Effect of Soil-pile Interaction on Inclined Pile Group Subjected to Axial and Lateral Loads

Sandeep G S, Arun Kumar Y M, Poornachandra Pandit and Varghese Basil Alexander

Abstract—**High-rise RCC buildings are generally subjected to a combination of gravity and lateral loads. The pile foundation is generally used in high-rise buildings to transfer higher axial loads to the soil at greater depths. Most of the pile systems are studied by considering either axial loads or lateral loads. In practice, groups of piles with different patterns are used by considering the spacing between the piles to avoid the overlapping of pressure bulbs. Inclination of piles leads to an increased resistance to lateral and vertical forces as they produce partial lateral resistance from their axial capacity, hence these piles are more efficient than vertical piles in resisting lateral loads. In the present study, various combinations of inclined piles have been analyzed under the effect of axial and lateral loads for high-rise buildings. Four different angles of inclination are considered for inclined piles with three distinct percentages of pile group combinations to find the optimum angle of inclination and optimum percentage of pile group combination. To study the effect of soil-structure interaction (SSI), a comparison of displacements has been carried out. Inclined pile groups produced better results in terms of vertical and lateral displacements as compared to that of vertical pile groups. The results revealed that 25^0 inclinations of piles reduce the lateral and vertical displacements to a greater extent.**

Index Terms— **Inclined piles; angle of inclination; time-history analysis; soil-structure interaction; vertical displacement; lateral displacement.**

I. Introduction

SHALLOW foundations are adopted when there is adequate bearing stress in the soil up to considerable depths from the ground level to support the load of the superstructure without causing considerable settlement. The structure's load must be transmitted to deeper, harder strata in locations where the topsoil is loose or weak [1]. In the current era of rapid urban growth, considering the scarcity of land, structures are being designed and constructed on relatively soft soil that was previously considered to be unsuitable for construction by adopting suitable ground improvement techniques. Pile foundations are one such advancement that is primarily used to transfer loads from superstructures through weak and compressible strata to stronger, more compact, and stiffer soil or rock at certain depths, thus increasing the effective size of a foundation and providing the required support to the superstructure. However, the axial stiffness of vertical piles resulting from soil-pile interaction is frequently greater than that along the inclined pile direction, giving inclined piles a higher lateral stiffness than vertical piles and reducing the maximum horizontal acceleration, horizontal displacement, and bending moment [2]–[7]. This is primarily because inclined piles produce partial lateral resistance from their axial capacity. When a pile is inclined along its length, two force components are generated due to the pile's inclination which results in an increase in the lateral resistance of the inclined pile. The natural period that corresponds to the global bending vibrations of the structures often decreases as lateral stiffness increases, which is likely to intensify the seismic response of the superstructure by considering soil-structure interaction (SSI) [8]–[11]. Horizontal deflections and story drifts are enhanced for end-bearing piles when fixed base structures excluding SSI are compared with end-bearing piles including SSI [12]. [13]–[15] investigated the response of a single pile and group of piles under the effects of seismic loading and noted that the size and material of piles affect the pile failure modes and grouping of piles reduces the peak response values. [13], [16]–[18] investigated the effects of SSI on the foundation and structural components of multi-story buildings and bridges respectively and found that the ductility demand was reduced by increasing the inclination of piles built with elastic behaviour. Structures with pile foundations considering various percentages of inclined pile group combinations have not been addressed in any of the literature. Moreover, not much information is found on the optimum angle of inclination and behaviour of inclined piles when subjected to combined axial and lateral loads. The present study draws inspiration from nature, specifically the fibrous root systems of many trees. These systems enhance a tree's stability by relying on the mother root and branching roots to firmly hold the soil in place. This paper conducts a study inspired by the fibrous root system to determine the optimal angle of inclination and the optimal percentage of inclined piles within a pile group subjected to combined axial, and combined axial and lateral loads, aiming to achieve maximum resistance.

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II. METHODOLOGY

A 15-story RCC building model with 15m x 15m in plan and 45m height has been analyzed for combined axial and lateral loads using ABAQUS software. The building model is supported by a pile cap of size 17m x 17m and 2.5m depth with a pile group consisting of vertical and inclined piles. Piles of 17.5m in length and 1m diameter are embedded in a homogeneous soil model of size 30m x 30m and depth 25m. The sizes of columns and beams in a building model are 0.45m x 0.60m and 0.45m x 0.45m, respectively. The numerical simulation of inclined piles with frame involves eight major steps, outlined as follows:

Step 1: Creation of solid models (pile, soil and pile cap).
Step 2: Creation of frame elements (beams and columns).
Step 3: Assigning material properties to solid and frame models.
Step 4: Assembly of all solid and frame elements.
Step 5: Assigning boundary and loading conditions to the soil and frame.
Step 6: Meshing of the solid and frame models.
Step 7: Defining the analysis procedure for analyzing the Model.
Step 8: Obtaining the results in the post-processing model.

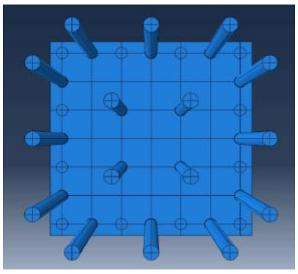
In step 1, three-dimensional parametric models are created to represent the pile, soil and pile cap as per the dimensions specified. In step 2, frame elements are created by using spar elements and connected based on the frame dimensions. In step 3, material properties are assigned to the solid and framed elements as per Table I. Once the properties are assigned to the models, in step 4, all elements are assembled to proper locations based on the coordinates. In step 5, boundary conditions and loading conditions are defined as per the analysis conditions. Before defining the analysis procedure for analyzing the model, it is very important that all the elements must be meshed which was done in step 6. In step 7, the analysis procedure is defined i.e. static/dynamic based on the condition. In the present study, dynamic explicit analysis method is adopted. In the final step, the results are obtained in the postprocessing module.

The properties that satisfy deflection tests have been determined by analyzing the building frame model as a fixed base structure. The mechanical properties of materials for different elements used in this study are tabulated in Table I.

