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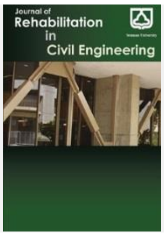

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Evaluation of Structure Frequency on the Dynamic Response of Piled Raft Foundations

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ABSTRACT

This study examines the impact of structural frequency under various input excitations on the dynamic behavior of a piled raft (PR) foundation embedded in a dry sand layer. Numerical modeling using the finite element method was evaluated by experimental results from centrifuge test. The findings reveal that the structure's natural frequency, affected by the dynamic characteristics of both the soil and the foundation, is significantly lower than that of the fixed-base condition. However, the structure's frequency changes are independent of the excitation dominant frequency. Furthermore, as the structure's natural frequency rises, the disparity between the fixed-base condition and the foundation-inclusive scenario becomes increasingly pronounced. These changes significantly affect the whole dynamic system responses, precisely the maximum bending moment along the piles. It highlights the importance of considering the soil-structure interaction in the design process. Additionally, when the frequency of the input excitation closely aligns with the system's natural frequency, it induces the most significant dynamic responses in the soil, pile, raft, and structure. Consequently, relying solely on fixed-based methods in design can lead to unrealistic and potentially unsafe technical decisions.

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1. Introduction

Given the critical importance of optimization in civil engineering design, it is essential to consider the interplay between different structural elements to meet both optimization and safety objectives. Extensive research on soil-structure interaction (SSI) has demonstrated how soil's mechanical properties influence the dynamic behavior of structures. The complexity of soil-pile interaction under dynamic loading further complicates the design process, with structural characteristics playing a crucial role in this interaction [1–3]. Specifically, the specifications of a structure significantly impact the internal forces within the foundation due to inertial interactions, with taller buildings exhibiting greater inertial effects and higher pile bending moments [4–6]. In seismically active regions, piles are subjected to larger lateral loads from the weight of building floors, making rigid connections between piles and rafts more prone to increased stresses, thereby necessitating specialized design considerations [7].

The presence of flexible subsoil can significantly alter internal forces within a structure, rendering fixed-base design methods inadequate for accurately assessing the system's true dynamic behavior. Notably, centrifuge test results have shown that the contact between the raft and soil in a piled raft system can reduce the dynamic response of the superstructure [8]. However, the inertial interactions between the superstructure and foundation system also influence the foundation's response and the internal forces within the piles [9]. Consequently, taller buildings experience greater inertial interactions, leading to higher pile bending moments [4,5].

Tao et al., studied the SSI model including an oscillator, a 3D rectangular foundation, and a multi-layered half-space [10]. Foundation impedance functions were derived using a high-precision indirect boundary element method. The study found that the soil acts like a cushion, providing additional flexibility. Consequently, the SSI system exhibits a lower frequency and greater damping compared to fixed-base structures, resulting in smaller peak amplitudes in the frequency domain.

Forcellini uses 3D numerical simulations with Opensees to evaluate the seismic performance of a 20-story building with a pile foundation, focusing on SSI through a probabilistic approach to develop analytical fragility curves. The key findings reveal that SSI can both reduce the vulnerability of the system and amplify site-specific effects (kinematic and inertial interaction) [6]. The study emphasizes that neglecting SSI can increase the overall vulnerability of the soil-foundation-superstructure system.

Zhang et al., conducted to analyze the seismic response of high-rise frame-core tube structures, incorporating the effects of Soil-Structure Interaction (SSI) [11]. The results showed that, in many cases, the inter-story drifts exceeded 1.5%, especially during near-field earthquakes, indicating that conventional design methods that exclude SSI may not adequately ensure the safety of high-rise structures. The study also found that while piled foundations reduce foundation rocking more effectively than classical compensated foundations, they tend to experience larger lateral deflections, particularly under near-field earthquake conditions. This is attributed to the higher shear forces observed in piled foundation structures compared to compensated or fixed-base structures.

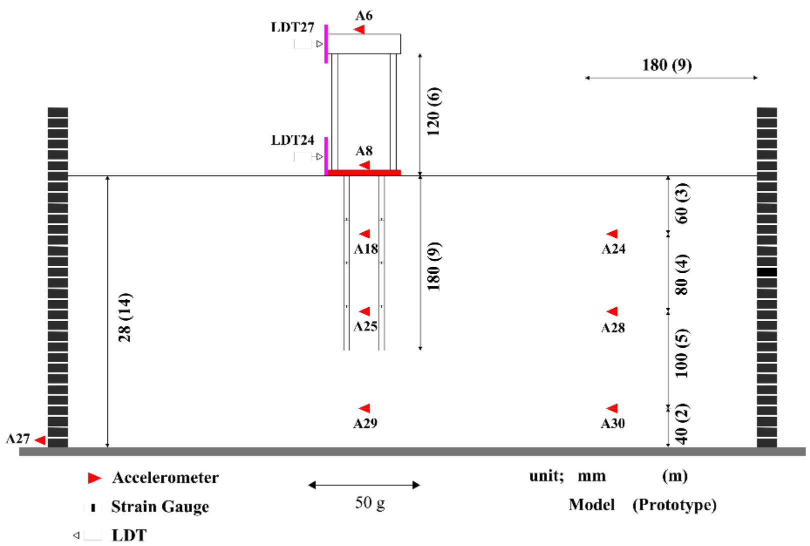
Hussien et al. [12,13] conducted numerical and experimental studies on the kinematic and inertial interactions affecting pile bending moments for single and grouped piles supporting structures with varying degrees of freedom. Their parametric analyses, assuming non-linear system behavior, showed a decrease in the effective fundamental frequency of the soil-pile-structure system and its resonant frequency. Increased pile flexibility resulted in higher maximum kinematic bending moments. In cases where the superstructure's frequency was lower than the ground's, kinematic interaction primarily influenced seismic forces along the piles at excitation frequencies differing from the system's natural frequency. Near the natural system frequency, inertial interaction caused significant bending moments at or near the pile head. Hence, kinematic interaction should be considered in pile design, especially at frequencies close to the soil's natural frequency [13,14].

In this paper, we utilized centrifuge tests [15] and simulated them using the finite element software ABAQUS 3D to investigate changes in system frequency and their effects on responses, including accelerations and pile bending moments. A one-degree-of-freedom system modeled the superstructure. By altering the column cross-section while keeping the superstructure's weight and height constant, the model's frequency was varied, and seismic loading with different excitation frequencies was applied. The numerical simulation results were validated using the aforementioned centrifuge physical modeling results.

