Research on Engineering Structures & Materials
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Research Article

Dynamic analysis of piled raft foundations: Influence of superstructure and geometric parameters

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Article Info

Article History:

Received 27 Oct 2025

Accepted 23 Feb 2026

Keywords:

Combined piled-raft foundation;
3D numerical analysis;
Natural radial frequency;
Pile and column head shear;
Plaxis 3D

Abstract

Designers opt for piled raft foundations in response to the rise in demand for high-rise structures and significant infrastructure in metropolitan regions with low soil-bearing capacity. However, analytical and numerical studies that consider both the foundation and the superstructure are scarce in the literature. Considering the superstructure, even in its simplest form, is decisive for assessing the combined behavior of the piled raft. This study aims to examine how variations in several significant factors affect the dynamic behavior of a piled raft foundation structure system in loose sand. The combined piled raft system (CPRF) is modelled using the three-dimensional finite element software Plaxis 3D. An extensive parameter-based investigation is performed to appraise the impact of crucial factors such as raft thickness, pile spacing-to-diameter ratios, and varied pile lengths on the dynamic and seismic behavior of the combined piled raft foundation structural system. It is noted that the fundamental time period of the piled raft structure system is increased substantially when compared to a piled raft foundation without a structure and with reduced raft thickness. Additionally, there is a noticeable decrease in base shear at the head of the pile.

1. Introduction

Over the past few decades, the accelerated pace of urbanization and the demand for vertical expansion have resulted in the proliferation of high-rise structures across seismic and non-seismic regions worldwide. In the early stages of development, many tall buildings were founded on shallow footings; however, these systems often encountered significant differential settlements, especially in soft or heterogeneous soil profiles, exceeding permissible serviceability limits [1]. To mitigate these issues, deep foundations—primarily in the form of pile groups—were introduced, offering improved load transfer to deeper, more competent strata. Nevertheless, the high construction costs and logistical challenges associated with installing a large number of piles posed economic constraints. To overcome these limitations, the Combined Piled Raft Foundation (CPRF) configuration emerged as a technically efficient and economically viable solution that leverages the load-sharing capability of both the raft and piles [2]. By optimizing the interaction between these elements and the supporting soil, CPRF systems significantly enhance bearing capacity, reduce settlement, and improve seismic performance. As a result, they have gained wide acceptance in geotechnical engineering practice for use in critical infrastructure projects, including high-rise buildings, towers, nuclear facilities, bridges, and large-diameter storage tanks—especially in soft to medium clay and sandy soils where both vertical and lateral demands are considerable.

During seismic events, these structures are experiencing dynamic loads with a wide frequency range, making the seismic behavior of the foundation system a subject of prime importance. A critical concern arises when the natural frequency of the soil-structure system aligns with the

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DOI: http://dx.doi.org/10.17515/resm2026-1302st1027rs

dominant frequency content of seismic events, potentially causing resonance and structural failure. Traditionally, the design of CPRF under static loading focuses on optimizing raft stiffness and soil bearing capacity, with piles primarily designed to control settlements by carrying gravity loads [3]. However, the conventional seismic design of such systems often provided a fixed-base condition and neglects the role of soil-structure interaction (SSI). While this assumption may be valid for lightweight structures on moderately stiff soils, it becomes inaccurate for heavy superstructures resting on soft to medium soils. Numerous case studies, including the 1995 Kobe earthquakes, 2001 Bhuj and 2011 Christchurch earthquake, have demonstrated that neglecting SSI can lead to unsafe designs and severe structural damage.

Soil introduces flexibility at the foundation level, thereby altering the dynamic properties of the system, such as the natural period and modal behavior. In piled raft systems, the significant mass of the raft further increases inertial forces, amplifying the impact of SSI during seismic excitation [4]. Therefore, incorporating SSI into the seismic analysis of structures founded on CPRF systems is essential for achieving realistic and safe designs. A recent study [5] conducted a comprehensive three-dimensional finite element analysis of CPRFs with both long and short piles under static and seismic loading. Their results showed that replacing long piles with short piles slightly reduces vertical load-sharing but significantly enhances lateral resistance under earthquake excitation. Furthermore, short piles were found to experience higher bending moments and shear forces at the pile head, while also contributing to substantial material savings (up to 32%) with only marginal increases in settlement. Their findings confirm that CPRF is an optimized and economical foundation system for mid- and high-rise buildings under both static and seismic loading conditions. Author [6] developed a MATLAB-based educational platform for slope stability analysis using Bishop and OMS methods, offering an intuitive GUI, transparent computational framework, and reliability validated against Slide with only 5–6% error, thereby supporting improved conceptual learning in geotechnical engineering.

In addition, researchers performed experimental investigations showing the impact of several key design parameters, such as the raft-soil relative stiffness, pile length, spacing-to-diameter (S/d) ratio, number of piles in a group, and the type of pile-raft connection significantly influence the static response of CPRF systems, considering SSI. Although recognized as critical for design optimization, these parameters have not been comprehensively investigated in the context of seismic loading, changing the behavior of the superstructure in previous studies [7-10]. This study addresses the effect of some of these parameters on the behavior of the superstructure in response to seismic load.

The study is conducted in three parts. In Part I, the numerical model considered for the current analysis is validated through the previously conducted study by Kumar et al. [10]. In Part II, the 3D numerical analysis is performed for the CPRF, including and excluding superstructure, and its impact on the natural radial frequency of the whole system is examined. Moreover, parametric research is conducted to look at how changes in the geometrical and stiffness characteristics of the CPRF system affect the natural frequency or time period of the whole system, (i) include the superstructure in the model, (ii) ignoring the superstructure. In Part III, the study aims to comprehend the seismic behavior of piled raft foundations by analyzing the intricate relationship between the soil, piled-raft foundation, and structure. This includes examining various parametric variations that are crucial design factors. The dynamic analysis is conducted using numerical modelling based on finite elements. Plaxis 3D [11] is used to model the soil-piled raft-structure system. In conclusion, the outcome from the present work project provides a better understanding into the problems and also seismic design guidance for structures constructed on CPRF systems in loose sand.

2. Finite Element Simulation of Combined Pile-Raft-Structure Systems

2.1. Idealization of the Superstructure

To capture a broad spectrum of structural behavior under dynamic loading, the analysis includes structures with four characteristic natural periods with a fully restrained base: 0.30 sec, 0.50 sec, 1.5 sec, and 3.0 sec. These values are selected to span the range from short-period to long-period structures, corresponding approximately to three-storey, five-storey, fifteen-storey, and thirty-storey buildings, respectively. Fig. 1 shows the superstructure combined with CPRF having fixed base time periods starting from 3 sec, 1.5 sec, 0.5 sec, and ending at 0.3 sec. Along with this, the figure shows the pile configuration for a three-story superstructure. These multi-degrees-of-freedom systems are analyzed through modelling first in ETABS [12] in order to fix the dimensions of the structural element, then again modelled in Plaxis 3D along with the soil domain and CPRF for further studies. The overall dimensions of the superstructure presented in Table 1 are determined based on an assumed bay size of 8.5 m × 8.5 m, with a storey height of 3.5 m at each level. The mass of the superstructure, considering dead load and live load, is calculated to be approximately 1755 kN, 2930 kN, 8780 kN, and 17550 kN for natural periods of 0.30 s, 0.50 s, 1.5 s, and 3.0 s, respectively. The material properties of the superstructure are considered elastic and presented in Table 2. For the case of comparative study of piled raft foundation with and without structure, the structure having a fixed base time period of 1.5s is considered, while for the piled raft foundation without superstructure, equivalent uniform loading of 175kPa is applied on the raft.

