Nonlinear Seismic Interaction of Soil–Foundation–Structure System in High-Rise Frames with Varying Pile Configurations

Shashank S. Sul[1], S. A. Rasal[2], Radhika Jadhav[3]
[1]Post Graduate Student, Dept. of Civil Engineering,
[2] Assistant Professor, Dept. of Civil Engineering,
[3] Assistant Professor, Dept. of Civil Engineering,
Datta Meghe College of Engineering, Airoli, Navi Mumbai 400708, Maharashtra, India

***Abstract*- India's high seismic vulnerability often results in substantial structural damage, largely due to the inadequate consideration of soil-structure interaction (SSI) in traditional design methodologies. Conventional approaches typically model the superstructure independently of the foundation and supporting soil, leading to oversimplified and inaccurate assessments of seismic behavior. This study investigates the seismic response of a 20-story (60-meter) reinforced concrete spaceframe by incorporating SSI using response spectrum analysis. The analysis employs ground motion data from the Bhuj earthquake (2001) to evaluate key response parameters, including lateral displacement and inter-storey drift across various floor levels. Results demonstrate that considering SSI leads to a more accurate and realistic representation of structural performance under seismic loading. The present study underscores the necessity of SSI-inclusive designs to enhance the safety, reliability, and resilience of high-rise buildings in seismically active regions.**

***Index Terms*— dynamic Soil-Structure Interaction, finite element analysis, space frame, high rise building, raft footing, pile foundation.**

I. INTRODUCTION

Urbanization is a global phenomenon characterized by increasing population densities and rising land costs in urban areas, which have driven the trend toward vertical development. This vertical growth optimizes land utilization, addressing the dual pressures of urban expansion and economic development. High-rise buildings are emblematic of modern cities, providing the necessary infrastructure to accommodate growing populations and economic activities within limited land areas. However, the construction of tall buildings, especially on soft soil, poses significant engineering challenges that require meticulous attention to ensure structural safety and integrity.

Soft soil, often found in urban environments, typically lacks the inherent load-bearing capacity and stability required to support tall structures. Without appropriate engineering interventions, the construction of high-rise buildings on such soil can lead to significant issues, including excessive settlement, differential settlement, and soil consolidation over time. These factors can compromise the structure's performance, functionality, and safety. Consequently, engineers and geotechnical experts must develop and implement advanced solutions that effectively manage soil-structure interaction (SSI) dynamics to maintain the stability and sustainability of high-rise buildings.

Traditional structural design methods have often simplified or neglected the effects of SSI. Conventional analysis commonly assumes that the motion at the foundation level mirrors the ground motion in a free-field scenario, effectively ignoring the real-world energy dissipation effects. This assumption may hold true for structures built on firm strata or rock, where the foundation's movement closely follows the ground motion. However, in structures with flexible foundations on soft soil, seismic or other dynamic loads transfer a portion of the vibrational energy to the soil layer, where mechanisms like radiation damping and hysteresis dissipate it. Design practices cannot overlook this energy dissipation effects, as they play a crucial role in the actual behavior of the structure.

The impact of soil on structural response varies significantly based on several factors, including the characteristics of the foundation, the type of structure, and the nature of the excitation forces. For example, buildings with deep foundations or piles interact differently with the soil than those with shallow foundations. Similarly, the structural response to seismic activity differs from that to wind or other dynamic loads. Understanding and accurately modeling SSI effects is essential for engineers to assess stress conditions, absolute displacements, and overall structural behavior under various loading scenarios.

This study focuses on the critical need to incorporate SSI into the design and analysis of high-rise buildings, particularly those situated on soft soil. This using the original ground acceleration data from the Bhuj earthquake in India, this research employs a response spectrum analysis on a 20-story (60-meter height) space frame structure. The study evaluates key parameters such as storey drift, pile settlement, maximum displacement at the pile tip, maximum shear stress. The goal is to provide a comprehensive understanding of SSI effects and improve design methodologies, ensuring that high-rise buildings in urban environments are safer, more stable, and more resilient to dynamic loads.