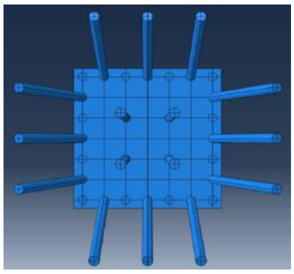
TABLE I
PROPERTIES OF BUILDING ELEMENTS AND COHESIONLESS SOIL

Parameter	Beam, column, pile cap and pile	Cohesionless soil
Density (kg/m^3)	2500	1400
Young's modulus (kg/m^2)	27.38×10^6	10^7
Poison's ratio	0.2	0.3
Dilation angle	-	0.1^0

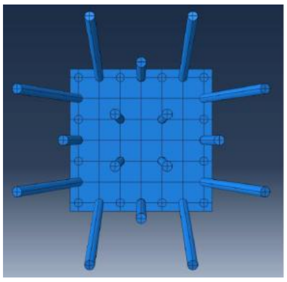
Four different angles of inclination w.r.t vertical axis are considered for inclined piles: 10^0, 15^0, 20^0 and 25^0. Three distinct percentages of pile group combinations are examined for each angle of inclination: 0%, 75%, 50% and 25% as shown in Fig. 1(a), (b), (c) and (d). Fig. 2 shows the 3D view of the high-rise RCC building model.



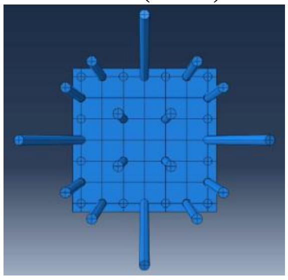
(a)Vertical piles



(b) Typical symmetrical arrangement of 75% of piles as inclined (75% IP)



(c) Typical symmetrical arrangement of 50% of piles as inclined (50% IP)



(d) Typical symmetrical arrangement of 25% of piles as inclined (25% IP)

Fig. 1 Bottom view of pile group arrangement.

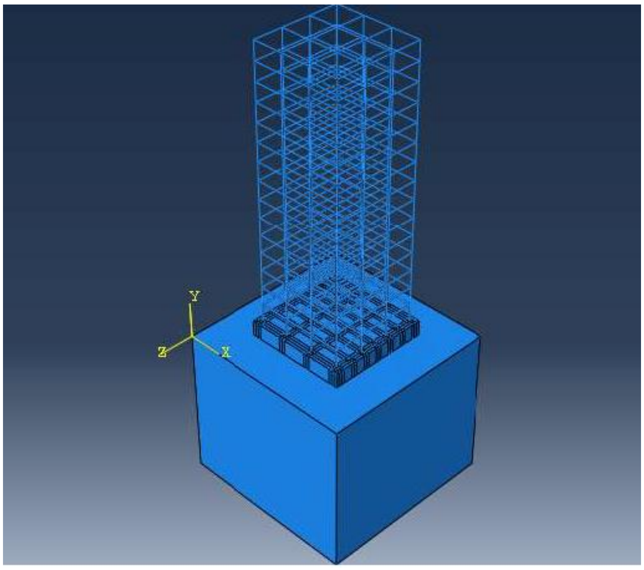


Fig. 2 3D view of high-rise RCC building model.

A. *Step and interaction properties*

For the analysis, two distinct steps were defined to appropriately capture both static and dynamic behavior. A Static, General step was created with a total time period of 1 second to perform the static analysis of the model. This step ensured that the equilibrium conditions were satisfied under applied loads without considering inertial effects. In contrast, a Dynamic, Implicit step was established with a time period of 31.18 seconds to conduct the dynamic analysis, allowing the model to account for time-dependent behavior and inertial forces.

To accurately define the interaction properties between contact surfaces, the penalty method was employed. The tangential behavior was characterized by using a friction coefficient of 0.5, ensuring realistic resistance to sliding between surfaces. For normal behavior, a hard contact condition was applied, which allowed separation between surfaces but prevented penetration, ensuring that normal forces were transmitted accurately. These interaction definitions provided a realistic representation of contact mechanics, improving the accuracy of the simulation results.

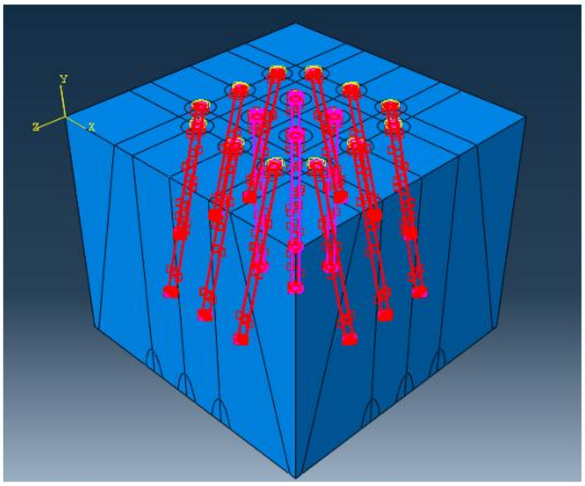


Fig. 3 Interaction between soil and pile.

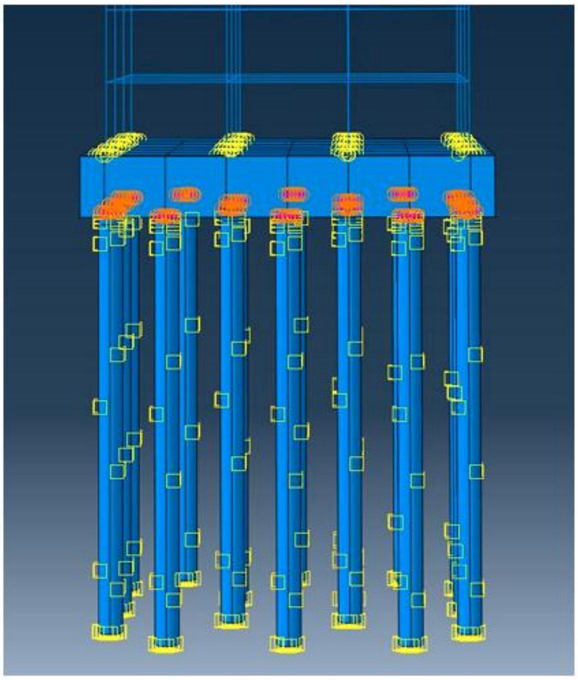


Fig. 4 Tie constraints at frame, pile cap and pile intersections.