Table 1. Dimension of superstructure

Parameters	Unit	$T_{fixed} = 0.3\ s$			$T_{fixed} = 0.5\ s$		
		Beam	Column	Slab	Beam	Column	Slab
Length/ Height	m	4.25	3.5	4.25	4.25	3.5	4.25
Width	m	0.3	0.4	4.25	0.32	0.44	4.25
Depth	m	0.3	0.4	0.1	0.32	0.44	0.1

Parameters	Unit	$T_{fixed} = 1.5\ s$			$T_{fixed} = 3.0\ s$		
		Beam	Column	Slab	Beam	Column	Slab
Length/ Height	m	4.25	3.5	4.25	4.25	3.5	4.25
Width	m	0.4	0.48	4.25	0.45	0.82	4.25
Depth	m	0.4	0.48	0.1	0.45	0.82	0.1

2.2. Modelling of the CPRF System

A square raft foundation measuring 10 m in width and 1 m in thickness was modelled using plate elements in PLAXIS 3D. While its safety against shear failure is verified, the settlement under vertical loads corresponding to 3-, 5-, 15-, and 30-story buildings exceeded the permissible limit of 75 mm for sandy soils, as recommended by Bowles [13]. To mitigate this excessive settlement, a combined piled raft foundation (CPRF) system is implemented. Initially, fixed-head piles—each 20 m long and 0.5 m in diameter are modelled in different configurations for different heights of superstructure using the embedded pile element feature in PLAXIS 3D [11]. A schematic diagram (Fig. 1) illustrates the CPRF configuration.

Several ways suggested by researchers [14,15] to model the soil domain are Winkler, macro modelling and continuum approach. In this study FEM method as part of continuum approach is adopted. The soil domain, modelled with 10-node tetrahedral elements, measured 65 m × 65 m × 45 m. A commonly used linear elastic-perfectly plastic Mohr-Coulomb model available in PLAXIS 3D [11] library is utilized to model loose sand in this study. The Mohr–Coulomb model was adopted due to its computational efficiency and suitability for large-scale SSI simulations where capturing first-order seismic response trends is the primary objective. While it does not explicitly model stiffness degradation and strain-dependent damping, similar simplifications are widely adopted in parametric SSI studies [16-18].

The modulus of elasticity of soil are taken as 5000 kN/m^2 considered to be constant throughout the depth to avoid computational complexity taking reference of other studies [19-20]. The value of the angle of frictional and dilation angles is taken as 27 degrees and zero, respectively. Interface set as strength determination manual with R_{inter} value 0.67 [21]. Standard boundary conditions are employed, restraining lateral movements of the sides and fully fixing the base.

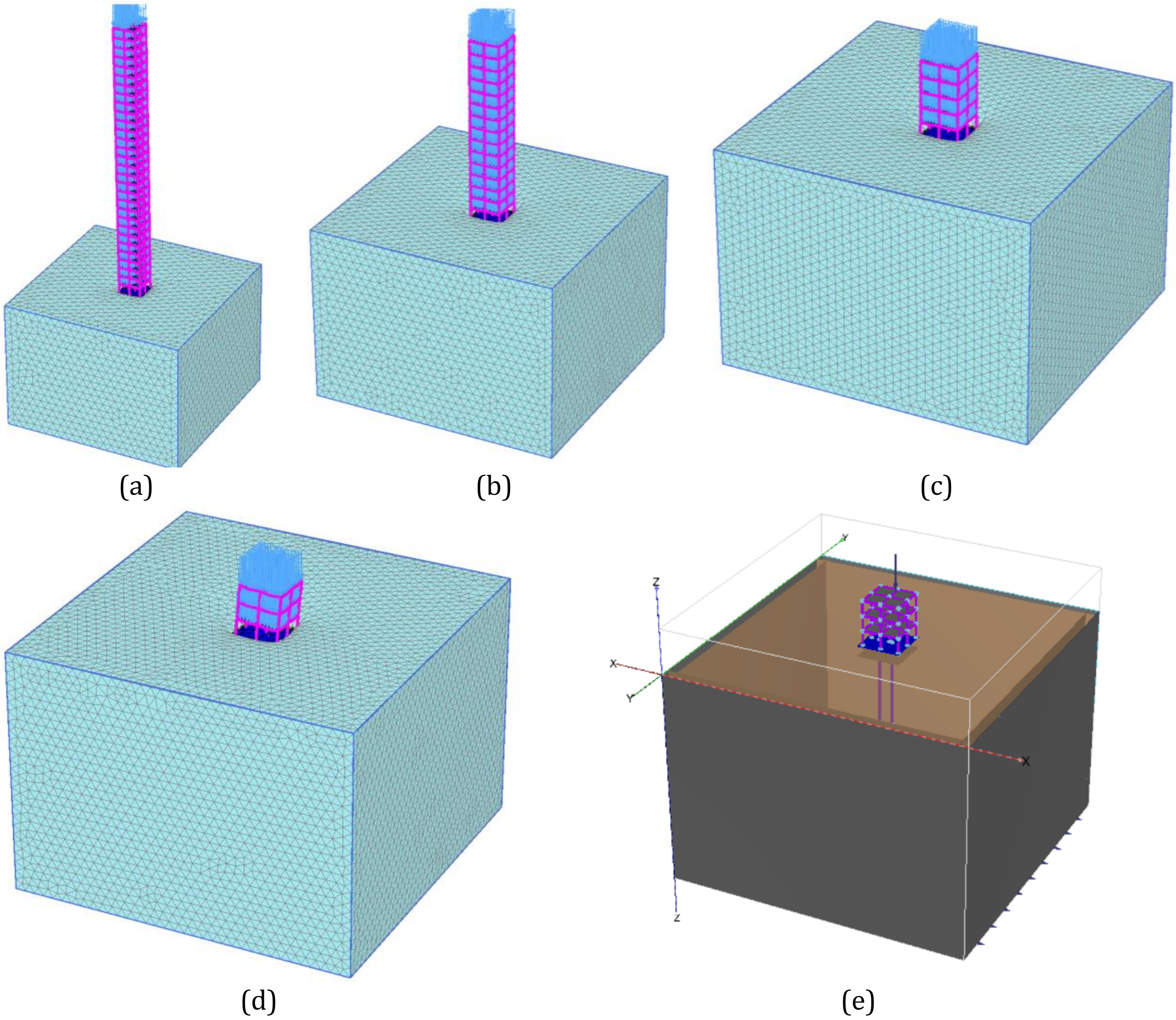


Fig. 1. Superstructure configurations (a) 30-story, (b) 15-story, (c) 5-story, (d) 3-story, (e) Pile Configuration for 3-story structure

A medium mesh was generated, consisting of 86,942 soil elements and 98,986 nodes, with an average element size of about 90 cm. In dynamic analysis, mesh distortion can affect wave propagation; to avoid this, the element size was selected based on the suggestion by researchers [15,22], which recommends it to be smaller than one-eighth to one-tenth of the shortest wavelength of the input motion. Accordingly, the mesh was refined to ensure accurate simulation of seismic wave propagation.