Incorporating SSI into structural design practices represents a paradigm shift from conventional methods, promising significant improvements in the safety and performance of tall buildings. This research aims to bridge the gap between geotechnical and structural engineering, fostering interdisciplinary approaches to tackle the challenges posed by urban vertical development on soft soil. It contributes to the advancement of engineering knowledge and practices, ultimately leading to the creation of more sustainable and resilient urban infrastructure.

II. REVIEW OF LITERATURE

Solanki et al. [1] and Swamy and Rasal [4] have conducted thorough research on the effects of soil-structure interaction (SSI) on pile raft foundations in multi-story reinforced concrete (RC) buildings with vertical irregularities. Their research highlights the critical role SSI plays in the overall stability and performance of such structures. By conducting detailed simulations and empirical analyses, they have demonstrated how variations in soil properties and foundation configurations can significantly impact the dynamic response of buildings, underscoring the necessity of incorporating SSI considerations in the design phase. OZ et al. [2] and Jarallah [13] have focused on the seismic response of existing RC buildings, taking into account SSI effects. Their studies provide valuable insights into how SSI influences the behavior of buildings during seismic events. They have shown that ignoring SSI can lead to an underestimation of seismic demands, which can compromise the safety and integrity of structures. Their work emphasizes the need for retrofitting and strengthening existing buildings to mitigate potential risks associated with seismic activities.

Scarfone et al. [3] have developed a 3D numerical approach to assess dynamic SSI effects for tall buildings. Their research introduces advanced modeling techniques to capture the complex interactions between soil and structure under dynamic loads. Based on their simulation results, dynamic SSI effects can significantly change the vibration characteristics and stress distribution within tall buildings. This implies that a more comprehensive design process must consider SSI. Several researchers, including Mondal [5], Krishna Chaitanya et al. [6], Mourlas et al. [8], Pallavi and Neelima [14], Shukla et al. [21], and Sushma and Pradeep Kumar [24], have explored the SSI effects on the dynamic behavior of tall buildings. Their collective work provides a broad spectrum of analyses, ranging from empirical studies to sophisticated simulations, all pointing to the significant impact of SSI on the dynamic performance of tall structures. These studies highlight the importance of integrating SSI effects into the design and analysis of tall buildings to ensure their safety and resilience against dynamic loads.

Researchers Rasal et al. [9] and Fatahi and Tabatabaiefar [20] conducted extensive research on the non-linear SSI analysis of mid-rise framed buildings on soft soils supported by piles. Their research delves into the complexities of non-linear soil behavior and its interaction with structural elements. They show that non-linear SSI effects can cause big differences in predicted structural responses compared to linear models. This shows how important it is to use non-linear analyses for more accurate and reliable design results. Researchers like Kumar et al. [11], Venkatesh and Deshpande [12], Roopa et al. [16], Halkude et al. [17], Abdel Raheem et al. [18], and Bhattacharya et al. [27] have looked at how the soil, foundation, and structure interact with each other to see how that affects the seismic response of moment-resisting frame (MRF) buildings on raft foundations. Their studies collectively underscore the importance of considering soil-foundation-structure interactions in seismic design. They provide evidence that SSI can alter the seismic demand on buildings, affecting both their safety and performance. Their findings advocate for incorporating detailed SSI analyses into the seismic design of buildings with raft foundations to achieve more accurate and safe designs.

The research by Visuvasam, Chandrasekaran [7], and Dode et al. [15] on the effects of SSI on the behavior of RC-framed structures during earthquakes has been summed up. Their research provides a comprehensive overview of how SSI can affect RC frame seismic response, emphasizing the importance of incorporating SSI effects in seismic design and analysis. Their findings support the development of more robust design methodologies that account for the complex interactions between soil and structure during seismic events. Rasal, Chore, et al. [10] have provided specific insights into the interaction analysis of a three-storeyed building frame supported on a pile foundation. Their work highlights the unique challenges and considerations in analyzing SSI for low-rise structures, particularly with respect to pile foundations. Their findings contribute to a broader understanding of SSI effects across different building types and foundation systems. Hokmabadi et al. [19] have assessed the influence of soil-pile-structure interaction on the seismic response of mid-rise buildings on floating pile foundations. Their research demonstrates that floating pile foundations introduce additional complexities in SSI analyses, affecting the overall seismic behavior of buildings. Their findings highlight the necessity for detailed SSI studies for buildings on floating pile foundations to ensure accurate seismic performance predictions.