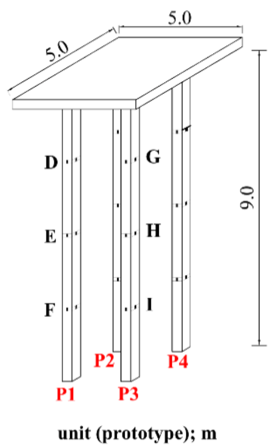
2. Numerical modeling

2.1. Model description

To investigate the effect of a structure's natural frequency on the seismic response of piled raft foundations, and considering the 3D interaction mechanism between soil, pile, raft, and structure, the results of physical models [15] were numerically simulated using ABAQUS 3D software. The studied model consisted of three main structural components: a raft, a one-degree-of-freedom superstructure, and a piled raft system, including a raft and four piles. The superstructure and piles were rigidly fixed to the raft, which was situated on a dry sand layer. The specific gravity (Gs) and relative density (Dr) of the sand were 2.65 and approximately 60%, respectively. A schematic configuration of the experimental model and the instrument positions are shown in Fig. 1. Two types of one-degree-of-freedom superstructures were modeled using the same cubic lumped mass and two types of columns with identical heights (120 mm in models) but different cross-sectional areas, isolating the effect of different natural frequencies for accurate measurement.



(a)



(b)

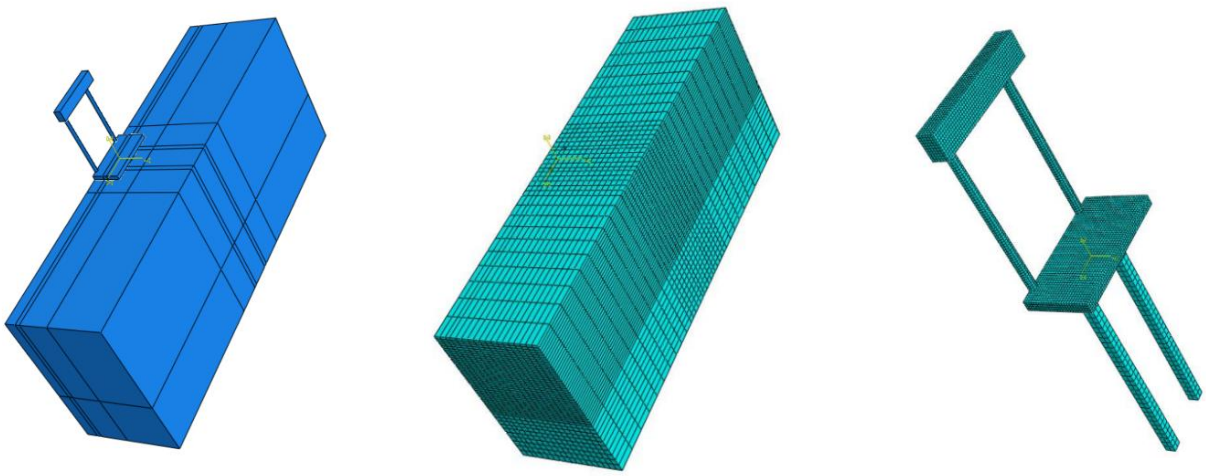
Fig. 1. Schematic diagram and dimensions (m) of (a) the model including the sand bed, the piled raft, the superstructure and the position of instrumentation, and (b) the piled raft model and the position of piles and strain gauges [15].

2.2. Modeling procedures

During the main shaking stage of the centrifuge test, uniaxial sine-wave motions with two different accelerations and frequencies were applied to the models. The uniaxial seismic loading was applied horizontally beneath the soil layer, as the tested models were vertically symmetric. Therefore, as shown in Fig. 2, half of the models were simulated in the numerical analyses. In other words, the seismic response of a prototype-sized symmetric 2×1 piled raft system was investigated using ABAQUS software.

Since the tests were conducted at 50g centrifuge acceleration, a geometric scaling factor (N) equal to 50 was used to calculate the size of the prototype model. Table 1 presents the geometrical specifications of the model, and Fig. 2 illustrates the basic configuration of the finite element modeling. In accordance with the prototype properties of the tested model, concrete piles with a Young's modulus (E) of 23 GPa, a diameter (d) of 0.4 m, a length (L) of 9 m, and a square raft width of 5 m were considered (Table 1). All the dimensions mentioned in Table 1 are based on the centrifuge scaling law [16].

The piles were modeled as a linear elastic material in the numerical analyses of the soil-pile interaction, as recommended by most researchers [17].



(a) (b) (c)

Fig. 2. The basic configuration of the 3D finite-element half-model (a) the whole system, (b) the mesh of soil and (c) the mesh of piled raft and super-structure.

In the numerical analysis, different cross-sections of the columns were assumed to achieve varying natural frequencies for the superstructures, such as 1.2, 2, 3.4, and 5 Hz. Table 2 presents the natural frequencies of the superstructures (supported by a rigid base) and the entire system (considering soil-structure interaction). Additionally, a dry unit weight of 1530 kg/m³ and a friction angle of 37° were selected for the tested sand profile (Table 3). It is important to mention that the soil parameters in Table 3, are based on the experimental results of centrifuge tests in National Central University of Taiwan conducted by Baziar et al. [15].

Table 1. Specifications of experimented model for the centrifuge tests in prototype scale (N=50).

Element	Properties	Model	Prototype
Pile	Material	Aluminum	Concrete
	Width	6 (mm)	0.4 (m)
	Length	180 (mm)	9 (m)
	Number	4	4
Raft	Material	Aluminum	Concrete
	Width × Length	75.6 (mm) × 75.6 (mm)	5 (m) × 5 (m)
	Thickness	6 (mm)	0.4 (m)
One-Degree-of-Freedom System	Mass	400 (gr)	50 (ton)
	Height	120 (mm)	6 (m)

Table 2. Frequency of the fixed based super-structure and frequency of the system considering the interactions.

Str. Freq.* (Hz)	Sys. Feq.** (Hz)	Excitation frequency (Hz)
1.2	0.9	1 – 2- 7
2	1.39	1 – 1.39 - 2- 7
3.4	2.17	1 – 2- 2.17 – 3.4 - 7
5	2.45	1 – 2- 2.45 – 5 - 7

* Obtained by fixed base method ** Obtained by ABAQUS software

Table 3. Physical properties of the sand used in numerical simulation.

Soil Type	Dr (%)	ρ (kg/m3)	E (MPa)	Friction angle Φ (°)	Dilation angle Ψ (°)
SP	60	1530	40	37	6

2.3. Simulation characteristics

As illustrated in Fig. 2, the finite element (FE) mesh for the entire system -including the soil, piled raft foundation, and superstructure- was meticulously defined using 8-noded hexahedral elements (C3D8R) (Table 4). The mesh was carefully optimized to balance the accuracy of numerical results with computational efficiency, ensuring convergence of the model. Given the critical need to accurately evaluate bending moments along the piles, particularly when compared with centrifuge test data, special emphasis was placed on refining the mesh along the pile length. Fully integrated elements were employed for the pile modeling to enhance the precision of moment calculations, thereby improving the reliability of the results.