Table 2. Input engineering properties of soil, pile, raft, and structural elements

Parameter	Unit	Raft	Pile	Structure	Soil
Material	-	Concrete	Concrete	Concrete	
Length	m	10	20	-	65
Width	m	10	-	-	65
Thickness/height/depth	m	1	-	3.5	45
Diameter	m	-	0.6	-	-
Modulus of Elasticity	kN/m^2	41×10^6	41×10^6	41×10^6	5000
Unit Weight	kN/m^3	24	24	24	15
Poisson's Ratio	-	0.2	0.2	0.2	0.3
Friction Angle	Degree	-	-	-	27

The chosen mesh size ensured convergence of results, alignment with experimental test simulations, and computational efficiency. Material damping—due to intrinsic soil properties such as viscosity, friction, and plasticity—is represented using Rayleigh damping, with a damping ratio of 5%, typical for geological materials [23]. Damping coefficients are calculated directly by Plaxis 3D based on the first and second modal frequencies of the soil-CPRF system for different configuration.

To simulate an infinite domain and minimize artificial wave reflections, PLAXIS 3D [11] employs viscous boundaries with normal and shear dampers. These boundaries absorb outgoing waves, mimicking energy dissipation in an unbounded medium and accurately capturing dynamic response. Table 2 shows the adopted material features for the Soil, Piled Raft, and Superstructure components for the current analysis.

2.3. Ground Motions

An earthquake ground motion of the 1994 Northridge seismic event [Magnitude (Mw) = 6.7], with a peak ground acceleration of 0.57 g, is considered for the present study, taken from the PEER strong ground motion database [24]. Station with record sequence number (RSN) 963, Epicenter 34.21°N and 118.5°W. Fig. 2 illustrates the acceleration time histories corresponding to the selected input ground motions.

3. Validation of Numerical Model

The developed CPRF model in PLAXIS 3D [11] was rigorously validated by reproducing the results of Kumar et al. [10], whose numerical simulations were themselves benchmarked against a comprehensive series of centrifuge shaking table experiments on piled raft foundations in sand [25]. Thus, the numerical model of the present study indirectly inherits validation against high-quality experimental data, ensuring reliability under static, pseudo-static, and dynamic loading conditions. The material and geometric properties used for the soil, piles, raft, and superstructure are taken from the referenced study and are summarized in Table 3.

Table 3 Detailed material characteristics of the soil, pile, raft and superstructure adopted for the validation study [10]

Parameters	Unit	Soil	Raft	Pile
Material	-	Toyoura sand	Aluminum	Concrete
Unit weight	(kg/m^3)	1662	2752	2446
Poisson's Ratio (μ)	-	0.3	0.35	0.2
Young's Modulus	(MPa)	40	41700	70000
Cohesion	(kN/m^2)	10	-	-
Dilation Angle	-	1	-	-
Friction Angle (Φ)	-	31	-	-

The soil domain is modeled as a 28 m × 28 m × 16 m block of Toyoura Sand using 10-noded tetrahedral finite elements, and the Mohr–Coulomb model is employed to simulate soil behavior. Standard fixities were applied at the boundaries, with lateral constraints on the vertical faces and full fixity at the base. The raft foundation is modelled as a square plate element, 4 m wide and 1 m thick. The foundation system includes four fixed-head piles, each 9 m in length and 0.5 m in diameter, spaced 2 m c/c, and modelled using the embedded pile option available in PLAXIS 3D [11]. Under static loading, a vertical pressure equivalent to a total load of 5,862.5 kN is applied over the raft area. Fig. 3 shows the model predicted a maximum settlement of 17.45 mm, which showed acceptable conformity with the 21 mm settlement stated by Kumar et al. [10] in their study.

In the pseudo-static loading analysis, lateral loads are applied by multiplying the vertical load with different seismic coefficients to simulate earthquake-induced effects. Maximum horizontal loads are applied to CPRF are 621.4kN, 1178.4kN, 1635.6kN and 2520.8kN, corresponding to Bhuj 2001 (PGA=0.106g), Sikkim 2011 (PGA=0.201g), Loma Prieta 1989 (PGA=0.279g) and El-Centro 1979 (PGA=0.43g) ground motion, respectively. Bending moment profiles shown in Fig. 4 indicated that the maximum moments occurred near the pile heads, and their magnitudes increased with higher seismic acceleration values, consistent with the trends observed in the referenced study [10].