Chaudhari, Kadam [22], and Hussien [25] have provided detailed analyses of the effect of pile group design under static and dynamic lateral loads on high-rise buildings, taking into account SSI. Their work highlights the critical role of pile group design in the overall performance of high-rise buildings, particularly under lateral loading conditions. They advocate for incorporating SSI effects into the design process to improve the safety and resilience of high-rise structures. Raychowdhury and Singh [23], as well as Tahghighi and Konagai [26], have investigated the effects of nonlinear SSI on the seismic response of low-rise special moment-resisting frame (SMRF) buildings and conducted numerical analyses of nonlinear soil-pile group interaction under lateral loads, respectively. Their research emphasizes the importance of accounting for nonlinear soil behavior and SSI effects in the seismic analysis and design of low-rise buildings. Their findings contribute to the development of more accurate and resilient design practices for low-rise structures. Radhika J., S.A. Rasal and H. S. Chore et al. [28,31] have investigated the dynamic soil-pile structure interaction (SSPSI) of a 15-story symmetric building frame resting on different pile configurations and provided with damping layers for studying the performance of such building under earthquake. Damping layers with increasing damping around the soil medium is introduced to absorb seismic energy, reduce resonance effects, and enhance the structures resilience. The results show that the addition of the damping layers and different types of piles greatly reduces the stress that earthquakes put on the structure by releasing vibrational energy. The research by Saad Kondkari, S. A. Rasal and Radhika Jadhav [30], aims to provide a comprehensive overview in current state of structure-soil-structure interaction issues in tall building frames supported by different types of foundations. Their analysis emphasizes the impact of adjacent structures and highlights the need for further academic research in this area. This literature review provides a comprehensive overview of the significant contributions made by various researchers in the field of soil-structure interaction, highlighting the critical importance of considering SSI effects in building design and analysis to ensure their safety and performance under various loading conditions.

III. OBJECTIVES OF THE STUDY

1. To realistically simulate nonlinear soil–structure interaction (SSI) by incorporating nonlinear

behavior of the supporting soil and linear response of the superstructure under seismic loading.

2. To study and compare how well a high-rise building frame performs during an earthquake when supported by different types of pile foundations—like 2×2 pile groups, bearing piles, floating piles, 2 piles in series, and parallel setups—focusing on side movement and how much each floor shifts.
3. To evaluate the effect of SSI on lateral displacement and inter-storey drift at different floor levels, using the original ground acceleration time history of the 2001 Bhuj earthquake (India).

IV. METHOD OF ANALYSIS

Response Spectrum Method

A sophisticated approach, the Response Spectrum Method (RSA), analyzes the seismic response of structures. A response spectrum depicts the structural response to various ground motions in the evaluation. This approach offers a comprehensive and precise evaluation, aiding engineers in the creation of buildings that are both safer and more efficient. Here is a comprehensive analysis of the RSA encryption algorithm: Examining the highest displacement, velocity, or acceleration values in a set of single-degree-of-freedom (SDOF) systems exposed to a specific ground motion creates a response spectrum. The spectrum graphically represents the systems' peak responses in relation to their natural frequencies, providing a thorough depiction of seismic demand at various frequencies. Modal Analysis: We represent the structure as a system with multiple degrees of freedom (MDOF). We use modal analysis to ascertain the inherent frequencies and mode shapes of a construction. Each mode shape corresponds to a unique configuration of deformation that the structure experiences at a particular frequency. The response spectrum yields the highest possible response for each indicated mode. This necessitates calculating modal displacements, velocities, and accelerations. The modal responses represent each mode's reaction to the seismic event, as specified by the response spectrum. To determine the structure's overall response, we aggregate the collective modal responses. Two commonly used combination procedures are the Square Root of the Sum of the Squares (SRSS) and the Complete Quadratic Combination (CQC). This stage ensures the consideration of the combined impact of all modes, leading to a precise evaluation of the structure's overall seismic performance. Dynamic response parameters: RSA offers comprehensive data on different dynamic response characteristics, including base shear, storey shear, and moments across the entire structure. These metrics assist engineers in understanding the interplay between various components of the structure during seismic occurrences and identifying critical regions that require attention. While RSA is generally a linear analysis technique, it has the ability to include elements of nonlinear behavior by utilizing response modification variables. RSA is well-suited for performance-based design, as it can accommodate inelastic deformation in structures during strong earthquakes. People favor the RSA because it accurately captures the dynamic behavior of structures under seismic loads. It offers a thorough study that takes into account the inherent response of the structure, making it an essential tool for designing earthquake-resistant buildings and structures. RSA is dynamic analysis of a structure, which considers mode shapes and modal mass participation of the structure for different building frequencies. It provides a more realistic "dynamic" response of the building.

