Effect of Seismic Soil Pile Interaction on RCC Building Frame Resting on a Group of Pile Foundations

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***Abstract*— India has been experiencing a huge number of hazards through various natural phenomena like floods, droughts, Hurricanes, Tsunamis, fires and Earthquakes with considerable infrastructures and casualty losses all over. In earthquakes the structural collapse occurs due to the insufficient or incorrect analysis and design techniques. In general, the design procedures of the foundations depend upon the load induced by the superstructure, local site parameters and the earthquake zones. In a conventional analysis of any civil engineering structure, the superstructure is usually analyzed by treating it as independent from the foundation and soil medium, assuming no interaction occurs. This usually means that providing fixity at the structural support analyst simplifies soil behavior, while the geotechnical engineer neglects structural behavior by considering only the foundation while designing. When a structure is built on soil, some of the elements of the structure are in direct contact with the soil. When the loads are applied to the system, internal forces are developed in both the superstructure and as well as in soil. This results in deformations of both the components (structure and soil), which must be compatible at the interface as they cannot be independent. The original ground acceleration time history data from the Bhuj earthquake, located in Seismic Zone V (Gujarat), is used for analysis. A 10-storey space frame structure with a total height of 30 meters is evaluated using the response spectrum method, focusing on the peak values from the time history data. The soil-structure interaction is modeled in SOLIDWORKS 2019, while the seismic analysis is carried out in ANSYS 18.1. Key response parameters calculated include lateral displacements in the X and Y directions, vertical displacement (Z), pile settlement, displacement at the pile tip, maximum shear stress, and inter-storey drift.**

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

I. INTRODUCTION

In urban areas globally, rising land costs and high population densities have favored vertical development over horizontal expansion. This strategy optimizes land utilization while meeting the demands of urban growth and economic development. However, constructing tall buildings on soft soil poses significant engineering challenges. Soft soil typically lacks adequate load-bearing capacity and stability required to support tall structures without meticulous engineering interventions. In the conventional structural design method, the soil structure interaction effect has been neglected. Factors such as settlement, differential settlement, and soil consolidation over time can profoundly impact the performance and functionality of these structures. Therefore, engineers and geotechnical experts play a pivotal role in devising and implementing solutions that effectively manage soil-structure interaction dynamics. This approach guarantees that tall buildings remain safe, stable, and sustainable in urban settings where land availability is constrained. In conventional structural analysis, it is commonly assumed that the motion at the foundation level mirrors the ground motion in a free-field scenario, overlooking energy dissipation effects. This assumption is accurate primarily for structures built on firm strata or rock. However, in structures with flexible foundations, a portion of the vibrational energy is transferred to the soil layer, where it dissipates through mechanisms like radiation damping and hysteresis in soft soil strata. The impact of soil on structural response varies based on foundation characteristics, the type of structure, and the nature of the excitation. Understanding soil-structure interaction enables engineers to accurately assess stress conditions and absolute displacements within the foundation system, thereby improving structural design and performance evaluation.

II. REVIEW OF LITERATURE

Tabatabaiefar et al. [1] developed an empirical formula to estimate the lateral drift of mid-rise buildings during earthquakes by incorporating soil-structure interaction (SSI), and found that SSI significantly increases lateral displacements, particularly in soft soil conditions. In 2013 Tabatabaiefar, Behzad Fatahi [3], extended this work by conducting dynamic nonlinear time-history analyses, showing that neglecting SSI leads to underestimation of structural response, and emphasizing the importance of including SSI for safe and realistic seismic design.Visuvasam and Chandrasekaran [10] focused on soil–pile–structure interaction (SPSI) in RC building frames, revealing that SPSI influences both lateral drift and base shear, especially in soft soils, and should be considered in seismic design of pile-supported buildings.Mourlas et al. [11] investigated the dynamic behavior of multistorey RC buildings under SSI and found that it increases the natural period and seismic displacement, thereby altering the expected dynamic response of the structure.Oz et al. [12] analyzed the seismic performance of existing low- and mid-rise RC buildings with and without SSI, concluding that while SSI reduces base shear, it increases inter-story drifts, which can be critical for older or non-ductile structures.