In the analysis, a standard surface-to-surface interaction was established between the pile and the surrounding soil to accurately simulate their interaction. Specifically, this interaction was defined between both the side and bottom surfaces of the pile and the corresponding surfaces of the soil. In this setup, the pile surfaces were designated as master surface, while the soil surfaces were assigned as slave surface, ensuring proper contact behavior and load transfer, as depicted in Fig. 3. Furthermore, to maintain structural continuity and realistic modeling of the pile foundation system, tie constraints were implemented at critical junctions, including the frame–pile cap and pile cap–pile intersections. These constraints ensured that the connected components moved together without relative displacement, effectively simulating rigid connections. In these cases, the frame and pile cap were designated as master surfaces to enforce the appropriate constraint relationships, as illustrated in Fig. 4. This approach aided to achieve a more realistic representation of the structural behavior under applied loads.

B. Loading and Boundary conditions

For the superstructure, a dead load of 4.75 kN/m^2 (considering the slab weight and floor finishes) and a live load of 3 kN/m^2 were considered as per IS 875 (Part 1):1981 and IS 875 (Part 2):1987 respectively. At the base of soil in the horizontal axis and across the diagonal for lateral loading, the 1940 El Centro earthquake's time history data was applied as an amplitude. The directional application of lateral loading is shown in Fig. 5.

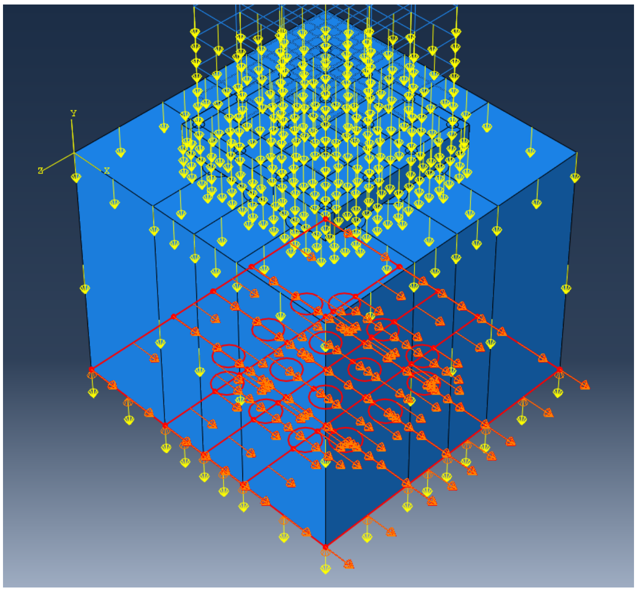


Fig. 5 Directional application of lateral loading.

For static analysis, the base of the soil was considered fixed, and the side faces of the soil were restrained for horizontal translations. For the first case of dynamic analysis, seismic loading was imposed at the base of the soil along the horizontal axis (x-axis) restraining the vertical translation. For the second case, to apply the seismic load diagonally, the whole model was rotated by 45^0 along the vertical axis and then the seismic loading was applied at the base of the soil through the horizontal axis (x-axis) restraining the vertical translation. Frames were modelled as wire elements and were meshed as B31 element which is a 2-noded linear beam element with a mesh size of 1m. Pile caps and piles were meshed as C3D8R element which is an 8-noded linear brick element with a mesh size of 0.6m. Soil elements were meshed as C3D10 element, which is a 10-noded quadratic tetrahedron element with a mesh size of 2.6m. In the present study, different mesh sizes were adopted based on the size of each component, i.e. frame, pile and soil assembly to reduce computational time.

III. Results and Discussions

A. Analyses of the SSI model for axial and horizontally applied lateral loads

The structural models with different pile groups and angles of inclinations were analyzed for axial and combination of axial (self-weight + live load) and lateral loads (EL Centro - time history data). Lateral loads are applied horizontally at the base of the soil. To study the effect of SSI, a comparison of displacements was made within pile group models with distinct inclined pile group percentages and pile inclinations. Table II shows the vertical and lateral displacements of the pile cap and frame for each of the models when subjected to only axial loads as well as combined axial and lateral loads applied at the base of the soil.

Comparison of vertical displacements of pile cap and frame

Fig. 6 and Fig. 7 show vertical displacements of pile cap for each of the inclined pile (IP) groups in comparison with the vertical pile group on being subjected to axial loads and combined axial and lateral loads respectively. Considerable positive impact in the reduction of vertical displacement of pile cap can be seen. It was observed that pile groups with 75% of piles being inclined (75% IP) have shown lesser vertical displacements for any pile inclinations as compared to the other percentages of pile groups considered in this study for the axial load. The maximum reduction in vertical displacement was 23.22% at an inclination angle of 25^0 w.r.t vertical axis. For the combined axial and lateral loads, it was observed that pile group with 25% of piles being inclined (25% IP) has shown the least vertical displacements for any pile inclinations as compared to the other percentages of pile groups considered in this study. The maximum reduction in vertical displacement was 24.45% at an inclination angle of 25^0 w.r.t vertical axis.

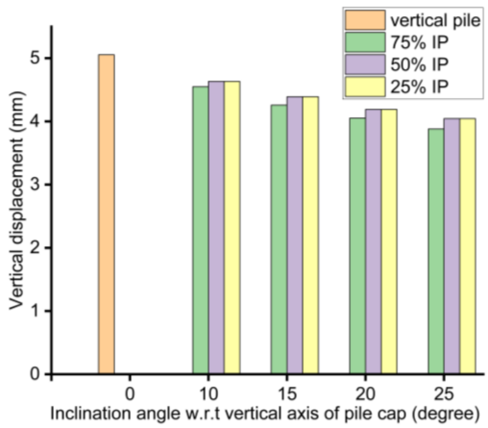


Fig. 6 Vertical displacement of pile cap subjected to axial load.

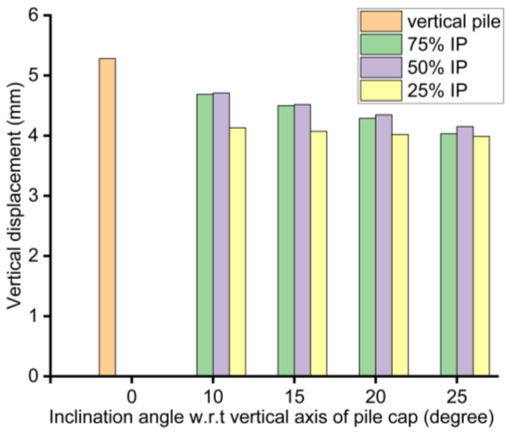


Fig. 7 Vertical displacement of pile cap subjected to combined axial and lateral loads.

