Nonlinear Soil-Structure Interaction Analysis of an Asymmetrical Building Frame on a Piled-Raft Foundation

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***Abstract* — Past earthquakes have shown that ground motion is the main cause of structural damage and human casualties. Traditional design methods often assume fixed-base conditions where structure rests on rigid foundations ignoring the influence of Soil-Structure Interaction (SSI). This simplification can lead to either unsafe or overly conservative designs especially for tall buildings on soft soils. A more accurate approach requires accounting for the interaction between the superstructure and foundation. This study evaluates the seismic response of a 20-storey asymmetrical reinforced concrete frame supported by a piled raft foundation using finite element analysis in ANSYS. The foundation system includes configurations with single piles and two piles in series and parallel with embedment ratios (L/D) of 10, 15, and 20. Each configuration is analyzed for both parallel and perpendicular orientations relative to seismic loading. The analysis uses an acceleration response spectrum based on the peak ground acceleration of the 2001 Bhuj earthquake. Key response parameters include lateral storey displacement, inter-storey drift ratio, foundation displacement and settlement. Results highlight the substantial impact of SSI, showing that flexible soil conditions significantly affect seismic performance. Incorporating SSI in design ensures safer, more reliable, and resilient structures in earthquake-prone regions.**

***Index Terms*— Soil-Structure Interaction, Finite Element Analysis, Lateral Storey Displacement, Storey Drift Ratio, Settlement, Piled Raft Foundation.**

I. INTRODUCTION

In metropolitan regions the rising land prices and dense populations have driven the need for vertical construction, maximizing space by building upward instead of outward. As socio-economic development accelerates and global populations surge, clusters of high-rise buildings are becoming more common. These structures are also built on comparatively soft soil because of a shortage of land. When a structure is built on soft soil some of the elements of the structure are in direct contact with the soil. When the loads are applied to the system the internal forces are developed in both the structure and as well as in soil. This causes deformations in both components (structure and soil) which must be compatible at the interface because they cannot be separated. Because of this reciprocal dependency also known as interaction, the stress resultants in structure as well as the stresses and strains in soil are considerably altered during loading. However, observations from some of the past seismic events such as 1989 Loma Prieta earthquake and 1995 Kobe Earthquake show evidences of detrimental nature of SSI in certain circumstances (Anand V. and Satish Kumar S. R., 2018). Therefore, it becomes imperative to consider the structure-foundation and soil as components of a single system to analyse and design the structure and its foundation. The analysis that treats structure foundation soil as a single system is called Soil-Structure Interaction (SSI) analysis.

Soil–Structure Interaction (SSI) is a complex phenomenon that describes the mutual interaction between a structure, its foundation and the surrounding soil. Unlike conventional analysis which assumes a fixed-base foundation where the structure is considered to be perfectly anchored to an immovable ground, SSI acknowledges the flexibility and deformability of both the supporting soil and the foundation. This interaction becomes particularly significant under dynamic loading conditions such as earthquakes. In which the response of the soil directly influences the motion and performance of the superstructure.

In recent decades the importance of incorporating SSI into structural analysis and design has gained wide recognition especially for tall, heavy or irregular buildings constructed on soft or heterogeneous soils. Neglecting SSI can lead to non-conservative estimates of structural response parameters such as lateral displacement, inter-storey drift, base shear, internal forces, etc. These inaccuracies may compromise the safety, serviceability and economic performance of the structure.

The role of SSI is even more pronounced in buildings with complex geometry such as asymmetrical frames, where mass and stiffness irregularities can induce torsional effects and uneven force distribution. The behavior of the foundation system whether shallow, deep or composite also significantly affects the way loads are transmitted and resisted. Among various foundation systems piled-raft foundations have emerged as a favorable solution for tall and heavy structures on soft soils. It offers benefits such as improved load sharing, reduced settlement and enhanced seismic performance.

Advanced numerical modelling techniques such as finite element analysis (FEA) now allow more accurate simulation of nonlinear soil behavior, foundation flexibility and dynamic interactions. By integrating SSI in seismic analysis engineers can achieve a more realistic and reliable assessment of structural performance which ultimately leads to safer and more efficient designs.

II. REVIEW OF LITERATURE

The relationship between soil and structure is inherently complex. Even a single pile is highly statically indeterminate and the situation becomes more intricate under dynamic forces such as earthquake-induced ground motion. Over the past few decades the role of Soil-Structure Interaction (SSI) in seismic design has gained increasing attention. This section reviews key studies exploring the dynamic behavior of structures resting on piled raft foundations.

S.A. Rasal et al. (2017) performed 3D finite element modelling of a three-storey building supported by a piled raft foundation embedded in compact soil. They used twenty-noded isoparametric continuum elements to model the piles, pile caps, beams, columns and slabs. The frame was initially analyzed without considering foundation flexibility. The piled raft was then assessed separately to estimate equivalent stiffness which was used in a subsequent interaction analysis. Their study found that SSI significantly increased displacement at each storey, especially when nonlinear soil behavior was considered. SSI also notably affected bending moments (B.M). Both linear and nonlinear SSI conditions had considerable influence on the structural response.

Mohsen Bagheri et al. (2018) conducted extensive numerical simulations on two superstructure types and six piled raft foundation configurations to understand seismic Soil-Pile-Structure Interaction (SSPSI). Their study incorporated 2D and 3D models to analyze the nonlinear seismic responses, optimize pile layout and improve the performance of long-short combination piled raft systems. Using finite element analysis on soft clay they found that configuration, pile length & diameter and structure height strongly affected structural response. While 2D and 3D models showed similar behavior under strong earthquakes discrepancies appeared under lower intensities. By varying pile geometry and arrangement they achieved better shear force distribution and reduced lateral displacements. The study emphasized the need for site-specific geotechnical earthquake engineering approaches.