V. STRUCTURAL MODELLING

A three-dimensional nonlinear finite element model with a symmetrical building and a pile foundation subsystem with changing pile configurations and L/D ratio is used to study how soil pile structures interact with each other. The frame is 60 meters tall and has a square plan of 10 meters by 10 meters. Each bay within the frame is 5 meters by 5 meters. The 60-meter-tall superstructure components, such as slabs, beams, and columns, have been represented using 3-D parts. The connections between the beam and column are assumed to be bonded. The foundation (pile or isolated cap) is presented as having rigid connections with the first-story column. The study used the Finite Element Method (FEM) and ANSYS, along with an object-oriented approach, to look at how pile-supported buildings interact with changing pile configurations.
The soil is modelled as a weak soil domain with dimensions of 50m × 50m × 25m.

The finite element model was meshed using a 20-noded hexahedral element and a 20-noded tetrahedral element. The beam, column, and slab components of the superstructure are divided into 20-noded hexahedral elements. The soil elements are also divided into 20-noded hexahedral elements, while the pile components are divided into 20-noded tetrahedral elements. In this study, three degrees of freedom at each node are considered, specifically displacement in the X, Y, and Z directions of the elements. Node-to-node contact is established at the interface to transfer the load from the pile to the earth. The linear interface is adopted in order to model the contact between soil and the pile surface. A finite element model of the SSI system was made to look at how the soil and structure behave in the different foundation systems, such as the piled isolated cap and fixed base models. A model of a 20-storey building with a piled isolated cap foundation was made using the engineering properties of several modelling parameters for the superstructure, soil, and pile parts, which are given in Table 1, table 2 and table 3 respectively.

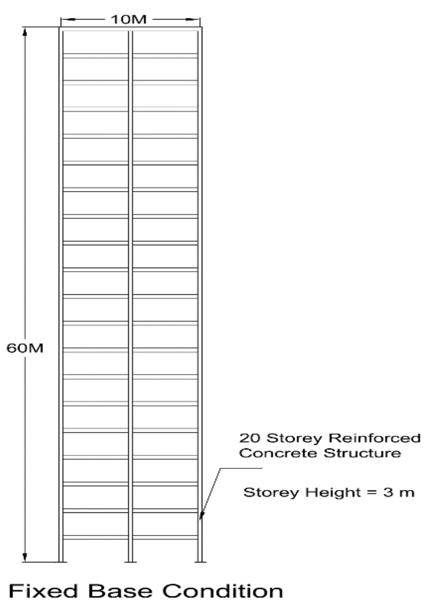


Fig. 1: 20 storey RCC building structure

These pile foundation circular piles, with a diameter of 1 m and a length of 18 and 9 m, were simulated using 3-D tetrahedral elements. The pile foundation consists of 2x2, two piles in series and parallel, each group consists of circular piles connected by a 500-mm-thick isolated cap.

The parametric study provided here considers the dead load as the standard gravity load applied based on the unit weight of the materials used in the structural components of the frame. Figure 2 displays the schematic of several pile configurations, such as 2 x 2, 2 pile components in series and parallel.