Gazetas et al. [2] investigated the nonlinear rocking stiffness of shallow foundations and demonstrated that foundation uplift and rocking can significantly influence the dynamic response of structures during earthquakes, especially when nonlinear soil behavior is considered.Hokmabadi, Fatahi, and Samali [4] studied soil–pile–structure interaction (SPSI) for mid-rise buildings on floating pile foundations and found that SSI effects can notably increase lateral displacements and inter-story drifts, emphasizing the need to consider pile flexibility and soil nonlinearity in seismic design.Shah and Swathy [6] presented an analytical study on dynamic soil-structure interaction for a pile-supported RC frame, showing that inclusion of SSI alters the natural frequency and overall dynamic behavior, potentially affecting seismic safety and design assumptions.Hokmabadi and Fatahi [7] compared different foundation types (shallow, pile, and floating piles) under seismic loading with SSI effects, concluding that foundation type plays a crucial role in seismic performance, and ignoring these differences can lead to unsafe structural assessments.

Abdel Raheem, Ahmed, & Alazrak [5] analyzed the effects of soil–foundation–structure interaction (SFSI) on the seismic response of multi-story moment-resisting frame (MRF) buildings resting on raft foundations, and concluded that SFSI significantly alters lateral displacement and inter-story drift, especially for flexible soils, suggesting its inclusion is essential in seismic design.Nitish Kumar & Praveen J V [8] conducted a study on multi-storey RC frame structures over raft foundations under seismic loads and found that soil-structure interaction increases the period of the structure and seismic demand, indicating the need for integrated SSI modeling in design for earthquake resistance.Khedikar & Tonde[14] investigated the dynamic response of multistory buildings supported by combined pile raft foundations (CPRF) and found that such systems effectively reduce seismic vibrations and settlements, making CPRF a viable solution for seismic zones with soft or layered soils.

P.Badry and R.S.Badry [9] studied the seismic response of mid-rise buildings resting on rigid piled isolated footings in weak soil using SSI analysis. They found that incorporating SSI significantly changes the dynamic behavior, increasing lateral displacement and reducing the base shear. The study emphasizes that designing without SSI consideration may lead to unsafe or overly conservative results in soft soil conditions.Tahghighi & Mohammadi [13] performed a numerical investigation on how SSI affects the seismic performance and vulnerability of reinforced concrete buildings. Their results showed that SSI alters natural frequencies, increases structural deformation, and influences seismic demand parameters. They concluded that ignoring SSI can lead to misjudging a building's vulnerability, particularly on soft or medium-stiff soils.

Wu and Finn [15] conducted a dynamic nonlinear analysis of pile foundations using the finite element method in the time domain, demonstrating that both soil and pile nonlinearity must be accurately modeled to predict realistic seismic responses.Cai, Gould, and Desai [16] developed a three-dimensional nonlinear finite element model for seismic analysis of soil–pile–structure systems, showing that pile-soil interaction and nonlinear soil properties significantly affect the overall seismic behavior of structures.Maheshwari et al. [17], in their study published in *Soil Dynamics and Earthquake Engineering*, presented a comprehensive 3D nonlinear analysis of soil–pile–structure interaction, concluding that pile flexibility and nonlinear soil response greatly influence lateral displacements and seismic forces.In a parallel study published in the *Canadian Geotechnical Journal*, Maheshwari et al. [18] further examined pile groups under lateral transient and seismic loads, revealing that the response is sensitive to soil stiffness, pile spacing, and dynamic loading, thus reinforcing the importance of full 3D dynamic SSI modeling in seismic design.