Fig. 8 and Fig. 9 show vertical displacements of the frame for each of the inclined pile (IP) groups in comparison with the vertical pile group on being subjected to axial and combined axial and lateral loads respectively. Considerably minimal positive impact in the reduction of vertical displacement of frame can be seen. For both axial and combined axial and lateral loads, it was observed that pile groups with any percentage of piles being inclined have shown minimal variations in vertical displacements for any pile inclination considered in this study. The pile group with 75% IP inclined at 25^0 has shown maximum reduction in vertical displacement of 4.93% for axial load. The pile group with 50% IP inclined at 25^0 has shown maximum reduction of 8.45% when subjected to the combination of axial and lateral loads followed by 8.16% reduction for the pile group with 25% IP inclined at 25^0.

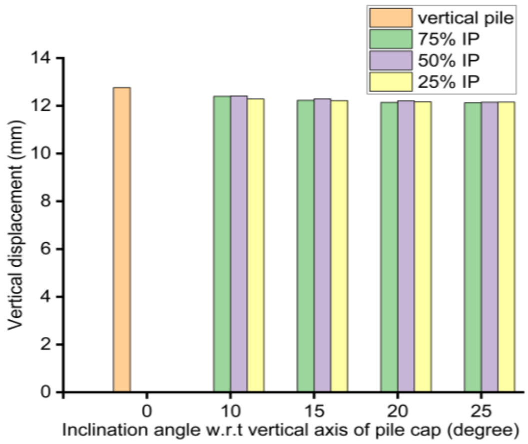


Fig. 8 Vertical displacement of frame subjected to axial load.

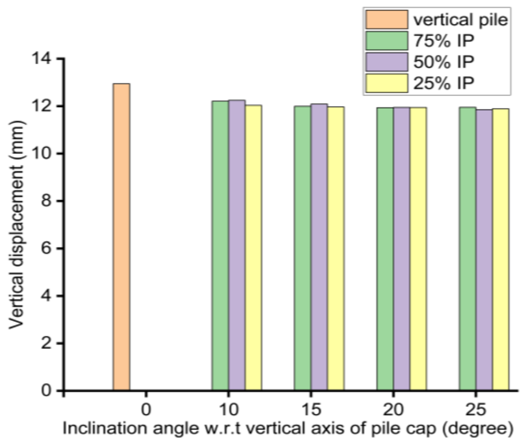


Fig. 9 Vertical displacement of frame subjected to combined axial and lateral loads.

Analysis of the SSI model for axial and horizontally applied lateral loads reveal that for any inclination angle of piles considered in the study, the adoption of inclined piles reduced the vertical displacement of pile cap and frame as compared to vertical pile groups. Also, for any pile group considered, the vertical displacement was observed to reduce with the increase in the pile inclination angle w.r.t vertical axis. The effect of percentage of inclined piles in a pile group in resisting vertical displacement varied for the load cases considered. Considering the percentage reduction in vertical displacement of both pile cap and frame, the pile group with 75% IP inclined at 25^0 for axial loading conditions and the pile group with 25% IP inclined at 25^0 for the combination of axial and horizontally applied lateral loading conditions are better options as compared to vertical pile groups.

Comparison of lateral displacements of pile cap and frame

Fig. 10 shows lateral displacements of pile cap for each of the inclined pile groups in comparison with the vertical pile group on being subjected to combined axial load and lateral loads. It was observed that the pile group with 50% IP inclined at 25^0 has shown a reduction in lateral displacement of 4.86%. It can also be observed that as the inclination of the pile increases, the lateral displacement of the pile cap decreases.

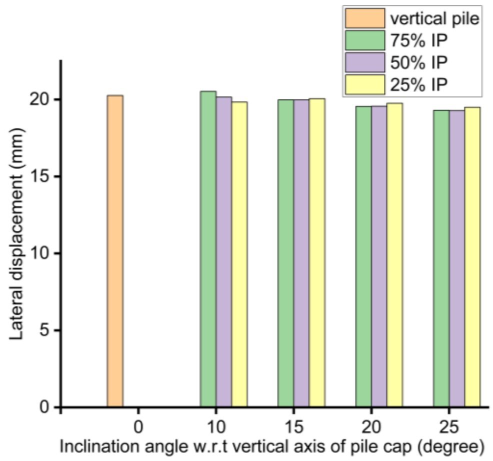


Fig. 10 Lateral displacement of pile cap subjected to combined axial and lateral loads.

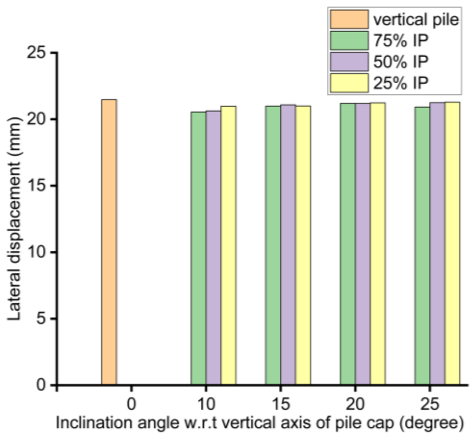


Fig. 11 Lateral displacement of frame subjected to combined axial and lateral loads.

Fig. 11 shows lateral displacements of the frame for each of the inclined pile groups in comparison with the vertical pile group on being subjected to combined axial and lateral loads. It was observed that the pile group with 75% IP inclined at 10^0 has shown maximum reduction in lateral displacement of 4.33%. Considerably minimal positive impact in the reduction of lateral displacement of frame was observed.