R.M. Swamy et al. (2019) modelled a G+2 structure with two bays on a piled raft foundation using finite element methods. Slabs were represented with 2D plate elements whereas beams, columns and piles as 1D elements. Their parametric study focused on raft thickness with uniform pile diameters. Results indicated that considering SSI with nonlinear soil behavior led to increased displacements compared to conventional analysis. While increasing pile diameter generally reduced storey displacement, thinner rafts combined with higher soil stiffness produced relatively larger displacements. Top-storey displacements in interactive analysis (with varying pile diameters) were greater than those from non-interactive analysis.

Manoj Sitaula et al. (2023) analyzed a 17-storey high-rise building with a piled raft and two basements, evaluating SSI in the context of the Nepalese National Building Code (NBC). They highlighted the lack of practical implementation guidelines for SSI in seismic design. Their study concluded that structures with SSI were less responsive than fixed-base models irrespective of soil class. On Site Class D seismic demands (displacement, drift, base shear, overturning moment, etc.) were reduced by more than 49%, a significantly higher reduction compared to Sites A, B, and C. Modal period elongation varied with foundation flexibility and with flexible systems requiring fewer modes to achieve 95% modal mass participation. These results indicate that SSI alters deformation patterns and can enhance structural performance.

Waleed Dawoud et al. (2024) conducted a direct SSI analysis on a 3D high-rise reinforced concrete building over a piled raft foundation using Plaxis 3D and nonlinear finite element analysis. They assessed the influence of pile embedment depth and base flexibility under El-Centro and Hachinohe earthquake records. Increasing pile embedment depth (by 20% to 80%) reduced peak displacements by 17.5% to 32.2% under El-Centro motion and by 15.8% to 26.7% under Hachinohe motion. Corresponding reductions in peak accelerations were 15 to 22.8% and 12.6 to 14.3%, respectively. Inter-storey drifts also declined, showing improved seismic performance. However, base shear and storey shear increased with greater embedment. Piles with embedment lengths of 1.4L to 1.8L showed similar responses, suggesting a 40% increase in pile length may be ideal. This optimal length depends on both building height and subsurface conditions.

III. OBJECTIVES OF THE STUDY

- To evaluate the effect of Soil-Structure Interaction (SSI) on response of asymmetric building frame by developing a finite element analysis-based software model.
- To assess the influence of Soil-Structure Interaction (SSI) is evaluated using an acceleration response spectrum derived from the peak ground acceleration time history of the 2001 Bhuj earthquake (India).
- To assess the influence of Soil-Structure Interaction (SSI) on the lateral storey displacement, Structure settlement, Inter-storey drift ratio, Pile displacement, Pile settlement, Raft displacement and Raft settlement.
- To evaluate the effects with different Pile configuration, Pile L/D ratios and Pile spacing on the response of superstructure for two different orientations of structure (EQ load along length of structure and EQ load along width of structure).
- To analyze and compare the seismic performance of an asymmetrical building frame supported on various piled raft configuration. Including Fixed base, Single piles, 2 piles arranged in series with length of structure and 2 piles arranged in parallel with length of structure. All configurations are compared with L/D ratio 10, 15 and 20.

IV. METHODOLOGY

The present study employs a finite element approach to investigate non-linear soil-structure interaction (SSI) using ANSYS Workbench. The complete geometry of the system including superstructure, substructure and the surrounding soil domain is initially modelled as a monolithic assembly in SolidWorks. It is then subsequently imported into ANSYS for simulation. The super structure is asymmetrical in plan with 2 × 3 bays with each bay being 5m × 5m. The frame is 20 storey tall with each storey being 3m. The column dimensions are considered as 0.3m × 0.4m in cross section. Beam width is taken as 0.3m and 0.4m and depth as 0.6m. The substructure consists of a piled-raft with pile diameter of 600mm. The raft is 1m thick and overhang portion of raft to pile is 0.5D. The spacing between piles are 2D and L/D ratio are 10, 15 and 20. Table 3. lists all pile configurations. Fig. 1 and 2 shows typical section of piled raft with single and two piles. Non-linear soil properties are assigned to soil component as mentioned in Table 1. Material properties of structural elements are listed in Table 2. Geometry refinement and contact definitions are performed in ANSYS *SpaceClaim* and all structural contact interfaces are initially assigned as bonded. Pile and soil interfaces are modelled with defined face sizing of 1 meter for both the pile and surrounding soil.

Both the structural and soil domains are discretized using three-dimensional tetrahedral elements to accommodate the geometric complexity of the model and the nonlinear response characteristics. A tetrahedral element is a four-faced, three-dimensional (3D) finite element. Each face of a tetrahedron is a triangle, and it typically has 4 corner nodes (linear element) or 10 nodes (quadratic element) depending on the order of the element. The soil domain is modelled as soft soil with finite volume of 50×50×30 m around the foundation. It is discretized using a quadratic-order tetrahedral mesh with a patch-conforming algorithm and an element size of 3 meters to ensure numerical accuracy and convergence.

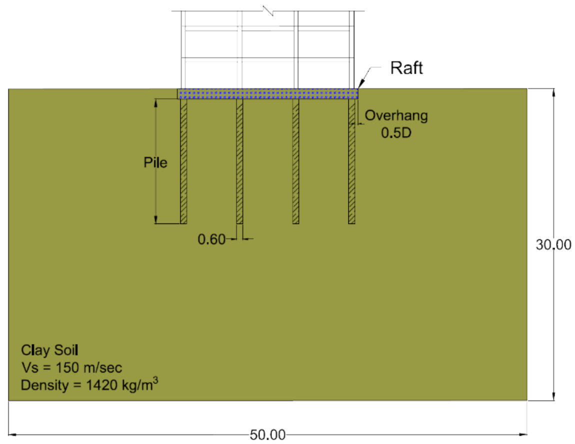

Fig. 1: Typical section of piled raft foundation with single piles.