H.S.Chore, R.K.Ingle, and V.A.Sawant [19] performed a nonlinear analysis of pile groups subjected to lateral loads using the 'p–y' curve approach, and found that the nonlinear behavior of soil significantly affects pile group response, particularly in soft soils, making accurate modeling essential for safe design under lateral loading.S.A.Rasal, Chore, and Sawant [20] analyzed the nonlinear soil–structure interaction of a framed structure with a pile foundation and concluded that ignoring SSI leads to underestimation of displacements and internal forces, emphasizing the importance of including SSI for more realistic seismic response assessment.P.A.Dode, Chore, and Shanmugan [22] studied the influence of SSI on framed structures through computational analysis and demonstrated that the stiffness of the supporting soil and foundation type significantly influence the seismic behavior of buildings, with more flexible soils leading to larger drifts and altered dynamic response.

Ravi and Suresh [21] conducted an experimental study on the performance of geopiles installed in expansive clay, finding that geopiles significantly improved the load-bearing capacity and reduced the swelling-induced deformations of the soil, making them effective for stabilizing structures in expansive soil conditions.Hussien et al. [23] investigated the soil–pile separation effect on the seismic and static performance of pile groups, using both numerical and experimental approaches. They concluded that separation between soil and pile during lateral loading reduces the stiffness and increases displacements, highlighting the need to consider this effect in SSI models for accurate seismic analysis.

Radhika Jadhav *et. al* [24] analyzed the dynamic soil–pile–structure interaction (SSPI) of a 15-storey symmetric RC building incorporating damping layers in the soil. The study found that damping layers significantly reduce lateral displacements and vibrations during seismic loading, thereby improving seismic performance. Radhika Jadhav et.al [25] conducted a comparative analysis of a 20-storey building supported by parallel vs. series pile configurations. Results showed that the pile configuration impacts the distribution of seismic forces and lateral stiffness, with series arrangements offering better energy dissipation in some soil conditions. Saad Kondkari, S.A.Rasal, & R.Jadhav [26] provided an overview of SSI for RC buildings resting on different foundation types, including shallow, pile, and combined foundations. The study highlighted how foundation type and soil flexibility influence structural performance, emphasizing the need for foundation-specific SSI considerations in design. R.Jadhav [27] investigated the seismic response and lateral deformation of multistorey buildings with pile foundations and damping soil layers. The study concluded that integrating energy-absorbing layers in the soil profile effectively controls seismic-induced lateral drift and improves overall stability in tall buildings.

This literature review offers a thorough summary of key research contributions in the field of soil–structure interaction, emphasizing the vital role of incorporating SSI effects in building design and analysis to enhance structural safety and performance under different loading scenarios.

III. OBJECTIVES OF THE STUDY

1. To enhance the mathematical modeling of the superstructure–pile–soil system by utilizing advanced techniques that accurately capture the behavior and interaction of each component.
2. To realistically simulate nonlinear soil–structure interaction, considering the nonlinear behavior of soil and linear behavior of the superstructure.
3. To analyze and compare the structural response of systems supported by various pile configurations, including 2×2 pile groups, bearing piles, floating piles, and piles arranged in series and parallel.
4. To assess the influence of different pile arrangements under both static and dynamic loading conditions.
5. To evaluate key structural response parameters such as pile settlement, maximum displacement at the pile tip, and maximum shear stress.
6. To study soil–structure interaction effects under seismic loading using the actual ground acceleration time history of the 2001 Bhuj earthquake (India).

IV. METHOD OF ANALYSIS

A. Equivalent Static Analysis Method

ESM is a simplified method used to analyze the behavior of structures under seismic loading conditions. It involves calculating the equivalent static force that would produce the same maximum response as the dynamic loads that the structure is expected to experience during an earthquake. This method assumes that the seismic load can be approximated by a single static force that acts on the structure along a particular direction. The equivalent static force is then used to determine the design forces and moments on the structure.

B. Response Spectrum Method

On the other hand, RSA is a more advanced method used to analyze the behavior of structures under seismic loading conditions. It involves calculating the response of the structure to a range of ground motions, which are represented by a response spectrum. RSA provides a more detailed analysis of the behavior of the structure, which can help engineers to design safer and more efficient structures. RSA is the preferred method for analyzing the nonlinear response of buildings and structures because it captures the more accurate "natural" response of the structure under seismic shaking.