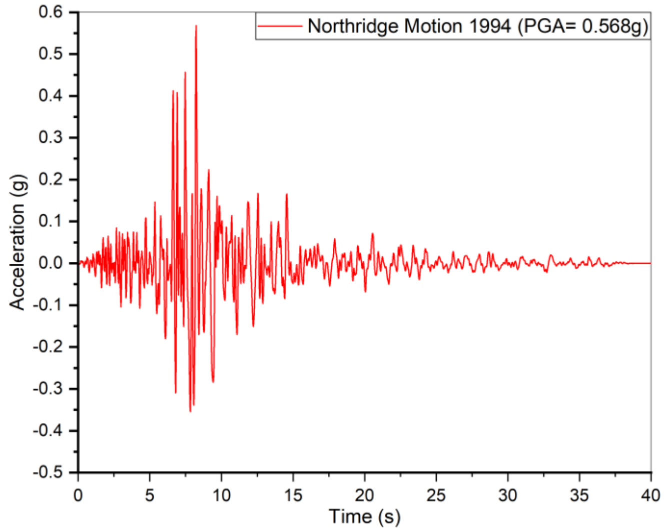


Fig. 2. Time history input motion

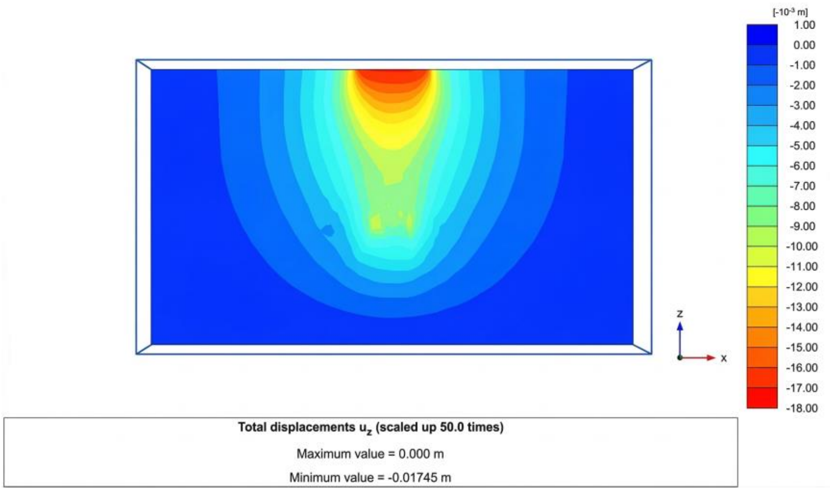


Fig. 3. Settlement of CPRF system due to applied vertical load

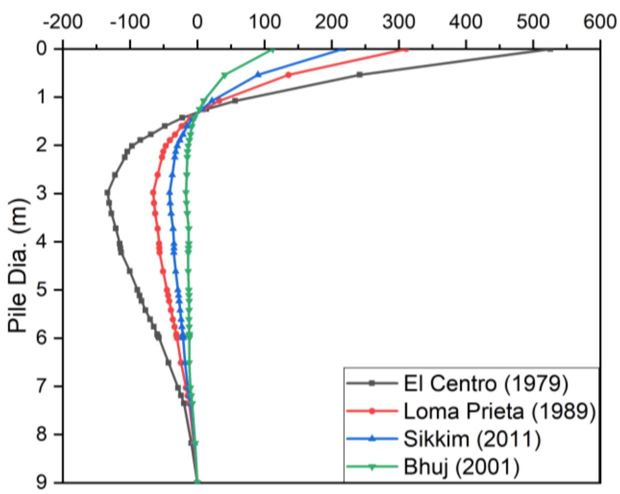


Fig. 4. Bending moment profile under different pseudo-static loading horizontally applied seismic load

In the dynamic analysis, a sinusoidal base acceleration with an amplitude of 1 m/s^2 and a frequency of 1 Hz was applied to simulate ground shaking. The maximum output acceleration noted at the uppermost location of the raft was 2.1 m/s^2 can be noted from Fig. 5, which showed reasonable alignment with the value reported by Kumar et al [10]. These comparisons across all loading conditions support the accuracy and robustness of the analyzed CPRF model in PLAXIS 3D [11].

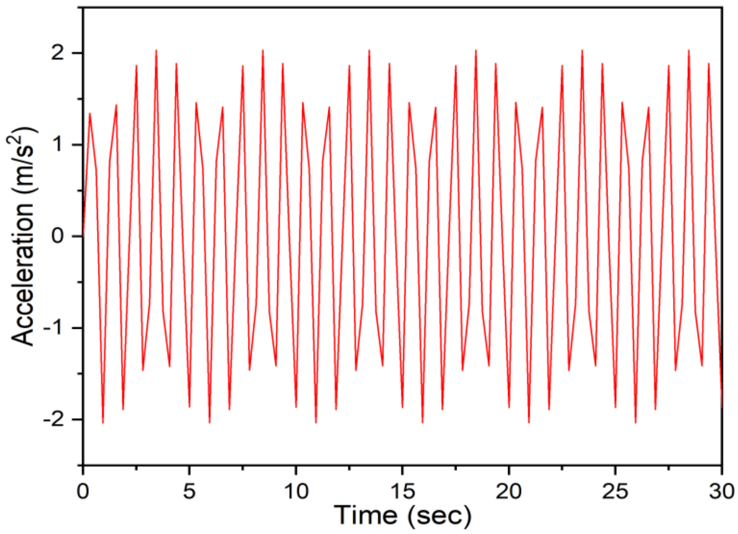
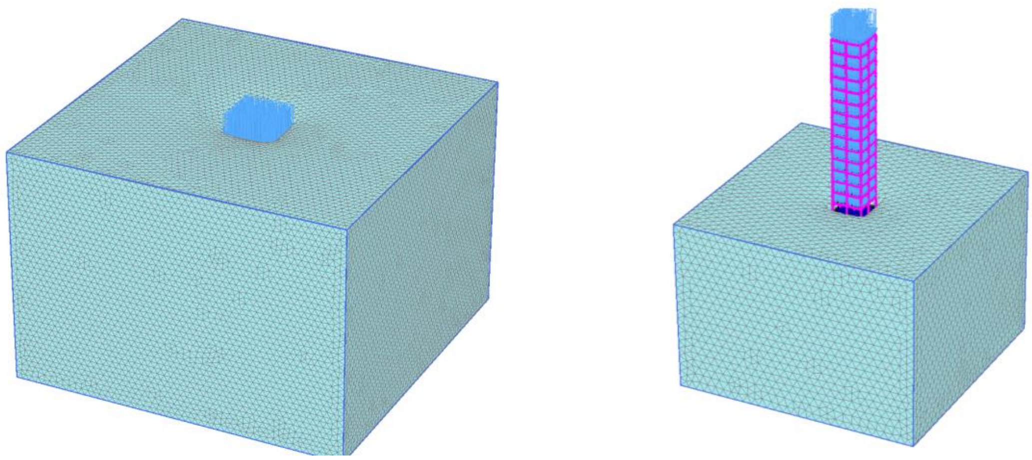


Fig. 5. Output Acceleration

4. Vibrational Behavior of Piled Raft Foundations Including and Excluding the Superstructure

A comparative analysis is performed on a 3×3 combined piled raft foundation system comprising 20 m long piles spaced at four times their diameter, embedded in loose sand, both with and without the inclusion of superstructure stiffness. A fifteen-story superstructure CPRF model has been considered. Also, the equivalent load of a fifteen-story structure is applied when the superstructure is neglected. All geometrical and material properties are given in Table 1. Fig. 6 represents the 3D FEM model for the CPRF system without and with superstructure.



(a) (b)

Fig. 6. CPRF (a) without and (b) with the superstructure

The results of a comparative analysis on combined piled raft foundations with and without the presence of a superstructure are shown in Fig. 7. The addition of superstructure stiffness increases the overall flexibility of the system, resulting in a decrease in its natural radial frequency. The percentage difference in natural frequency (ω) between the cases with and without superstructure reduces from 10% to 16% as the pile diameter increases from 0.5 m to 1.0 m, primarily due to the corresponding increase in foundation mass. These findings indicate that the presence of the superstructure in the model significantly affects the dynamic attribute of the system. Therefore, it is essential to account for the superstructure in the analysis of CPRF.