Fig. 12 and Fig. 13 show lateral displacements of pile cap and frame for each of the inclined pile groups respectively in comparison with the vertical pile group on being subjected to axial load. It was observed that the pile group with 50% IP inclined at 20^0 has shown a reduction in pile cap lateral displacement of 97.67% and the pile group with 75% IP inclined at 20^0 has shown maximum reduction in frame lateral displacement of 94.87%. It is evident that as the inclination of the pile increases, the lateral displacement of the pile cap decreases. Additionally, as inclination increases, the variations in the lateral displacement was based on the percentage of IP, with 25% IP experiencing the highest displacement among the inclined cases.

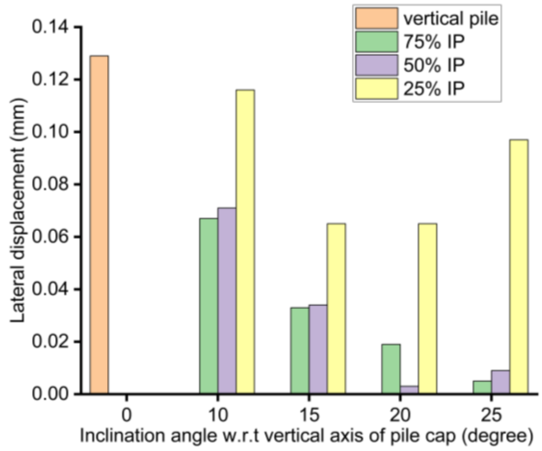


Fig. 12 Lateral displacement of pile cap subjected to axial loads.

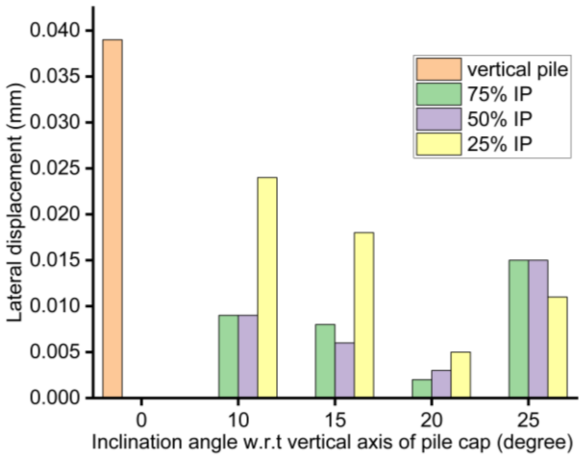


Fig. 13 Lateral displacement of frame subjected to axial loads.

Lateral displacement values of both pile cap and frame were considerably less as compared to vertical displacements for axial loads even though percentage reductions are considerable for various pile groups and inclination angles considered. So, these variations are not considered in evaluating the efficacy of pile groups and pile inclinations in the study in resisting displacements. Considering the percentage reduction in lateral displacement of both the pile cap and frame under combined axial and horizontally applied lateral loads, none of the inclined pile group combinations at different inclination angles proved to be significantly superior. All pile arrangements exhibited a reduction in lateral displacements of the pile cap and frame of less than approximately 5%.

B. Analyses of the SSI model for axial and diagonally applied lateral loads

The structural models with different pile groups and angles of inclinations were analyzed for axial and combination of axial (self-weight + live load) and lateral loads (EL Centro - time history data). Lateral loads are applied diagonally at the base of the soil. Table III shows the vertical and lateral displacements of pile cap and frame for each of the models.

Comparison of vertical displacements of pile cap and frame

Fig. 14 and Fig. 15 show vertical displacements of pile cap for each of the inclined pile groups (IP) in comparison with the vertical pile group on being subjected to axial loads and combined axial and diagonally applied lateral loads respectively.

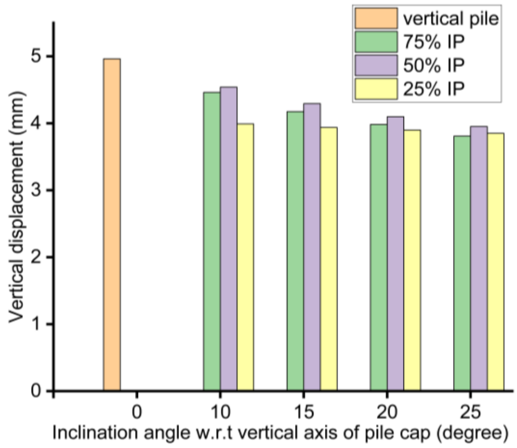


Fig. 14 Vertical displacement of pile cap subjected to axial load.

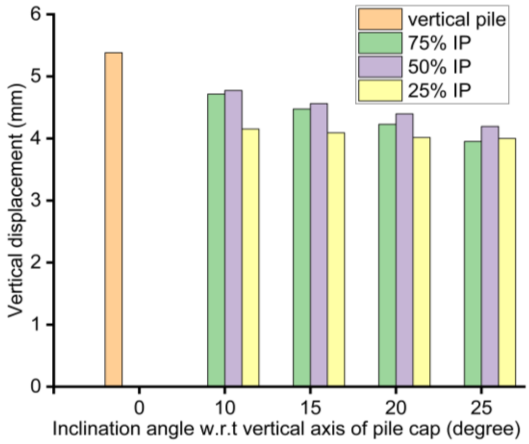


Fig. 15 Vertical displacement of pile cap subjected to combined axial and diagonally applied lateral loads.

Considerable positive impact in the reduction of vertical displacement of pile cap can be seen similar to that of horizontal lateral loading condition.

For pile cap subjected to axial load and combined axial and lateral loads, it was observed that pile groups with 25% of piles being inclined (25% IP) has shown almost lesser vertical displacements for any pile inclination as compared to the other percentage of pile groups considered in this study. For pile cap subjected to axial loading, the maximum reduction in vertical displacement observed was 23.23% for the pile group with 75% IP inclined at 25^0 w.r.t vertical axis followed by 22.39% for the pile group with 25%IP inclined at 25^0 w.r.t vertical axis. For pile cap subjected to combined axial and lateral loading, the maximum reduction in vertical displacement observed was 26.57% for the pile group with 75% IP inclined at 25^0 w.r.t vertical axis followed by 23.82% for the pile group with 25%IP inclined at 25^0 w.r.t vertical axis.

Fig. 16 and Fig. 17 show vertical displacements of the frame for each of the inclined pile (IP) groups in comparison with the vertical pile group on being subjected to axial load and combined axial and lateral loads respectively. Considerably minimal positive impact in the reduction of vertical displacement of frame was seen. For both axial and combined axial and lateral loads, it was observed that pile groups with any percentage of piles being inclined have shown minimal variations in vertical displacements for any pile inclination considered in this study.