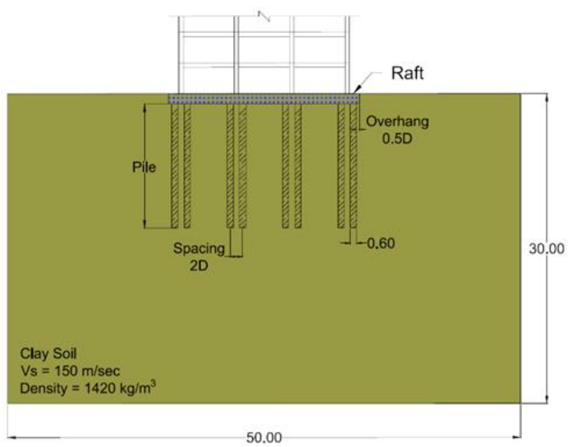

Fig. 2: Typical section of piled raft foundation with Two piles.

A site-specific acceleration response spectrum derived from the peak ground acceleration time history of the *Bhuj* earthquake, India (2001) is applied as seismic input. The frequencies generated from the peak ground acceleration during the 20-second interval between the 30th and 50th seconds are used in seismic analyses. The spectrum is defined as a single-point excitation, with mode combinations performed using the Square Root of the Sum of the Squares (SRSS) method. Seismic loading is applied in both the global X and Z directions, with gravity applied in the negative Y direction, and a unit scaling factor of 1.0 is used for input acceleration. Appropriate boundary conditions are applied to all supports. This methodology enables the evaluation of key response parameters including lateral storey displacement, inter-storey drift and settlement. Providing a detailed assessment of non-linear SSI effects on tall structures supported by piled raft foundations under seismic loading.

Table 1. Material property for clay soil.

Property	Corresponding Value
Density (γ_s)	1420
Young's Modulus (E_s)	8.5E+06
Poisson's Ratio (μ_s)	0.35
Bulk Modulus (K_s)	9.444E
Shear Modulus (G_s)	3.148E
Yield Strength (σ_y)	95000
Tangential Modulus (E_t)	5.1325E+05

Table 2. Clay Soil properties

Property	Corresponding Value
Grade of Concrete	M25
Density (γ_c)	2350
Young's Modulus (E_c)	2.5E+10
Poisson's Ratio (μ_c)	0.20
Bulk Modulus (K_c)	1.3889E+10
Shear Modulus (G_c)	1.0417E+10
Tensile (f'_t)	2.5E+06
Compressive (f'_c)	2.5E+07

Table 3. Piled-Raft Configurations

Notation	Model Configuration
a	Fixed Base with EQ along X Direction
b	Fixed Base with EQ along Z Direction
c	Single Piles (L/D = 10) with EQ along X Direction
d	Single Piles (L/D = 10) with EQ along Z Direction
e	Single Piles (L/D = 15) with EQ along X Direction

f	Single Piles (L/D = 15) with EQ along Z Direction
g	Single Piles (L/D = 20) with EQ along X Direction
h	Single Piles (L/D = 20) with EQ along Z Direction
k	Two Piles in series (L/D = 15) with EQ along X Direction
l	Two Piles in series (L/D = 15) with EQ along Z Direction
m	Two Piles in series (L/D = 20) with EQ along X Direction
n	Two Piles in series (L/D = 20) with EQ along Z Direction
o	Two Piles in parallel (L/D = 10) with EQ along X Direction
p	Two Piles in parallel (L/D = 10) with EQ along Z Direction
q	Two Piles in parallel (L/D = 15) with EQ along X Direction
r	Two Piles in parallel (L/D = 15) with EQ along Z Direction
s	Two Piles in parallel (L/D = 20) with EQ along X Direction
t	Two Piles in parallel (L/D = 20) with EQ along Z Direction

Note: Since changing the global coordinate system is not possible in ANSYS software the default (fixed) global coordinate system is used for creating geometry, applying loads, defining boundary conditions and interpreting output results. In this system, the X-axis is oriented along the length of the element, the Y-axis is lateral to the cross-section and the Z-axis is taken as the applicate (vertical direction).

V. RESULTS AND DISCUSSION

This study examines the seismic response of a 20-storey symmetrical reinforced concrete structure on a uniform soil profile, subjected to the 2001 Bhuj (India) ground motion. Analyses are performed under both fixed-base and flexible-base conditions to assess the influence of Soil–Structure Interaction (SSI) on structural behavior. Key responses such as lateral storey displacements, drift ratios and settlement values are evaluated for various pile configurations, including single piles with different L/D ratios and two-pile systems arranged in series and parallel. Results show that fixed-base structures have the least displacement and settlement.

5.1 Lateral Displacement and Settlement of Frame.

For single pile foundations with L/D ratios of 10, 15 and 20 lateral displacements in the EQ X direction increased by 142.82% to 161.94% while in EQ Z direction the increase ranged from 182.91% to 184.24% compared to the fixed-base model. In two-pile configurations arranged in series with increasing in L/D ratio leads to a noticeable reduction in displacement. EQ X displacements decreasing from 208.85 mm at L/D = 10 to 141.64 mm at L/D = 20. Despite this improvement, SSI still causes 133.20% to 183.38% higher displacement than fixed-base conditions with the EQ Z direction consistently yielding the highest values. The results corresponding to these pile configurations with fixed-base conditions are presented in Table 4 and 5.