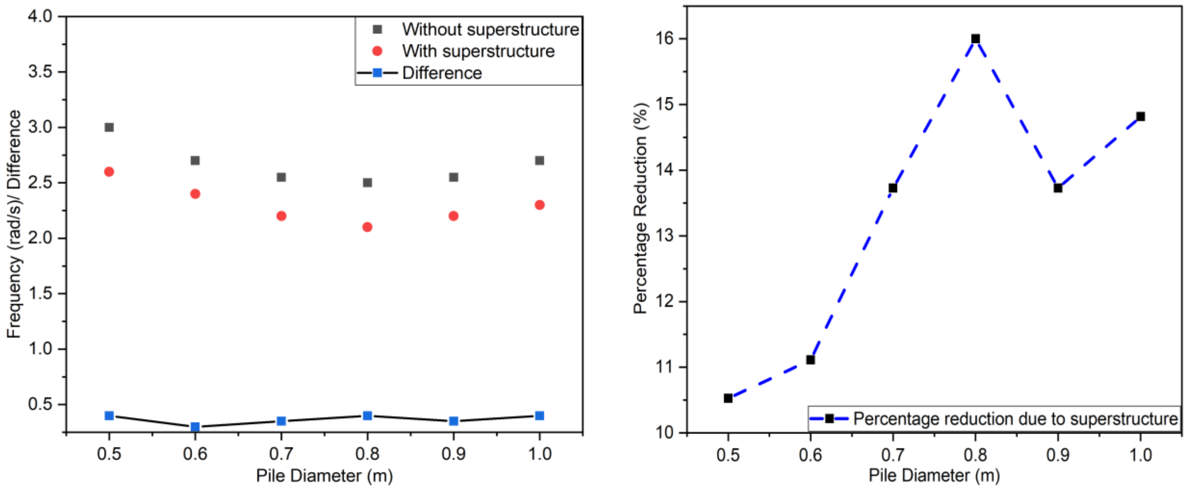


Fig. 7. Comparison between CPRF with and without superstructure

5. Impact of Governing Parameters on the Natural Circular Frequency of CPRF without Superstructure

To investigate the influence of different geometric parameters on the natural radial frequency of piled raft foundations, a comprehensive parametric analysis is performed by changing pile lengths, diameters and spacing. A uniformly distributed load of 175 kPa was considered to represent the superstructure load on the raft. The material and geotechnical characteristics used in the analysis are listed in Table 2.

5.1 Impact of Pile Length and Pile Diameter on Natural Frequency

As illustrated in Fig. 8, the natural circular frequency (ω) of the piled raft system diminishes with increasing pile length. This behavior is attributed to a decrease in the overall rigidity of the combined foundation system as pile length increases. Additionally, ω initially decreases with increasing pile diameter up to an optimum point, beyond which it begins to rise. This trend is explained by the dominance of the increase in mass over the gain in stiffness at smaller diameters, while at larger diameters, stiffness begins to govern the response, leading to an increase in ω.

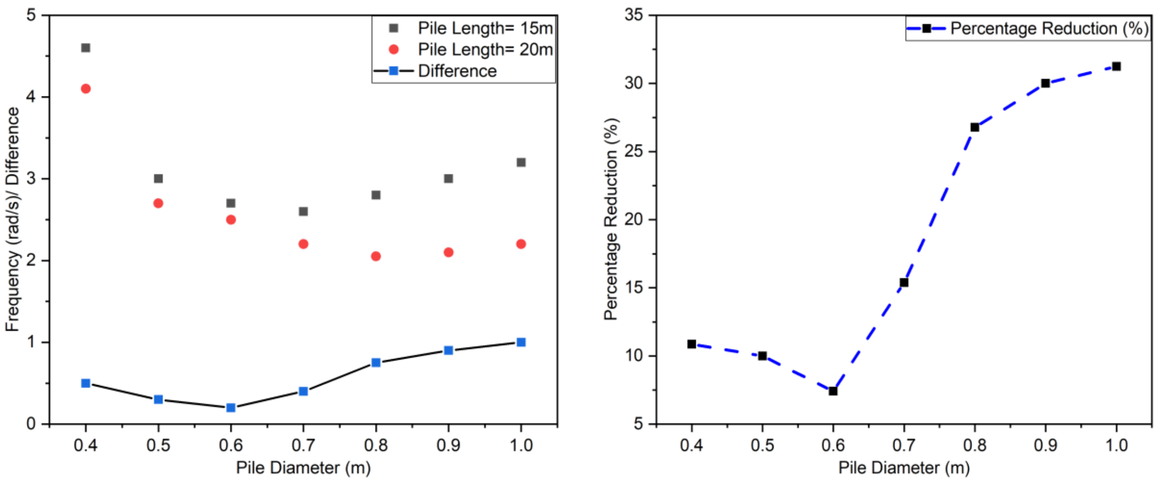


Fig. 8. Change in natural circular frequency with pile diameter for varying pile lengths

5.2 Impact of Variation on Pile Spacing-To-Diameter on Natural Frequency

In this part of the analysis, the pile spacing-to-diameter ratio (S/d) is varying from 2.5 to 8 for piles placed in the soil deposit. Initially, the diameter of the pile is held fixed at 0.6 m, while the pile length ranges from 15 m to 20 m. As illustrated in Fig. 9, these changes in pile geometry (i.e spacing) have no substantial impact on the natural radial frequency of the piled raft.

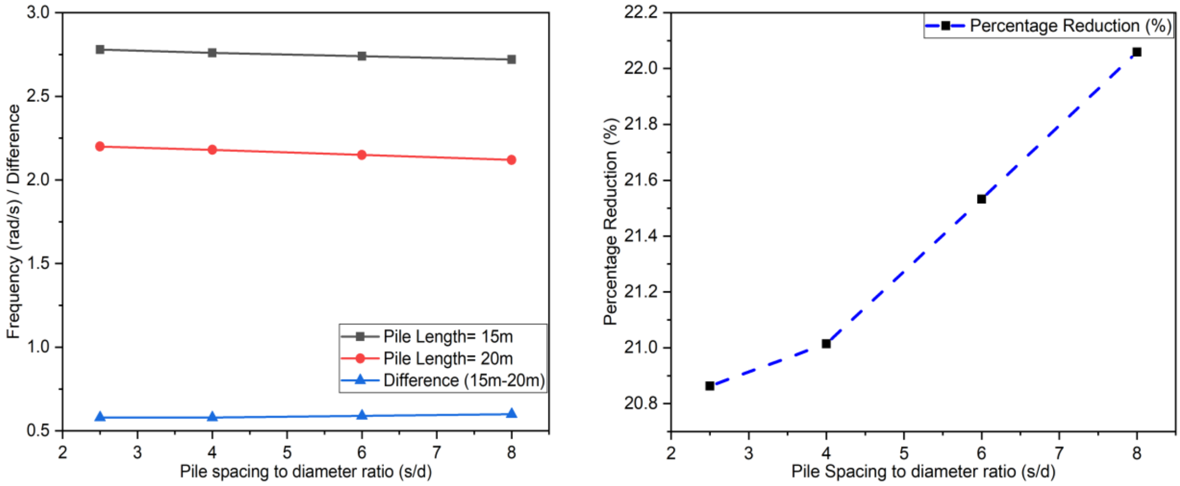


Fig. 9. Variation in natural circular frequency with change in pile spacing for different pile lengths