Table 4. The number and types of the elements.

Section Name	Number of Elements	Type of Elements
Soil	29090	C3D8R
Pile	140	C3D8R
Raft	5000	C3D8R
Column	360	C3D8R
Mass	3000	C3D8R

On the other hand, acknowledging the importance of soil-structure interaction, the mesh density for the soil elements varied strategically. Finer elements were utilized in the vicinity of the piles to more accurately capture the complex interactions between the piles and the surrounding soil, which is essential for a precise representation of the piled raft system's behavior (Fig. 2b).

Minimizing lateral boundary effects on system response is a critical challenge in physical modeling. To address this, all centrifuge models in this study were tested in a laminar container box, designed to reduce wave reflections through an infinite soil layer during dynamic tests. Lee et al. thoroughly investigated and reported on the boundary effects associated with this laminar container used in centrifuge tests [18]. In this research, to accurately simulate soil behavior in small-scale testing, various types of absorbing boundary conditions in numerical modeling were considered [19–21]. Among these, the consideration of far-field boundary conditions provided the most accurate numerical results, as the simulation was modeled at full scale. To assess this assumption, the Fourier amplitude of three accelerometers (A30, A28, and A24) in 3D modeling was compared with physical modeling results. As a result, the numerical outputs exhibit excellent precision compared to the physical measurements, validating that far-field boundary conditions are a sound and logical assumption.

To define the interaction parameters, the Penalty method was employed. A tangential friction factor of 0.7 was used for interactions between the soil and the piled-raft foundation, while a friction factor of 0.35, as specified by Bhowmik et al., was applied for the interaction between the soil and the raft [22]. Additionally, to prevent overlap between the soil and pile elements, normal stiffness was defined.

Since the degree of restraint of connections during an earthquake in centrifuge tests is not a definitive parameter, connections are modeled using two types: Tie and MPC. These models were compared with laboratory results. According to the results, the differences between these two connection types and the experimental values were not significant. Therefore, connections between columns and masses, as well as between piles and the raft, were modeled by Tie connections.

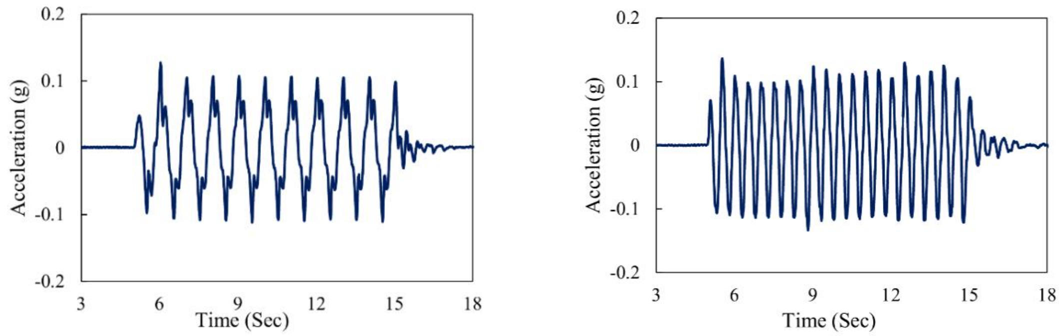
2.4. Dynamic excitation

In the numerical simulations, dynamic loads were applied as sine waves with a constant acceleration amplitude of 0.14 g, and frequencies of 1 Hz, 2 Hz, and 7 Hz (Table 2). The 7 Hz frequency was chosen to be sufficiently distinct from the natural frequency of the superstructures, thereby avoiding resonance effects. Since the natural frequency of the sand deposit was approximately 2 Hz (based on the soil samples free vibration), the 2 Hz dynamic load could induce resonance within the soil layer. This resonance could lead to significant displacements and increased damping. As a result, models subjected to dynamic loading at around 2 Hz experienced 10% damping, while those subjected to frequencies of 1 Hz and 7 Hz exhibited a damping value of 5%.

2.5. Verification of the numerical modeling

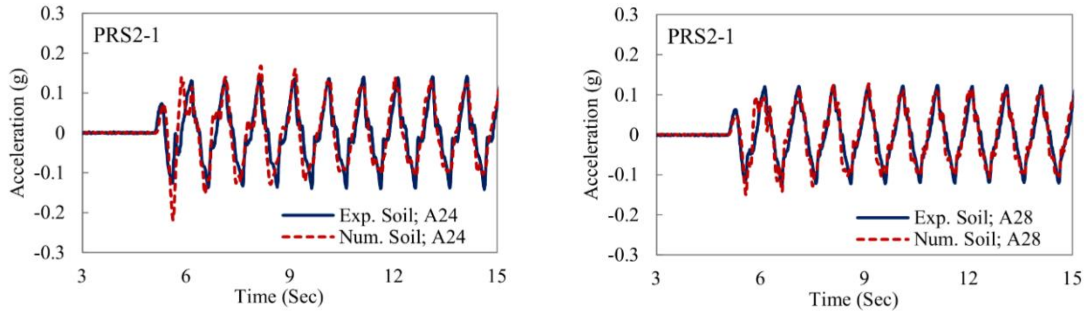
The results from the finite element analysis were compared with those from physical modeling (centrifuge tests). Using ABAQUS 3D, four models were simulated, each comprising two superstructures with different frequencies (1.2 Hz and 3.4 Hz) subjected to dynamic loading at frequencies of 1 Hz and 2 Hz, with an acceleration amplitude of 0.14 g. The frequency of the entire system was determined through frequency analysis in ABAQUS and then compared to the superstructure's frequency on a rigid foundation using fixed-base approaches (Table 2).

Figs. 3a and 3b show the acceleration histories for the input motions of the numerical models, represented by sine waves with an acceleration amplitude of 0.14 g and frequencies of 1 Hz and 2 Hz, respectively. Fig. 4 compares the accelerations recorded from physical modeling with those from numerical analysis at various soil levels for models subjected to 1 Hz dynamic loading, with a superstructure frequency of 3.4 Hz. Similarly, Fig. 5 presents a comparison for models under 2 Hz dynamic loading. Figs. 6 and 7 illustrate the bending moments along the piles for the four models, recorded using three strain gauges placed at different points along the piles (Fig. 1b). Although the results from both physical and numerical models exhibit similar trends, the bending moment recorded at the uppermost strain gauge (D gauge in Fig. 1b) is slightly higher in the numerical analysis compared to the physical testing. This discrepancy is caused by the completely rigid connections between the raft and piles in the numerical analysis. Nevertheless, the close alignment between the results of experimental centrifuge tests and numerical analyses confirms the accuracy of the numerical modeling in analyzing dynamic behavior, assumptions, and parameters.



