DYNAMIC ANALYSIS OF LATERALLY LOADED PILES IN GROUP

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Abstract - *In this study, the construction of multi-storey buildings is rapidly increasing worldwide, necessitating robust foundation solutions such as pile foundations. These foundations are crucial for transferring vertical (axial) forces in structures like tall buildings, bridges, offshore platforms, defense structures, dams, and wharfs. However, piles also often bear lateral (horizontal) forces and moments. A recent study using STAAD Pro software analyzed the behavior of piles in groups subjected to dynamic loads, such as those from earthquakes. The analysis focused on responses like deflection, axial force, shear force, and bending moment. It was found that deflection initially increases with pile length and then decreases, with higher deflection observed in closely spaced piles. Axial force consistently increases with pile length, while bending moment and shear force decrease as pile length increases, with maximum values observed in closely spaced piles. This study highlights the importance of considering both vertical and horizontal forces in the design and analysis of pile foundations for multi-storey buildings.*

Key Words: Dynamic Analysis, Laterally Loaded Piles, Earthquake Loads, Axial Force, Structural Stability, Multi-Storey Building Foundations.

1. INTRODUCTION

A pile is a deep foundation element constructed or inserted into the ground to transfer loads from a structure to deeper, more stable soil layers. Made from materials such as concrete, timber, or steel, piles are essential for supporting structures where the surface soil lacks sufficient bearing capacity. They are commonly used for tall buildings, bridges, offshore platforms, defence structures, dams, earth-retaining structures, wharfs, and jetties. Piles carry both vertical (axial) loads and lateral (horizontal) forces and moments. They are particularly useful in conditions with heavy, unevenly distributed loads, or in areas near riverbeds where scouring and high subsoil water levels make shallow foundations impractical. Piles can be classified by their material and installation method (e.g., driven, cast-in-place) and by their function (e.g., end-bearing, friction, compaction). Laterally loaded piles behave like transversely loaded beams, using the lateral resistance of the surrounding soil to transfer loads. Designing these foundations involves managing displacement and bending moments, which depend on soil and pile properties. The design is challenging due to the unpredictable nature of subsoil profiles and varying architectural load requirements. When subjected to lateral loads, piles may bend, rotate, or translate, pressing against the soil and generating compressive and shear stresses that resist movement.

1.1 Aim & Objective

To find most suitable design combination for laterally loaded piles

After exclusive study of literature review carried by various researcher, on dynamic analysis lateral pile group.

1] Analyze the various group of piles with varying spacing.

2] Analyze the consider group of piles for different soil condition

3] Identify effect of lateral load on piles and it consideration for design of piles

4] Developed variation of various geometrical parameters of pile for above mentioned.

2. Literature Review

Current literature survey focuses on the analysis of piles, which are designed to transfer moments, shear forces, and axial loads from the structure above to the soil below. Research has provided insights into the behavior of pile group's subjected to dynamic loads, such as those caused by earthquakes. This includes examining the effects of pile spacing within a group and conducting comparative studies of axial forces, shear forces, bending moments, and stresses under various conditions. These studies aim to enhance the understanding of pile performance under seismic loads, informing better design and construction practices for pile foundations in earthquake-prone areas. Research papers and journal papers were reviewed among which some of the concern related papers are there central idea for their research are presented below.

Contributions of researchers are presented as follows,

M. khari, danieal jahed armaghanai [1] lateral deflection on small scale piles using hybrid method. The authors has published Piles, as a type of geotechnical structures, was widely utilized to resist different lateral loads sources such as inclined loads and earthquakes. Therefore, the behavior of such structures under lateral loads needs to be investigated. Accordingly, this study examines the piles' lateral deflection (LD) under various conditions. The proposed PSO–ANN model was found capable of providing a high accuracy level and, at the same time, a low system error in the LD prediction process. The RMSE values of 0.072 and 0.085 were determined, respectively, for training and testing datasets of the developed PSO–ANN model, while these values were 0.121 and 0.103 for the same datasets of the ANN predictive technique, respectively. It can be concluded that the PSO–ANN model can be relied on as a new hybrid model in field of this study, and also it can be used in other related studies with caution.