6. Parametric Study of Piled Raft Foundation Incorporating Superstructure

This part describes the range of parametric cases considered in the current analysis. These cases are developed based on the design of CPRF subjected to gravity loads, tailored considering four typical superstructures characterized by fundamental fixed base time periods of 0.3 s, 0.5 s, 1.5 s, and 3 s, as outlined earlier in subsection 2.1. Initially, a raft foundation of dimensions 10 m × 10 m with a thickness of 1 m is assumed, corresponding to the structural configurations of the selected buildings. The pile and raft are both modelled, considering concrete as a material with a modulus of elasticity $E_{concrete} = 41 \times 10^6 \ kN/m^2$ and a mass density of 2400 kg/m^3. Each pile is modelled as a solid circular section of 20 m long, a dia. of 0.6 m, and a spacing-to-diameter ratio (S/d) varied according to the values in Table 4. The pile is assumed to be founded in the soil, with an overall depth of soil of 45 m.

Once the appropriate pile group configurations are determined for each case, further analyses are conducted to study how variations in the spacing of piles and raft thickness influence the time period and seismic (namely, base shear) behavior of the combined piled raft system. Two levels of raft-soil relative stiffness (k_{rs}), approximately 3.3 and 51.5, are considered by choosing two values of the raft thickness, which are 1 m and 2.5 m, to capture both flexible and rigid raft behavior on application Northridge ground motion. The k_{rs} is calculated based on the approach proposed by Clancy and Randolph [26], given in Eq (1).

$$k_{rs} = \frac{4E_r B_r t_r^3 (1 - \nu_s^2)}{3\pi E_s L_r^4 (1 - \nu_r^2)} \tag{1}$$

where, E_r and E_s are Young's modulus of Raft and soil, B_r, L_r and t_r are the width, length and thickness of the raft respectively, ν_s and ν_r are the Poisson's ratio of soil and raft. Moreover, the impact of different pile spacing-to-diameter ratios is examined by considering (S/d) values of 2.5 and 8 for the two most suitable superstructure cases with fixed base periods of 0.3 s and 0.5 s. A detailed summary of all these parametric variations is provided in Table 4.

Table 4. Outline of the parametric study framework

Structure with Fixed base Time Period (Tfixed)	Thickness of raft (m)	Raft-soil relative stiffness (krs)	S/d	Pile Configuration
0.3	2.5 1	51.5 (Rigid) 3.3 (Flexible)	2.5 8	1×2
0.5	2.5 1	51.5 (Rigid) 3.3 (Flexible)	2.5 8	2×2
1.5	2.5 1	51.5 (Rigid) 3.3 (Flexible)	2.5 8	3×3
3	2.5 1	51.5 (Rigid) 3.3 (Flexible)	2.5 8	4×4

7. Results and Discussion

7.1 Impact of (S/d) Ratio on The Time Period Of The Structure

At T_{fixed} = 0.3 s, the change in the (S/d) ratio has little to no impact on period lengthening can be observed from Fig. 10, regardless of the k_{rs} value (3.3 or 51.5). The absence of period lengthening at T_{fixed}=0.3 may be attributed to the fact that increasing the (S/d) ratio in a 1×2 pile group has only a minimal influence on the overall foundation stiffness, resulting in negligible impact on the overall system time period. However, for a slightly more flexible structure with T_{fixed} = 0.5 s, the period lengthening shows a noticeable decrease—from 100% to 78%—as the (S/d) ratio increases from 2.5 to 8 for k_{rs} = 51.5. A similar declining trend is observed for k_{rs} = 3.3, where the period lengthening reduces from 180% to 150% over the same (S/d) range, which shows with the increase in number of pile (2×2) stiffness plays an important role in altering the time period of system.

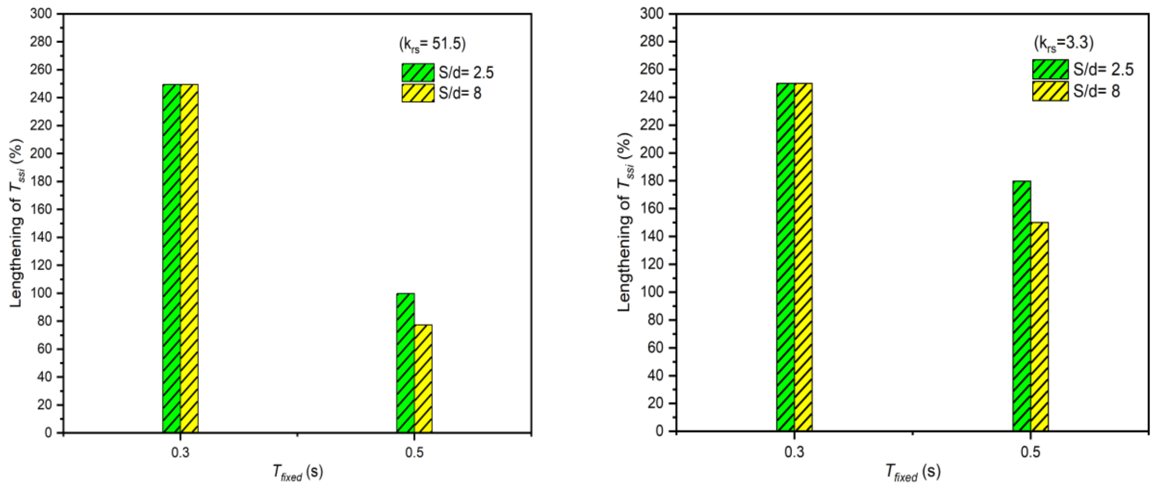


Fig. 10. Impact of S/d ratio on time period for different raft soil stiffnss

7.2 Impact of Stiffness of Raft on Time Period of The Structure

From Fig. 11, it is evident, for T_{fixed} = 0.5 s, the period of the superstructure constructed on a CPRF increases from 100% to 180% as k_{rs} decreases from 51.5 to 3.3. A similar trend is observed for longer periods: for T_{fixed} = 1.0 s, the period lengthening varies from 75% to 92%, and for T_{fixed} = 3.0 s, it ranges from 7.8% to 37% over the same reduction in k_{rs}. These results indicate that increasing raft flexibility significantly influences the extent of period lengthening.