(a) (b)

Fig. 3. Time history of base acceleration with (a) 1 Hz frequency, and (b) 2 Hz frequency.



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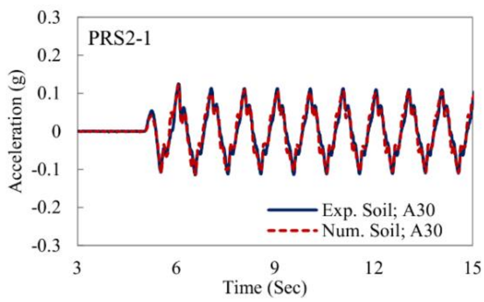
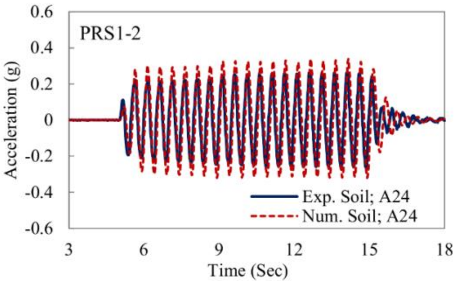


(c)

Fig. 4. Recorded time history for three accelerations were through the soil: (a) A24, (b) A28, and (c) A30 for model with 3.4 Hz structural frequency under dynamic loading with 0.14g acceleration amplitude and 1 Hz frequency.



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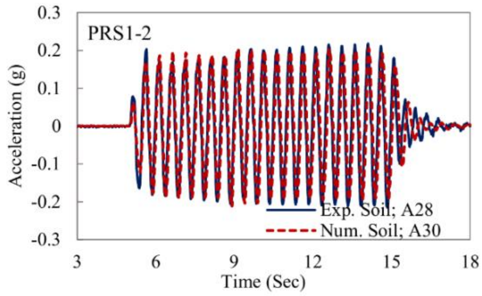

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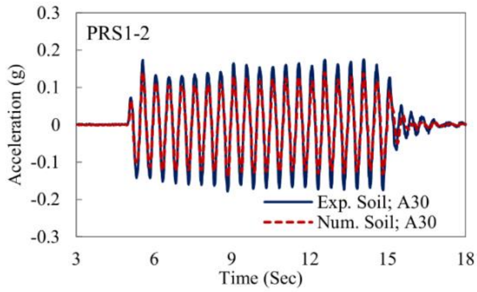
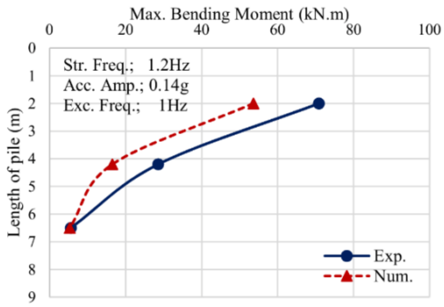


(c)

Fig. 5. Recorded time history for three accelerations placed through the soil (a) A24, (b) A28 and (c) A30 for model with 3.4 Hz structural frequency under dynamic loading with 0.14g acceleration amplitude and 2 Hz frequency.



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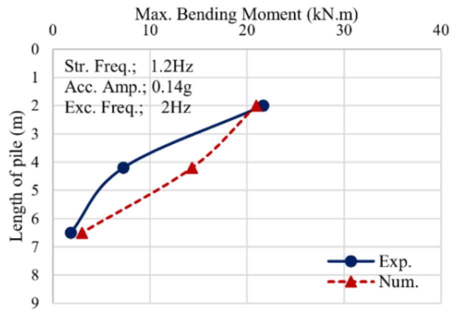
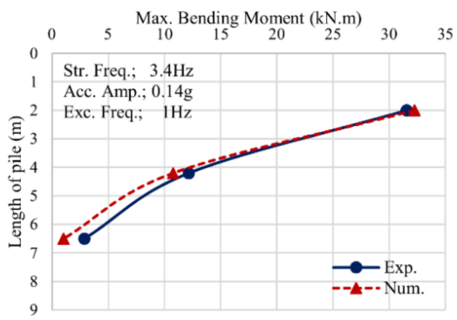


(b)

Fig. 6. Comparison of the maximum bending moments obtained from the numerical and recorded experimental tests, for the models with a super-structure possessing 1.2 Hz frequency under dynamic loading with (a) 1 Hz frequency, and (b) 2 Hz frequency.



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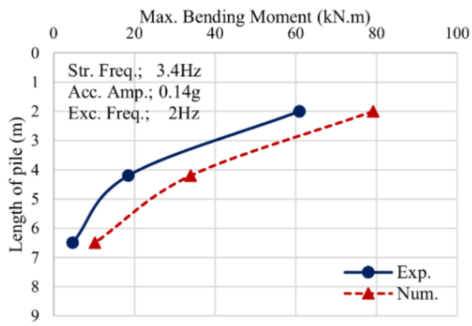


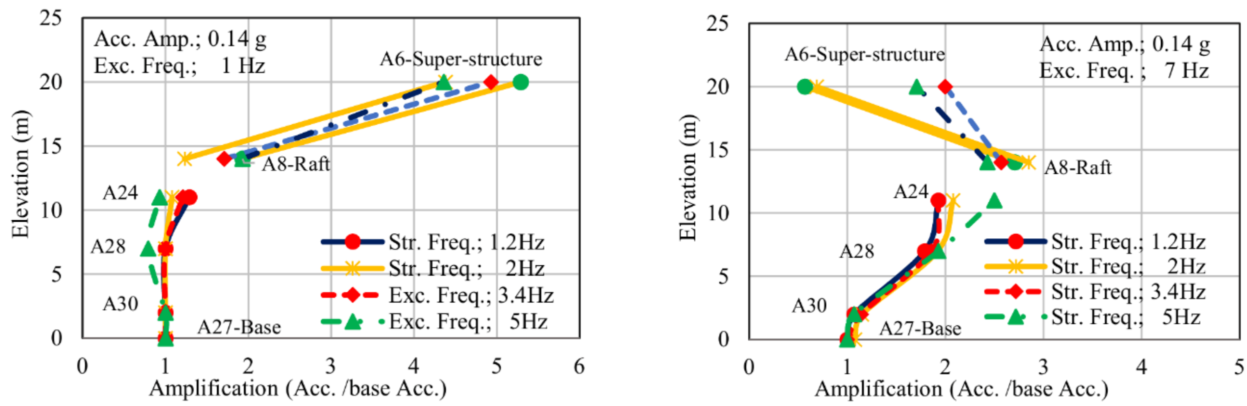
(b)

Fig. 7. Comparison of the maximum bending moments obtained from the numerical and recorded experimental tests for the models with a super-structure possessing 3.4 Hz frequency under dynamic loading with (a) 1 Hz frequency, and (b) 2 Hz frequency.

