

Effects of Near-Fault and Far-Fault Ground Motions on Pile Sections of Integral Abutment Bridges Considering Soil Liquefaction

Abdul Hakim Hotak

hakim@lu.edu.af

Laghman University

QiuHong Zhao

Tianjin Chengjian University

Mohammad Khalid Nasiry

Laghman University

Research Article

Keywords: Integral abutment bridges, Ground Motions, Soil liquefaction, Seismic behavior, Pile section

Posted Date: October 30th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11367032/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Effects of Near-Fault and Far-Fault Ground Motions on Pile Sections of Integral Abutment Bridges Considering Soil Liquefaction

Abdul Hakim Hotak^{*2,3}, Qihong Zhao^{1,2}, Mohammad Khalid Nasiry³

1. Tianjin Key Laboratory of Civil Structure Protection and Reinforcement, Tianjin Chengjian University, Tianjin, 300192 China.
2. School of Civil Engineering, Tianjin University, Tianjin, 300350, China.
3. Department of Civil Engineering, Laghman University, Mehtarlam, Laghman 270101, Afghanistan.

Email of the corresponding authors: hakim@lu.edu.af

Author Contributions

Qihong Zhao: Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. Abdul Hakim Hotak: Writing – original draft, Visualization, Investigation, Data curation, and Methodology. Mohammad Khalid Nasiry: Writing – review & editing, Resources. All authors engaged in the review of results and sanctioned the final manuscript.

Acknowledgments

The authors gratefully acknowledge the financial support for this research by the Tianjin Science and Technology Bureau Key Research and Development Program under grant number 23YFXTHZ00010, and the National Natural Science Foundation of China (NSFC) under grant number No.52208193 and No.51878447; this support is greatly appreciated.

Declaration of Competing Interest

The authors wish to state that they have no conflicts of interest or competing financial or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

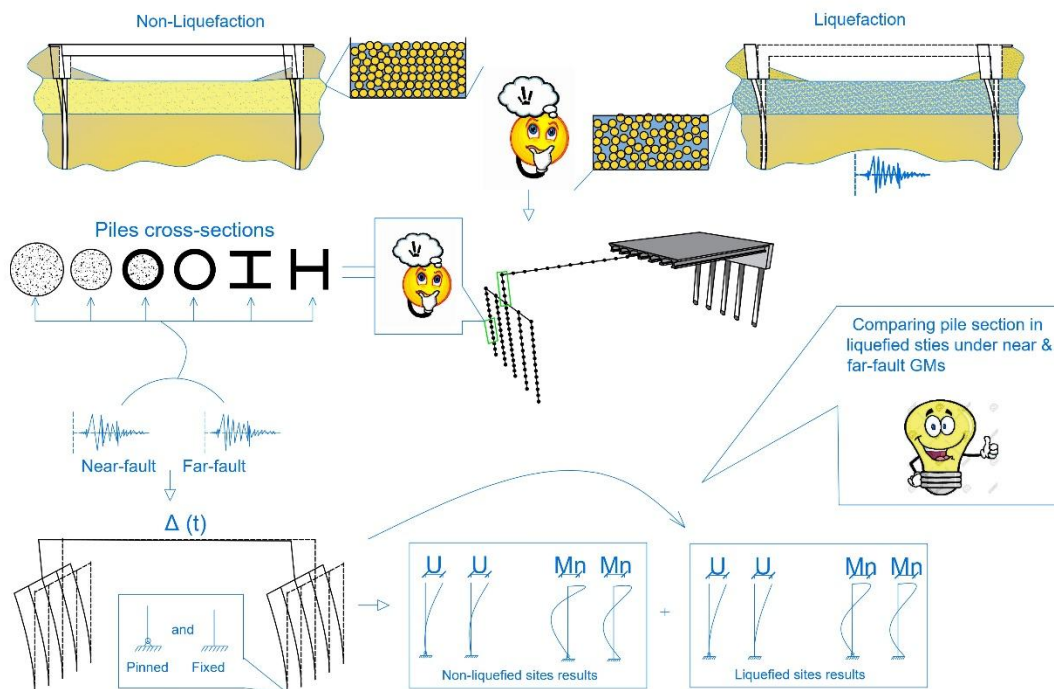
The datasets used or analyzed during the current study are available from the corresponding author upon reasonable request.

Abstract

Integral abutment bridges (IABs) provide a frame-like structure without construction joints, and it is advised to support them with flexible piles. Soil liquefaction, which reduces strength and stiffens the soil, may impact the seismic response of IABs. This study investigates the impact of liquefaction on IAB piles, concentrating on the parametric study of different pile sections exposed to near-fault and far-fault ground motions (GMs). The Pyliq1 material model and zero-length elements in OpenSees were employed to simulate soil liquefaction around the piles, with numerical results corroborated by the experimental centrifuge tests. Results indicated that pile response differs with GM type; RCC piles demonstrated higher response under near-fault GMs, whereas steel piles showed higher response under far-fault GMs. CFST (Concrete-filled steel-tube) piles exhibited superior seismic resilience due to their flexibility. In summary, suggested to use CFST for support of IAB in liquefied soil or when using H-steel piles in liquefied soil, reinforce the piles in high-stress regions using available strengthening techniques.

Keywords: Integral abutment bridges, Ground Motions, Soil liquefaction, Seismic behavior, Pile section.

Graphical Abstract



1. Introduction

The integrity and performance of infrastructure, such as bridges, can be damaged when saturated soils undergo liquefaction, resulting in a loss of strength and stiffness during seismic activity (Kwon and Yoo 2020), hence diminishing the axial and lateral bearing capacities of piles (Setyadi, Rifa'i, and Indrawan 2024). Catastrophic earthquakes, including the Maduo earthquake in China (Jinyuan et al. 2023), the Kahramanmaraş earthquake in Turkey (Ozkaynak and Cetin 2024), and the Bhuj, Niigata, Alaska, and Tangshan earthquakes (Satyam 2012; Bhattacharya and Kappos 2014a; Mohanty and Bhattacharya 2019), have all demonstrated this propensity. These instances underscore the necessity for earthquake design to consider dynamic soil-structure interaction (SSI) and soil liquefaction.

Integral abutment bridges (IABs) offer a frame-type structure without construction joints, where flexible piles are suggested to support the IAB for lateral movement. The type of foundation and the condition of the soil have a significant impact on the dynamic response between SSI and substructures (abutments, piles, and piers) of IAB. Due to soil liquefaction, the soil loses its strength and stiffness, causing seismic energy to disperse and reducing the acceleration amplitudes of structures (Wang, Luo, and Ye 2023; AASHTO 2011). However, the response of IAB pile sections in liquefied soil under near-fault and far-fault ground motions remains unclear.

During an earthquake, a bridge experiences longitudinal and transverse forces due to ground shaking, which can lead to displacement and deformation of its components. To mitigate this, bridge elements are designed to resist lateral movements, transferring earthquake forces from the superstructure (bridge deck) to the substructure (abutments and piers) (Greimann et al. 1984). The typical foundation type for IABs is steel H-piles, which provide flexibility under thermal and seismic excitation, and simplify design and construction (Naji and Firoozi 2020; Alshawabkeh et al. 2023). However, depending on specific project requirements, such as bridge length, skew angle, and site conditions alternative foundation methods may be used (Dunker and Liu 2007). Salman and Issa (Salman and Issa 2021) modeled an IAB supported by steel H-piles to examine the limitations of various design criteria. They recommend using larger H-pile sections for piles embedded in soft soil to minimize stress and extend the bridge's service life. When smaller H-pile sections are used, the researchers suggest reinforcing the piles in high-stress regions using available strengthening techniques. Recent studies have introduced the use of pre-drilled holes in the soil to improve pile flexibility, enhance resistance to lateral loads, and mitigate excessive pile stress (Xue et al. 2021; Rui-Huan et al. 2022). Chen et al. (2024) suggested that an economical option for IABs is the novel HS-RC stepped pile idea (HS is H-shaped steel and RC is reinforced concrete), where a lower stiffness ratio improves crack resistance and raises plastic deformation capacity. Alshawabkeh et al. (2023) demonstrated that the lateral buckling capability of IAB piles is inversely related to pile length and axial compressive magnitude and directly relates to pile size and material yield strength. In order to avoid the degradation of their axial load-bearing capacity, pile sections must be meticulously selected. Alshawabkeh and Issa (2024) proposed a design aid approach to help bridge engineers determine the maximum safe length of steel and concrete IABs, taking into account pile size, soil stiffness, and climate variables.

A crucial field of study in earthquake engineering is SSI, especially in light of the consequences of soil liquefaction. Liquefaction is a phenomenon whereby cyclic loading, such as shaking from earthquakes, reduces the strength and stiffness of soil. Many infrastructure components, such as bridges, buildings, dams, highways, and pipelines, are seriously threatened by soil liquefaction (Deierlein and Zsarnóczay 2021; Zhao et al. 2025; Gingery 2014). There is strong evidence from all across the world that earthquake loads can cause soil liquefaction (Maugeri and Soccodato 2014)(Cubrinovski et al. 2017). For instance, the Kanto region, which is more than 200 kilometers from the earthquake fault, saw widespread liquefaction in the wake of the 2011 Tohoku Pacific Ocean earthquake (M9.0). In the Kanto region, which includes Ibaraki, Chiba, and Tokyo, there was a notable degree of liquefaction in reclaimed deposits along rivers and bay areas. These regions are located up to 300–400 km southwest of the main shock's epicenter, and an estimated 70 km² of land was covered by the liquefaction signs that were seen. Even though they were as far as 450–500 km from the epicenter of the earthquake, large swaths of Tokyo Bay and the Tone River downstream suffered liquefaction-related damage (Maugeri and Soccodato 2014). In several New Zealand cities, the Kaikoura Earthquake (M7.8) in November 2016 showed evidence of soil liquefaction (Cubrinovski et al. 2017). Soil liquefaction in a bridge's foundation extends the unsupported length of piles, which can result in the failure of both the superstructure and substructure. Additionally, in liquefied soil, the bridge's natural period increases, leading to greater component displacement, higher bending moments, buckling, and cracking—ultimately causing structural failure (Inqualabi, Garg, and Rao 2017; Bhattacharya and Kappos 2014b; Mohanty, Dutta, and Bhattacharya 2017; Song et al. 2023; AASHTO 2011; Turner, Brandenburg, and Stewart 2016; Zhang et al. 2020; Meyersohn 1994).