Table 4. Displacement and Settlement Results for Fixed Base and Single Piles Model.

Model	Max. Displacement (X) mm	Max. Displacement (Z) mm	Max. Settlement (Y) mm
a	28.375	0.028	1.156
b	0.016	25.088	0.872
c	269.090	2.396	23.399
d	3.957	610.800	38.969
e	209.340	1.753	17.160
f	3.607	581.740	35.425
g	169.740	1.220	13.114
h	2.898	561.37	32.679

Similarly, for two piles arranged in parallel the maximum displacement of 592.14 mm is observed at L/D = 10 under EQ Z loading reflecting a 181.7% increase. Two-pile systems outperform single piles, with two piles in series (L/D = 20) showing the best performance. Across all configurations, SSI amplifies displacement by approximately 135% to 182% emphasizing the critical influence of SSI on deep foundation behavior and the necessity of its consideration in seismic design.

Table 5. Displacement and Settlement Results for Two Piles in Series and Parallel Model.

Model	Max. Displacement (X) mm	Max. Displacement (Z) mm	Max. Settlement (Y) mm
i	208.17	2.003	17.067
j	3.781	577.940	34.818
k	166.880	2.870	12.844
l	3.156	550.530	31.511
m	141.280	1.443	10.264
n	2.259	435.02	23.848
o	220.880	1.860	18.348

p	3.551	591.04	36.6
q	175.510	1.361	13.700
r	3.058	566.580	33.458
s	146.930	0.978	10.826
t	2.326	483.37	27.234

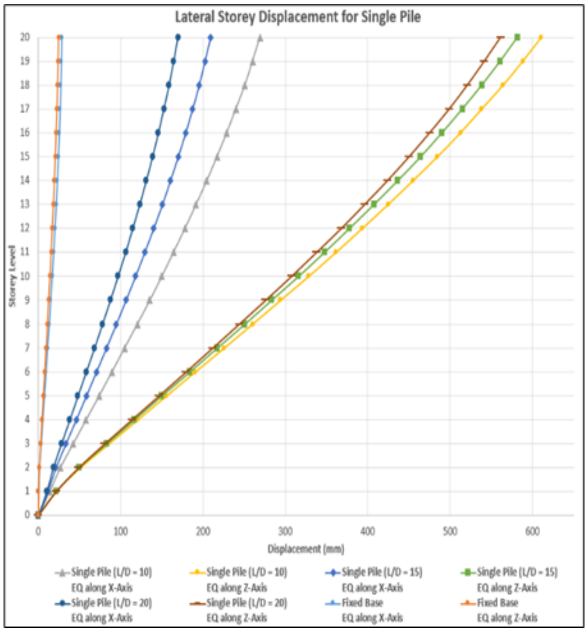

Fig3: Lateral Storey Displacement for Fixed Base and Single Pile models.

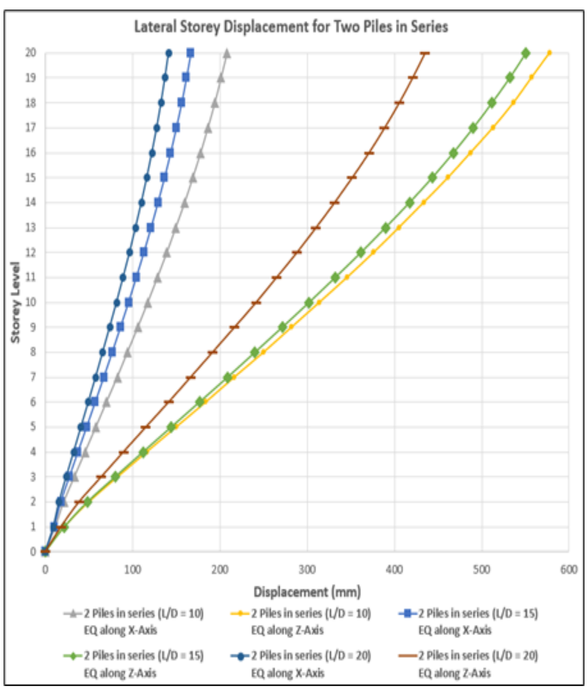

Fig. 4: Lateral Storey Displacement for Fixed Base and Single Pile models.

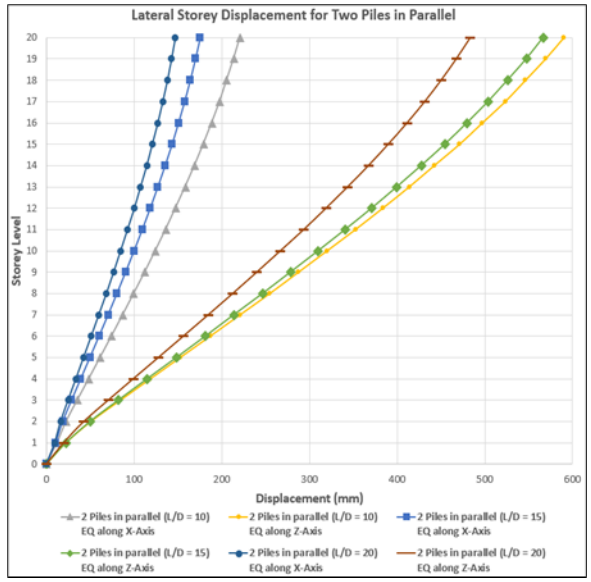

Fig. 5: Lateral Storey Displacement for Fixed Base and Single Pile models.