Km Panchal [2] author was published paper on dynamic analysis and comparatively study of 3 piles and 4 piles paper studied the behavior of the piles in group arranged in series subjected to dynamic load due to earthquake. Various combinations of group piles in series like 2 piles, 3 piles and 4 piles are considered for various spacing 2D, 3D, 4D, 5D and 6D, where D is the diameter of the pile. The pile foundation is assumed to be enclosed within cohesion-less soil and soil properties are considered from a live soil report and similarly the load applied is also considered from the same live project report. The models are analyzed in the finite element method based software naming STAAD Pro to obtain the responses such as deflection, axial force, shear force and bending moment for piles in group. Furthermore, during the construction stages, the concrete strength also increasing from its initial value fci to its full value fc'. In that paper a simple and straight forward method will be used to solve this problem and used a stadd pro software to obtain a responses such as, deflection ,displacement, axial force, compression and tensile force.

M. khali [3] author have studied on dynamic behavior of pile foundations under vertical load and lateral vibrations. Pile foundations supporting machines, buildings under seismic effect, and wind turbines are subjected to dynamic loads. Under such conditions, there is a necessity to evaluate the dynamic behavior of piles. Therefore, a 3D numerical modeling technique is needed to consider the complicated dynamic interaction between the piles and soil (pile-soil interaction) and between adjacent piles in the same group (pile-soil-pile interaction). To validate the results of 3D numerical simulation of piles, the results obtained from the numerical model has been compared to the mea segments of selected case study.

Stefano stacual and nunziante squeglia [4] author reviews on analysis method for laterally loaded pile groups using an advanced modeling of reinforced concrete sections. A Boundary Element Method (BEM) approach was developed for the analysis of pile groups. The proposed method includes the non-linear behavior of the soil by a hyperbolic modulus reduction curve; the non-linear response of reinforced concrete pile sections, also taking into account the influence of tension stiffening; the influence of suction by increasing the stiffness of shallow depth portions of a soil and modeled using the Modified Kovacs model pile groups have doing effect, modeled using an approach similar to that proposed in the Strain Wedge Model for pile groups analyses. The reliability of this method was verified by comparing results from data from full scale and centrifuge tests on single piles and pile groups. A comparison is presented between measured and computed data on a laterally loaded fixed-head pile group composed by reinforced concrete bored piles.

B.n.huyen, etal. [5] Author was published on paper evaluation of dynamic p-y curves of group piles using centrifuge model. Dynamic soil-pile interaction is the main concern in the design of group piles under earthquake loadings. The lateral resistance of the pile group under dynamic loading becomes different from that of a single pile due to the group pile effect. However, this aspect has not yet been properly studied for the pile group under seismic loading condition. Thus, in this study the group pile effect was evaluated by performing a series of dynamic centrifuge tests on 3×3 group pile in dry loose sand. The multiplier coefficients for ultimate lateral resistance and subgrade reaction modulus were suggested to obtain the p-y curve of the group pile. The suggested coefficients were verified by performing the nonlinear dynamic analyses, which adopted Beam on Nonlinear Winkler Foundation model. The predicted behavior of the pile group showed the reasonable agreement compared with the results of the centrifuge tests under sinusoidal wave and artificial wave. The lateral resistance of the pile group under dynamic loading becomes different from that one pile due to the group pile effect.

S.kim,kah etal [6]author was published paper on “dynamic behavior of group piles according to pile cap embedded in sandy ground” Dynamic interaction of the ground-foundation-structure must be considered for safety of earthquake resistant design for piles supported structures. The p-y curve, which is proposed in the static load and cyclic load cases, is used for the earthquake resistant design of piles. The p-y curve does not consider dynamic interaction of the ground-foundation-structure on dynamic load cases such as earthquake. Therefore, it is difficult to apply the p-y curve to earthquake resistant design. The dynamic structure has been studied, and researches had same conditions that pile caps were on the ground surface and superstructures were added on pile caps for the simple weight. However, group piles are normally embedded into the ground except for marine structures, so it seems that the embedding the pile cap influences on the dynamic p-y curve of group piles. In this study, the shaking table model test was conducted to confirm dynamic behavior of group piles by the embedded pile cap in the ground. The result showed that dynamic behavior was different between two cases by embedding the pile cap or not.

Sweeta moahanty etal [7] author has published paper on parametric study of laterally loaded piles This research investigated the effect of the pile rigidity (pile- length, diameter), pile spacing under the pile cap, the corresponding variations of the bending moment, shear forces, deflection, skin friction and the soil behavior surrounding the pile. The finite element analysis is carried out to analyze the behaviors of pile foundation system subjected to lateral .The behavior of pile foundation for lateral loading was analyzed with consideration of influence factors. Influence factors considered were pile diameter, pile length and soil behavior. It has been observed that the increasing pile length induces higher bending moment in pile but, simultaneously control other effect such as shear force and settlement. Based upon the results of analysis, the effect of various influence factors on foundation behavior is determined.