In earthquake engineering, distinguishing between near-fault and far-fault ground motions is essential for infrastructure safety. Near-fault motions, occurring close to the fault (less than 10 km), are characterized by high peak velocities, permanent displacements, and strong directivity pulses, posing significant challenges for structural design, especially in critical infrastructure (Xiang et al. 2023; Bilgin 2024; Kazaz, Bilge, and Gürbüz 2024). In contrast, far-fault motions, occurring at greater distances, have lower peak velocities and more gradual shaking but can still impact structures due to their broad frequency content (Hotak, Zhao, and Gui 2025). A thorough understanding of both motion types is crucial for resilient seismic design, as near-fault motions often include highly dynamic, long-period velocity pulses. Therefore, it is necessary to evaluate the effect of soil liquefaction on integral abutment bridges under near-fault and far-fault ground motions.

In summary, the seismic response of IAB pile sections in liquefied soil may differ significantly from that in non-liquefied soil. However, to our knowledge, no published research has specifically addressed this issue, particularly regarding the effects of near-fault and far-fault GMs on IAB pile sections. This study investigates these effects through finite element analyses using the OpenSees computational framework, validated against a centrifuge experimental model provided by Wilson (1998). Nonlinear time-history analyses were performed on refined models of single-span IABs subjected to 10 recorded near-fault and far-fault GMs, incorporating p-y springs to account for soil liquefaction. The findings highlight the importance of enhancing IAB resilience against natural hazards, particularly earthquakes and soil liquefaction.

2. Bridge modeling and soil properties

The integral abutment bridge was modeled as a prestressed concrete girder bridge, with its key features outlined in **Table 1**. The bridge details were obtained from a previous study by Erhan and Dicleli (2014). **Figure 1** presents the elevation layout, typical cross-section of the bridge, and different pile sections. Additionally, the number of piles was determined based on the soil's bearing capacity, following the guidelines of Joseph and Bowles (1997). The IAB was analyzed using six types of pile cross-sections: RCC8 and RCC5 (reinforced concrete piles with diameters of 0.8 and 0.5 meters, respectively), HSST (HSS20.000x05 steel-pipe piles), HPW and HPS (H-steel piles oriented along the strong and weak axes, respectively), and CFST (concrete-filled steel tubes). The CFST piles consist of HSS20.000x05 steel pipes filled with concrete. All piles extend 20 meters below the abutment. The steel has a yield strength of 420 MPa and Young's modulus of 210 GPa, while the concrete in the piles has a compressive strength of 30 MPa.

The pile foundations were embedded in a two-layer soil system. The upper layer is composed of saturated sand with an effective density of 17.33 kN/m³ and a friction angle of 36°, which extends to a depth of 8.5 meters. Beneath this, the second layer, ranging from 8.5 to 20 meters, consists of stiff clay with an effective density of 18.14 kN/m³ and an undrained shear strength of 200 kPa. The abutment backfill was assumed to be made of densely compacted sand, characterized by a soil density of 23.2 kN/m³ and a friction angle of 45°, as specified in the reference (Vasheghani-Farahani, Zhao, and Burdette 2010).

Table 1. Bridge details and material

Type of bridge		Details	Number of element	Young's modulus of Material	
				Concrete	Steel
Bridge details	Single span	41m	41 x 1	E = 33.234 GPa	
	Width of bridge	16m			
	Girder information	AASHTO type-VI girders	7		
	Deck thickness	0.225m			
	Abutment	15 x 4 x1		E = 25.742 GPa	E = 210 GPa
	Pile Type	HPW	HP14 x 117 about weak axis (HPW)		

	HPS	HP14 x 117 about strong axis (HPS)	9
	RCC5	D = 0.5m	6
	RCC8	D = 0.8m	3
	HSST	HSS20.000 x 05	9
	CFST	CFST	6
Pile depth		20m	

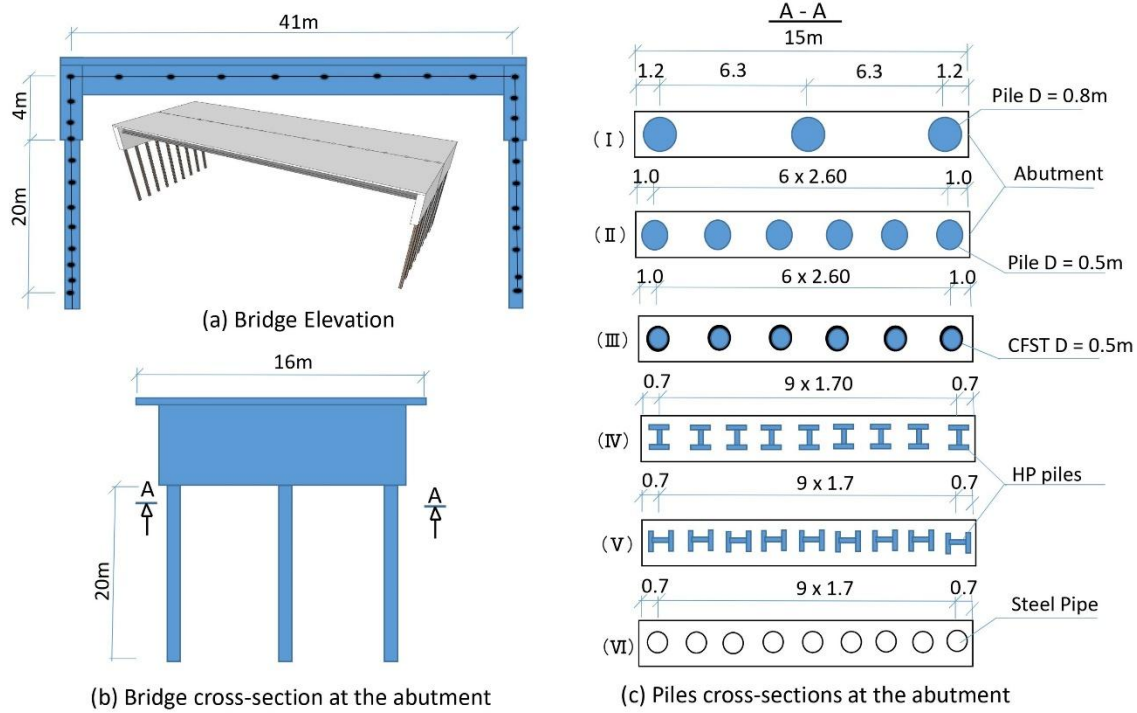


Fig. 1. Integral abutment bridge details and piles cross-sections

2.1. Nonlinear soil spring

In this study, the soil surrounding the piles was assumed to be sand, considering the potential for soil liquefaction. To account for soil-structure interaction, nonlinear discrete Winkler spring elements were placed perpendicular to the rear of the abutment and around the piles. The p-y spring element material developed by Brandenburg et al. (2013), known as PyLiq1, was used to model soil liquefaction effects, with the residual soil resistance set to 0.1 based on previous studies (Rabeti Moghadam, Alielahi, and Sadeghi 2017; Mazzoni et al. 2006). Nonlinear p-y springs were implemented using zero-length elements, linking pile nodes to soil nodes to simulate the soil foundation (Gergely 2016).

For the clay layer, the PySimple1 material in OpenSees was applied. Both PyLiq1 and PySimple1 materials are defined by ultimate resistance (P_u) and y_{50} , the displacement at 50% of ultimate resistance. A key distinction lies in the ultimate capacity of the p-y spring material, which depends on the mean effective stress in the free field. As pore pressure rises in the free field, the ultimate capacity of the p-y spring decreases. When the mean effective stress reaches zero, the ultimate capacity reduces to a residual value (Aygün et al. 2011; Brandenburg et al. 2013; Bowers 2007; Xie, Zhang, and Huo 2018).

The ultimate soil capacity was calculated following API guidelines (API (American Petroleum Institute) 1993), with p-y springs spaced at 0.5 meters. The ultimate soil resistance for various pile sections was represented through p-y curves, as illustrated in Fig. 2. Additionally, nonlinear compression p-y spring elements

incorporating HyperbolicGap Material characteristics were used to simulate the soil behind the abutment (Shamsabadi, Rollins, and Kapuskar 2007).

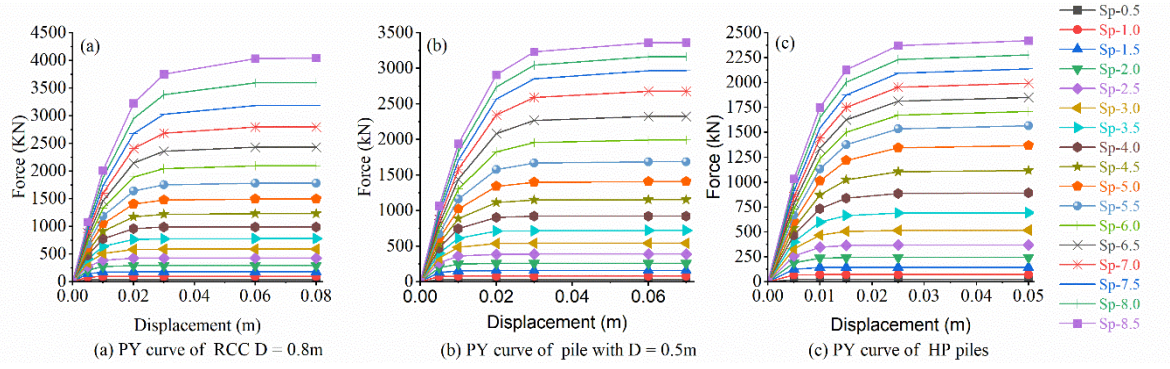


Fig. 2. Force and displacement py curves

3. Validation and numerical modeling

3.1. Validation

Experimental investigations and numerical simulations utilizing OpenSees were performed to deepen the understanding of pile foundation behavior in liquefied soils under seismic loading. This approach aims to refine the numerical model, ensuring a more precise representation of the physical phenomena observed in experimental studies. To validate the numerical methodology, a single vertical pile was simulated, and its results were compared with those from Wilson's 1998 centrifuge experiment (CSP2) (Wilson 1998). **Fig. 3a** presents the configuration of the partial model prototype. In this setup, a 6061-T6 aluminum pipe, with an outer diameter of 0.67 m and a thickness of 0.072m, was embedded in stratified Nevada sand. The relative densities of the soil, in liquefied and non-liquefied conditions, were approximately 40% and 80%, respectively. The effective unit weight of the liquefied soil was 19.0 kN/m³, with a friction angle of 32°, whereas for the non-liquefied soil, these values were 20.0 kN/m³ and 38°, respectively. A superstructure weighing 49.1 tons was positioned atop the pile at a height of 3.81 meters above the ground surface. Nonlinear discrete Winkler spring elements (*p-y* springs) were placed along the perimeter of the piles. The ultimate soil capacity was determined based on API guidelines, with the springs spaced at 0.5-meter intervals as shown in **Fig. 3b**. Additional details regarding the nonlinear springs have been discussed in previous sections. The acceleration data from the 1995 Kobe earthquake (depicted in **Fig. 3c**) was scaled to a peak magnitude of 0.46g and utilized as the input ground motion for the experiment.