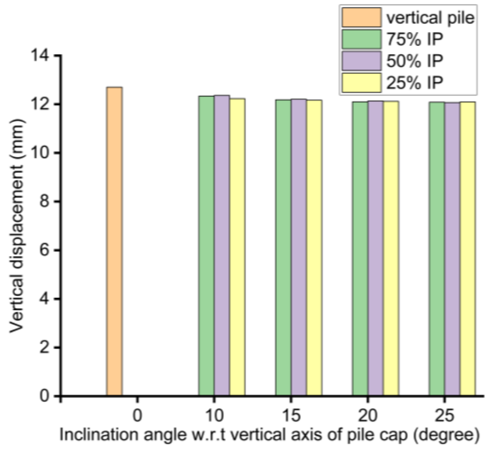


Fig. 16 Vertical displacement of frame subjected to axial load.

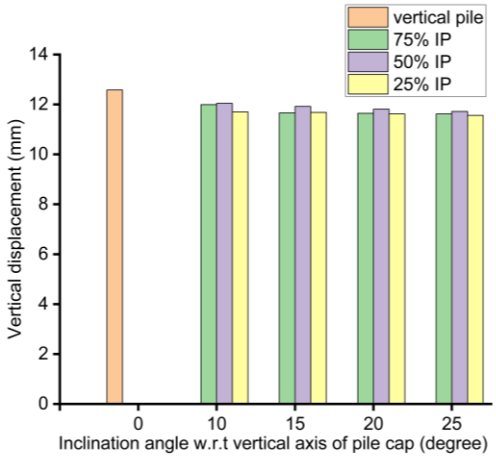


Fig. 17 Vertical displacement of frame subjected to combined axial and diagonally applied lateral loads.

For frame subjected to axial loading, the maximum reduction in vertical displacement observed was 4.98% for the pile group with 50% IP inclined at 25^0 w.r.t vertical axis followed by 4.84% for the pile group with 75%IP inclined at 25^0 w.r.t vertical axis. For frame subjected to combined axial and lateral loading, the maximum reduction in vertical displacement observed was 8.07% for the pile group with 25% IP inclined at 250 w.r.t vertical axis followed by 7.62% for the pile group with 75%IP inclined at 25^0 w.r.t vertical axis.

Similar to that of horizontal lateral loading condition, for any pile group considered, the vertical displacement was observed to reduce with the increase in the pile inclination angle w.r.t vertical axis. Also, adoption of inclined piles reduced vertical displacement of pile cap to the considerable extent and frame to the minimal extent in most of the cases considered in the study. Considering the percentage reduction in vertical displacement of both pile cap and frame, the pile group with 75% IP inclined at 25^0 for axial loading conditions and the pile group with 25% IP inclined at 25^0 for the combination of axial and diagonally applied lateral loading conditions are better options as compared to vertical pile groups.

Comparison of lateral displacements of pile cap and frame.

Fig. 18 shows lateral displacements of the pile cap for each of the inclined pile groups in comparison with the vertical pile group on being subjected to combined axial load and lateral loads. It was observed that the pile group with 50% IP inclined at 25^0 has shown a reduction in lateral displacement of 5.49%. It can also be observed that as the inclination of the pile increases, the lateral displacement of the pile cap decreases.

Fig. 19 shows lateral displacements of the frame for each of the inclined pile groups in comparison with the vertical pile group on being subjected to combined axial and lateral loads. It was observed that the pile group with 75% IP inclined at 10^0 has shown maximum reduction in lateral displacement of 2.11%.

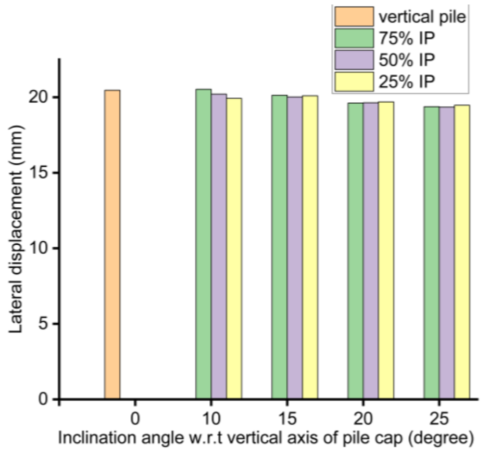


Fig. 18 Lateral displacement of pile cap subjected to combined axial and diagonally applied lateral loads.

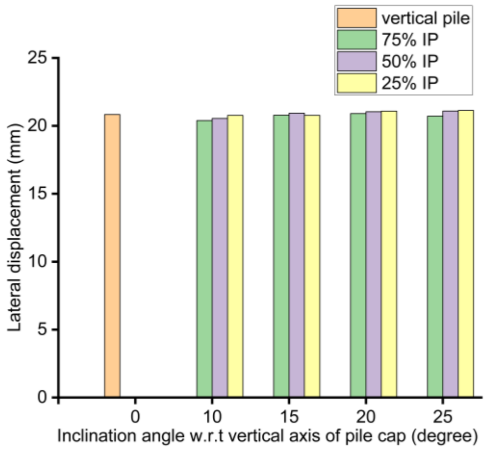


Fig. 19 Lateral displacement of frame subjected to combined axial and diagonally applied lateral loads.

Fig. 20 and 21 show lateral displacements of the pile cap and frame for each of the inclined pile groups respectively in comparison with the vertical pile group on being subjected to axial load. It was observed that the pile group with 75% IP inclined at 20^0 has shown a reduction in pile cap lateral displacement of 88.57% and 75% IP inclined at 20^0 has shown maximum reduction in frame lateral displacement of 63.63%. It was observed that as the inclination of the pile increases, the lateral displacement of the pile cap decreases.

Considering the percentage reduction in lateral displacement of both the pile cap and frame under combined axial and diagonally applied lateral loads, no single arrangement of inclined pile group combinations at different inclination angles emerged as a significantly better performer. All pile arrangements demonstrated a similar reduction in lateral displacements of the pile cap and frame, ranging from approximately 2% to 5%.