Junaid maste, p. j. salunke, n. g.[8] author has published paper on dynamic analysis of laterally loaded piles analysis of group of piles in cohesion less soil with the diameter vary and spacing between the piles varied from 2D to 3D by means of the FB-multiplier software. Hence by developed a finite element model soil structure interaction study was carried out considering nonlinear soil behavior in time domain analysis with the help of Newmark's beta method. There were various methods available to carry out the analysis of laterally loaded piles like finite difference, elastic continuum approach, subgrade reaction & finite element etc. Amongst all these nowadays the most realistic and accurate method is finite element method. Hence finite element method was adopted for the work; while dealing with very high excitation like wind gusters, one must have to take into consideration the effect of non-linearity. In order to consider soil non-linear behavior, the springs can have a varying stiffness given through a non-linear load-deflection relationship that depends on the type of soil and type of pile therefore nonlinear curves were used called p-y curves, where p is pressure and y is corresponding deflection. Design engineers often prefer to use the Beam-on-Dynamic Winkler-Foundation (BDWF) model for design purposes rather than the Finite difference method or elastic continuum solutions. These curves represent the nonlinear soil behavior by a series of nonlinear springs. The entire analysis was carried out in FB multiplier software.

V. Sawant, Hemant chore, Ramakant ingale [9] author was studied on the problem of laterally loaded piles was particularly a complex soil-structure interaction problem. The flexural stresses developed due to the combined action of axial load and bending moment must be evaluated in a realistic and rational manner for safe and economical design of pile foundation. The paper reports the finite element analysis of pile groups. For this purpose simplified models along the lines similar to that suggested by Desai used for idealizing various elements of the foundation system. The pile were idealized one dimensional beam element, pile cap as two dimensional plate element and the soil as independent closely spaced linearly elastic springs. The analysis takes into consideration the effect of interaction between pile cap and soil underlying it. The pile group was considered to have been embedded in cohesive soil. The parametric study was carried out to examine the effect of pile spacing, pile diameter, number of piles and arrangement of pile on the responses of pile group. The responses considered include the displacement at top of pile group and bending moment in piles. The results obtained using the simplified approach of the F.E. analysis are further compared with the results of the complete 3-D F.E. analysis published earlier and fair agreement were observed in the either result.

3. THEROTICAL formulation

Many buildings and structures require deep foundations to leverage the bearing capacity of stronger soil layers. Pile groups, a common type of deep foundation used for large structures, must support not only vertical loads but also significant lateral loads from sources like wind, collisions, wave or ice impact, earthquakes, liquefaction, and slope failure. Understanding the nonlinear response of pile groups is crucial for designing civil engineering structures such as bridges, high-rise buildings, and towers. Analytical and numerical methods for analyzing pile groups consider varying spacing and interactions between the pile-cap, piles, and the soil medium. The present study focuses on the response of pile groups subjected to lateral loads in soft and medium soil categories, examining the effects of varying pile spacing and diameter on their lateral load-carrying capacity. The interaction between pile groups and soil configuration is also analyzed to provide comprehensive insights into their behavior under lateral loading conditions.

3.1 Effect of soil condition

Soil-structure interaction plays a crucial role in the dynamic response of structures, influencing both the behavior of the soil and the response of piles under loading. Accurate analysis of this interaction is essential for predicting structural behavior and ensuring the safety of structures under extreme loading conditions. For laterally loaded piles, the load resistance is governed by the soil-pile interaction, which depends on factors such as soil properties, pile diameter, pile loading, pile material, and ground slope. Pile foundations are designed to transfer loads from structures to the soil. In axially loaded piles, this load transfer occurs through side friction at the soil-pile interface and base resistance from the soil bed. Pile foundations often face significant lateral forces in addition to vertical loads, making a comprehensive understanding of soil-structure interaction vital for their effective design and performance under various loading conditions.