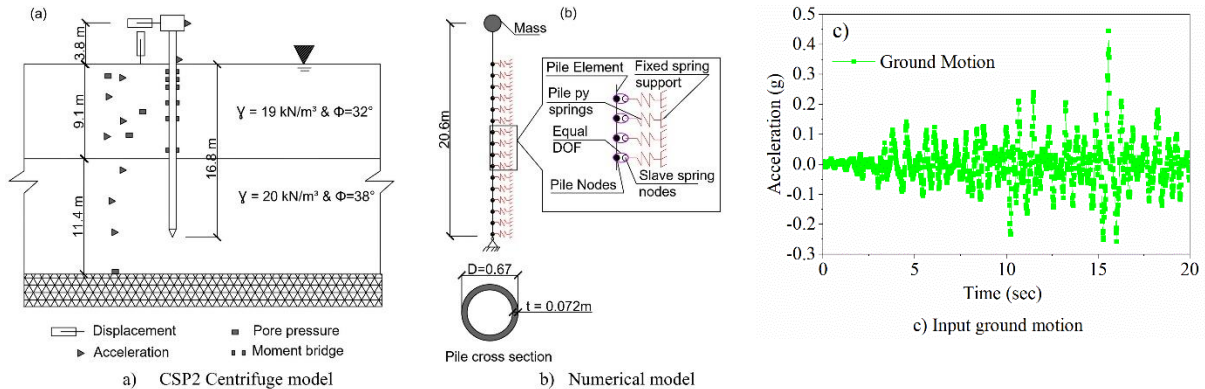


Fig. 3. Wilson experimental model and numerical model in OpenSees

Validating the numerical model is crucial to ensure its accuracy in predicting the seismic response of pile foundations. The strong correlation between the numerical simulations and Wilson's (1997) experimental data for the CSP2-J model, as shown in Fig. 4, provides substantial evidence of the model's accuracy. The consistency in pile acceleration trends (Fig. 4a), displacement responses (Fig. 4b) and bending moments at different points

of piles (Fig. 4c and 4d) further confirms its ability to accurately capture the superstructure's dynamic behavior. The lack of comprehensive soil data is probably the cause of the disparities seen, especially in amplitude and phase. It's possible that the lack of thorough information affected the realistic depiction of vital soil characteristics, such as stiffness and damping, which are critical when simulating soil-structure interactions under seismic loading. Despite these difficulties, the numerical model's performance has been greatly enhanced by the addition of nonlinear soil behavior and sophisticated calibration methods. Overall, the good agreement between the numerical and experimental results supports the suggested modeling strategy.

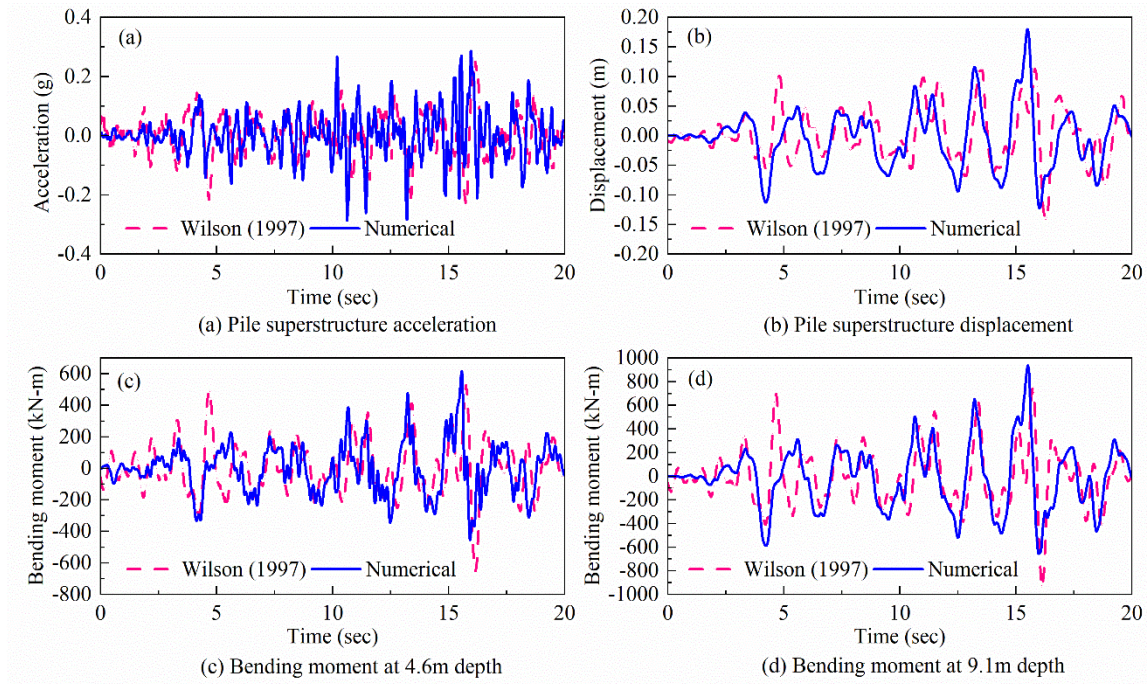


Fig. 4. Experimental and numerical analysis results of pile response.

3.2. Finite element model

Based on previous studies, the selected bridges were transformed into a 3D line element model and implemented in OpenSees. In this model, nodes had six degrees of freedom (DoFs), while the soil was assigned three DoFs (Gergely 2016). Following established methodologies, the bridge superstructure was represented using ElasticBeamColumn elements, the abutment was modeled as a NonlinearBeamColumn element, and the piles were defined as DisplacementBeamColumn elements to account for plasticity distribution along their length. To ensure a monolithic connection between the superstructure, abutment, and piles, rigid link elements were incorporated, as shown in **Fig. 5**. Additionally, nonlinear p-y spring links (Zero-Length elements) were used to establish the interaction between the soil and the bridge components (i.e., abutment and piles). Rayleigh damping, based on the first and second vibration modes, was applied with a 5% damping coefficient. This advanced modeling approach enhances conventional structural engineering methodologies, offering improved accuracy and realism.

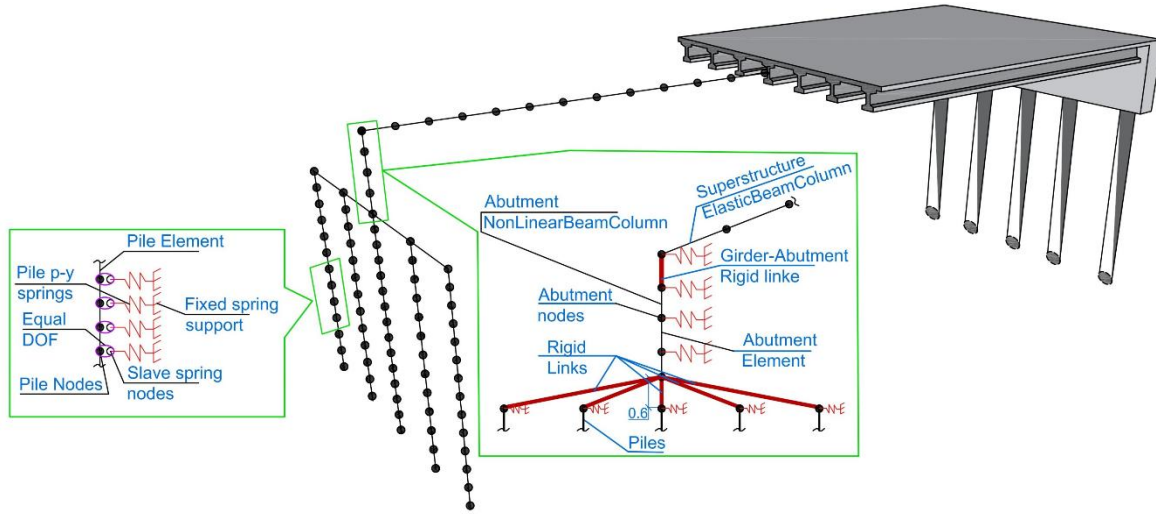


Fig. 5. Analytical model of integral abutment bridge

3.3. Time history analysis

A total of ten recorded ground motions were selected as input data from the 1989 Loma Prieta, 1999 Kocaeli-Turkey, 1999 Chi-Chi Taiwan, and 2010 Darfield New Zealand earthquakes. The properties of these ground motions (GMs) are detailed in **Table 2**. These records were sourced from the PEER NGA West2 database (PEER 2023). A peak ground acceleration (PGA) of 0.5g was assumed, corresponding to Site Class D, a seismic fortification intensity of VIII, and Design Seismic Category C. Nonlinear time-history analysis was chosen as the preferred method for identifying detrimental mechanisms in highway bridges subjected to seismic excitation and lateral spreading due to soil liquefaction. Accordingly, this study utilized nonlinear time-history analyses. The research focuses on a scenario involving six integral abutment bridge (IAB) models, all featuring single-span configurations. The seismic loading was analyzed independently in the longitudinal and transverse directions. Hence, a total of 120 analyses were performed, 60 in the longitudinal and 60 in the transverse direction of IAB. The data were averaged across the ten GMs to provide a complete picture of the outcomes.

Table 2. Ground motion properties

Earthquakes	ChiChi, Taiwan 1999			Kocaeli Turkey 1999			Darfield NewZealand 2010		Loma Prieta 1989	
Station location	H WA 032	C HY 024	Iz nik	Du zce	Iz mit	Yari mca	CC C*	HO RC	G02 _UP	GMR 000
Mw	7.62				7.51			7		6.93
PGA	0.296	0.284	0.344	0.289	0.362	0.287	0.276	0.356	0.244	0.277

* Christchurch Cathedral College

4. Result and discussion

Maintaining IAB stability during earthquakes depends on the seismic performance of pile foundations, especially when taking soil liquefaction into account. This study investigates the impact of liquefaction on IAB piles' response, concentrating on the parametric study of different pile sections exposed to near-fault and far-fault ground motions (GMs). The results were assessed according to the maximal pile response under near-fault and far-fault GMs. The maximal pile response, including displacement, moment stress, and strain, was calculated using finite element analysis. The middle pile of the left abutment in the IAB was chosen to illustrate the maximal pile response along the pile depth under both near-fault and far-fault GMs. Similarly, the upper portion of the

left abutment was used to illustrate abutment displacement under near-fault and far-fault GMs. The next sections discuss the responses of IAB piles and abutments to different pile cross-sections.