3. Results and discussion

3.1. Effect of excitation and different structural frequencies

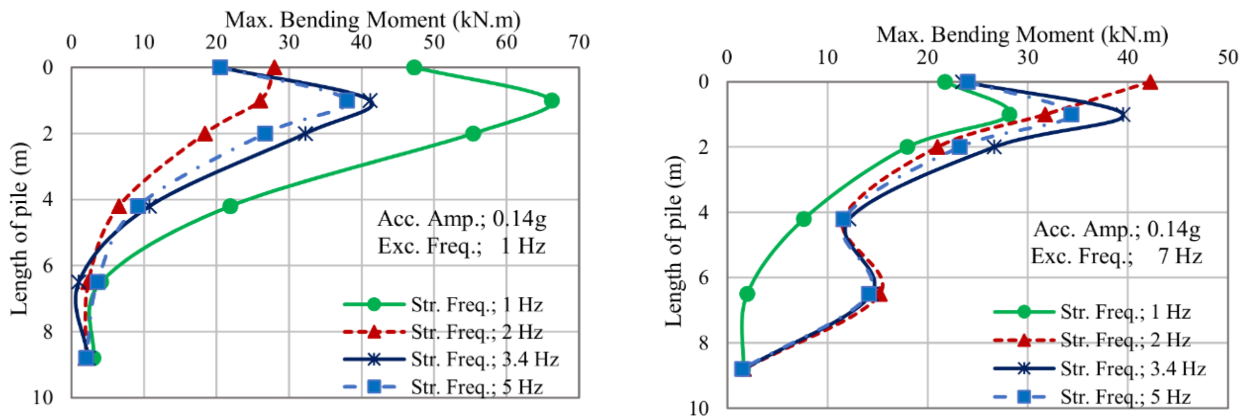
To investigate the impact of excitation characteristics, the dynamic responses of models with different superstructures under identical loading conditions were compared. Figs. 8a and 8b illustrate the acceleration amplifications for the dry sand layer, raft, and superstructure subjected to 0.14g shaking at frequencies of 1 Hz and 7 Hz. Amplifications were determined by normalizing the maximum acceleration at various elevations to the maximum base excitation acceleration. According to Fig. 9a, the greatest amplification occurs in the superstructure with a natural frequency of 1.2 Hz, and structural amplification decreases as the structural frequency increases. In contrast, Fig. 8b demonstrates that for seismic loading at 7 Hz, the amplification is higher in superstructures with higher natural frequencies. Specifically, the superstructure with a frequency of 5 Hz exhibits the greatest amplification, while superstructures with lower frequencies, such as 1.2 Hz and 2 Hz, show lower amplification. The high acceleration values in the superstructure lead to significant lateral inertial forces on the foundation, which result in larger bending moments in the piles.



(a) (b)

Fig. 8. Amplification of acceleration in soil layer at different elevation, in raft, and in super-structure for excitation with 0.14 g acceleration amplitude and (a) 1 Hz frequency, and (b) 7 Hz frequency.

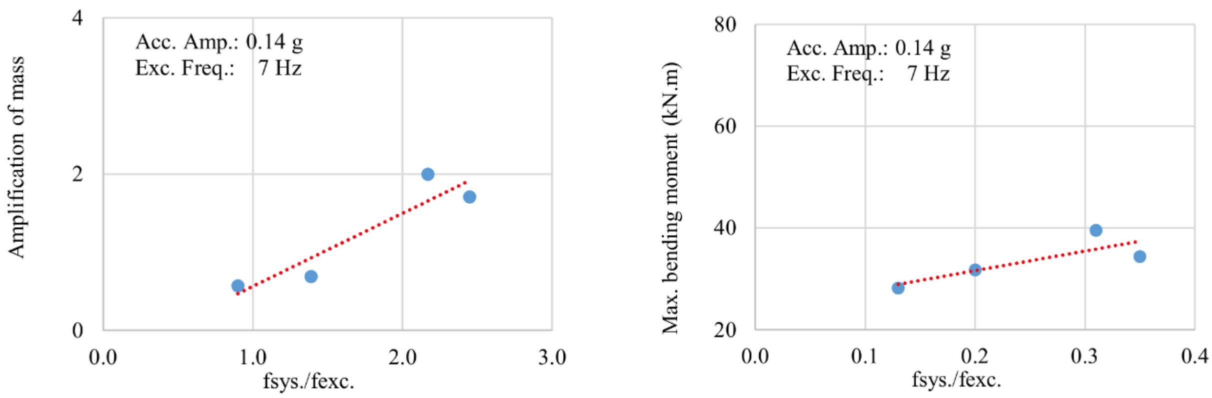
Figs. 9a and 10b depict the bending moments along the piles for models subjected to shaking at 1 Hz and 7 Hz, respectively. Fig. 9a indicates that the pile supporting the superstructure with a frequency of 1.2 Hz experiences a greater bending moment than those in other models. Similarly, the superstructure with a frequency of 5 Hz experiences the highest acceleration under 7 Hz excitation (Fig. 8b), leading to maximum inertial forces on the foundation and, consequently, greater bending moments along the piles (Fig. 9b). However, the effect of inertial interaction diminishes with increasing soil depth, resulting in only minor differences in bending moments, as observed in Fig. 9.



(a) (b)

Fig. 9. The bending moment along the pile for four numerical models subjected to 0.14g shaking with 0.14 acceleration amplitude and (a) 1 Hz frequency, and (b) 7 Hz frequency.

The comparison of results confirms that at an excitation frequency of 7 Hz, due to the significant difference between the system frequency (f_{sys}) and the excitation frequency (f_{exc}), the system's response is less pronounced than at lower input frequencies, such as 1 Hz. It appears that the ratio of system frequency to excitation frequency (f_{sys}/f_{exc}) is a critical factor influencing inertial forces. Figs. 10a and 10b illustrate the superstructure amplification and the maximum bending moment of the pile, respectively, in relation to f_{sys}/f_{exc} for 7 Hz excitation. For excitation at 7 Hz, as the system frequency approaches the input frequency, the structural acceleration and inertial forces increase, leading to greater maximum bending moments along the piles.



(a) (b)

Fig. 10. (a) Amplification of the super-structure and (b) The maximum bending moment of the pile for upper gauges (D) to fsys/fexc for the excitation with 7 Hz frequency.

Figs. 11a and 11b show the amplification of the superstructure and the maximum bending moment of the pile versus f_{sys}/f_{exc} for 1 Hz excitation. Comparing these results with those for 7 Hz excitation reveals differing response trends for the two excitation frequencies. Similar to the 1 Hz excitation case, an increase in structural frequency results in a higher system frequency, which increases the difference between the system and excitation frequencies. Amplification is more pronounced in models with higher structural frequencies, leading to a reduction in superstructure acceleration and pile bending moments.