Table 1. Characteristics of 20 Storey RCC Building

Property	Dimensions/ corresponding Value
Grade of Concrete	M25
Beam Size (m)	0.30 x 0.45
Column Size (m)	0.30 x 0.40
Density (kg/m^3)	2350
Youngs Modulus (Pa)	2.5E+10
Poisson's Ratio	0.20
Bulk Modulus (Pa)	1.3889E+10
Tensile Strength (N/m$^{2)}$	2.5E+06

Table 2. Clay Soil properties

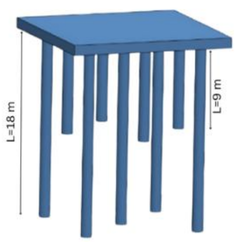
Property	Dimensions/ corresponding Value
Soil size (m)	50 x 50 x 25 m
Density (kg/m$^{3)}$	1420
Young's Modulus (Pa)	8.5E+06
Poisson's Ratio	0.35
Bulk Modulus (Pa)	9.444E+06
Yield Strength (N/m$^{2)}$	95000

Table 3. Pile configuration properties:

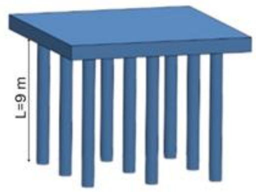
Property	Dimensions/Corresponding Value
Pile Length (m)	18 & 9
Pile Dia. (m)	1.0
L/D Ratio	18 & 09
Pile Spacing (2D)	2D
Pile-Soil edge Dist.	14D
Density (kg/m$^{3)}$	2350
Youngs Modulus (Pa)	2.5E+10
Poisson's Ratio	0.20

In this study, the pile sections were rigidly connected to the pile cap, with boundary conditions specified at the edges of the soil model. The bottom face of the soil model was fixed in all directions to represent a rigid base. Initially, the system was analysed under static gravity loads to establish initial stress conditions. For dynamic analysis, the earthquake ground motion record from the 2001 Bhuj (*India*) event was employed, with a peak ground acceleration (PGA) of 0.31g in the E-W direction applied at the fixed base of the soil domain.

The focus was on capturing the peak structural reactions at 20 seconds. Detailed characterization and input of soil properties, including density, elastic modulus, and damping ratio, were crucial. Accurate modelling of pile-soil interaction, considering nonlinear behaviour effects, was emphasized. Figure 3 shows the some of the pile configurations with space frame used in this study.



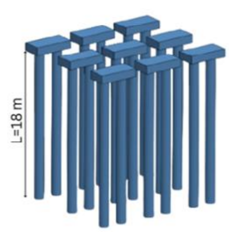
(a) Diagonal floating pile



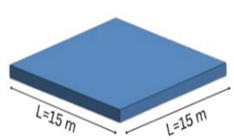
(b) Floating pile

(c) bearing pile

(d) 2x2 pile group



(e) 2 piles in series & parallel



(f) Raft footing.

Fig. 2. Different pile configurations used

VI. RESULTS AND DISCUSSION

In the present study the 20-storey reinforced concrete symmetrical building with a various base system in a uniform soil layer is investigated under the Bhuj (*India*) ground motion (2001). The study examines the building under both fixed and flexible base circumstances in order to figure out how the interaction between the soil foundation and the superstructure and substructure affects the buildings responses.

The study considers the following types of foundations:

1) Analysis of non-soil structural interactions in cases where column bases are fixed.
2) A building with a raft foundation.
3) A structure that is supported by a raft foundation with piles that extend to a depth of 9 meters.
4) A structure that is supported by a raft foundation with piles that extend to a depth of 18 meters.
5) A structure that is supported by a raft, with a middle pile length of 18 meters and an outer edge center pile length of 9 meters.
6) A structure that is supported by a pile cap with two piles arranged in a series.
7) A pile cap supports a structure with two piles arranged in parallel.
8) A structure that is supported by a pile cap with 2x2 box piles.