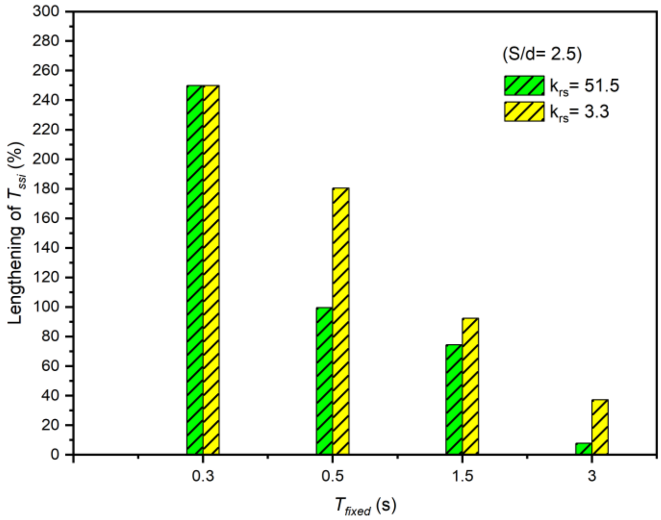


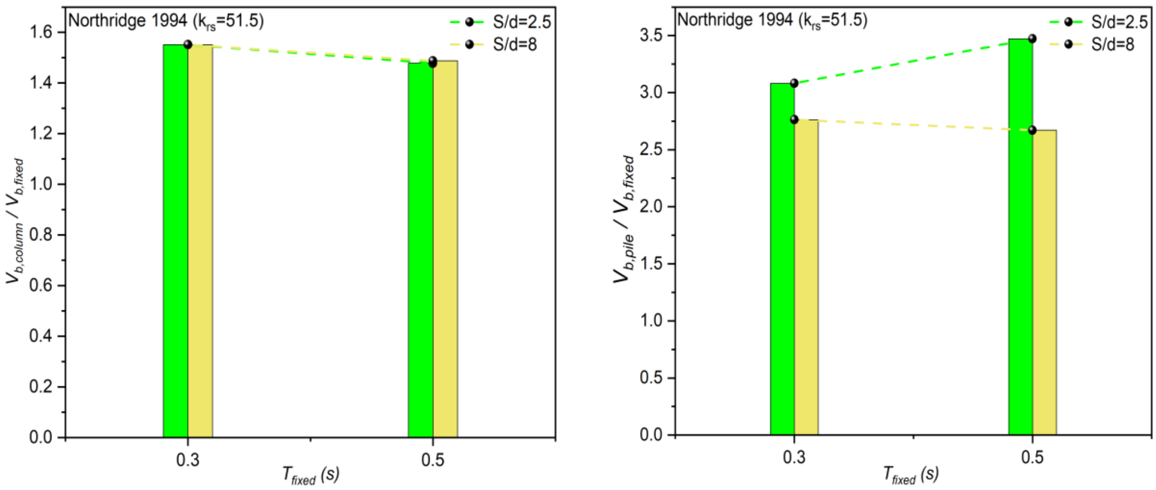
Fig. 11. Impact of raft soil stiffness on time period

7.3 Dynamic Response of Piled Raft Foundation Systems Under Seismic Loading

Under the elastic deformation range, base shear at the column head, as well as at the pile head, serves as a key factor for the evaluation, design and optimization of piled raft-supported structural systems. The column head shear ($V_{B,column}$) and pile head shear ($V_{B,Pile}$) are normalised with reference to the base shear from the fixed-base condition of the superstructure ($V_{B,fixed}$), and expressed as ($V_{B,column}/V_{B,fixed}$) and ($V_{B,Pile}/V_{B,fixed}$) respectively. These normalised shear values provide valuable insight into how the inclusion of a dynamic interaction factor between soil, pile, raft and superstructure affects the seismic force distribution between the superstructure and foundation elements.

7.3.1 Impact of S/d Ratio

Fig. 12 and Fig. 13 depict the impact of the S/d ratio on the normalized shear at the column and pile heads under the input ground motion from the 1994 Northridge earthquake, for k_{rs} = 51.5 and 3.3, respectively. For k_{rs} = 51.5, the variation in S/d shows negligible impact on the normalized column head shear ($V_{B,column}/V_{B,fixed}$). However, for k_{rs} = 3.3, a slight decrease in ($V_{B,column}/V_{B,fixed}$) is observed upon increasing S/d ratio. In contrast, the shear transmitted to the pile head exhibits its most significant variation at T_{fixed} = 0.5 s for k_{rs} = 51.5. Overall, it can be concluded that the normalized pile head shear tends to reduce as the S/d ratio increases.



(a) (b)

Fig. 12. Impact of S/d ratio on Normalized base shear (a) For, const. k_{rs} = 51.5; varying S/d ratio and (b) For, const. k_{rs} = 3.3; varying S/d ratio

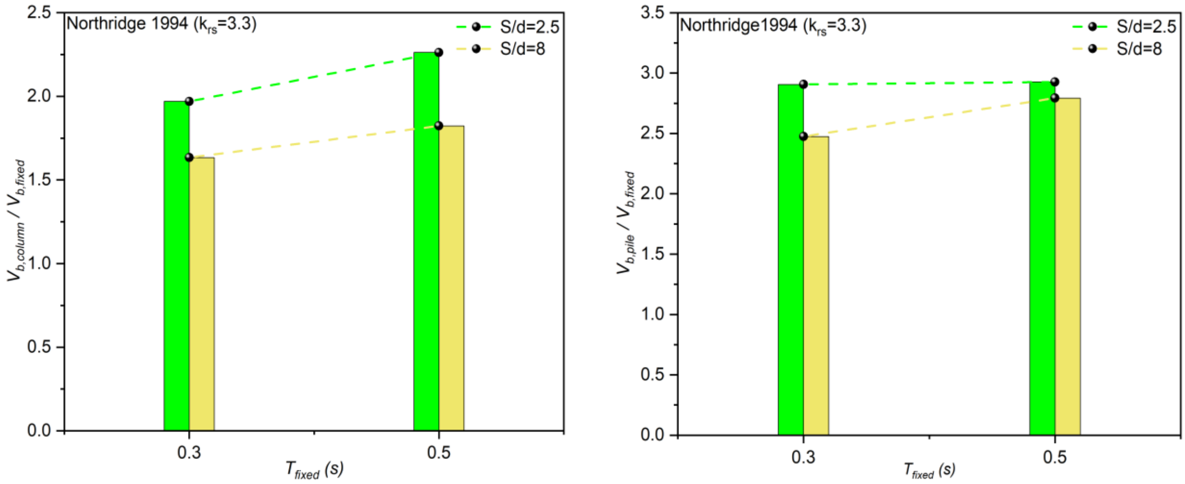
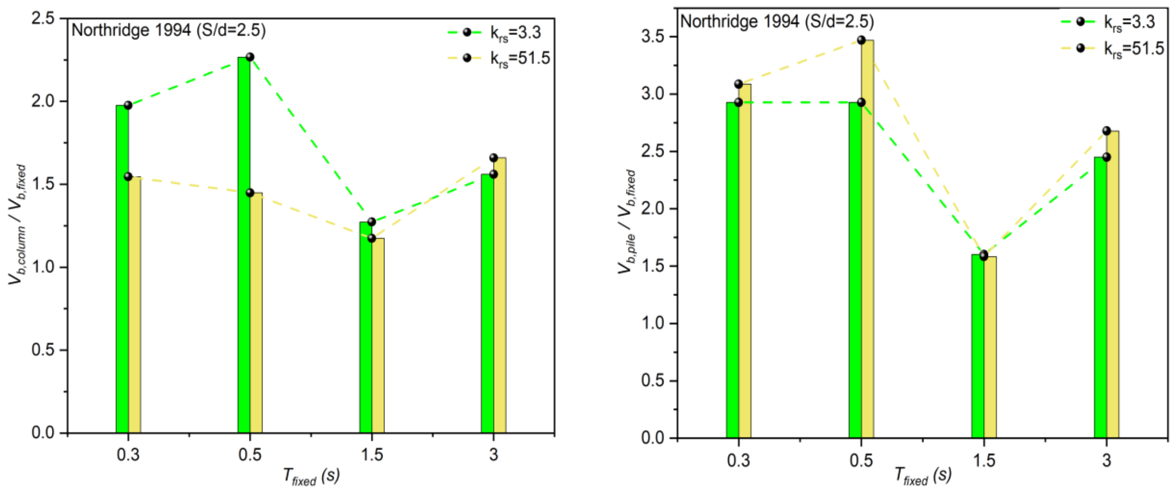