The analysis shows that seismic loading in the EQ Z direction consistently results in greater settlement than EQ X across all foundation configurations. For single pile systems increasing the ratio (L/D) from 10 to 20 reduces maximum settlement which improves vertical stability. However, even the best-performing case L/D = 20 under EQ X still exhibits a 167 to 191% increase in settlement compared to the fixed-base model. In two pile in series configurations settlement also decreases with increasing L/D with the lowest settlement of 10.264 mm observed at L/D = 20 under EQ X and the highest (34.818 mm) at L/D = 10 under EQ Z. Despite the improvements all configurations still show over 159% higher settlement than the fixed base.

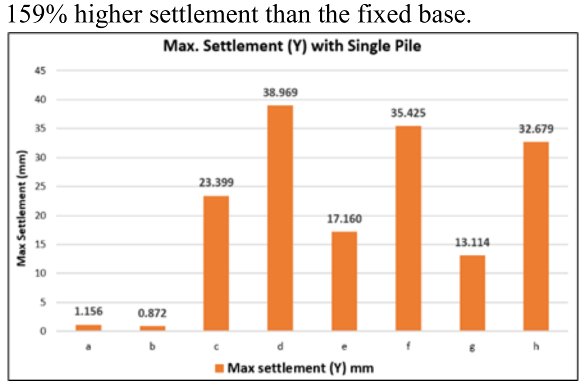

Fig. 6: Max. Settlement for Fixed Base and Single Pile models.

A similar trend is observed in two piles arranged in parallel, where longer piles again reduce settlement. The minimum settlement of 10.826 mm occurs at L/D

= 20 under EQ X while the maximum of 36.600 mm is noted at L/D = 10 under EQ Z. Even in the best case, settlement is still 161% higher than the fixed base, underscoring the persistent influence of SSI.

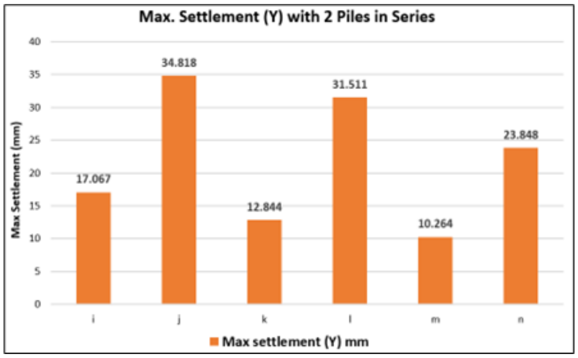

Fig. 7: Max. Settlement for Two Piles in Series.

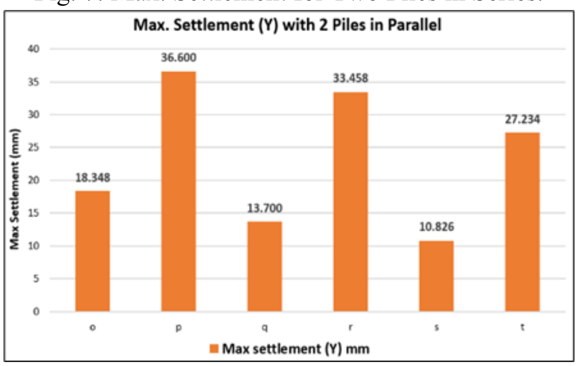

Fig. 8: Max. Settlement for Two Piles in Parallel.

5.2 Storey Drift Ratio of Frame.

The storey drift ratios for single pile configurations reveal a marked influence of both pile L/D ratio and the direction of seismic loading. The maximum drift ratio of 0.754% was observed for L/D = 10 under EQ Z while the minimum of 0.170% occurred at L/D = 20 under EQ X. This highlights the drift-reducing effect of increased slenderness. A consistent pattern emerges where seismic loading in the EQ Z direction results in significantly higher drift ratios across all L/D values. For instance, at L/D = 15 the drift under EQ Z is 0.697% compared to 0.235% under EQ X. In contrast, the fixed base condition exhibits the lowest drift values 0.0186% for EQ X and 0.0196% for EQ Z indicating superior lateral stiffness and serving as a benchmark for evaluating pile-supported systems.

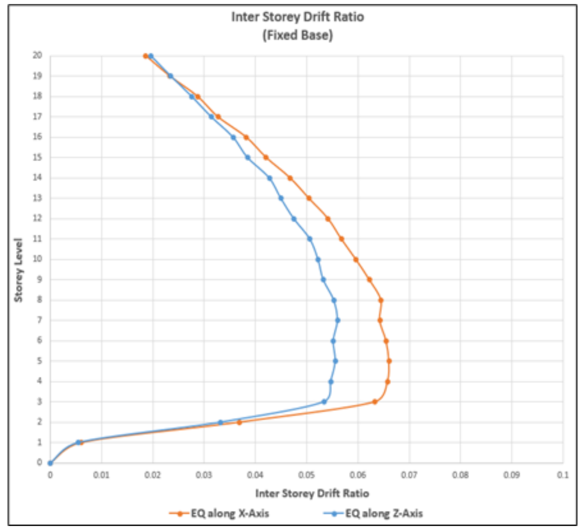

Fig. 9: Storey Drift Ratio for Fixed Base Model.

The storey drift ratios for two piles in series under seismic loading reveal notable variation based on both the L/D ratio and the direction of seismic excitation. The highest storey drift ratio of 0.694% was observed for L/D = 15 under EQ Z followed by 0.618% for L/D = 15 under EQ X. It indicates significant lateral deformation at this intermediate slenderness of piles. In contrast, the lowest drift of 0.139% occurred at L/D = 20 under EQ X demonstrating improved lateral stiffness with increased L/D ratio. EQ Z loading consistently resulted in higher drift ratios than EQ X for the same L/D, except at L/D = 10 where EQ X produced 0.231% slightly lower than 0.31% under EQ Z. Overall, increasing the L/D ratio tends to reduce storey drift where drift amplification suggests a possible dynamic resonance or flexibility condition.

