Finite Element Analysis of Soil-Structure Interaction in Piled Framed Structures Under Seismic Loading Conditions

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Abstract:

Framed structures are typically analysed by assuming either rigid or hinged bases. However, when foundations rest on deformable soils, they also undergo deformation, influenced by the relative stiffness of the foundation, superstructure, and soil. Therefore, interactive analysis is essential for accurately evaluating the superstructure's response. A logical approach to designing structures on soil must consider both the soil's deformation characteristics and the structure's flexibility. Analysing such interaction problems involves significant mathematical and computational work, often relying on elasticity, plasticity, or both. This type of analysis, which considers the flexibility of the foundation and soil, is termed "Interaction Analysis." The interaction between the structure, foundation, and soil impacts load distribution across the structural components. Previous interpretations of these interactions have used relative stiffness ratios for different parts of the system, including the superstructure's flexural rigidity, foundation elements, and soil stiffness, as key parameters for understanding the results.

In this study, soil-structure interaction effects on a three-story, three-bay by two-bay space frame on a pile group embedded in soil are examined. A more rational approach is taken using finite element analysis with realistic assumptions. Initially, the frame is analysed independently with fixed column bases, followed by a separate model for the pile foundation using beam, plate, and spring elements for the piles, pile cap, and soil. The foundation stiffness obtained is then used in the interaction analysis to quantify soil-structure interaction effects on the superstructure's response. A parametric study, using the substructure approach (uncoupled analysis), explores how pile configuration, pile diameter, and soil type affect the superstructure's response. ETABS software is employed for the structural analysis. The superstructure's responses, including column moments, beam moments, and axial forces in the columns, are considered. A non-interaction analysis is also performed to assess the differences.

Keywords- Finite Element Analysis, Soil-Structure Interaction, Seismic Loading Conditions

INTRODUCTION

Reinforced cement concrete framed structures are widely used in residential, commercial, and public utility buildings. Typically, these structures are analysed by assuming the base is fixed, preventing any relative movement between columns, which leads to uniform soil pressure distribution. This assumption is then used to estimate foundation settlements, assuming the structure is flexible enough to adjust to soil settlements. However, these assumptions are often contradictory.

Traditional design methods do not account for differential settlement between column footings, despite varying subsurface conditions and loading introducing such settlements, which cause secondary stresses in framed structures. The ratio of secondary forces to member end forces in fully fixed structures is referred to as "Interaction effects." Hence, the soil, foundation, and superstructure form a single interacting system, not independent ones. This study focuses on analysing a structure resting on a pile foundation.

1.2 PILING MATERIALS

Common piling materials include steel, concrete, and timber, which are preferred due to their excellent performance as construction materials.

1. Steel Piles: Steel piles, usually H or pipe piles, offer high compressive and tensile strength with superior load-carrying capacity. They are easy to splice and drive through various soil layers, including soft rocks.
2. Concrete Piles: Concrete, the most traditional construction material, handles significant axial and bending forces when reinforced with steel. Concrete piles come in three types: pre-cast, cast-in-place, and composite piles.
3. Timber Piles: Timber piles are straight tree trunks, stripped of branches, and are used as friction piles in soils like sand and clay. They are easy to handle and durable under typical environmental conditions.

1.3 PILE SECTIONS

Piles come in various cross-sectional shapes, such as H-sections for steel, circular sections for concrete, and polygonal sections for pre-stressed piles.

1.4 SOIL-PILE BEHAVIOR

Analysing and designing piles requires understanding soil-pile interaction. Soil is generally non-homogeneous, with varying properties along the pile's length. Pile behaviour can be categorized as axial load-friction behaviour and lateral load-displacement behaviour. In axial behaviour, skin friction and shear stress vary with depth, while lateral behaviour involves lateral soil pressure when piles face shear or moment loads.

1.5 LOAD-DISPLACEMENT BEHAVIOR

Soil's load-displacement response is typically depicted by three curves: lateral load-displacement (p-y), load-slip (f-z), and load-settlement (q-z). These curves are generally nonlinear. The modulus of sub-grade reaction, commonly used in pile analysis, represents the soil surrounding the pile as a series of springs. The load-displacement curves are often derived from field experiments with instrumented piles, with their accuracy depending on how similar the tested and study piles are in terms of soil conditions and loading.