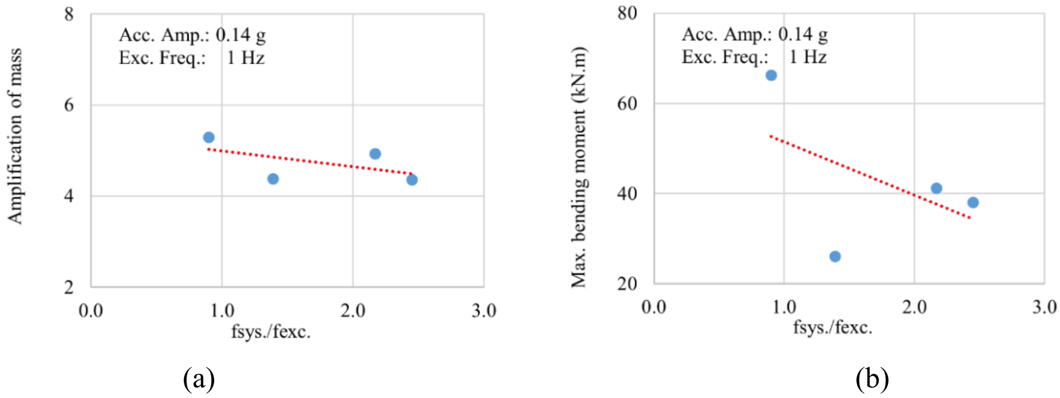


Fig. 11. (a) Amplification of the super-structure and (b) The maximum bending moment of the pile for upper gauges (D) to fsys/fexc for the excitation with 1 Hz frequency.

Figs. 12a to 12d present the bending moments of the pile for the four models with varying superstructure frequencies under dynamic loading at different frequencies. The greatest bending moments occur when the load frequency is close to or matches the system frequency, rather than the superstructure's natural frequency. This finding is crucial for superstructure design, as the system frequency plays a more significant role than the superstructure or soil frequency. Therefore, in designing structures on piled raft foundations, it is essential to consider the characteristics of the soil, piled raft, and superstructure simultaneously.

As shown in Fig. 12, bending moments along the pile decrease as the excitation frequency diverges from the system frequency, while the maximum bending moment is observed when the excitation frequency (1.39 Hz) equals the system frequency (1.39 Hz).

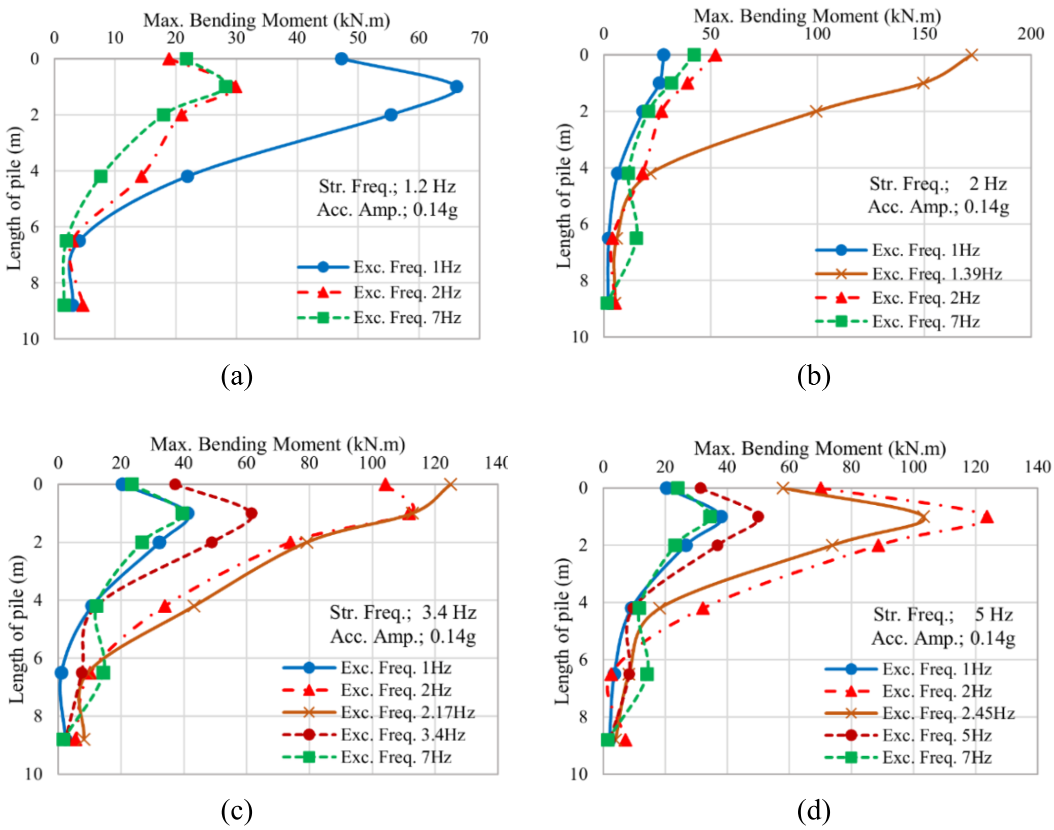


Fig. 12. (a) Amplification of the super-structure and (b) The maximum bending moment of the pile for upper gauges (D) to fsys/fexc for the excitation with 1 Hz frequency.

3.2. Considering the foundation and superstructure individually (Fixed- Base Analysis)

To compare two design approaches—one where the superstructure is considered independently (fixed-base analysis) and one where interaction effects are considered simultaneously—the bending moment of the pile was also calculated using SAP, Fig. 13, a common engineering practice software. The results were then compared with those obtained from this research. The comparison of maximum pile moments between the two software programs reveals significant differences, with the fixed-base method yielding higher values (Figs. 14).

As shown in Fig. 14a, when the excitation frequency is close to the natural frequency of the structure, the pile moments near the pile head increase in comparison to the ABAQUS analysis. In other words, in the fixed-base method, the natural frequency of the structure plays a crucial role. However, as the numerically verified results discussed in previous sections indicate, the system frequency is the actual resonant frequency of the system. On the other hand, when the excitation frequency is near the system frequency, the difference between the two methods is not as pronounced. Therefore, considering the piled raft system and superstructure together leads to a more economical and secure design (Fig. 15). It is also worth noting that the difference between the results decreases with increasing depth. Consequently, ignoring soil characteristics and inertial interaction in the design process may result in an imprecise and uneconomical design of the superstructure and foundation.