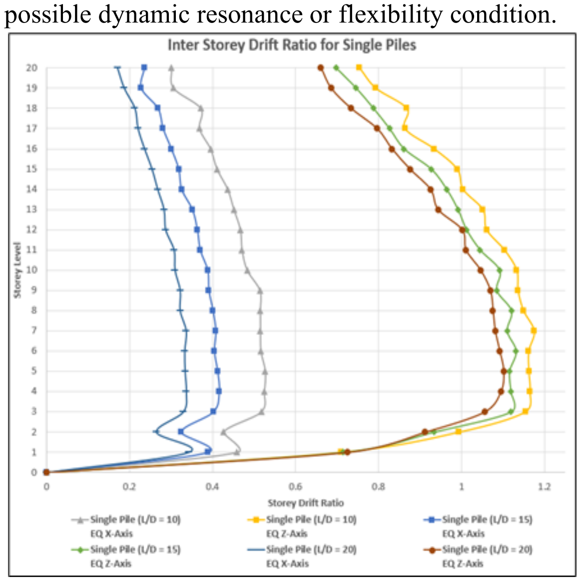

Fig. 10: Storey Drift Ratio for Single Piles.

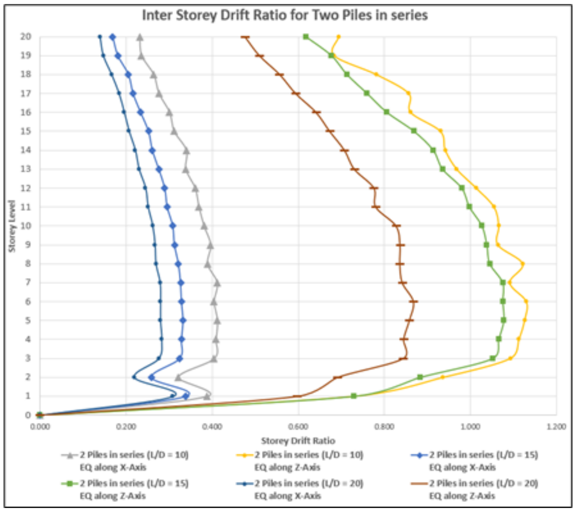

Fig. 11: Storey Drift Ratio for Two Piles in Series.

The storey drift behavior for two piles arranged in parallel under seismic loading shows significant sensitivity to both the pile slenderness ratio (L/D) and the direction of earthquake excitation. The maximum drift ratio of 0.697 was observed at L/D = 15 under EQ Z, closely followed by 0.6639 for the same L/D under EQ X, indicating that intermediate slenderness may induce amplified lateral displacements. The drift ratio consistently decreased with increasing L/D ratio, reaching a minimum of 0.144 at L/D = 20 under EQ X, and 0.536 under EQ Z for the same L/D. At L/D = 10, EQ Z produced higher drift (0.242) compared to EQ X (0.181), reinforcing the trend that seismic loading in the Z direction generally results in greater lateral response. Overall, increasing pile slenderness tends to reduce storey drift, while the EQ Z direction remains more critical in terms of deformation demands.

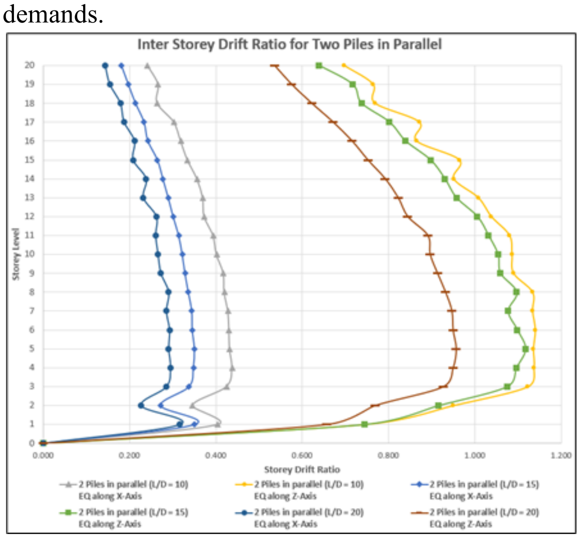

Fig. 12: Storey Drift Ratio for Two Piles in Parallel.

5.3 Lateral Displacement and Settlement of Piled-Raft.

Table 6. Displacement and Settlement Results for Piled-Raft Foundation.

Model	Max. Foundation Displacement (mm)	Max. Foundation Settlement (mm)
c	11.502	18.57
d	16.119	30.258
e	10.083	13.082
f	16.87	26.242
g	9.114	9.567
h	17.698	23.032
i	10.07	13.879
j	17.517	28.124
k	9.0408	9.954
l	18.098	24.021
m	8.436	7.58
n	15.243	17.179
o	10.458	14.162
p	17.546	27.75
q	9.303	10.11
r	18.19	24.012
s	8.577	7.623
t	16.56	18.524

Foundation displacement results indicate that seismic loading in the EQ Z direction consistently causes higher displacement than EQ X across all configurations. For piled-raft with single piles displacement decreases by increasing L/D ratio with the minimum of 9.114 mm observed at L/D = 20 under EQ X. While the maximum of 17.698 mm occurs under EQ Z for the same L/D. Foundation with two piles in series show a similar trend with displacements reducing as L/D increases. The lowest value is 8.436 mm (L/D = 20, EQ X) and the highest is 18.098 mm (L/D = 15, EQ Z). In the foundation with two piles in parallel configuration, displacement under EQ X decreases from 10.458 mm at L/D = 10 to 8.577 mm at L/D = 20. Across all cases, the EQ Z direction consistently results in greater pile movement.