4.1. Pile Displacement

Longitudinal and transverse pile response is essential for assessing the seismic resilience of foundation systems, as excessive displacement and deformation may lead to structural instability and failure. The longitudinal displacement of the IAB pile foundation supported by different pile types RCC8, RCC5, HSST, CFST, HSP, and HWP pile under both near-fault and far-fault GMs are shown in **Fig. 6**. The graphs are represented by two colors, where the green hatched bars represent near-fault GMs, and the orange bars represent far-fault GMs. The average displacement trends as a solid orange line depicted far-fault and a dashed green line depicted near-fault GMs.

Analysis results indicated that the IAB supported by the RCC8 pile which has a larger diameter exhibited lower displacement compared to others. When comparing the effects of GMs, no clear tendency was observed initially between near and far-fault GMs. But, based on the average displacement, the near-fault GMs exhibited greater displacement compared to far-fault GMs, as shown in **Fig. 6a**. In the case of IAB supported by the RCC5 pile, the average pile displacement under near-fault and far-fault GMs was approximately the same, as shown in **Fig. 6b**. On the other hand, the steel piles were shown higher displacement compared to reinforced concrete piles (RCC8 and RCC5). Among the steel piles, the CFST exhibited lower displacement compared to HSST, HSP, and HWP. Where the CFST had 0.042m and HSST, HSP, and HWP had 0.044, 0.046, and 0.047 respectively. When comparing the effect of near-fault and far-fault GMs on steel piles, based on the average displacement it appeared that the effect of far-fault GMs was slightly higher compared to near-fault GMs, as shown in **Figs. 6c-f**. This behavior can be explained by the inherent flexibility and ductility of steel-based piles, which facilitate improved energy dissipation. Furthermore, RCC piles' relatively higher cross-sectional stiffness makes them more vulnerable to dynamic amplification effects, particularly under the impulsive loading conditions characteristic of near-fault excitations.

The transverse displacement of the IAB pile foundation supported by different pile types RCC8, RCC5, HSST, CFST, HSP, and HWP pile under near-fault and far-fault GMs are shown in **Fig 7**. Analysis results indicated that the IAB supported by RCC8 and RCC5 piles exhibited lower displacement compared to steel piles and composite piles (HSST, CFST, HSP, and HWP). Among the reinforced concrete piles, the larger-diameter RCC8 pile resulted in lower displacement in the transverse direction of the bridge compared to the RCC5 pile, as shown in **Figs. 7a and 7b**. Among the IABs supported by steel piles, those with HSST and HWP piles exhibited lower displacement compared to those with HSP piles. In the transverse direction, the HSP piles had their weaker axis aligned with the transverse direction of the IAB, resulting in greater displacement. The average displacements of HSST, HSP, and HWP piles were 0.208 m, 0.324 m, and 0.0208 m, respectively, as shown in **Figs. 7c-f**. The IABs supported by CFST piles had an average pile displacement of 0.210 m. When comparing the effects of near-fault and far-fault GMs in the transverse direction of the IAB, the average displacement values indicate that most pile sections supporting the IAB exhibited approximately the same displacement under both near-fault and far-fault GMs.

In summary, based on the analysis results, RCC8 piles supporting IAB were found to be better suited for high-seismic zones, while CFST piles supporting IAB demonstrated superior performance and should be prioritized for IABs, where pile flexibility is a key requirement for IABs.

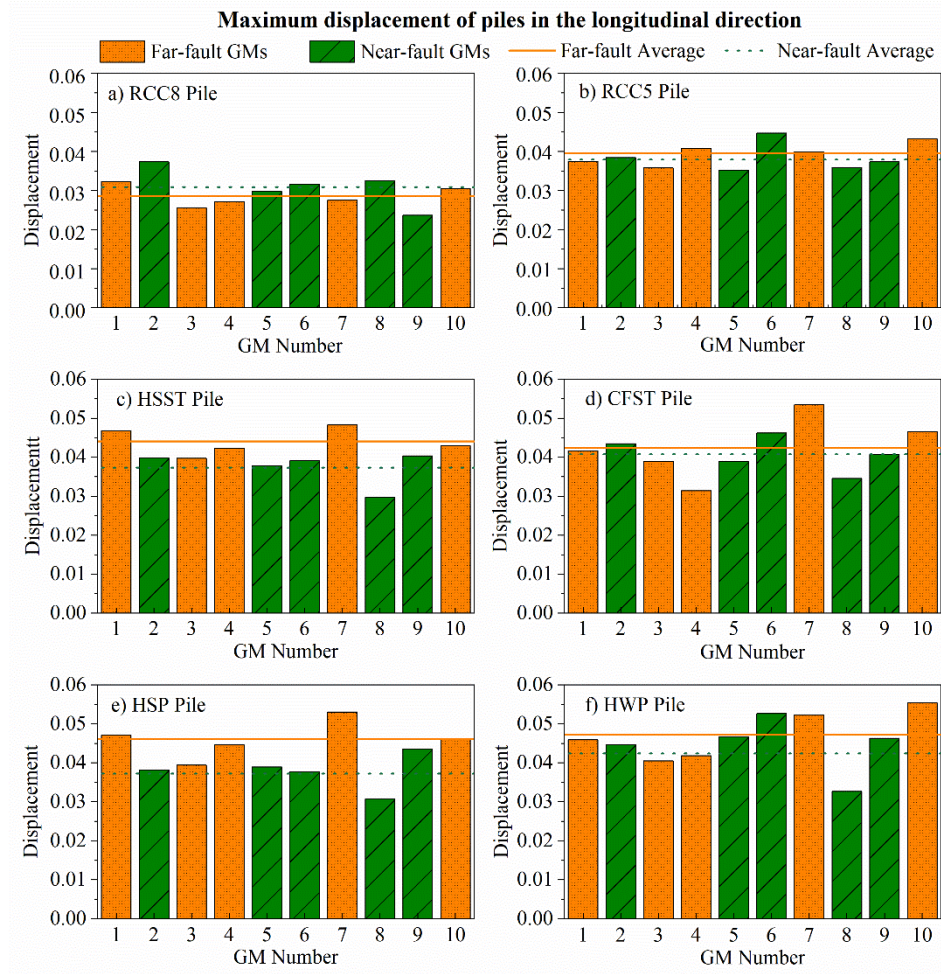


Fig. 6. Maximum piles displacement along the longitudinal direction.

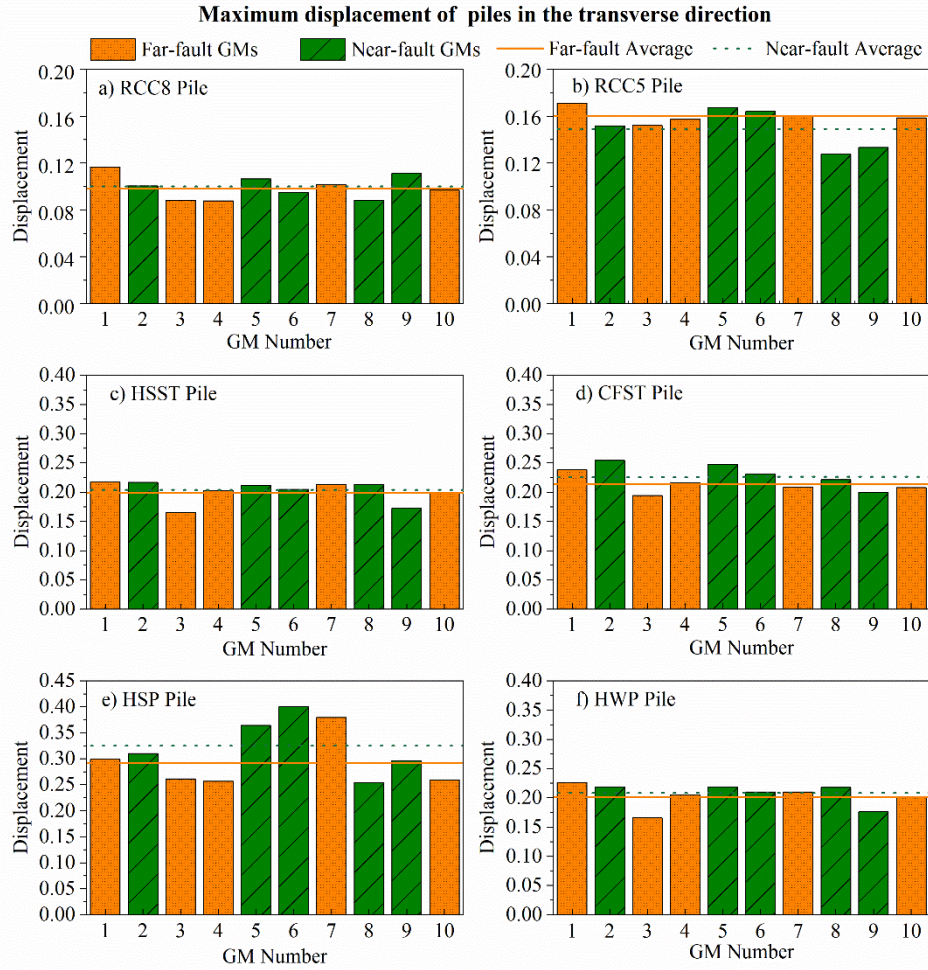


Fig. 7. Maximum pile displacement along the transverse direction

4.2. Pile Bending Moments

The investigation of maximum bending moments of piles in the longitudinal direction (M_z) of IAB demonstrates that the seismic response of pile foundations is highly dependent on the pile type and the GM characteristics. The results indicate that reinforced concrete piles with diameters of 0.8m and 0.5m (RCC8 and RCC5) are subjected to significantly higher bending moments than steel piles. Moreover, the RCC8 and RCC5 piles moment under near-fault GMs appeared higher than far-fault ground motions, as shown in **Figs. 8a** and **8b**. This may be due to the rapid velocity pulses and high energy content of near-fault vibrations, causing additional stresses on pile sections. In contrast, HSST, HSP, and HWP piles (steel piles) display a higher moment, with far-fault GMs than near-fault GMs as shown in **Figs. 8c-f**. The IABs supported by CFST pile, CFST piles exhibited higher moments compared to steel piles, and the moment of piles under near-fault and far-fault GMs were approximately equal. It may be due to the intrinsic flexibility and ductility of steel-based piles, which allow for better energy dissipation. Furthermore, the comparatively increased cross-sectional stiffness of RCC piles renders them more susceptible to dynamic amplification effects, especially under the impulsive loading circumstances associated with near-fault excitations. In summary, the analysis results highlight the crucial role of pile material and sectional parameters in seismic performance, with RCC piles being more sensitive to near-fault shaking, whereas steel-based piles perform more consistently across GM types. These findings underscore the importance of specialized seismic design methodologies for various pile types, particularly in near-fault zones where RCC piles may require additional reinforcement and detailing to mitigate the risk of excessive bending moments.