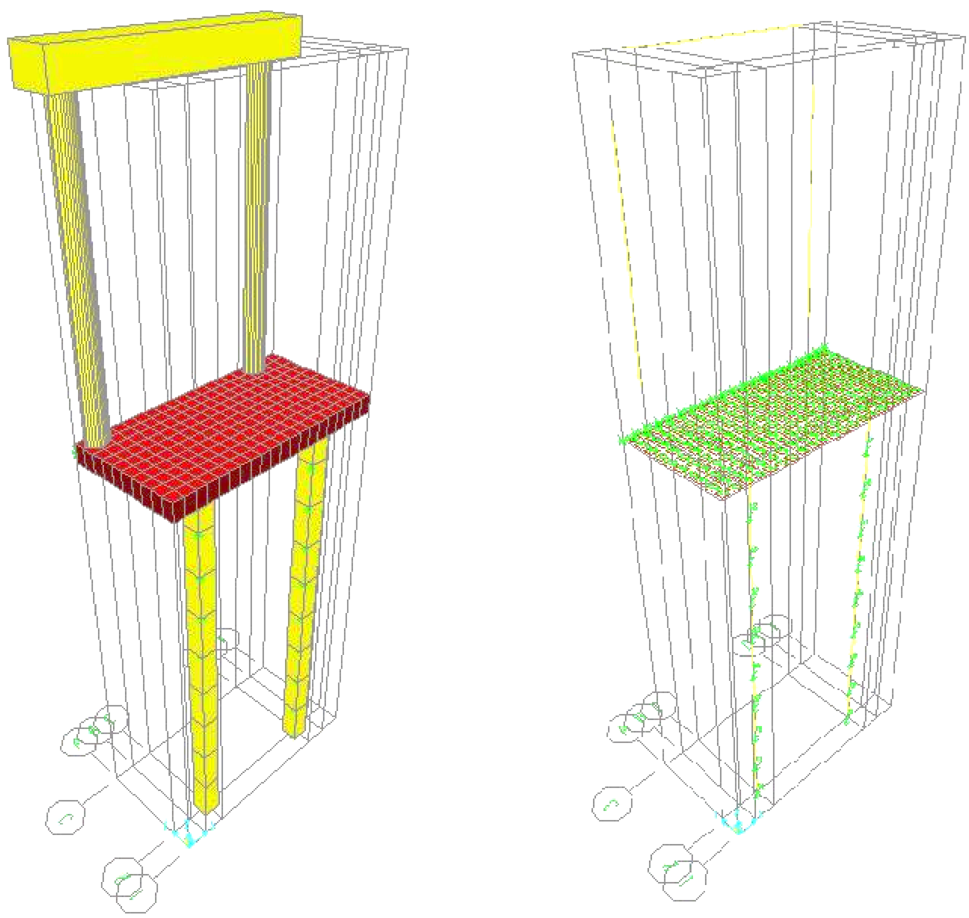
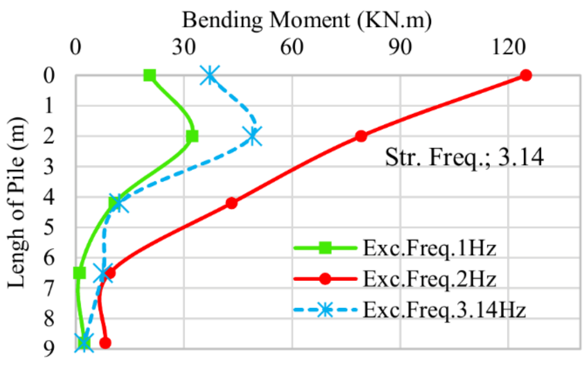


Fig. 13. A view of the 3D half-model created in SAP.



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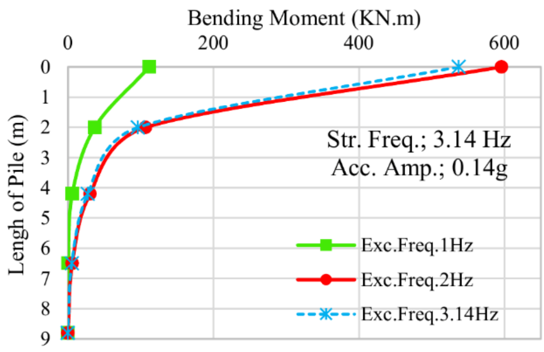

(b)

Fig. 14. Comparison of the numerical maximum bending moment along the pile for excitation with 0.14 g acceleration amplitude and 1 Hz, 2.17. 3.14 frequency for structure frequency 3.14HZ calculated using (a) ABAQUS and (b) SAP.

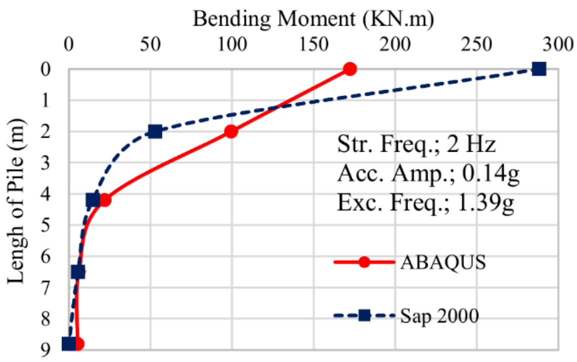

Fig. 15. Comparison of the numerical maximum bending moment along the pile for excitation with 0.14 g acceleration amplitude and 1.39 Hz for structure frequency 2 HZ.

4. Conclusions

1- The results indicated that accounting for the interaction between soil, foundation, and superstructure in the simulation of a piled raft system leads to a reduction in the overall system frequency. This reduction was more pronounced when the superstructure had a higher natural frequency.

2- The structural frequency significantly impacted the system's overall response due to its influence on the inertial forces generated on the foundation. The superstructure tended to vibrate at a frequency corresponding to the system frequency, making the system frequency a critical parameter that affects both the foundation and superstructure behavior. Consequently, it should be a key consideration in optimal design.

3- Changing the excitation frequency did not alter the system frequency, indicating that the structural frequency, which decreases during the dynamic response, is independent of the excitation frequency.

4- The effect of soil-structure interaction that shows in the system frequency is the critical factor in the dynamic responses of the structural elements of the system. Hence, measuring the effect of resonance response by considering the structure's natural and excitation frequencies would lead to incorrect engineering judgment and design.

5- The study also found that the ratio of system frequency (f_{sys}) to excitation frequency (f_{exc}) influenced the system's response. When $f_{sys}/f_{exc} \geq 1$, superstructures with lower frequencies resulted in greater system responses. Conversely, when $f_{sys}/f_{exc} \leq 1$, systems with higher structural frequencies exhibited increased responses.

6- Under excitation at a frequency of 7 Hz, increasing the structural frequency led to an increase in both superstructure amplification and inertial forces, resulting in a higher maximum bending moment at the pile head. The system with a structural frequency of 5 Hz demonstrated the greatest bending moment response under 7 Hz excitation.