3.2 Elements on piles

Main Elements

- Column
- Pile
- pile cap

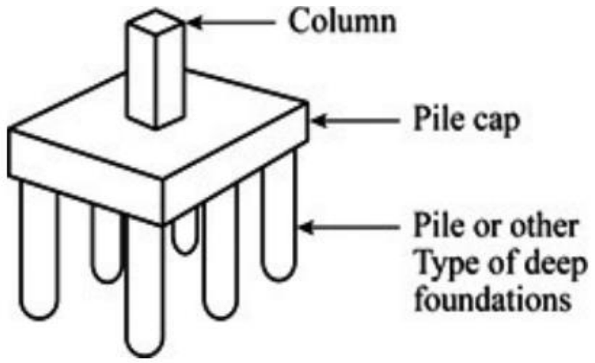


Fig 3.1 Elements on pile foundation

4. PROBLEM FORMULATION

The response of every structural model can be determined using advanced software tools, which offer high proficiency in integrated analysis approaches. These tools are essential for evaluating the combined effects of vertical and lateral loadings on structures. In particular, the behavioral variations of pile groups are examined by considering different soil types. This approach allows for a comprehensive understanding of how piles respond to various loading conditions and soil characteristics, ensuring more accurate predictions and safer structural designs.

4.1 Pile group and their responses to the loadings

Factored loads from the superstructure are noted, and vertical and lateral loads are estimated using the Response Spectrum Method (RSM). This method dynamically estimates horizontal reactions, which are then applied to the pile cap. Assuming material homogeneity, the cap and piles are subjected to both lateral and vertical loading. The analysis results for lateral deformations, stresses, and axial forces in the piles are tabulated. This study examines these factors under G+15 and G+20 storied structures, observing the response of pile groups in different soil types (soft and medium). Additionally, the effects of varying center-to-center spacing (1.0 m and 1.5 m) and different pile systems (2-pile, 3-pile, and 4-pile) are analyzed to understand how these variations impact pile performance under combined loading conditions.

5. RESULTS

As discussed in methodology, various cases of PEB and CEB for span of 15m, 18m, 20m, 25m with various height variations and different code provisions are analyzed Using the software Staad pro. The design parameters like axial force, shear force and bending moment are computed and comparison for these PEB and CSB has been performed. Also, the comparison of steel take off for both types of structures is done for the optimum design of the warehouse. In this work the stresses, axial forces and lateral deformations in the pile set is observed under G+15 and G+20 storied structure. Further the response of the pile group is noticed by variation in soil type i.e. Soft soil and medium soil. These things further studied by varying center to center spacing as 1.0 m and 1.5 m with 2 Pile, 3Pile and 4 Pile System. Obtained results and their discussions are summarized in this chapter

5.1 Stresses in pile – two pile

Table: 5.1: Compressive and Tensile Stresses in pile for various frames (Pile spacing=1.0m),

Spacing of Piles = 1.0 m

G+15 Storied Structure stresses in pile (N/sq.mm)												
Ordinate	3x3 Frame				4x4 Frame				5x5 Frame			
	Medium Soil		Soft Soil		Medium Soil		Soft Soil		Medium Soil		Soft Soil	
	σc	σt	σc	σt	σc	σt	σc	σt	σc	σt	σc	σt
1	11.94	0.81	12.89	1.85	13.78	0.12	12.1	3.36	14.3	0.16	20.19	0.25
2	12.01	0.92	12.94	1.93	13.86	0.24	12.1	3.3	14.4	0.05	20.24	0.36
3	12.19	1.11	13	2.08	14.01	0.46	12.1	3.22	14.59	0.17	20.41	0.54
4	12.46	1.41	13.2	2.28	14.34	0.78	12.19	3.1	14.89	0.5	20.65	0.8
5	12.83	1.81	13.44	2.54	14.73	1.23	12.33	2.94	15.29	0.95	20.98	1.17
6	13.3	2.32	13.74	2.87	15.25	1.78	12.5	2.74	15.83	1.5	21.41	1.62
7	13.89	2.94	14.11	3.28	15.91	2.43	12.71	2.5	16.48	2.19	21.93	2.18
8	19.33	8.21	19	8.16	21.7	8.25	15.92	0.75	22.39	8.13	28.94	9.21

Table: 5.2: Compressive and Tensile Stresses in pile for various frames (Pile spacing=1.5m)