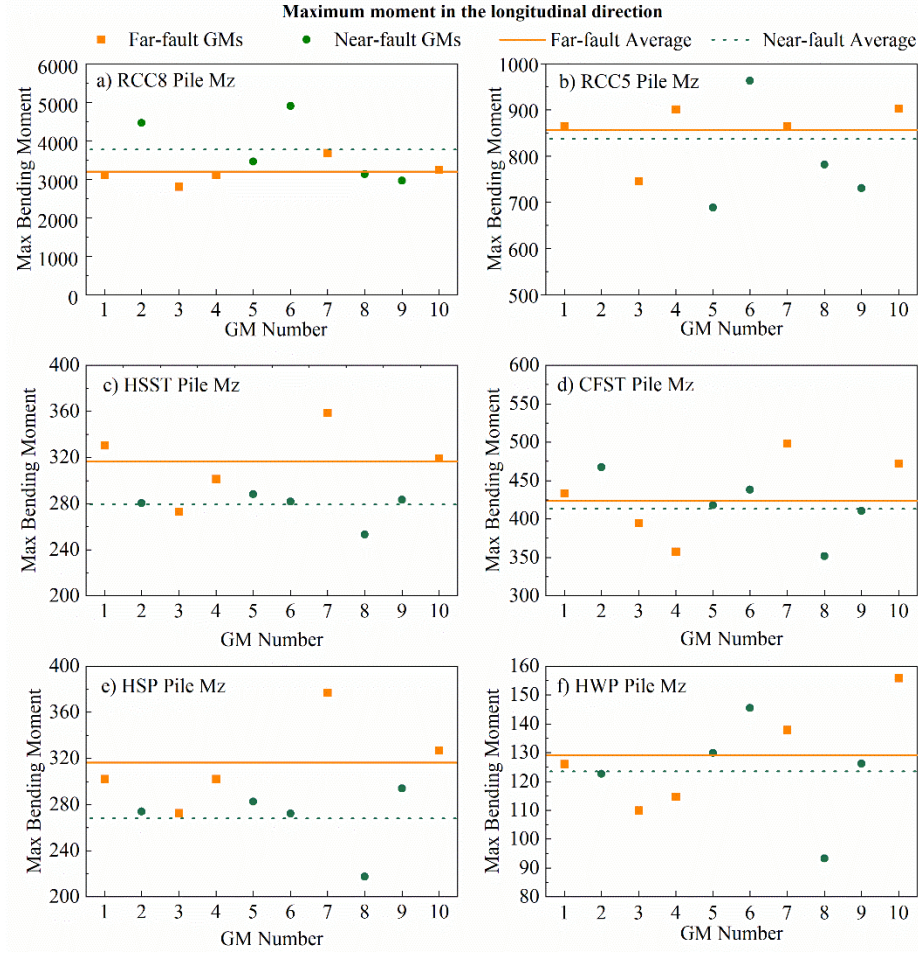


Fig. 8. Maximum moment of piles in the longitudinal direction of IAB

In the transverse direction of IABs, under seismic excitation of various pile sections, there appeared a three times higher bending moment compared to seismic excitation in the longitudinal direction of IABs piles moment. RCC8 piles similar to longitudinal direction exhibit the highest bending moments compared to others and most of the pile sections in the transverse direction with near-fault GMs generated significantly larger moments than far-fault GMs as illustrated in Figs. 9a-b. The phenomenon was most obvious in the RCC8 pile, where near-fault excitations frequently result in greater peak moments, highlighting rigid sections' vulnerability to the powerful velocity pulses associated with near-fault motions. The HSST, CFST, HSP, and HWP piles (steel and composite piles) exhibit slightly higher bending moments distributed, which may be assumed as uniform reactions under near-fault and far-fault GMs, as illustrated in Figs. 9c-f. However, in other cases, in the transverse direction, far-fault GMs result in significantly lower bending moments.

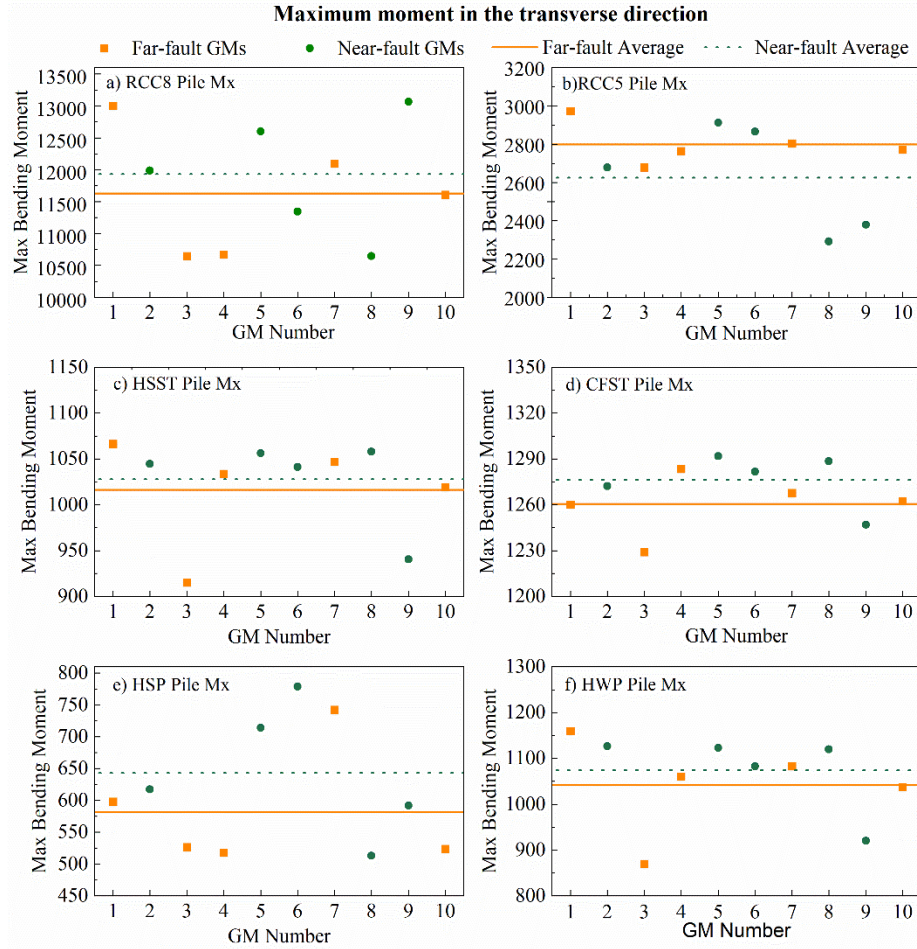


Fig. 9. Maximum moment of piles in the transverse direction of IAB

This behavior of steel piles was largely attributed to the superior ductility and energy dissipation capacity of steel-based piles, which effectively limit excessive moment amplification under severe seismic conditions. The analytical results highlight the importance of considering the directional impacts of seismic loading into pile design, especially for RCC piles, which require greater detailing and reinforcing to meet the elevated transverse bending demands imposed by near-fault conditions.

4.3. IAB Abutment Displacement

The longitudinal displacement of the IAB abutment supported by different pile types RCC8, RCC5, HSST, CFST, HSP, and HWP pile under near-fault and far-fault GMs are shown in Fig. 10. The top portion of the left abutment was chosen to represent the abutment displacement under near-fault and far-fault GMs.

Analysis results of the IAB abutment supported by the RCC8 pile exhibited lower displacement compared to the abutment supported by RCC5, HSST, HSP, HWP, and CFST. On the other hand, the abutment supported by the CFST exhibited lower displacement compared to the abutment supported by steel piles (HSST, HSP, and HWP). Where the average abutment displacement under far-fault GMs, supported by CFST had 0.039m and HSST, HSP, and HWP had 0.040, 0.040, and 0.041 respectively. When comparing the displacement of abutment with the effects of GMs, no clear tendency was observed initially between near and far-fault GMs. However, based on the average displacement of abutment supported by reinforced concrete piles (RCC8 and RCC5), the near-fault GMs exhibited greater displacement compared to far-fault GMs, as shown in Figs 10a-b. In the case of IAB supported by the steel and composed piles (HSST, HWP, and CFST), the average abutment displacement under far-fault GMs appeared higher compared to near-fault GMs, as shown in Figs 10c-f.

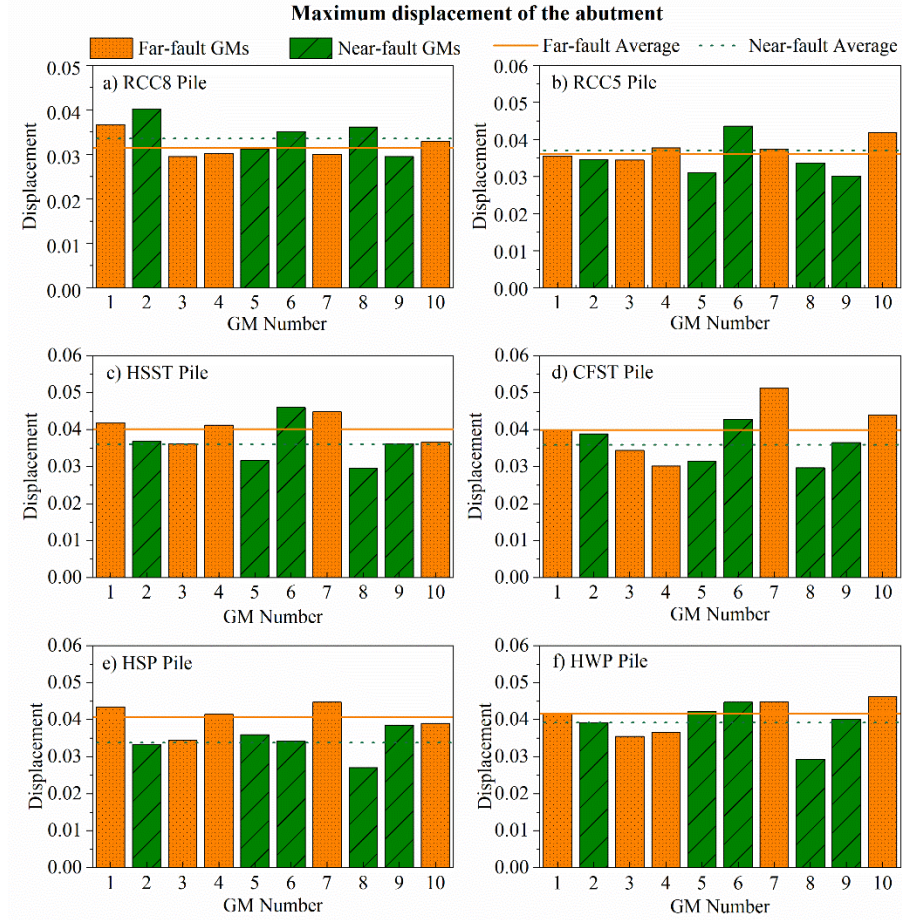


Fig. 10. Maximum displacement at the top portion of abutment.