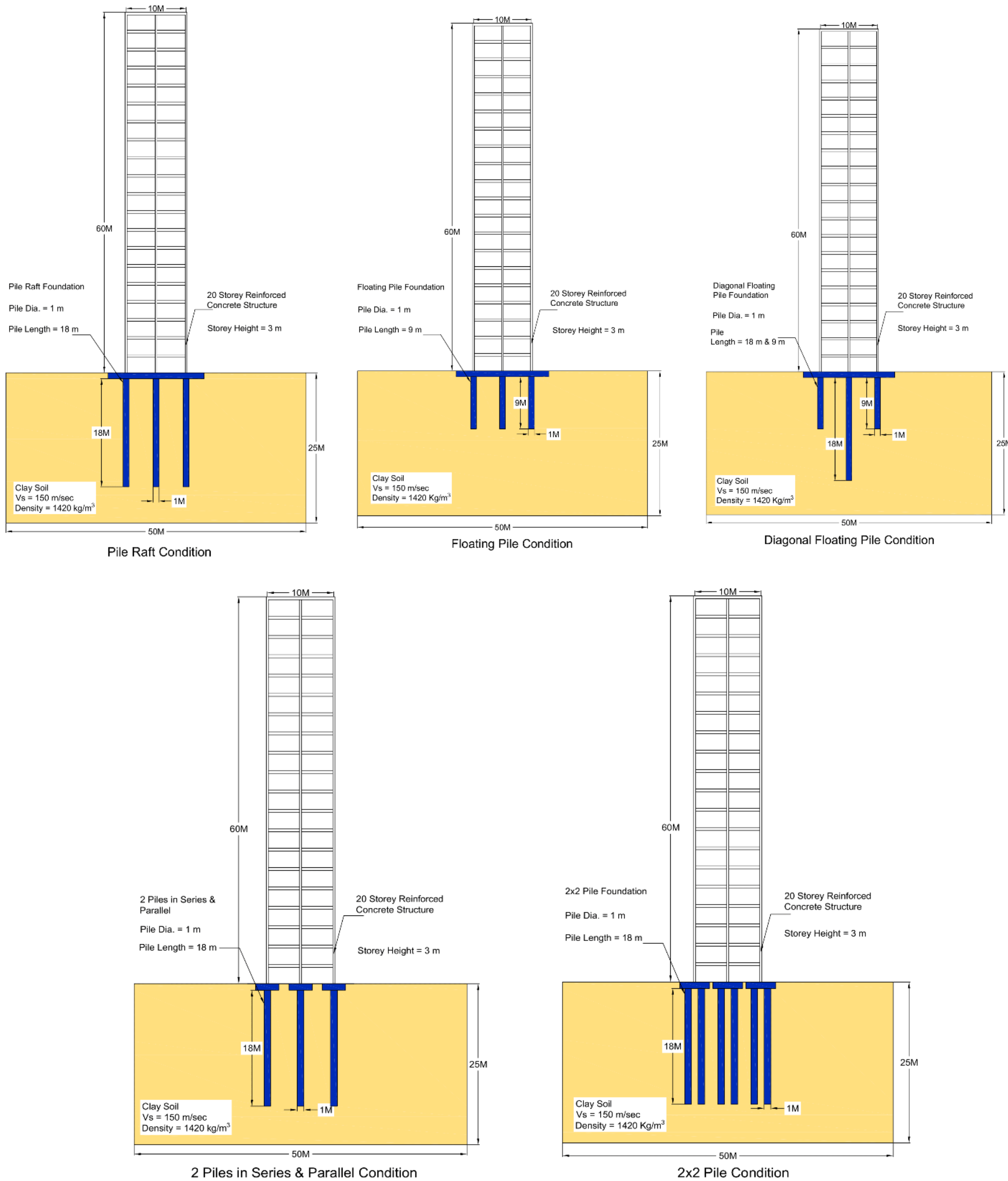


Fig. 3. Cases of analysis used in this study consists of 20-storey building frame that has a raft and different pile configurations.