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, and it captures the overall response of the system in terms of base shear, story shear, and moments in the building.

V. STRUCTURAL MODELLING

This study investigates the effects of seismic soil–structure interaction (SSI) on a 10-storey reinforced concrete (RC) building, considering the nonlinear behavior of the soil under various pile foundation configurations. The Response Spectrum Method is employed to analyze the seismic response and ensure reliable and accurate results. To capture detailed structural and geotechnical responses, comprehensive three-dimensional finite element (3D FE) models of the building and foundation system are developed using ANSYS 18.1, based on preliminary design parameters of the structural components.as shown in Fig. 1.

The following data is considered for analysis:

Reference Name	No. of Stories	No. of Bays	Storey Height (m)	Bay Width (m)	Total Height (m)	Total width (m)
10 Storey Building	10	4	3	5	30	10

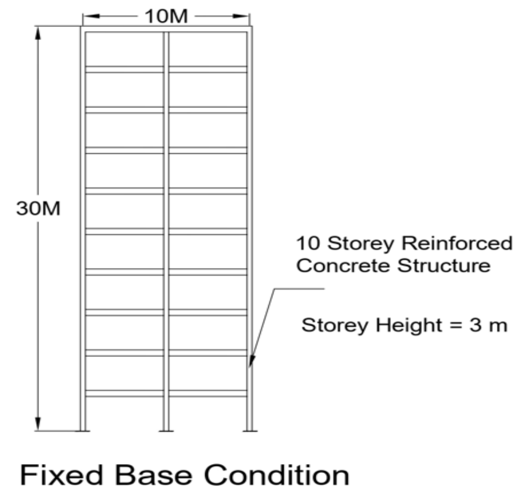

Fig. 1. 10 storey RCC building structure

The soil is modeled as a weak domain with dimensions of 50 m × 50 m × 25 m. The finite element model is discretized using 20-noded hexahedral and tetrahedral elements. Structural components such as beams, columns, and slabs are meshed using 20-noded hexahedral elements, while the soil domain is also represented with hexahedral elements. The pile elements, however, are modeled using 20-noded tetrahedral elements to better capture geometric complexity. Each node in the model incorporates three translational degrees of freedom—displacements along the X, Y, and Z axes. To simulate interaction between the pile and the surrounding soil, node-to-node contact elements are introduced at the interface, facilitating load transfer. A linear contact interface is used to represent the pile–soil interaction behavior. The finite element model is developed to investigate the soil–structure interaction (SSI) behavior under various foundation configurations, including piled isolated cap and fixed base models. A detailed 3D model of a 10-storey RC building with a piled isolated cap foundation is created using the engineering properties of the superstructure, soil, and pile components. These parameters are summarized in Table 1, Table 2, and Table 3, respectively.

In this study, circular pile foundations with a diameter of 1 meter and lengths of 9 m and 18 m were modeled using three-dimensional tetrahedral elements. The pile foundation configurations include 2×2 pile groups and two piles arranged in series and parallel, with each group of piles connected by an isolated cap of 500 mm thickness.

A parametric study was conducted by applying dead loads as standard gravity loads, based on the unit weights of the materials used in the building frame.

In the simulation, piles were assumed to be rigidly connected to the pile cap. The edges of the soil model were assigned boundary conditions, and the bottom surface was fixed in all directions to simulate a rigid base. The system was first analyzed under static gravity loading to establish initial stress conditions. For the dynamic analysis, the earthquake ground motion record from the 2001 Bhuj earthquake (India) was used, with a peak ground acceleration (PGA) of 0.31g in the East–West direction, applied at the fixed base of the soil domain.

Table 1. Characteristics of the studied frame

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
Meshing element order	Quadratic

The analysis mainly focused on capturing the peak structural response at 20 seconds during the seismic event. To ensure the accuracy and reliability of the simulation, the model was validated against available experimental or field data. Detailed input of soil properties such as density, elastic modulus, and damping ratio was carefully considered. The study also emphasized accurate modeling of pile–soil interaction, especially accounting for nonlinear soil behavior. Figure 3 illustrates some of the pile configurations integrated with the space frame structure used in the analysis.