Spacing of Piles = 1.5 m

G+15 Storied Structurev stresses in pile (N/sq.mm)												
Ordinate	3x3 Frame				4x4 Frame				5x5 Frame			
	Medium Soil		Soft Soil		Medium Soil		Soft Soil		Medium Soil		Soft Soil	
	σc	σt	σc	σt	σc	σt	σc	σt	σc	σt	σc	σt
1	12.92	0.13	13.92	0.87	15.03	1.07	13.69	4.91	15.65	1.43	22.14	1.6
2	12.99	0.1	13.96	0.95	15.1	0.96	13.71	4.85	15.73	1.32	22.22	1.49
3	13.66	0.18	14.07	1.08	15.3	0.73	13.77	4.77	15.93	1.1	22.37	1.31
4	13.44	0.48	14.24	1.28	15.6	0.41	13.87	4.64	16.23	0.77	22.61	1.03
5	13.8	0.88	14.48	1.55	16	0.25	14	4.47	16.64	0.33	22.95	0.67
6	14.28	1.39	14.78	1.88	16.52	0.58	14.17	4.27	17.16	0.25	23.37	0.23
7	14.87	2	15.15	2.28	17.16	1.26	14.39	4.01	17.83	0.93	23.9	0.34
8	18.18	5.34	18.19	5.35	20.77	4.89	16.14	2.24	21.5	4.63	28.1	4.58

Table: 5.3: Compressive and Tensile Stresses in pile for various frames (Pile spacing=1.0m;G+20)

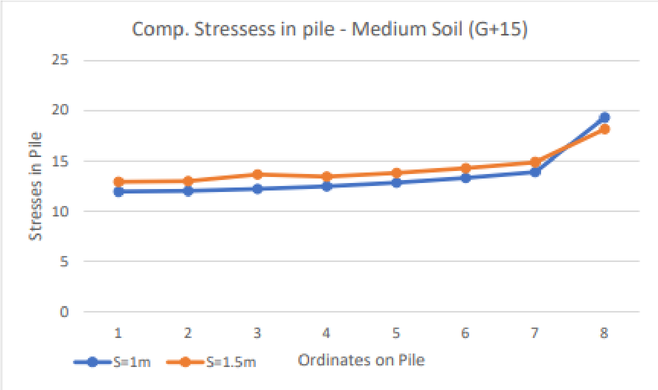
Spacing of Piles = 1.0 m

G+20 Storied Structure stresses in pile (N/sq.mm)												
Ordinate	3x3 Frame				4x4 Frame				5x5 Frame			
	Medium Soil		Soft Soil		Medium Soil		Soft Soil		Medium Soil		Soft Soil	
	σc	σt	σc	σt	σc	σt	σc	σt	σc	σt	σc	σt
1	14.41	1.05	19.19	0.58	15.95	1.57	22.14	1.88	18.43	2.96	23.01	1.63
2	14.5	0.94	19.26	0.68	16	1.44	22.22	1.78	18.52	2.83	23.15	1.53
3	14.67	0.73	19.4	0.85	16.23	1.21	22.37	1.59	18.73	2.59	23.32	1.33
4	14.96	0.42	19.65	1.12	16.54	0.89	22.61	1.32	19	2.23	23.58	1.05
5	15.35	0.4	19.97	1.47	16.96	0.45	22.94	0.96	19.51	1.75	23.93	0.68
6	15.85	0.52	20.38	1.91	17.5	0.13	23.36	0.51	20.1	1.15	24.37	0.2
7	16.46	1.18	20.88	2.44	18.16	0.83	23.88	0.1	20.82	0.39	24.91	0.38
8	22.13	6.88	27.62	9.21	24.3	7	31.01	7.21	27.54	6.36	32.44	7.94

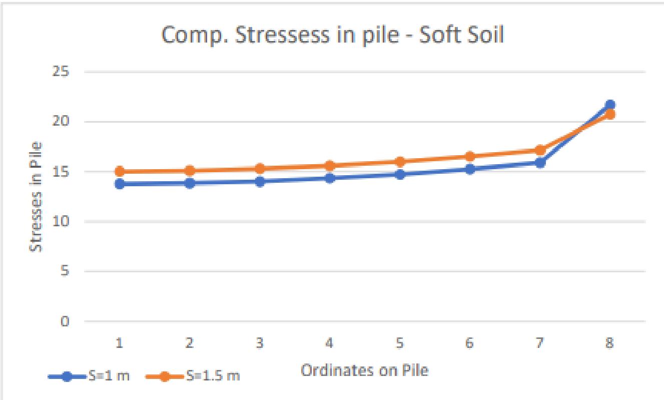
Table: 5.4: Compressive and Tensile Stresses in pile for various frames (Pile spacing=1.5m;G+20)