Table 4. Maximum displacement of the frame

Notation	Foundation	Max Displacement (Z) mm
(a)	Fixed Base	27.593
(b)	Raft Foundation	527.430
(c)	Raft with 9 m pile depth	406.180
(d)	Raft with 18 m pile depth	266.530
(e)	Raft with 18 m and 9 m pile depth	289.490
(f)	2 Piles in Series	243.330
(g)	2 Piles in Parallel	230.21
(h)	2x2 Box Pile	201.160

1. Lateral displacement of the frame:

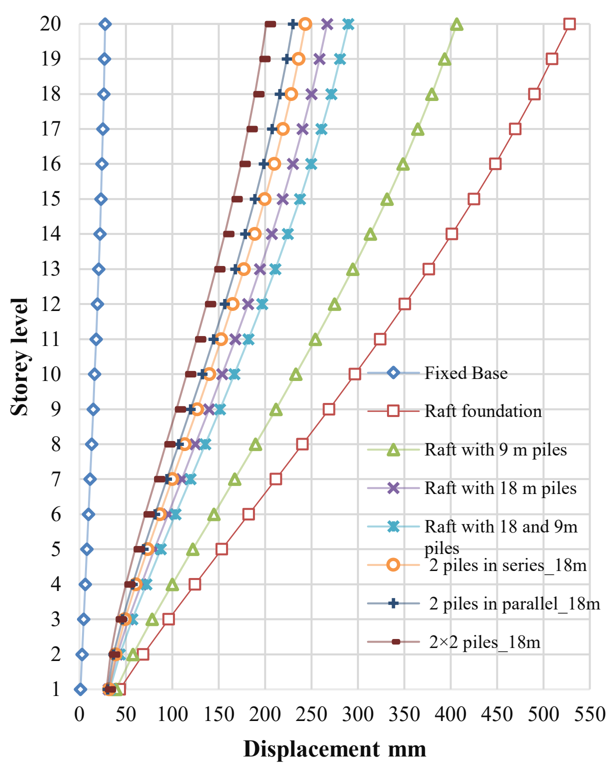


Fig. 4 Lateral displacement of 20 storey building frame.

The impact of soil–structure interaction (SSI) on lateral deformation at the 20th storey level was evaluated for various foundation configurations relative to the fixed base condition. The fixed base model, representing an idealized rigid support, showed the lowest lateral displacement, serving as the baseline for comparison.

In contrast, the raft-only foundation exhibited the highest increase in top-storey lateral displacement, with a value of 1814.5%, highlighting the inadequate lateral stiffness provided by shallow foundations in seismic conditions. The inclusion of 9 m piles reduced this increase to 1373.2%, though still indicating limited resistance to lateral forces.

Significant improvement was observed with 18 m deep piles, which lowered the increase to 866.8%, confirming the importance of engaging deeper, stiffer soil strata. The combined pile system (18 m + 9 m) yielded a similar displacement increase of 949.9%, indicating marginal benefit at the top level.

Among alternative pile configurations, two piles in series (18 m) and parallel (18 m) showed further reduction in displacement, with increases of 782.4% and 733.9%, respectively. However, the most effective configuration was the 2×2 pile group (18 m), which recorded the lowest increase of 629.5%, demonstrating superior performance due to increased group stiffness and efficient load distribution.

Overall, these results emphasize that incorporating SSI and selecting optimal pile configurations significantly reduce top-storey lateral deformations. The 2×2 pile arrangement proves most effective, making it a preferred option for high-rise buildings in seismic zones.

2. Percentage Storey drift:

The variation of storey drift across the height of the 20-storey building frame was analysed for multiple foundation systems to assess the influence of soil–structure interaction (SSI) under seismic loading. The fixed base condition, which neglects soil flexibility, showed the lowest and most uniform drift values, with a peak drift of only 0.021% at the top storey. This served as the baseline for comparison.

When SSI was considered using a raft foundation on sandy soil, the drift increased substantially across all storeys, reaching a peak value of 0.633% at the top level. This significant increase indicates that the absence of deep foundation elements leads to excessive flexibility and deformation, especially in taller structures.