1.6 FORCES ACTING ON PILES

Pile foundations support structures by transferring loads. Piles, which are prefabricated elements, differ from cast-in-place columns and must be designed to withstand various forces, including:

1. Crushing under design load.
2. Crushing due to impact during driving.
3. Bending stresses from horizontal forces.
4. Bending stresses from pile curvature.

Friction piles also need adequate surface area to effectively transfer loads to the surrounding soil.

1. Axially Loaded Piles: Piles are designed for maximum load-bearing capacity, ensuring the stress remains within allowable limits. Potential failure modes include structural failure, buckling, soil bearing failure, or excessive settlement. Piles may also buckle under service loads, especially end-bearing piles in soft soils or piles partially embedded during driving.
2. Laterally Loaded Piles: Lateral forces on piles may come from wind, live loads, earth pressure, and more. Piles must be designed to handle these forces without failing. Previously, only axial forces were considered in pile design, but modern practices include lateral loads as well. The key design factors are lateral deflection and the pile’s structural capacity, not the ultimate soil capacity.

1.7 CRITERION FOR SAFE AND ECONOMIC DESIGN

Piles must meet specific safety and economic criteria. Pile design involves challenges like load uncertainties and soil variability. The soil's unpredictability and unforeseen loads can cause settlement problems, which are hard for designers to control. Environmental factors also impact pile selection and design. For example, loss of pile section due to environmental effects can reduce load capacity over time, eventually leading to structural failure.

Designing piles involves selecting appropriate types based on the structure and soil conditions. For instance, foundations may require large-diameter drilled shafts or groups of steel piles. The depth to bedrock or bearing soil is critical in determining the foundation type. Key factors in pile design include axial and lateral load considerations, ultimate load capacity, settlement, and safety against soil or pile failure.

LITERATURE REVIEW

2.1 SOIL-STRUCTURE INTERACTION

Typically, structures are analysed with fixed bases under dynamic loading. However, considering the actual flexibility of supports reduces overall stiffness and lengthens the system's period. Unlike concrete and steel, whose properties are fairly predictable, soil's natural variability requires large safety factors. To simplify analysis, soil is assumed to be linearly elastic, with several models frequently used:

1. **Winkler Spring Model**: The simplest and most popular, representing soil as a series of independent, vertical springs reacting proportionally to deflection.
2. **Elastic Half Space Model**: Considers the foundation soil as an elastic, isotropic, homogeneous semi-infinite continuum, represented by a stiffness matrix based on the plate's interaction with the soil.
3. **Two-Parameter Model**: Developed to bridge the gap between the Winkler and elastic continuum models, offering a balance between simplicity and complexity.

2.2 NUMERICAL METHODS FOR SOIL-PILE INTERACTION

Designing pile foundations for lateral forces and moments involves three criteria: 1) soil must not exceed its capacity, 2) deflections must be within acceptable limits, and 3) structural integrity must be maintained. Various studies have focused on piles under working loads, with methods that can be adapted for pile groups. The following approaches are commonly used:

1. **Winkler Approach**: The oldest method, where piles are modelled as beams and soil as continuous springs. Despite its popularity, it has limitations, such as the modulus of sub-grade reaction being dependent on pile characteristics, and it ignores axial load effects.
2. **P-y Curve Analysis**: A modification of the Winkler model, where soil is represented by nonlinear p-y curves based on test results. The accuracy depends on factors like soil properties and pile geometry.
3. **Elastic Continuum Approach**: Assumes the pile as a vertical strip, with horizontal displacements equal to the soils. The method is complex and requires determining an appropriate soil modulus.