7- Comparisons of four identical systems, with the same foundation but different superstructure stiffness and structural frequencies, revealed varying responses. The results underscored that the ratio of structural frequency to excitation frequency plays a significant role in system behavior. This finding suggests that buildings may interact differently with their foundations, leading to varying forces and bending moments in piled raft foundations.

8- Considering the superstructure and foundation as a unified system was shown to be crucial in the design process. Neglecting this holistic approach and designing a building on a fixed-base foundation, followed by separate analysis of the foundation loading, may yield misleading results.

9- In cases where the structural frequency brings the system frequency close to the dominant frequency of regional earthquake ($f_{sys}/f_{exc} \cong 1$), rather than altering the dimensions of the foundation or structural elements (which could lead to suboptimal design), increasing the structural frequency - such as by stiffening the frame - would be an optimal solution. This approach raises the system frequency and improves the f_{sys}/f_{exc} ratio without changing the structural dimensions.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contribution statement

Boshra Razmi: Conceptualization, Data curating, Formal Analysis, Methodology, Software, Writing, Review & Editing.

Fahime Rafiee: Conceptualization, Data curating, Formal Analysis, Methodology, Experimental Investigation, Software, Original Draft, Review & Editing.

Mohammad Hassan Baziar: Project administration, Supervision, Methodology, Review & Editing.

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References

[1] Han Y. Seismic response of tall building considering soil-pile-structure interaction. Earthq Eng Eng Vib 2002;1:57–64. https://doi.org/10.1007/s11803-002-0008-y.

[2] Finn WD., Fujita N. Piles in liquefiable soils: seismic analysis and design issues. Soil Dyn Earthq Eng 2002;22:731–42. https://doi.org/10.1016/S0267-7261(02)00094-5.

[3] Garala TK, Madabhushi GSP, Di Laora R. Experimental investigation of kinematic pile bending in layered soils using dynamic centrifuge modelling. Géotechnique 2022;72:146–61. https://doi.org/10.1680/jgeot.19.P.185.

[4] Giannakou A, Gerolymos N, Gazetas G, Tazoh T, Anastasopoulos I. Seismic Behavior of Batter Piles: Elastic Response. J Geotech Geoenvironmental Eng 2010;136:1187–99. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000337.

[5] Hokmabadi AS, Fatahi B, Samali B. Physical Modeling of Seismic Soil-Pile-Structure Interaction for Buildings on Soft Soils. Int J Geomech 2015;15. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000396.

[6] Forcellini D. Seismic fragility of tall buildings considering soil structure interaction (SSI) effects. Structures 2022;45:999–1011. https://doi.org/10.1016/j.istruc.2022.09.070.

[7] SaeediAzizkandi A, Baziar M.H, Razmi B. Experimental Study on Seismic Response of Structure with Piled Raft Foundation. 19th Int. Conf. Soil Mech. Geotech. Eng., 2017, p. 835–8.

[8] Nakai S, Kato H, Ishida R, Mano H, Nagata M. Load Bearing Mechanism of Piled Raft Foundation during Earthquake. 3third UJNR Work. soil–structure Interact. Menlo Park. California, USA, 2004.

[9] Chiou J-S, Hung W-Y, Lee Y-T, Young Z-H. Combined dynamic structure-pile-soil interaction analysis considering inertial and kinematic effects. Comput Geotech 2020;125:103671. https://doi.org/10.1016/j.compgeo.2020.103671.

[10] Tao W, Fu J, Li Y. The Possibility of Detrimental Effects on Soil–Structure Interaction in Seismic Design Due to a Shift in System Frequency. Appl Sci 2024;14:7519. https://doi.org/10.3390/app14177519.

[11] Zhang X, Far H. Seismic behaviour of high-rise frame-core tube structures considering dynamic soil–structure interaction. Bull Earthq Eng 2022;20:5073–105. https://doi.org/10.1007/s10518-022-01398-9.

[12] Hussien MN, Karray M, Tobita T, Iai S. Kinematic and inertial forces in pile foundations under seismic loading. Comput Geotech 2015;69:166–81. https://doi.org/10.1016/j.compgeo.2015.05.011.

[13] Hussien MN, Tobita T, Iai S, Karray M. Soil-pile-structure kinematic and inertial interaction observed in geotechnical centrifuge experiments. Soil Dyn Earthq Eng 2016;89:75–84. https://doi.org/10.1016/j.soildyn.2016.08.002.

[14] Yamashita K, Hamada J. Kinematic and inertial effects on piled rafts in soft ground supporting isolated and non-isolated buildings observed during the 2011 Tohoku earthquake. Soils Found 2023;63:101372. https://doi.org/10.1016/j.sandf.2023.101372.

[15] Baziar MH, Rafiee F, Saeedi Azizkandi A, Lee CJ. Effect of super-structure frequency on the seismic behavior of pile-raft foundation using physical modeling. Soil Dyn Earthq Eng 2018;104:196–209. https://doi.org/10.1016/j.soildyn.2017.09.028.

[16] Schofield AN. Cambridge Geotechnical Centrifuge Operations. Géotechnique 1980;30:227–68. https://doi.org/10.1680/geot.1980.30.3.227.

[17] Rovithis EN, Pitilakis KD, Mylonakis GE. Seismic analysis of coupled soil-pile-structure systems leading to the definition of a pseudo-natural SSI frequency. Soil Dyn Earthq Eng 2009;29:1005–15. https://doi.org/10.1016/j.soildyn.2008.11.005.

[18] Lee C-J, Wang C-R, Wei Y-C, Hung W-Y. Evolution of the shear wave velocity during shaking modeled in centrifuge shaking table tests. Bull Earthq Eng 2012;10:401–20. https://doi.org/10.1007/s10518-011-9314-y.

[19] Reza Tabatabaiefar SH, Fatahi B, Samali B. Seismic Behavior of Building Frames Considering Dynamic Soil-Structure Interaction. Int J Geomech 2013;13:409–20. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000231.

[20] El Naggar MH, Novak M. Nonlinear analysis for dynamic lateral pile response. Soil Dyn Earthq Eng 1996;15:233–44. https://doi.org/10.1016/0267-7261(95)00049-6.

[21] Baziar MH, Moghadam MR, Kim D-S, Choo YW. Effect of underground tunnel on the ground surface acceleration. Tunn Undergr Sp Technol 2014;44:10–22. https://doi.org/10.1016/j.tust.2014.07.004.

[22] Bhowmik D, Baidya DK, Dasgupta SP. A numerical and experimental study of hollow steel pile in layered soil subjected to lateral dynamic loading. Soil Dyn Earthq Eng 2013;53:119–29. https://doi.org/10.1016/j.soildyn.2013.06.011.