Spacing of Piles = 1.5 m

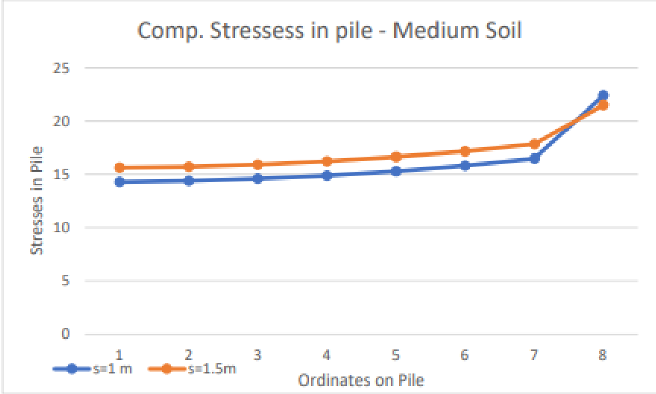
G+20 Storied Structure stresses in pile (N/sq.mm)												
Ordinate	3x3 Frame				4x4 Frame				5x5 Frame			
	Medium Soil		Soft Soil		Medium Soil		Soft Soil		Medium Soil		Soft Soil	
	σc	σt	σc	σt	σc	σt	σc	σt	σc	σt	σc	σt
1	15.89	2.44	21	1.14	17.64	3.15	24.59	4.15	20.55	4.95	25.59	3.97
2	15.98	2.33	21	1.05	17.73	3.04	24.67	4.05	20.65	4.82	25.66	3.87
3	16.16	2.12	21.23	0.87	17.93	2.81	24.82	3.87	20.86	4.58	25.83	3.67
4	16.44	1.8	21.41	0.6	18.23	2.47	25.06	3.6	21.2	4.22	25.08	3.38
5	16.83	1.39	21.78	0.3	18.66	2.02	25.4	3.24	21.65	3.73	26.43	3
6	17.33	0.86	22.2	0.2	19.2	1.45	25.87	2.79	22.23	3.11	26.88	2.53
7	17.96	0.3	22.7	0.74	19.87	0.75	26.33	2.24	22.96	2.36	24.43	1.95
8	21.41	3.29	26.77	4.83	23.59	3	30.5	1.95	26.96	1.66	31.84	2.49



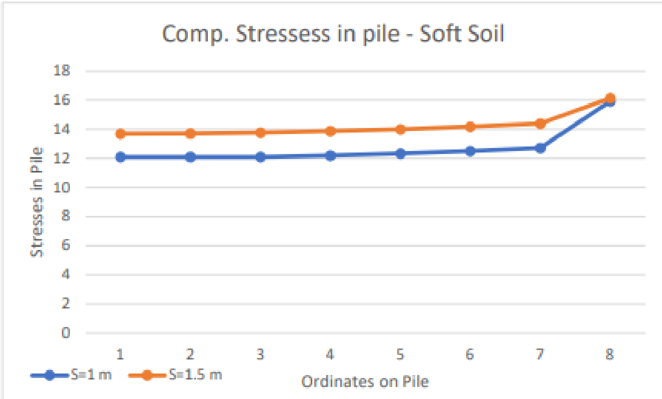
Graph G1: Compressive Stresses in pile for Pile spacing=1.0m;G+15



Graph G2: Compressive Stresses in pile for Pile spacing=1.5m;G+15



Graph G3: Compressive Stresses in pile for various spacing (Pile spacing=1.0m;G+20)



Graph G4: Compressive Stresses in pile for various spacing (Pile spacing=1.5m;G+20)

Observation:

i. From Resultant Graph 1 to 4 the maximum stresses in the pile is observed when pile spaced at 1.5m from center to center.

ii. Same variation is observed in 3x3 frame, 4x4 frame and 5x5 frame.

iii. Stresses in pile for soft soil was 11 to 15% more than medium soil category.

6. CONCLUSIONS

The analysis concludes that pile foundations exhibit higher stresses and lateral deformations in soft soil compared to medium soil. Increasing the number of piles in a group reduces these responses, with more pronounced effects in soft soil. Uniform stress variations were observed in medium soil, unlike the significant variations in soft soil. The joint between the pile and pile cap experiences the highest stresses, necessitating specific stress efficacy checks. Additionally, soil stiffness inversely affects pile responses, underscoring the need for accurate lab evaluations of soil lateral stiffness for proper modeling. For high-rise buildings on medium to soft soil, using at least three piles in a group is recommended to significantly reduce compressive stresses and axial forces.

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