Fig. 13. Impact of S/d ratio on normalised base shear

7.3.2 Impact of Flexibility of The Raft

Under the Northridge 1994 ground motion, a significant alteration in both column and pile head shear is noticed primarily for the structure with T_{fixed} = 0.5 s, which is considered to be moderately stiff. As shown in Fig. 14, the column head shear increases by 57%, while the pile head shear decreases by 20% with increasing raft flexibility. However, the effect of raft flexibility on pile head shear is comparatively less pronounced for this ground motion. The non-monotonic variation of normalized base shear with period arises from frequency-dependent load sharing between piles, columns, and the raft. At short periods, the system behaves rigidly and piles attract higher shear, especially for higher raft–soil stiffness (k_{rs}). Around intermediate periods (1.5 s), foundation flexibility reduces the transmitted shear to both piles and columns. At longer periods, soil–foundation interaction amplifies displacements, causing renewed increases in pile and column shear. Thus, the observed trend reflects the combined influence of raft–soil stiffness, pile–soil interaction, and the dynamic characteristics of the superstructure.



(a) (b)

Fig. 14. Impact of raft soil stiffness on Normalised base shear (a) Const. $S/d = 2.5$; Varying k_{rs} ; column head shear, (b) Const. $S/d = 2.5$; Varying k_{rs} ; pile head shear

8. Conclusion

The dynamic behavior of CPRF under seismic loading is governed by complex interactions among soil, piles, raft, and superstructure. This study presents a comprehensive assessment of key parameters influencing the seismic response, such as pile length, superstructure mass, soil flexibility, S/d ratio, and raft stiffness. Observations include shifts in natural frequency, period lengthening, and reductions in pile head shear, all strongly affected by soil–structure interaction. These findings highlight the critical need for integrated analysis and design approaches to ensure safety, resilience, and performance efficiency of CPRF systems in seismic regions.

- Decrease in natural circular frequency with increasing pile length: As the pile length increases, the natural circular frequency of the foundation system reduces due to a reduction in overall stiffness. This reduction is primarily attributed to the increased flexibility and diminished lateral stiffness of longer piles, which lowers the effective stiffness of the entire foundation system.
- Impact of superstructure on natural radial frequency: The natural circular frequency of a CPRF, when incorporating superstructure, lessens by 10–30% compared to a piled raft foundation that excludes superstructure. This reduction is due to the additional mass and flexibility introduced by the superstructure, which affects the free vibration behavior of the foundation system.
- Lengthening of fundamental period due to soil flexibility: The inclusion of soil flexibility into the soil–piled raft–superstructure system leads to a substantial increase in the fundamental period, with maximum lengthening observed as 250%, 180%, 92%, and 37% for superstructures having fixed-base fundamental time periods (T_{fixed}) of 0.30 s, 0.50 s, 1.5 s, and 3.0 s, respectively. This effect is particularly pronounced in CPRF systems with relatively low raft–soil stiffness. These findings highlight the significant impact of soil–foundation–structure interaction on the free vibration response of the overall system, especially for short-period structures, where the interaction causes more pronounced shifts in the fundamental period.
- Effect of S/d ratio and raft-soil relative stiffness on period lengthening: For structures with moderate fundamental periods (e.g., T_{fixed} = 0.5 s), an increase in the pile spacing-to-diameter ratio (S/d) and the relative stiffness between the raft and soil can reduce the extent of period lengthening. However, minimal or no variation is noted in the extent of period lengthening for short-period structures (e.g., T_{fixed} = 0.3s) with variations in both the S/d ratio and raft flexibility. This suggests that for shorter period structures, the influence of these parameters is less significant.
- Effect on base shear and pile head shear due to S/d ratio and raft flexibility: The impact of the S/d ratio and flexibility of the raft on base shear at the column and pile head is almost the same. Additionally, the incorporation of raft flexibility significantly alleviates the pile head shear response under seismic ground motions, such as the Northridge ground motion. This reduction in pile head shear can be attributed to the increased energy dissipation and damping provided by the flexible raft, which helps to mitigate the forces transmitted to the pile heads during seismic events.
- Dynamic interaction between soil, piles, raft, and superstructure: The dynamic interaction between the soil, piles, raft, and superstructure significantly influences the overall seismic behavior of the foundation system. The interaction between soil, structure and piled raft can lead to changes in the natural frequencies, damping ratios of soil or structure, and different mode shapes of the system, affecting its performance during seismic events.
- Importance of accurate modelling and analysis: Accurate modelling and analysis of the soil-pile-raft-structure system are essential for predicting its seismic behavior. Factors such as soil nonlinearity, pile-soil interaction, and the dynamic characteristics of the superstructure must be considered to ensure realistic assessments of the foundation's performance.
- Design implications for piled raft foundations: The findings emphasize the importance of considering soil flexibility and superstructure stiffness in the design of combined piled raft foundations. Design strategies should account for the potential lengthening of the fundamental time period and the reduction in shear at the pile head to enhance the seismic resilience of the foundation system.

8.1 Recommendations for Future Research

Further research is recommended to examine the effects of layered soil, pile configurations, and superstructure designs on the dynamic behavior of the CPRF. Experimental studies and advanced numerical simulations can offer a more detailed understanding of the complex interactions within the system.

Acknowledgement

The authors acknowledge that the software used in this study is provided by the Indian Geotechnical Society (IGS), New Delhi.

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