VI. RESULTS AND DISCUSSION

The results presents an investigation of a 10-storey reinforced concrete (RC) symmetrical building resting on a uniform soil layer, subjected to seismic loading using the Bhuj (India) earthquake ground motion (2001). The analysis is conducted under both fixed-base and flexible-base conditions to evaluate how soil–foundation–structure interaction (SFSI) influences the response of the building, including both the superstructure and substructure

The study includes the following foundation types for comparison:

1. A building with fixed column bases, representing a condition with no soil–structure interaction.
2. A structure supported by a raft foundation.
3. A raft foundation combined with 9-meter-deep piles.
4. A raft foundation combined with 18-meter-deep piles.
5. A raft foundation with a hybrid pile arrangement, using 18-meter piles at the center and 9-meter piles at the edges.
6. A pile cap foundation with two piles arranged in series.
7. A pile cap foundation with two piles arranged in parallel.
8. A pile cap supporting a 2×2 box pile configuration.

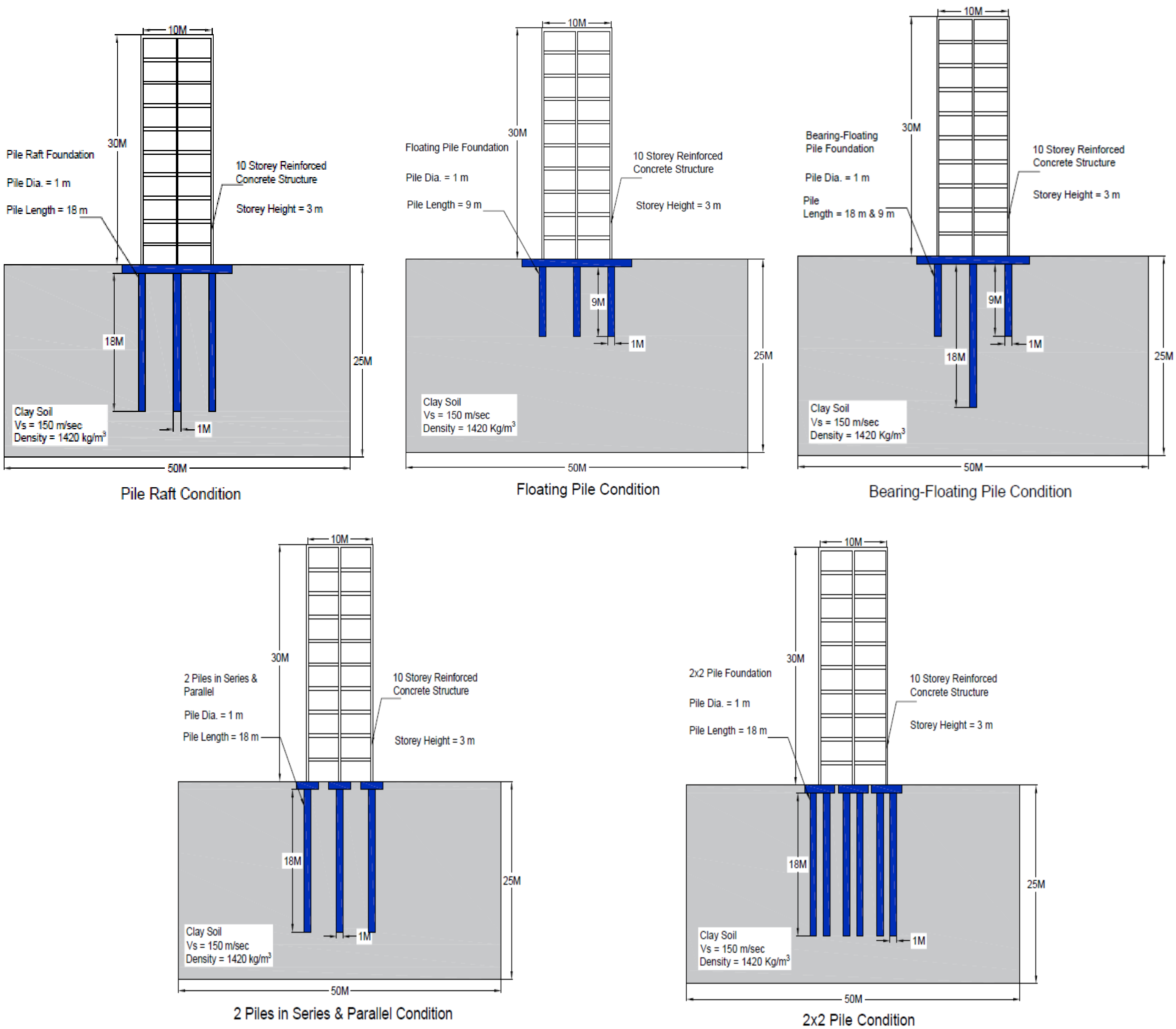

Fig. 3. Cases of analysis used in this study consists of 10-storey building frame that has a raft and different pile configurations.

Table 5. Maximum displacement in (x) & (y) direction, maximum shear stress and maximum foundation displacement with respect to the Fixed base.

Notation	Foundation	Max Displacement (X) mm	Max Dispacement (Y) mm	Max Displacement (Z) mm	Foundation Displacement (Z) mm	Pile Settlement (Y) mm	Max Shear Stress (N/mm^2)