2.3 REVIEW OF STUDIES

- **Mayerhof (1953)**: Highlighted the importance of superstructure-foundation-soil interaction and suggested using relative stiffness to study forces and settlements in deformable soils.
- **Lee and Brown (1972)**: Analysed column loads and moments in a framed structure using relative flexibility parameters for different soil models.
- **Yuanbiao Yin, Kazuo Konagai, and Hikaru Hotta**: Developed a simplified method to evaluate the stiffness of closely spaced piles, modelling them as a single upright beam, effective for both linear and nonlinear soils.
- **Nan Deng, Richard Kulesza, and Farhang Ostadadan (2007)**: Conducted a 3D seismic analysis on battered piles, showing that they attract larger seismic loads than vertical piles due to soil-pile interaction.
- **Chore H.S., Ingle R.K., and Sawant V.A. (2009)**: Studied soil-structure interaction for a space frame on piles embedded in cohesive soil, finding that SSI increases column moments and top displacement compared to a fixed base scenario.

2.4 SOIL PROPERTIES

- **Modulus of Elasticity (Es)**: Typically determined from lab tests or in-situ tests, Es increases with confining stress but can vary significantly, especially in granular soils.
- **Poisson's Ratio (μs)**: Evaluated from triaxial tests, μs varies with stress conditions and is influenced by test procedures. For design, a value of 0.2 is commonly used for a wide range of soils.
- **Modulus of Subgrade Reaction (Ks)**: A key parameter in foundation analysis, Ks relates soil pressure to deflection and is often estimated from empirical equations or in-situ tests like pressure meters.

Problem Considered and Method of Analysis

3.1 PROBLEM CONSIDERED

The study focuses on a three-bay by two-bay, three-story reinforced cement concrete (RCC) structure supported by a pile foundation. Each span measures 5 meters in both directions, and the height of each story (ground, first, and second floors) is 3.5 meters. The structure is subjected to a uniform live load of 3 kN/m², with an additional floor finish load of 1 kN/m². Seismic loading is considered along the global X-axis, following load combinations as per IS-1893 (Part 1): 2002.

For the analysis, the modulus of elasticity for the superstructure's concrete is set at 2.23606×10^7 N/m², with a Poisson's ratio of 0.17. The concrete grade for the superstructure is M20, while for the pile and pile cap, the modulus of elasticity is 3.16227 $\times 10^7$ N/m², and the concrete grade is M40.

The building is located in Seismic Zone 3 (z = 0.16) with an importance factor (I) of 1.5, a response reduction factor (R) of 3, and a rock and soil site factor of 2. A damping factor of 5% is assumed for the ordinary moment-resisting frame.

For the interaction analysis, pile diameter, orientation, and soil conditions are varied. The initial pile diameter considered is 300 mm, with hard strata located 5 meters below ground level. The pile length is set at 5 meters. The study also evaluates piles with diameters of 400 mm and 500 mm to examine how variations affect superstructure parameters. The analysis includes three soil types represented by relative subgrade moduli as per IS 1893/IRC 6 standards.

Table 3.1 Modulus of subgrade reaction for different soil

Sr. No.	Nature of Soil	Designation	Modulus of Subgrade Reaction , ks (MN/m³)
1	Rocky soil (coarse crushed stone)	Type I	225
2	Medium soil (very well compacted sand and clays soil with sand)	Type II	90
3	Soft soil (Fine or slightly compacted soil)	Type III	15

3.2 METHOD OF ANALYSIS

For the substructure, specifically the pile foundation, a simplified modeling approach based on Desai et al. (1981) is employed. This involves using beam elements, plate elements, and spring elements. The pile itself is represented as a beam element, while the surrounding soil is modeled with a series of continuously distributed springs and dashpots, particularly when dynamic loads are considered. The pile cap is modeled as a two-dimensional plate element, as illustrated in the figure below.