4.4. Stress and strain distribution in pile sections

The subsequent sections discuss the maximum stress and strain distribution in IAB piles within liquefied soil, focusing on parametric studies of pile sections subjected to near-fault and far-fault ground motions (GMs). Figures 11 and 12 illustrate the maximum stress and strain along the pile for all types of pile sections. Based on the time history analysis results, the pattern of maximum stress and strain distribution along the pile varied significantly among different pile sections.

4.4.1. Piles stress and strain in the longitudinal

When considering the RCC8 piles supporting IAB the maximum stress and strain distributed along the pile depth were observed across the entire pile depth, as illustrated in Figures 11a1 and 12a1. The higher stress and strain values appeared at the pile apex, gradually decreasing along the depth and slightly increasing again between the interface of the liquefied and non-liquefied layers. In the RCC8 pile the higher stress and strain appeared under near-fault GMs compared to far-fault ground motion. However, the maximum stress and strain in the RCC5 piles supporting IAB appeared approximately at the depth of 3m and 9m, where the effect of far-fault GMs appeared higher compared to near-fault GMs, as shown in Figs. 11a2 and b2 and 12a2 and b2. The maximum stress and strain of HSST, HPS, and HPW piles sections, appeared at the pile apex, then gradually decreased along the depth, and then increased again between the interface of the liquefied and non-liquefied layers. In the HSST, HPS, and HPW piles the effect of far-fault GMs appeared higher compared to near-fault GMs, as shown in Figs. 11a3 and b3 and 12a3 and b3. When considering the CFST piles supporting IAB the maximum stress and strain appeared at the interface of liquefied and non-liquefied soil, as illustrated in Figs. 11a4, b4 and 12a4, b4.

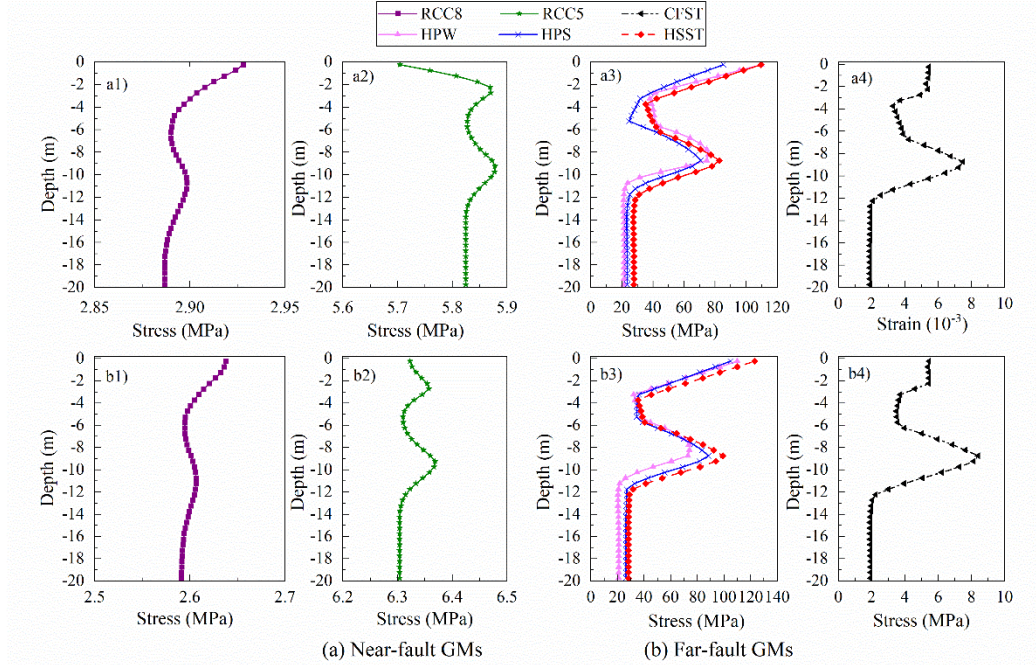


Fig. 11. Pile Stress in Longitudinal Direction

In summary, under longitudinal seismic excitation, IABs supported by HSST, HPS, and HPW piles, the piles exhibited higher stress and strain values in the longitudinal direction compared to other pile sections. Lower stress and strain values were observed in RCC8 piles, followed by RCC5 and CFST piles. Moreover, HSST, HPS, and HPW piles had higher stress and strain, which may make them more susceptible to buckling. In contrast, CFST piles may be a better choice for supporting IABs due to their flexibility, which allows them to resist higher strain and stress. Furthermore, the effects of near-fault and far-fault GMs were approximately the same in CFST piles.

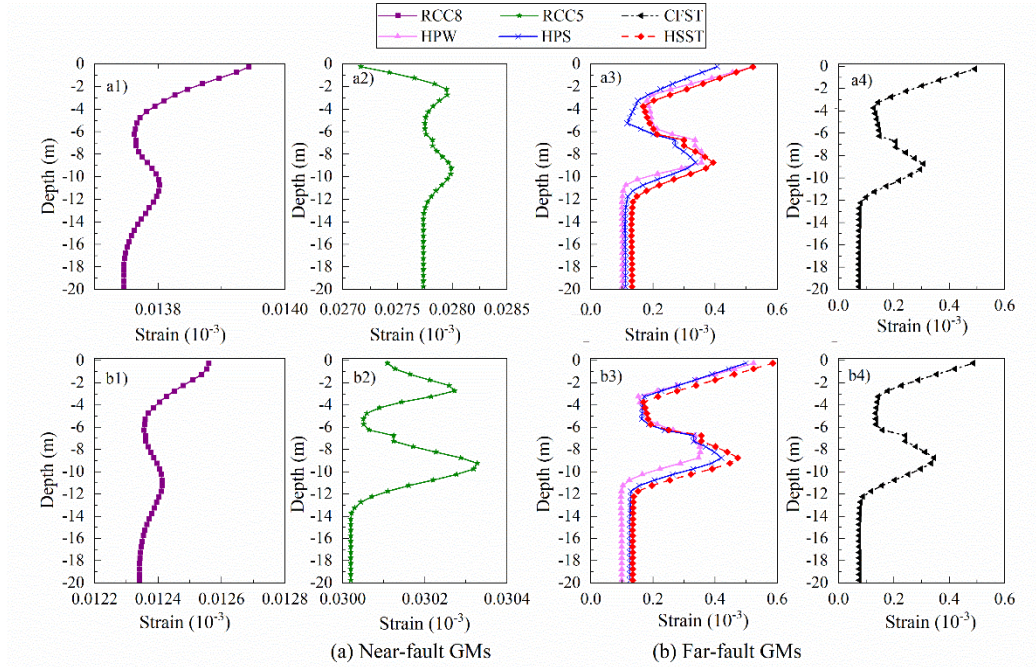


Fig. 12. Pile Strain in Longitudinal Direction

4.4.2. Piles stress and strain in the transverse

When the earthquake effect was considered in the transverse direction of IAB. The stress and strain values of piles in the transverse direction were over three times higher compared to the longitudinal direction. The stress and strain distribution along the pile was approximately the same as the longitudinal direction of IAB with a slight difference. For instance, in the IAB supported by RCC8 piles the maximum stress and strain distributed along the pile depth were observed across the entire pile depth. The higher stress and strain values appeared at the pile apex, gradually decreasing to the depth of 4m and then increasing again, and with RCC8 piles the higher stress and strain appeared under near-fault GMs compared to far-fault GMs, as illustrated in Figures 13a1-b1 and 14a1-b1. However, the maximum stress and strain in the RCC5, HSST, HPS, and HPW piles sections appeared at the pile apex and between the interface of liquefied and non-liquefied soil. Where the stress and strain distribution along the pile under far-fault and near-fault GMs were approximately the same, as shown in Figs. 13a-b and 14a-b. When considering the CFST piles supporting IAB the maximum stress of the pile appeared at the interface of liquefied and non-liquefied soil under near-fault GM, and at the apex under far-fault GMs, as illustrated in Figs. 13a4, b4. and the maximum strain appeared at the pile apex as shown in Fig. 14a4 and b4.

Based on the analysis results, HSST, HPS, and HPW piles exhibited higher stress and strain values under transverse seismic excitation of the IAB compared to other pile sections. The lowest stress values were found in CFST piles, followed by RCC8 and RCC5 piles. Additionally, HSST, HPS, and HPW piles exhibited higher stress and strain, which may making them more susceptible to buckling. In contrast, CFST piles may be a better choice for supporting IAB bridges due to their flexibility, which results in higher strain but lower stress. Furthermore, the effects of near-fault and far-fault GMs under transverse seismic excitation were approximately the same, considering soil liquefaction around the piles.

