy rain in Cuba. News On Natural Disasters/Failures. https://www.thestructuralengineer.info/news/bridge-collapse-due-to-heavy-rain-in-cuba#:~:text=As%20a%20result%20of%20the,Cuba%20collapsed%20on%20Monday%20afternoon

[5] Kawashima, K., & Matsuzaki, H. (2012). Damage of road bridges by 2011 Great East Japan (Tohoku) earthquake. Proceeding of the 15th World Conference on Earthquake Engineering, 2, 82-101.

[6] Argyroudis, S., Tubaldi, E., Pregnolato, M., & Aristoteles Mitoulis, S. (2019). Fragility of bridges exposed to multiple hazards and impact on transport network resilience. SECED 2019: Earthquake Risk and Engineering Towards a Resilient World. https://www.researchgate.net/publication/336851412

[7] Bouassida, Y., Bouchon, E., Crespo, P., Croce, P., Davaine, L., Denton, S., Feldmann, M., Frank, R., Hanswille, G., Bouassida, Y., Bouchon, E., Crespo, P., Croce, P., Davaine, L., Denton, S., ... & Tsionis, G. (2012). Bridge Design to Eurocodes Worked Examples. JRC European Commission.

[8] Chavan, V. S., Chen, S. E., Shanmugam, N. S., Tang, W., Diemer, J., Allan, C., Braxtan, N., Shukla, T., Chen, T., & Slocum, Z. (2022). An analysis of local and combined (global) scours on piers-on-bank bridges. Civil Engineering, 3, 1–20. https://doi.org/10.3390/civileng3010001

[9] Cinitha, A., Umesha, P. K., & Iyer, N. R. (2014). Soil structure interaction analysis for seismic response of an asymmetric RC building. Proceeding of the 5th International Congress on Computational Mechanics and Simulation, Chennai, India. https://doi.org/10.3850/978-981-09-1139-3_225

[10] EN 1998-1 (2004). Eurocode 8: Design of Structures for Earthquake Resistance–Part 1: General Rules, Seismic Actions and Rules for Buildings. European Committee for Standardization.

[11] Banerjee, S., & Prasad, G. G. (2011). Analysis of bridge performance under the combined effect of earthquake and flood-induced scour. Vulnerability, Uncertainty, and Risk: Analysis, Modeling, and Management, pp. 889-896. https://doi.org/10.1061/41170(400)10

[12] Hwang, H., Liu, J. B., & Chiu, Y. H. (2001). Seismic Fragility Analysis of Highway Bridges. Mid-America Earthquake Center.

[13] Jain, A., Davis, R., & Nanda Kumar, C. G. (2020). Seismic fragility analysis of bridge pier. IOP Conference Series: Materials Science and Engineering, 936, 012014). https://doi.org/10.1088/1757-899X/936/1/012014

[14] Kim, H., Sim, S. H., Lee, J., Lee, Y. J., & Kim, J. M. (2017). Flood fragility analysis for bridges with multiple failure modes. Advances in Mechanical Engineering, 9, 1-11. https://doi.org/10.1177/1687814017696415

[15] Mansouri, S., Kontoni, D. P. N., & Pouraminian, M. (2022). The effects of the duration, intensity and magnitude of far-fault earthquakes on the seismic response of RC bridges retrofitted with seismic bearings. Advances in Bridge Engineering, 3, 19. https://doi.org/10.1186/s43251-022-00069-8

[16] Nofal, O. M., van de Lindt, J. W., & Do, T. Q. (2020). Multi-variate and single-variable flood fragility and loss approaches for buildings. Reliability Engineering & System Safety, 202, 106971. https://doi.org/10.1016/J.RESS.2020.106971

[17] Pandikkadavath, M. S., Jithiya, K. K., Nagarajan, P., & Mangalathu, S. (2022). Seismic mainshock–aftershock response assessment of reinforced concrete bridges pre-exposed to flood induced local scouring. Bulletin of Earthquake Engineering, 20, 8253–8275. https://doi.org/10.1007/s10518-022-01519-4

[18] Rajkumari, S., Thakkar, K., & Goyal, H. (2022). Fragility analysis of structures subjected to seismic excitation: A state-of-the-art review. Structures, 40, 303-316. https://doi.org/10.1016/j.istruc.2022.04.023

[19] Priestley, M. J. N., Seible, F., & Calvi, G. M. (1996). Seismic Design and Retrofit of Bridges. John Wiley and Sons.

[20] Zampieri, P., Zanini, M. A., Faleschini, F., Hofer, L., & Pellegrino, C. (2017). Failure analysis of masonry arch bridges subject to local pier scour. Engineering Failure Analysis, 79, 371-384.

[21] Mackie, K. R., & Stojadinović, B. (2007). Performance-based seismic bridge design for damage and loss limit states. Earthquake Engineering & Structural Dynamics 36, 1953-1971. https://doi.org/10.1002/eqe.699

[22] McKenna, G., Argyroudis, S. A., Winter, M. G., & Mitoulis, S. A. (2021). Multiple hazard fragility analysis for granular highway embankments: Moisture ingress and scour. Transportation Geotechnics, 26, 100431. https://doi.org/10.1016/j.trgeo.2020.100431

[23] Yuan, L. F. V., Argyroudis, S. A., Tubaldi, E., Pregnolato, M., & Mitoulis, S. A. (2019). Fragility of bridges exposed to multiple hazards and impact on transport network resilience. Proceedings of the 2019 Society for Earthquake and Civil Engineering Dynamics conference (SECED 2019). Society for Earthquake and Civil Engineering Dynamics (SECED).

[24] Kim, S. H., & Shinozuka, M. (2004). Development of fragility curves of bridges retrofitted by column jacketing. Probabilistic Engineering Mechanics 19, 105-112. https://doi.org/10.1016/j.probengmech.2003.11.009

[25] Annad, M., Zourgui, N. H., Lefkir, A., Kibboua, A., & Annad, O. (2023). Scour-dependent seismic fragility curves considering soil-structure interaction and fuzzy damage clustering: A case study of an Algerian rc bridge with shallow foundations. Ocean Engineering, 275, 114157. https://doi.org/10.1016/j.oceaneng.2023.114157

[26] Zhang, G., Zhang, J., Liu, Y., & Cao, Y. (2024). Seismic fragility analysis of long-span rigid-frame bridge on mountainous soft clay site. Advances in Bridge Engineering, 5, 25. https://doi.org/10.1186/s43251-024-00136-2