(a)	Fixed Base	0.025	0.263	10.385	-	-	0.319
(b)	Raft Foundation	37.682	60.420	441.070	143.990	32.498	7.702
(c)	Raft with 9 m pile depth	39.790	61.067	399.220	140.060	21.867	7.023
(d)	Raft with 18 m pile depth	63.506	64.120	348.890	142.250	17.747	6.275
(e)	Raft with 18 m and 9 m pile depth	21.801	60.498	363.530	143.880	17.642	6.367
(f)	2 Piles in Series	21.559	60.977	352.360	152.910	13.799	6.234
(g)	2 Piles in Parallel	37.902	61.925	339.120	147.270	17.052	6.044
(h)	2x2 Box Pile	46.909	62.840	333.880	145.940	16.838	6.022

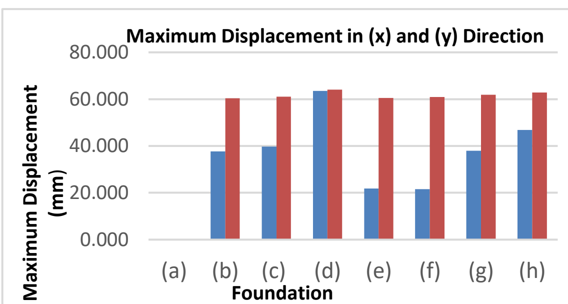

Fig.4. Representation of maximum displacement of 10-storey structure with various foundation systems in the (X) and (Y) direction.

All models show a substantial increase, with values ranging from 199.54% to 199.85%, indicating a significant difference in deformation behavior relative to the fixed base. The raft with 18 m piles exhibits the highest increase in both displacement and settlement (199.85%), while the lowest displacement increase (199.54%) is observed in the 2 piles in series configuration. Most other models, including raft foundation, raft with 9 m piles, 2 piles in parallel, and 2×2 piles, show very similar results with minor variations. These findings suggest that while all foundation types significantly increase deformation compared to a fixed base, the impact of pile length and arrangement on structural response is relatively small but noteworthy.

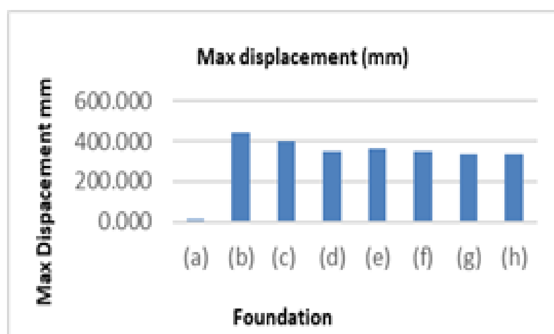

Fig.5. maximum displacement (Z).