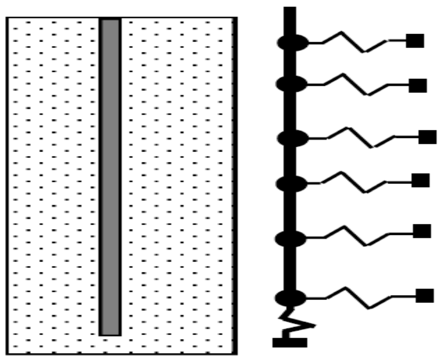

Fig 3.1 Pile in soil and its mathematical model

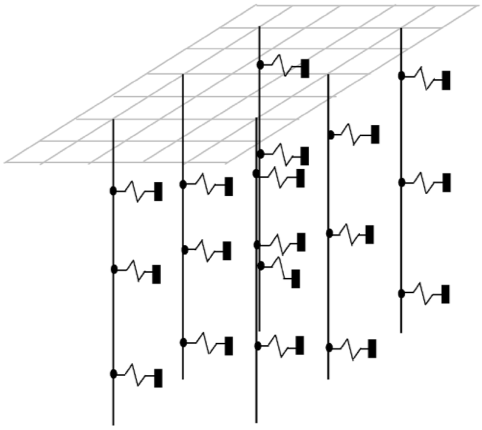

Fig 3.2 Mathematical model of pile cap, piles with soil springs.

The behavior of a single pile can be analyzed using the equation of an elastic beam supported on an elastic foundation (Hetenyi 1946), which is represented by the 4th order differential beam bending equation:

$$E_p I_p \frac{d^4 y}{dz^4} + Q \frac{d^2 y}{dz^2} + E_s y = 0$$

The approach uses Winkler's modulus of sub-grade reaction concept to model the soil as a series of unconnected linear springs with stiffness, Es, expressed in units of force per length squared (FL-2).

The governing equation for the deflection of a laterally loaded pile, obtained by ignoring the axial component, is:

$$\frac{d^4 y}{dz^4} + \frac{E_s}{E_p I_p} y = 0$$

Solution to above equation has been obtained by making simplifying assumptions regarding the variation of Es (or kh) with depth. Es is the modulus of soil reaction (or soil modulus) defined as:

$$Kh = -p/y$$

p = the lateral soil reaction per unit length of the pile, and

y = the lateral deflection of the pile (Matlock and Reese, 1960)

The negative sign indicates the direction of soil reaction is opposite to the direction of the pile deflection.

The solution of the differential equation is obtained by employing appropriate boundary conditions, soil response and soil modulus values respectively. The boundary conditions at the top are shear force is equal to lateral load applied and bending moment applied is equal to applied moment.

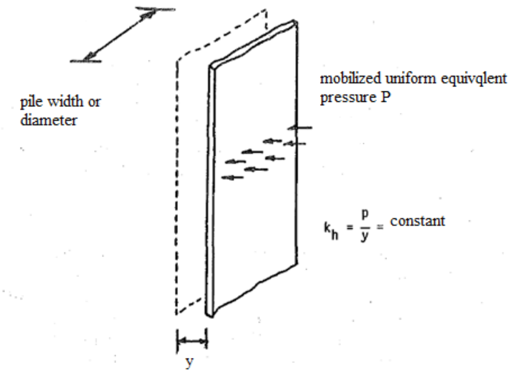

Figure 3.3 Effective area of lateral soil pressure

The soil reaction modulus or spring constant 'Ks' along the length of well foundation of diameter 'D' is determined as follow:

$$K=D^* k_s$$

$$K_i = k_s * Z_i * B_i * D$$

$$\text{where } B_i= (Z_{i+1} – Z_{i-1})/ 2$$

In the elastic range the discrete soil springs with the stiffness k and is dependent on soil type, depth z (effective influence length) and pile diameter D was specified.

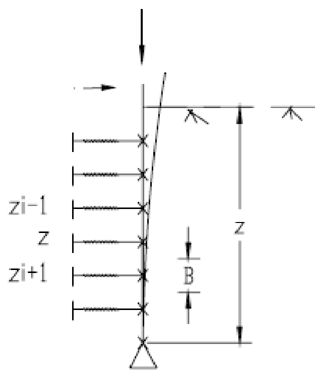

Fig 3.4 Soil stiffness model

Table 3.2 Stiffness values of hard soil for different diameter of piles

Type of soil	Pile diameter mm	Zi(m)	Bi(m)	Ki (KN/m)
Hard	300	1	0.3	67500
		2	0.3	135000
		3	0.3	202500
		4	0.3	270000
		5	0.3	168750
	400	1	0.4	90000
		2	0.4	180000
		3	0.4	270000
		4	0.4	360000
		5	0.4	225000
	500	1	0.5	112500
		2	0.5	225000
		3	0.5	337500
		4	0.5	450000
		5	0.5	281250