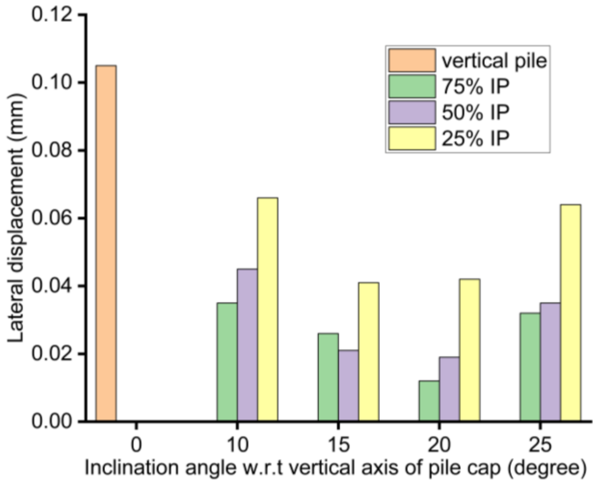


Fig. 20 Lateral displacement of pile cap subjected to axial loads.

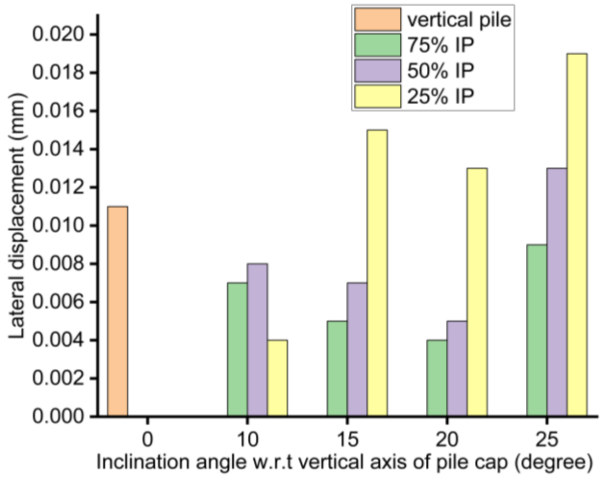


Fig. 21 Lateral displacement of frame subjected to axial loads.

C. Effectiveness of soil-pile interaction on inclined pile groups subjected to combined axial and lateral loads

Providing inclination for piles helped in minimizing vertical displacement to considerable extent as compared to lateral displacement and hence effectiveness of soil-pile interaction is analyzed for vertical displacement only. Analyzing the effectiveness of inclined pile groups for combined axial and lateral loads is more critical from the perspective of practical applications.

The percentage reduction in vertical displacements of pile cap and frame subjected to combined axial and lateral loads (both horizontally and diagonally applied lateral loads) for the pile group with 25% IP, 50% IP and 75% IP are shown in Fig. 22, Fig. 23 and Fig. 24 respectively. From these plots it can be observed that with the increase in inclination of piles from 0^0 to 25^0, vertical displacements of pile cap and frame reduced.

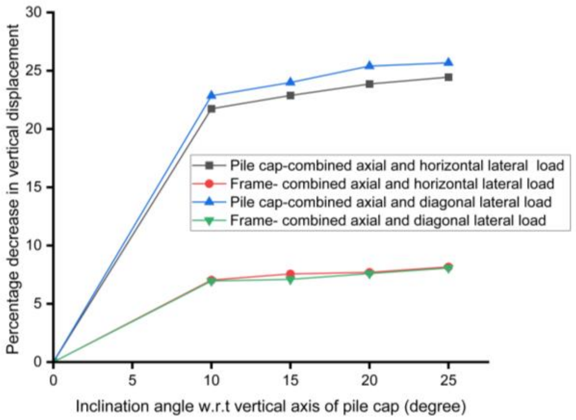


Fig. 22 Percentage decrease in vertical displacement of pile cap and frame subjected to combined axial and lateral loads for the pile group with 25% IP.

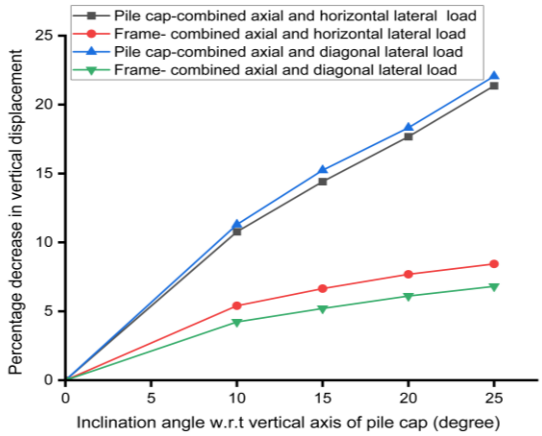


Fig. 23 Percentage decrease in vertical displacement of pile cap and frame subjected to combined axial and lateral loads for the pile group with 50% IP.

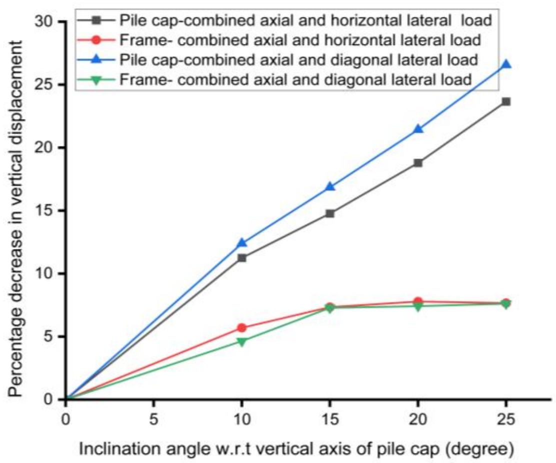


Fig. 24 Percentage decrease in vertical displacement of pile cap and frame subjected to combined axial and lateral loads for the pile group with 75% IP

The maximum reduction in vertical displacements can be observed for piles with 25^0 inclinations for all pile groups considered. Also, the pile group with 25% IP and 75% IP can be observed to reduce vertical displacement of pile cap to the maximum extent of around 25% as compared to around 22% in case of the pile group with 50% IP.