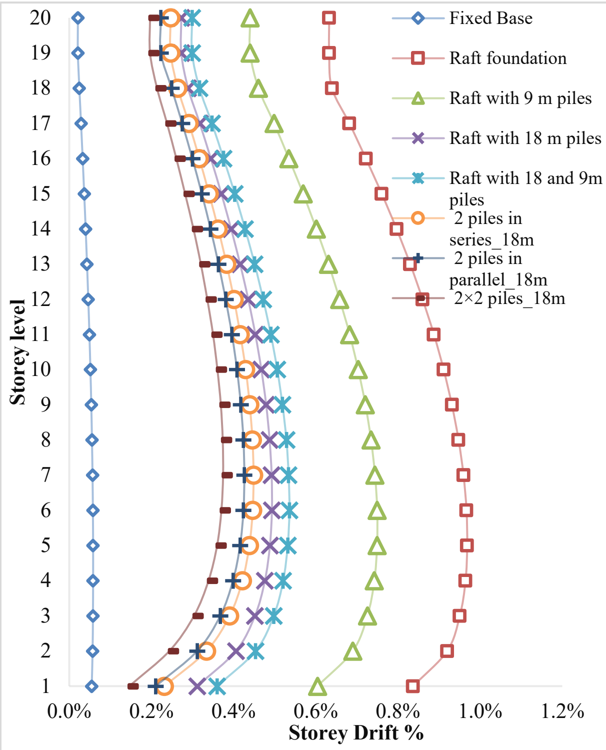


Fig. 5: Percenetage Storey Drift for various pile configuration

Incorporating pile foundations helped mitigate this effect. Floating piles of 9 m reduced the maximum storey drift to 0.440%, while longer piles of 18 m brought it down further to 0.273%, due to better mobilization of deeper, stiffer soil strata. The combined (18 m + 9 m) pile system yielded a drift of 0.299%, showing marginal improvement compared to 18 m piles alone, but confirming the benefit of increased depth and interaction zones.

Among the advanced configurations, the 2 piles in series (18 m) and 2 piles in parallel (18 m) configurations resulted in reduced peak drifts of 0.247% and 0.223%, respectively. These systems enhance energy dissipation and lateral stiffness due to their extended embedment and interaction mechanisms.

The 2×2 pile group (18 m) exhibited the best performance, limiting the top-storey drift to 0.197%, and showing consistently lower drift values throughout the height of the building. This confirms the superior stiffness and load-sharing capacity of dense pile group arrangements, making them highly effective for high-rise buildings in seismic zones.

In summary, the results clearly demonstrate that accounting for SSI significantly alters the drift profile of the structure. Without considering soil flexibility, conventional designs may underestimate lateral deformations. Optimized pile configurations, particularly the 2×2 group with adequate embedment, can closely replicate fixed-base behavior while ensuring realistic and safe performance under seismic excitations.

VII. CONCLUSION

1. The fixed-base model underestimates seismic demands by ignoring foundation flexibility, leading to non-conservative design assumptions.
2. The raft foundation exhibited the maximum lateral displacement (up to 101.3 mm) and storey drift (0.96%), nearly 14 to 16 times higher than the fixed-base values, as it lacks deep anchorage and mobilizes more soil deformation.
3. Introducing 9 m piles reduced lateral displacement and drift by 30–35% compared to the raft alone, as shallow piles provide partial confinement and base stiffness.
4. Replacing 9 m with 18 m piles further reduced drift and displacement by around 50–60% compared to the raft case, due to better mobilization of deeper soil layers and higher lateral stiffness.
5. The combined 18 m and 9 m pile system showed moderate improvement, with drift values lower by 45% than raft, though slightly higher than uniform long piles due to inconsistent load transfer.
6. The two piles in series (18 m) configuration reduced lateral displacement by up to 77% and drift by 74% compared to the raft case, as the series action allows deeper load transfer and greater energy dissipation.
7. The parallel pile configuration achieved a slightly better reduction (79% in displacement, 78% in drift), likely due to improved distribution of lateral loads and minimized pile-soil interaction effects.
8. The 2×2 pile group with 18 m length demonstrated the best performance, with displacement and drift reduced by 85–87% over raft and 60–65% over 9 m piles, attributed to optimal spacing, enhanced group stiffness, and uniform load sharing.
9. These results confirm that increasing pile depth, selecting appropriate configurations, and

considering SSI effects are essential for minimizing seismic deformations and improving the seismic safety of high-rise buildings on soft or layered soil profiles.

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