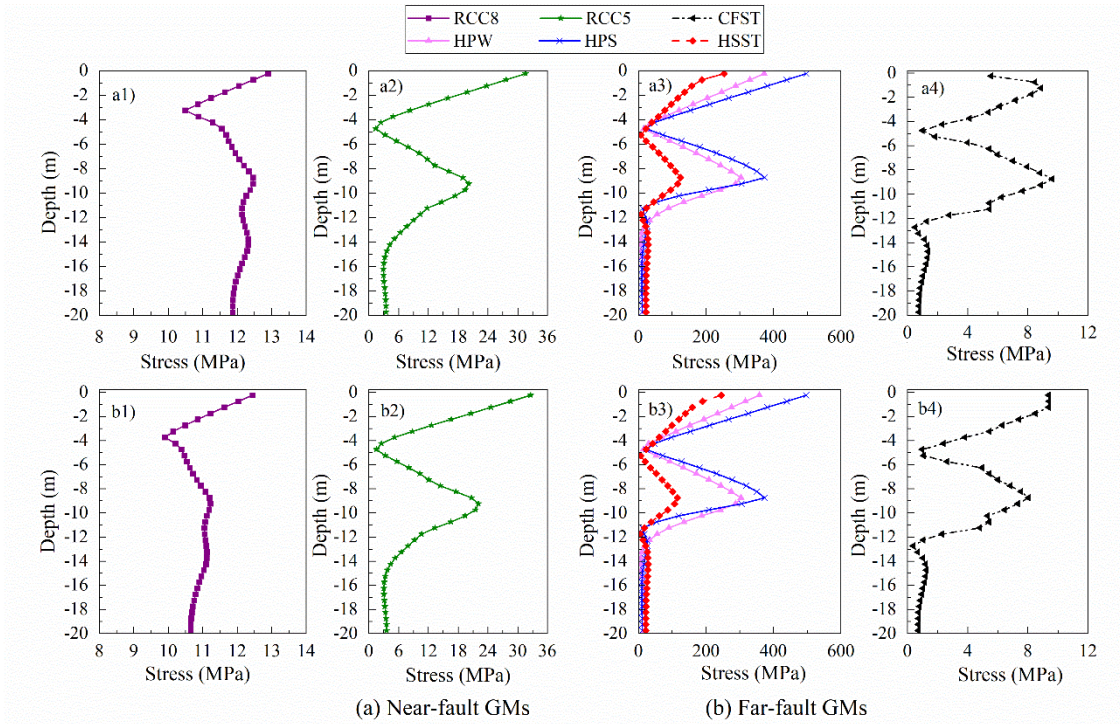


Fig. 13. Pile Stress in Transverse Direction

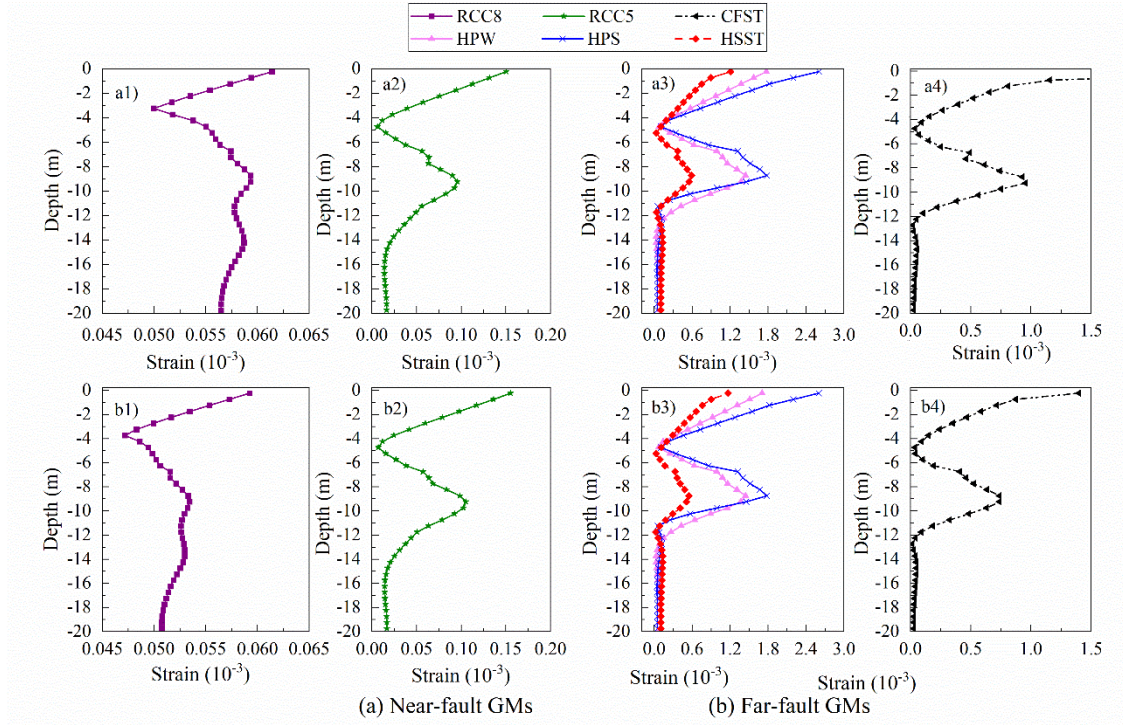


Fig. 14. Pile Strain in Transverse Direction

5. Conclusion

This work investigated the performance of IABs by performing parametric analyses on pile sections subjected to near-fault and far-fault GMs considering soil liquefaction around the pile foundation. Six types of pile sections were selected to evaluate their responses, including RCC8 and RCC5 (reinforced concrete piles with diameters of 0.8m and 0.5m), HSST (steel pipe), HPS and HPW (H-steel piles oriented along the strong and weak axes of the bridge), and CFST (concrete-filled steel tube) piles. The primary objective was to assess pile flexibility in IABs while considering the influence of soil liquefaction around the piles.

In general, when comparing the piles responses of IABs under near-fault and far-fault GMs in liquefiable soil, no clear trend was observed initially between them. But, based on the average response values of near-fault and far-fault GMs, the following conclusions were drawn from the analysis:

Under seismic excitation in the longitudinal direction of the IAB, reinforced concrete piles with greater diameters (RCC8) displayed lower displacement and higher moments, although near-fault GMs induced larger displacements and moments compared to steel piles and CFST pile. In contrast, steel piles (HSST, HSP, and HWP) experienced higher displacement, and moment under far-fault GMs. The CFST piles supporting the IAB exhibited approximately the same displacement and moment under both near-fault and far-fault GMs.

In the transverse direction under seismic excitation, most pile sections supporting the IAB showed approximately similar displacement under near-fault and far-fault GMs, except for HSP, which exhibited significantly larger displacement under near-fault GMs.

The displacement of the IAB abutment in the longitudinal direction was lower when supported by RCC8 and RCC5 piles compared to steel and CFST piles, and near-fault GMs caused larger abutment displacement. Conversely, IAB abutments supported by the steel piles (HSST, HSP, and HWP) and CFST pile showed greater displacement under far-fault GMs compared to near-fault GMs.

Based on the stress and strain evaluation, the IABs supported by HSST, HPS, and HPW piles, piles exhibited higher stress and strain values in the longitudinal and transverse direction compared to other pile sections, which may make them more susceptible to buckling. In contrast, CFST piles may be a better choice for supporting IAB

bridges due to their flexibility, which results in higher strain but lower stress. Furthermore, the effects of near-fault and far-fault GMs under longitudinal and transverse seismic excitation were approximately the same, considering soil liquefaction.

The comparative evaluation of the IAB pile's performance under seismic loading reveals that CFST piles represent the most optimal option for bridge foundations, especially in high-seismic zones. CFST piles demonstrate exceptional seismic resilience, attributed to their combination of high compressive strength, ductility, and energy dissipation capacity. These properties enable them to effectively mitigate excessive bending moments in both the longitudinal and transverse directions, ensuring robust performance under dynamic loading conditions. Additionally, suggested when using H-steel piles in liquefied soil, reinforce the piles in high-stress regions using available strengthening techniques.

References

- AASHTO. 2011. AASHTO Guide Specifications for LRFD Seismic Bridge Design. 2nd Editio. Washington DC: American Association of State Highway and Transportation Officials.
- Alshawabkeh, Yazan M, and Mohsen A Issa. 2024. "Maximum Permissible Safe Length of Integral Abutment Bridges Supported by Steel H-Piles." *Structures* 62 (March). Elsevier Ltd: 106130. doi:10.1016/j.istruc.2024.106130.
- Alshawabkeh, Yazan M, Mohsen A Issa, Mohammad R Abandah, and Nassr N Salman. 2023. "Lateral Buckling Capacity of Steel H-Piles Supporting Integral Abutment Bridges (IABs)." *Structures* 50 (February). Elsevier Ltd: 896–907. doi:10.1016/j.istruc.2023.02.043.
- API (American Petroleum Institute). 1993. Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms - Load and Resistance Factor Design. First Edit. Washington DC: American Petroleum Institute (API).
- Aygün, Bayram, Leonardo Dueñas-Osorio, Jamie E. Padgett, and Reginald DesRoches. 2011. "Efficient Longitudinal Seismic Fragility Assessment of a Multispan Continuous Steel Bridge on Liquefiable Soils." *Journal of Bridge Engineering* 16 (1): 93–107. doi:10.1061/(asce)be.1943-5592.0000131.
- Bhattacharya, Subhamoy, and Andreas Kappos. 2014a. "On The Collapse of Bridge Foundations in Liquefiable Soil During Earthquakes." Second European Conferaence on EE& Seismology 2014 (Istanbul 2014).
- . 2014b. "On The Collapse of Bridge Foundations in Liquefiable Soil During Earthquakes." In Second European Conference on Earthquake Engineering and Seimology. Istanbul: ResearchGate.
- Bilgin, Huseyin. 2024. "Effects of Near-Fault and Far-Fault Ground Motions on Nonlinear Dynamic Response and Seismic Damage of Masonry Structures." *Engineering Structures* 300 (August 2023). Elsevier Ltd: 117200. doi:10.1016/j.engstruct.2023.117200.
- Bowers, Matthew E. 2007. "Seismic Fragility Curves for a Typical Highway Bridge in Charleston, SC Considering Soil-Structure Interaction and Liquefaction Effects." Clemson University TigerPrints.
- Brandenberg, Scott J, Minxing Zhao, Ross W Boulanger, Daniel W Wilson, Daniel W Wilson, and M. 2013. "P-y Plasticity Model for Nonlinear Dynamic Analysis of Piles in Liquefiable Soil." *Journal of Geotechnical and Geoenvironmental Engineering* 139 (8): 1262–74. doi:10.1061/(asce)gt.1943-5606.0000847.
- Chen, Liang, Yi-zhou Zhuang, Kun-sheng Song, Said M Easa, and Hong-jie Zhu. 2024. "Novel HS-RC Stepped Pile Foundation : Experimental and Numerical Evaluation." *Ocean Engineering* 299 (March). Elsevier Ltd: 117196. doi:10.1016/j.oceaneng.2024.117196.
- Cubrinovski, Misko, Jonathan D. Bray, S Bastin, B A Bradley, C Cappellaro, and L Wotherspoon. 2017. *Geotechniel Reconnaissance of The 2016 Mw7.8 Kaikoura, New Zealand Earthquake*. Vol. GEER-053. New Zealand.
- Deierlein, Gregory, and Adam Zsarnóczy. 2021. *State of the Art in Computational Simulation for Natural Hazards Engineering*. Edited by Adam Zsarnoczy Gregory G. Deierlein. NHERI SimCenter. doi:10.5281/zenodo.2579581.
- Dunker, Kenneth F., and Dajin Liu. 2007. "Foundations for Integral Abutments." *Practice Periodical on Structural Design and Construction* 12 (1): 22–30. doi:10.1061/(asce)1084-0680(2007)12:1(22).
- Erhan, Semih, and Murat Dicleli. 2014. "Effect of Dynamic Soil-Bridge Interaction Modeling Assumptions on the Calculated Seismic Response of Integral Bridges." *Soil Dynamics and Earthquake Engineering* 66. Elsevier: 42–55. doi:10.1016/j.soildyn.2014.06.033.
- Gergely, Jozsef Simon; Laszlo. 2016. "Seismic Fragility Assessment of Integral Precast Multi-Span Bridges in