Similarly, Maximum reduction of around 8% in frame displacement was observed for the pile group with 25% IP and 50% IP. Compared to the inclinations provided for the pile groups with 50% IP and 75% IP in controlling vertical displacements, the inclinations provided for the pile group with 25% IP were observed to be more effective since the considerable percentage reduction in vertical displacement can be observed to be initiated from the inclination angle of 10^0 for a high-rise RCC building model with different pile group combinations considered in the study. This implies that effectiveness of pile inclination is more pronounced for the pile group with 25% IP than other combinations considered in the study. Since the percentage reduction in vertical displacement for frame is considerably less than pile cap, which is hardly around 8%, suitable base isolation techniques can be adopted to improve the effectiveness of pile inclinations and pile group arrangements.

IV. CONCLUSIONS

A high-rise RCC building model with three distinct percentages of pile group combinations (75%, 50% and 25% inclined) and four different angles of inclination (10^0, 15^0, 20^0 and 25^0) has been considered for the study. A structural model is formed over a homogeneous soil profile and has been subjected to a combination of axial and lateral loads. The lateral load has been applied horizontally and diagonally. Vertical and lateral displacements of pile cap and frame have been studied. Based on the analysis results obtained, the following conclusions are drawn:

1) By providing inclination to the piles, vertical and lateral displacements can be reduced. For any pile group considered, the displacement was observed to be reduced with the increase in the pile inclination angle w.r.t vertical axis. The reduction is considerable for vertical displacements as compared to lateral displacements. Also, adoption of inclined piles reduced vertical displacement of pile cap to the considerable extent and frame to the minimal extent in most of the cases considered in the study.
2) Considering the percentage reduction in vertical displacement of both pile cap and frame, the pile group with 75% IP inclined at 25^0 for axial loading conditions and the pile group with 25% IP inclined at 25^0 for the combination of axial and horizontally/diagonally applied lateral loading conditions are better options as compared to vertical pile groups.
3) Considering the percentage reduction in lateral displacement of both pile cap and frame subjected to the combination of axial and horizontally applied lateral loading conditions, inclined pile group combinations at different inclination angles considered have shown lesser than 5% reduction in lateral displacements of pile cap and frame.
4) Inclined pile group combinations at different inclination angles considered were observed not to give any single arrangement as a better performer in resisting lateral displacements when subjected to the combination of axial and horizontally/diagonally applied lateral loads and all pile arrangements have shown around 2-5% reduction in lateral displacements of pile cap and frame.
5) Compared to the inclinations provided for the pile groups with 50% IP and 75% IP in controlling vertical displacements, the inclinations provided for the pile group with 25% IP were observed to be more effective since the considerable percentage reduction in vertical

displacement was observed from 10^0 which implies that effectiveness of pile inclination is more pronounced for the pile group with 25% IP than any other combinations considered in the study.

TABLE II
PILE CAP AND FRAME DISPLACEMENTS FOR AXIAL AND COMBINED (AXIAL + LATERAL) LOADS

Pile Group arrangement	Inclination angle w.r.t vertical axis of pile cap	Pile Cap Displacement				Frame Displacement			
		Axial load		(Axial + Lateral) loads		Axial load		(Axial + Lateral) loads	
		lateral (mm)	vertical (mm)	lateral (mm)	vertical (mm)	lateral (mm)	vertical (mm)	lateral (mm)	vertical (mm)
75% of piles inclined	0^0	0.129	5.055	20.262	5.280	0.039	12.759	21.479	12.947
	10^0	0.067	4.549	20.527	4.686	0.009	12.396	20.547	12.210
	15^0	0.033	4.258	19.979	4.500	0.008	12.232	20.991	11.996
	20^0	0.019	4.054	19.557	4.288	0.002	12.145	21.199	11.939
	25^0	0.005	3.881	19.302	4.031	0.015	12.130	20.919	11.954
50% of piles inclined	10^0	0.071	4.633	20.156	4.711	0.009	12.413	20.632	12.247
	15^0	0.034	4.391	19.976	4.519	0.006	12.290	21.084	12.086
	20^0	0.003	4.191	19.564	4.347	0.003	12.205	21.186	11.951
	25^0	0.009	4.045	19.278	4.152	0.015	12.151	21.243	11.854
25% of piles inclined	10^0	0.116	4.071	19.834	4.132	0.024	12.284	20.987	12.036
	15^0	0.065	4.007	20.055	4.072	0.018	12.217	20.995	11.968
	20^0	0.065	3.954	19.757	4.020	0.005	12.170	21.231	11.945
	25^0	0.097	3.922	19.495	3.989	0.011	12.156	21.288	11.890

TABLE III
PILE CAP AND FRAME DISPLACEMENTS FOR AXIAL AND COMBINED (AXIAL + DIAGONALLY APPLIED LATERAL) LOADS

Pile Group arrangement	Inclination angle w.r.t vertical axis of pile cap	Pile Cap Displacement				Frame Displacement			
		Axial load		(Axial + Lateral) loads		Axial load		(Axial + Lateral) loads	
		lateral (mm)	vertical (mm)	lateral (mm)	vertical (mm)	lateral (mm)	vertical (mm)	lateral (mm)	vertical (mm)
75% of piles inclined	0^0	0.105	4.963	20.465	5.382	0.011	12.700	20.833	12.578
	10^0	0.035	4.462	20.530	4.715	0.007	12.338	20.393	11.994
	15^0	0.026	4.175	20.134	4.475	0.005	12.183	20.783	11.662
	20^0	0.012	3.983	19.616	4.229	0.004	12.101	20.908	11.645
	25^0	0.032	3.810	19.374	3.952	0.009	12.085	20.718	11.620
50% of piles inclined	10^0	0.045	4.541	20.212	4.774	0.008	12.359	20.543	12.046
	15^0	0.021	4.295	20.016	4.562	0.007	12.208	20.935	11.923
	20^0	0.019	4.099	19.636	4.396	0.005	12.135	21.043	11.809
	25^0	0.035	3.953	19.341	4.195	0.013	12.068	21.090	11.721
25% of piles inclined	10^0	0.066	3.991	19.920	4.152	0.004	12.229	20.775	11.702
	15^0	0.041	3.938	20.094	4.091	0.015	12.165	20.772	11.681
	20^0	0.042	3.899	19.695	4.015	0.013	12.119	21.086	11.622
	25^0	0.064	3.852	19.474	4.000	0.019	12.097	21.134	11.563

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