The raft foundation shows the highest increase at 190.80%, indicating the most settlement. In contrast, the 2X2 piles configuration performs best with the lowest increase of 187.93%, followed closely by 2 piles in parallel (188.11%) and 2 piles in series (188.55%)**.** Among raft-pile combinations, the raft with 18 m piles shows better performance (188.44%) than shorter or mixed pile setups. Overall, foundation systems with piles—especially in grouped or parallel arrangements—significantly reduce settlement compared to a raft alone.

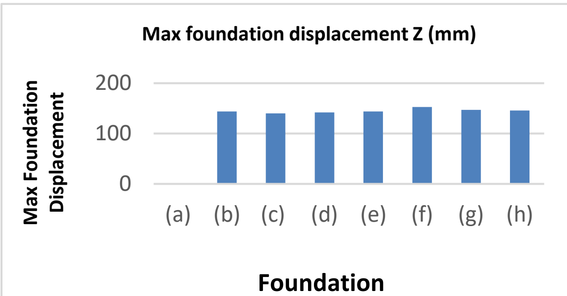

Fig. 6. Maximum foundation displacement.

The table presents the percentage increase in maximum foundation displacement in the Z-direction relative to a fixed base. The raft with 9 m pile shows the lowest displacement (140.06 mm), indicating the most effective settlement control. This is followed by the raft with 18 m pile (142.25 mm) and the raft with 18 and 9 m piles (143.88 mm), all performing better than the raft foundation alone (143.99 mm).In contrast, 2 piles in series exhibit the highest displacement (152.91 mm), suggesting the greatest settlement. Other configurations like 2X2 piles (145.94 mm) and 2 piles in parallel (147.27 mm) also show increased settlement compared to single-pile raft systems.Overall, raft–pile combinations, especially with single piles, are more effective in reducing Z-direction displacement than multi-pile arrangements.

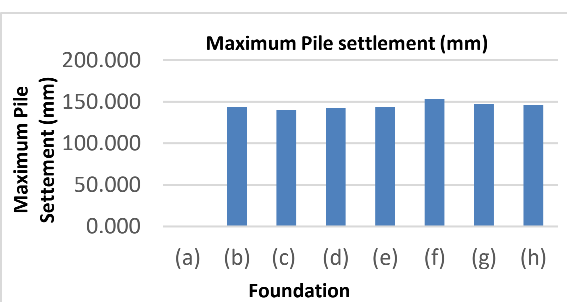

Fig. 7. Graphical representation of Maximum pile settlement.

The table shows the percentage increase in maximum pile settlement in the Y-direction relative to a fixed base. The raft with 9 m pile exhibits the lowest settlement (140.06 mm), indicating the most effective performance. It is followed by the raft with 18 m pile (142.25 mm) and the raft with 18 and 9 m piles (143.88 mm), all of which perform slightly better than the raft foundation alone (143.99 mm). In contrast, 2 piles in series show the highest settlement (152.91 mm), indicating the least efficiency. The 2 piles in parallel (147.27 mm) and 2X2 piles (145.94 mm) also show increased settlement compared to single-pile raft systems. Overall, raft–pile combinations with single piles are more effective in reducing Y-direction settlement than multi-pile arrangements.

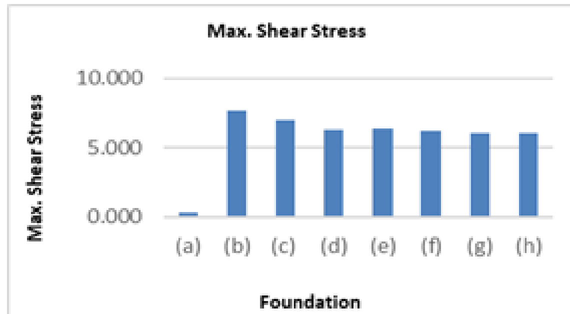

Fig. 8. Graphical representation of maximum shear stress.