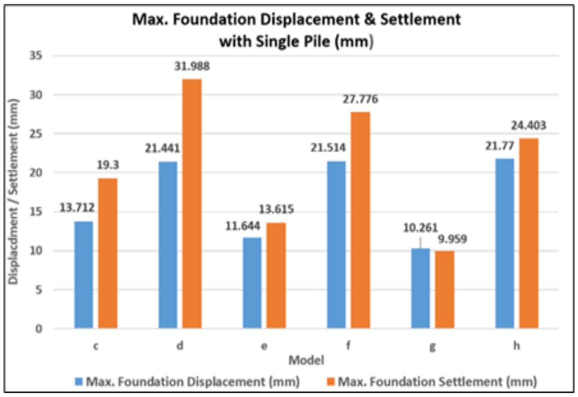

Fig. 13: Max. Foundation Displacement and Settlement with Single Piles.

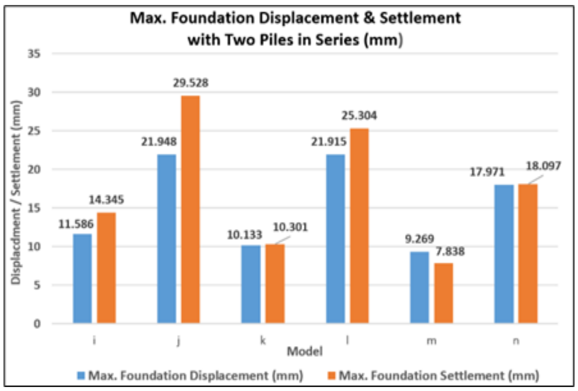

Fig. 14: Max. Foundation Displacement and Settlement with Two Piles in Series.

The Piled-raft settlement analysis under seismic loading reveals that for all configurations, settlement is consistently higher under EQ Z direction than EQ X. It highlights the greater impact of transverse seismic forces. For single piles the maximum settlement of 30.258 mm occurs at L/D = 10 under EQ Z. While the minimum is 9.567 mm at L/D = 20 under EQ X which indicates that increasing L/D significantly reduces settlement. Similarly, two piles in series show improved performance with settlement reducing from 28.124 mm (L/D = 10, EQ Z) to 7.580 mm (L/D = 20, EQ X). It demonstrates better control over seismic-induced deformation. The parallel configuration follows the same trend with settlement decreasing from 27.75 mm to 7.623 mm across the same L/D and loading conditions.

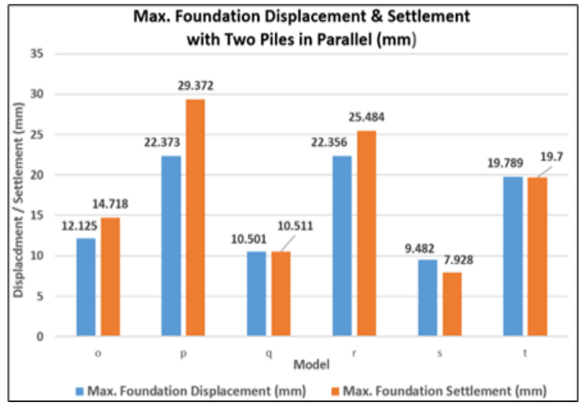

Fig. 15: Max. Foundation Displacement and Settlement with Two Piles in Parallel.

VII. CONCLUSION

- It is observed that variations in pile spacing, orientation and L/D ratio have a significant effect on lateral displacements, storey drifts and settlement particularly when comparing fixed-base and SSI models.
- Results highlights the significance of soil flexibility in seismic performance which demonstrate that incorporating SSI yields a more accurate and realistic assessment of structural behavior.
- These findings highlight the effectiveness of increasing pile length in controlling settlement and the critical role of seismic loading direction in foundation performance.
- Study concludes that with longer pile systems particularly those arranged in series to seismic loading direction are effective in reducing lateral displacement of structure to those with transverse seismic loading direction.
- Overall, using two piles particularly in series and with higher L/D proves more effective in limiting seismic-induced lateral displacements.
- Piled-raft foundation displacement results highlights that foundation increases sensitivity to transverse seismic forces, while higher L/D ratios enhance performance by minimizing displacement. This highlights the need for additional design measures to control lateral displacements in foundation.
- Both dual-pile arrangements show comparable improvements. The series configuration slightly

outperforms the parallel one in reducing settlement. Overall, increasing pile slenderness and using dual-pile systems effectively enhance resistance to seismic-induced settlement especially under transverse loading.

REFERENCE

[1]. S.C. Dutta and R. Roy (2002). "A critical review on idealization and modelling for interaction among soil–foundation–structure system". Computers and Structures, 80, 1579-1594.

[2]. Koushik Bhattacharya, Sekhar Chandra Dutta and Suman Dasgupta (2004). "Effect of soil-flexibility on dynamic behaviour of building frames on raft foundation". Journal of Sound and Vibration, 274, 111–135.

[3]. Chore H.S. and R.K. Ingle (2008). "Soil Structure Interaction Analysis of Building Frame Supported on Pile Group". Asian Journal of Science and Technology for Development (AJSTD), 25 (2), 457-467.

[4]. Chore H.S, R.K. Ingle and V.A. Sawant (2009). "Building Frame-Pile Foundation-Soil Interactive Analysis". Interaction and Multiscale and Mechanics (IMM), An International Journal, 2 (4), 397-411.

[5]. Dr. D. Daniel Thangaraj and Dr. K. Ilamparuthi (2012). "Interaction Analysis of MAT Foundation and Space Frame for the Non-Linear Behaviour of the Soil". Bonfring International Journal of Industrial Engineering and Management Science, 2(4), 33-40.