- Areas of Moderate Seismicity.” *Bulletin of Earthquake Engineering*, no. November. doi:10.1007/s10518-016-9947-y.
- Gingery, James Robert. 2014. “Effects of Liquefaction on Earthquake Ground Motions.” University of California, San Diego. <https://escholarship.org/uc/item/3q3212r5>.
- Greimann, L F, P S Yang, S K Edmunds, and A M Wolde-Tinsae. 1984. *Design of Piles for Integral Abutment Bridges*, Report HR-252. Iowa State.
- Hotak, Abdul Hakim, Qihong Zhao, and Kui Gui. 2025. “Optimizing Pile Foundation Selection for Integral Abutment Bridge in Liquefied Soil.” *Structure and Infrastructure Engineering*. doi:doi.org/10.1080/15732479.2025.2491140.
- Inqualabi, Kashif Quamar, Rajeev Kumar Garg, and K. Balaji Rao. 2017. “Seismic Vulnerability of Urban Bridges Due to Liquefaction Using Nonlinear Pushover Analysis and Assessing Parameters for Damage Detection.” *Procedia Engineering* 173: 1739–46. doi:10.1016/j.proeng.2016.12.211.
- Jinyuan, Yuan, Wang Yunlong, Ma Jiajun, Zhan Beilei, Yuan Xiaoming, Wang Lanmin, and Wu Xiaoyang. 2023. “Study Regarding Typical Liquefaction Damage during the 2021 Maduo Ms 7.4 Earthquake in China.” *Earthquake Engineering and Engineering Vibration* 22 (4): 895–908. doi:doi.org/10.1007/s11803-023-2208-6.
- Joseph E. Bowles, RE., S.E. 1997. *Foundation Analysis and Design International Fifth Edition*. Fifth Edit. Singapore: McGraw-Hill Companies.
- Kazaz, İlker, İsmail Hakkı Bilge, and Muhammed Gürbüz. 2024. “Near-Fault Ground Motion Characteristics and Its Effects on a Collapsed Reinforced Concrete Structure in Hatay during the February 6, 2023 Mw7.8 Kahramanmaraş Earthquake.” *Engineering Structures* 298 (June 2023). doi:10.1016/j.engstruct.2023.117067.
- Kwon, Sun Yong, and Mintaek Yoo. 2020. “Study on the Dynamic Soil-Pile-Structure Interactive Behavior in Liquefiable Sand by 3D Numerical Simulation.” *Applied Sciences (Switzerland)* 10 (8): 1–22. doi:10.3390/AP10082723.
- Maugeri, Michele, and Claudio Soccodato. 2014. *Earthquake Geotechnical Engineering Design*. Edited by Claudio Soccodato Michele Maugeri. Geotechnical, Geological and Earthquake Engineering. Vol. 28. Switzerland: Springer. doi:10.1007/978-3-319-03182-8.
- Mazzoni, S.; F.; McKenna, H. M.; Scott, L. G. Fenves, and Et Al. 2006. “OpenSees Command Language Manual.” *Pacific Earthquake Engineering Research (PEER) Center* 246 (1): 137–58.
- Meyersohn, Wolfgang Daniel. 1994. “Pile Response to Liquefaction-Induced Lateral Spread.” Cornell University.
- Mohanty, and Bhattacharya. 2019. “Case Studies of Liquefaction-Induced Damages to Two Pile-Supported River Bridges in China.” *Journal of Performance of Constructed Facilities* 33 (5): 5. doi:10.1061/(asce)cf.1943-5509.0001306.
- Mohanty, Piyush, S C Dutta, and S Bhattacharya. 2017. “Proposed Mechanism for Mid-Span Failure of Pile Supported River Bridges during Seismic Liquefaction.” *Soil Dynamics and Earthquake Engineering* 102 (May). Elsevier Ltd: 41–45. doi:10.1016/j.soildyn.2017.08.013.
- Naji, M, and A A Firoozi. 2020. “A Review: Study of Integral Abutment Bridge with Consideration of Soil-Structure Interaction.” *Latin American Journal of Solids and Structures* 17 (2): 1–27. doi:10.1590/1679-78255869.
- Ozkaynak, M. Irsad, and Kemal Onder Cetin. 2024. “The Performance of Karasu Bridge Following the February 6, 2023 Kahramanmaraş-Türkiye Earthquake Sequence.” *Engineering Geology* 335 (April). Elsevier B.V.: 107512. doi:10.1016/j.enggeo.2024.107512.
- PEER. 2023. “PEER Strong Motion Database.” PEER. <http://PeerBerkeleyEdu>.
- Rabeti Moghadam, Masoud, Hamid Alielahi, and Alireza Sadeghi Abdollahi. 2017. “Numerical Evaluation of Liquefaction-Induced Damages in Composite Breakwaters and Its Application for Performance-Based Improvement Design.” *Marine Georesources and Geotechnology* 35 (3): 376–96. doi:10.1080/1064119X.2016.1190428.
- Rui-Huan Fu, Bruno Briseghella, Jun-Qing Xue, Angelo Aloisio, Yi-Biao Lin, Camillo Nuti. 2022. “Exoerunebtak Abd Finite Element Analyses of Laterally Loaded RC Piles with Pre-Hole Filled by Various Filling Materials in IABs.” *Engineering Structures*. doi:doi.org/10.1016/j.engstruct.2022.114991.
- Salman, Nassr N., and Mohsen A. Issa. 2021. “Calibration and Parametric Investigation of Integral Abutment Bridges.” *Engineering Structures* 227 (October 2020). Elsevier Ltd: 111381. doi:10.1016/j.engstruct.2020.111381.
- Satyam, Neelima. 2012. “Review on Liquefaction Hazard Assessment.” *Advances in Geotechnical Earthquake Engineering - Soil Liquefaction and Seismic Safety of Dams and Monuments*. doi:10.5772/27295.
- Setyadi, G P, A Rifa'i, and I G B Indrawan. 2024. “Effects of Soil Liquefaction to Foundation Bearing Capacity Based on Empirical and Numerical Simulation.” *IOP Conference Series: Earth and Environmental Science*

- 1373 (1): 012011. doi:10.1088/1755-1315/1373/1/012011.
- Shamsabadi, Anoosh, Kyle M Rollins, and Mike Kapuskar. 2007. "Nonlinear Soil – Abutment – Bridge Structure Interaction for Seismic Performance-Based Design." *Journal of Geotechnical and Geoenvironmental Engineering*, no. June: 707–20.
- Song, Jia, Yu Yang, Kemin Jia, Pengfei Dou, Xuelian Ma, and Haohao Shen. 2023. "Seismic Response and Instability Analysis of the Liquefiable Soil-Piles-Superstructure Interaction System." *Structures* 54 (May). Elsevier Ltd: 134–52. doi:10.1016/j.istruc.2023.05.048.
- Turner, Benjamin J., Scott J. Brandenburg, and Jonathan P. Stewart. 2016. "Case Study of Parallel Bridges Affected by Liquefaction and Lateral Spreading." *Journal of Geotechnical and Geoenvironmental Engineering* 142 (7): 1–12. doi:10.1061/(asce)gt.1943-5606.0001480.
- Vasheghani-Farahani, Reza, Qihong Zhao, and Edwin G. Burdette. 2010. "Seismic Analysis of Integral Abutment Bridge in Tennessee, Including Soil-Structure Interaction." *Transportation Research Record* 2010 (2201): 70–79. doi:10.3141/2201-09.
- Wang, Xiaowei, Fuyuan Luo, and Aijun Ye. 2023. "A Holistic Framework for Seismic Analysis of Extended Pile-Shaft-Supported Bridges against Different Extents of Liquefaction and Lateral Spreading." *Soil Dynamics and Earthquake Engineering* 170 (March). Elsevier Ltd: 107914. doi:10.1016/j.soildyn.2023.107914.
- Wilson, Daniel W. 1998. "Soil-Pile-Superstructure Interaction in Liquefying Sand and Soft Clay." University of California at Davis.
- Xiang, Ping, Shipeng Xu, Han Zhao, Lizhong Jiang, Hongkai Ma, and Xiang Liu. 2023. "Running Safety Analysis of a Train-Bridge Coupled System under near-Fault Ground Motions Considering Rupture Directivity Effects." *Structures* 58 (May). Elsevier Ltd: 105382. doi:10.1016/j.istruc.2023.105382.
- Xie, Yazhou, Jian Zhang, and Yili Huo. 2018. "Simplified Drift Demand Prediction of Bridges under Liquefaction-Induced Lateral Spreading." *Journal of Bridge Engineering* 23 (8): 1–13. doi:10.1061/(asce)be.1943-5592.0001266.
- Xue, Junqing, Angelo Aloisio, Yibiao Lin, Massimo Fragiaco, and Bruno Briseghella. 2021. "Optimum Design of Piles with Pre-Hole Filled with High-Damping Material : Experimental Tests and Analytical Modeling." *Soil Dynamics and Earthquake Engineering* 151 (May). Elsevier Ltd: 106995. doi:10.1016/j.soildyn.2021.106995.
- Zhang, Xiaoyu, Liang Tang, Xianzhang Ling, and Andrew Chan. 2020. "Critical Buckling Load of Pile in Liquefied Soil." *Soil Dynamics and Earthquake Engineering* 135 (March). doi:10.1016/j.soildyn.2020.106197.
- Zhao, Qihong, Abdul Hakim Hotak, Kui Gui, Baochun Chen, and Zhihua Chen. 2025. "Unveiling Seismic Impact : A Detailed Study on Integral Abutment Bridges amid Liquefied Soil Subjected to Far-Fault and near-Fault Ground Motions." *Bulletin of Earthquake Engineering*.