The raft foundation exhibits the highest increase at 184.10%, indicating the least effective performance. In contrast, the 2X2 piles configuration shows the lowest increase at 179.89%, followed closely by 2 piles in parallel (179.96%) and 2 piles in series (180.54%), demonstrating better shear stress control. Among raft–pile systems, the raft with 18 m pile (180.66%) and raft with 18 and 9 m piles (180.92%) outperform the raft with 9 m pile (182.63%), suggesting longer or combined piles are more effective. Overall, pile-supported foundations—especially in grouped or parallel forms—reduce shear stress more efficiently than raft-only systems.

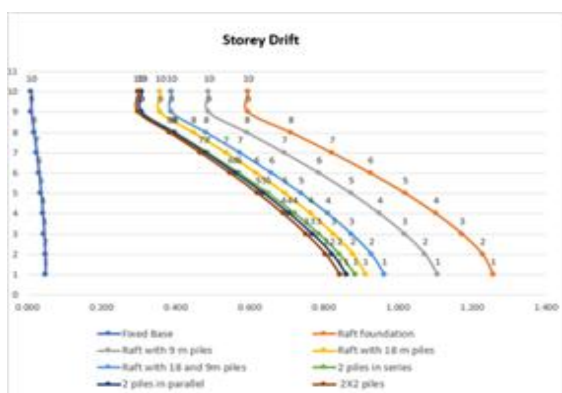

Fig. 9. Storey Drift of all eight configurations

The table compares structural response values—likely displacement or stress—across different foundation systems under increasing load or time. The raft foundation consistently shows the highest values, indicating the least effectiveness in controlling structural response. In contrast, the 2X2 piles configuration records the lowest values throughout, demonstrating the best performance.Raft–pile combinations, especially with 18 m piles or combined 18 m and 9 m piles, perform significantly better than the raft alone. Grouped pile systems, such as 2 piles in parallel and 2X2 piles, are more effective than series arrangements, particularly under higher load levels. Overall, foundation systems with deeper or grouped piles significantly reduce structural response, with 2X2 piles offering the most efficient performance.

VII. CONCLUSION

From the present studies following broad conclusion are drawn :

- The analysis demonstrates a substantial increase in structural displacements and settlements for all foundation configurations when compared to a fixed-base model, confirming the significant influence of soil–structure interaction on dynamic response.
- In lateral directions, foundation systems incorporating pile elements exhibited enhanced flexibility, with the configuration involving longer piles displaying the greatest lateral deformation. Conversely, the serial arrangement of piles exhibited relatively lower lateral displacements, though the variation among all models remained marginal.
- Regarding vertical settlement behavior, isolated raft foundations were found to be the least effective, resulting in the highest magnitude of vertical displacement. In contrast, grouped pile systems—particularly the four-pile (2×2) configuration—proved more efficient in mitigating settlement, highlighting the benefits of load sharing among grouped piles.
- The evaluation of foundation displacement further reinforced the effectiveness of short single-pile raft combinations, which demonstrated better settlement control compared to multi-pile or deeper pile configurations. Serial pile arrangements, by contrast, were associated with the highest foundation displacements, indicating less favorable performance in managing vertical loads.
- The assessment of pile settlement in the transverse direction yielded similar trends. Single-pile systems provided superior settlement resistance, while multi-pile configurations, particularly those arranged in series, exhibited amplified displacements, likely due to increased structural flexibility and non-uniform load transfer.
- Shear stress analysis revealed that raft-only foundations were subjected to higher stress concentrations, making them less efficient in dissipating seismic loads. Grouped pile configurations, especially those arranged in parallel or grid patterns, were more effective in moderating shear forces, and foundations incorporating longer or hybrid pile lengths offered improved stress distribution.
- The investigation of interstorey drift across all models identified raft-only foundations as the least effective in controlling seismic-induced deformation. In contrast, deeper and grouped pile systems, particularly the four-pile arrangement, consistently outperformed other configurations by minimizing lateral drift and enhancing overall seismic resilience.

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