[6]. Dr. Rolf Katzenbach and Dr. Deepankar Choudhury (2013). "Combined Pile-Raft Foundation Guideline". International Society for Soil Mechanics and Geotechnical Engineering.

[7]. S. Hamid Reza Tabatabaiefar, Behzad Fatahi and Bijan Samali (2013). "Seismic Behavior of Building Frames Considering Dynamic Soil-Structure Interaction". International Journal of Geomechanics,13(4), 409-420.

[8]. A. Iqbal and T. M. Al-Hussaini (2014), "Soil-Structure Interaction Effects on Tall Buildings with Mat Foundation". Journal of Structural Engineering Society of New Zealand Inc, 27(2), 48-60.

[9]. J. Nadar, H. S. Chore, P. A. Dode (2015). "Soil Structure Interaction of Tall Buildings". International Conference on Quality Up-gradation in Engineering, Science and Technology (ICQUEST), B.D. College of Engineering, Sewagram, Nagpur (India), 11 April, 2015.

[10]. S.A. Rasal, H.S. Chore and V. A. Sawant (2015). "Effect of Embedment Depth of Piles on Response of Three Storeyed Building Frame Incorporating Non-Linear Behaviour of Soil". Journal of Structural Engineering (JoSE), 45(6), 520-545.

[11]. Harry G. Poulos (2016). "Tall Building Foundations: Design Methods and Applications". Innovative Infrastructure Solutions, 1(10).

[12]. Ashutosh Kumar, Deepankar Choudhury and Rolf Katzenbach (2016). "Effect of Earthquake on Combined Pile–Raft Foundation". International Journal of Geomechanics, 16(5).

[13]. V. Srivastava, H. S. Chore, P. A. Dode (2016). "Interaction of Building Frame with Pile Foundation". Open Journal of Civil Engineering, 6, 195-202.

[14]. Henry Far (2017). "Advanced computation methods for soil-structure interaction analysis of structures resting on soft soils". International Journal of Geotechnical Engineering, 13, 352-359

[15]. S.A. Rasal, H.S. Chore and D. R. Suroshe (2017). "Interaction Analysis of Building Frame Supported on Piled Raft". 6th Int. Conf. Quality Up-gradation in Engineering, Science and Technology (ICQUEST-2017), Bapurao Deshmukh College of Engineering, Nagpur (India), 28th September, 2017.

[16]. S.A. Rasal, H.S. Chore and V.A. Sawant (2017). "Non-linear Soil-structure Interaction Analysis of Framed Structure with Pile Foundation". 3rd International Conference on Advancement in Engineering, Applied Science and Management (ICAEASM-

2017), Centre for Development of Advanced Computing, Mumbai (India), pp-452-460.

[17]. Anand V. and Satish Kumar S. R. (2018). "Seismic soil-structure interaction: a state-of-the-art review." Structures, 16, 317-326.

[18]. Mohsen Bagheri, Mehdi Ebadi Jamkhaneh and Bijan Samali (2018). “Effect of Seismic Soil-Pile-Structure Interaction on Mid and High-Rise Steel Buildings Resting on a Group of Pile Foundations”. International Journal of Geomechanics, 18(9), 01-27.

[19]. George Markou, Mohammad Al-Hamaydeh and Dina Saadi (2018), “Effects of The Soil-Structure-Interaction Phenomenon on RC Structures with Pile Foundations”. 9th GRACM International Congress on Computational Mechanics, Chania, 4-6 June, 2018.

[20]. K. Pratyusha, D. Nagaraju, K. D. Kumar (2019). “Effect of Soil Structure Interaction on Multi-Storeyed Building with Raft Foundation”. International Journal of Innovative Technology and Exploring Engineering (IJITEE), 9(1), 557-570.

[21]. R. M. Swamy, S.A. Rasal (2019). “Effect of Soil- Structure Interaction on Response of Building Frame with Piled-Raft Foundation”. International Research Journal of Engineering and Technology (IRJET), 6(2), 2290-2295.

[22]. Shubham S. Koparde, S.A. Rasal (2023). “Analysis of Building Frame Supported on Different Pile configurations Incorporating Soil-Structure Interaction”. Journal of Emerging Technologies and Innovative Research (JETIR), 10(12), 495-503.

[23]. M. Sitaula, S. Karanjit and C. Kawan (2023). “Study of Dynamic Soil Structure Interaction of RC Building with Piled Raft Foundation on Different Soil Classes”. 3rd International Conference on Earthquake Engineering and Post Disaster Reconstruction Planning (ICEE-PDRP 2023), Bhaktapur (Nepal), 17-19 October, 2023.

[24]. W. Dawoud, M. Nazim, O. El-Mahdy and M. Adam (2024). “Soil-Structure Interaction Assessment for Seismic Performance of High-Rise RC Building on Piled-Raft Foundation”. Engineering Research Journal (ERJ), 53(2), 203-211.

[25]. IS 456:2000, Code of Practice for Plain and Reinforced Concrete, Bureau of Indian Standards (New Delhi).

[26]. IS 1893-1, Criteria for earthquake resistant design of structures - Part 1: General provisions and buildings. Bureau of Indian Standards (New Delhi), 2016.

[27]. IS 2911 (Part 1), Design and Construction of Pile Foundations – Part 1: Concrete Piles, Bureau of Indian Standards (New Delhi).

[28]. IS 1904 (1986): Code of practice for design and construction of foundations in soils: General requirements, Bureau of Indian Standards (New Delhi).

[29]. IS 2950 (Part 1): 1981 Design and Construction of Raft Foundations – Part 1: Design, Bureau of Indian Standards (New Delhi).