Similarly, Stiffness values medium soil and soft soil considered for different diameter of piles

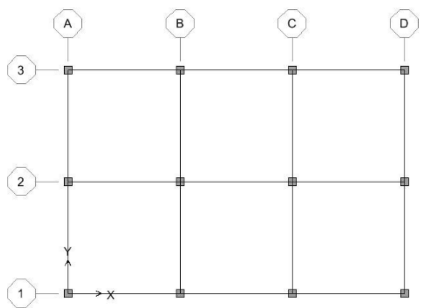

Fig 3.5 Plan of the structure considered for Non-interaction analysis

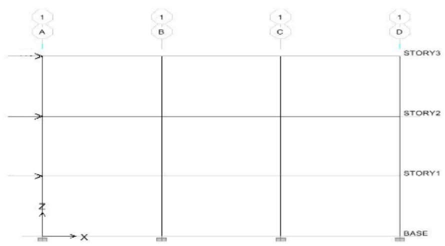

Fig 3.6 Elevation of the structure considered for Non-interaction analysis

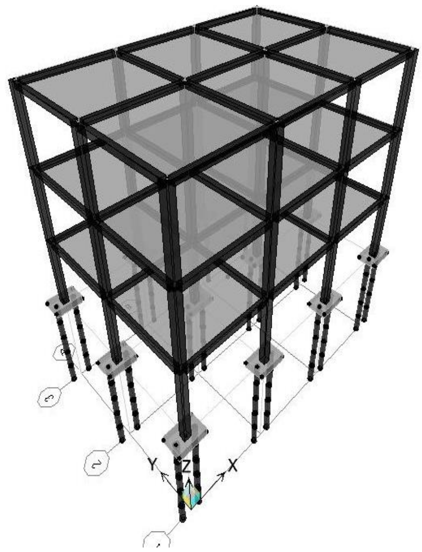

Fig 3.7 piles in series with lateral force considered

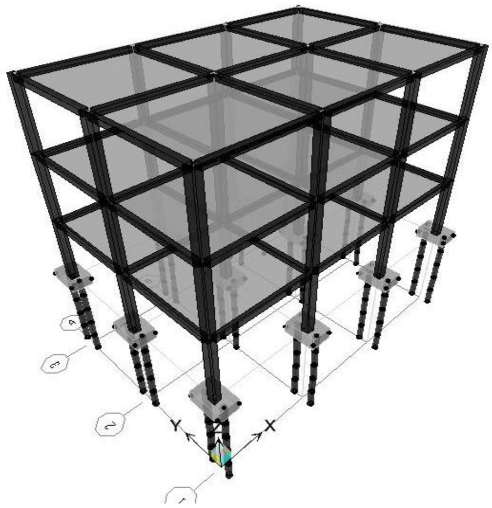

Fig 3.8 piles in parallel with lateral force considered

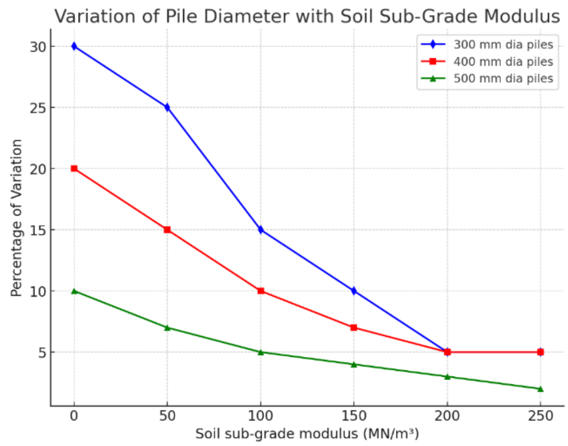

Fig 3.9 Variation of Moments in column 1C (End Bay, moment at base of column)

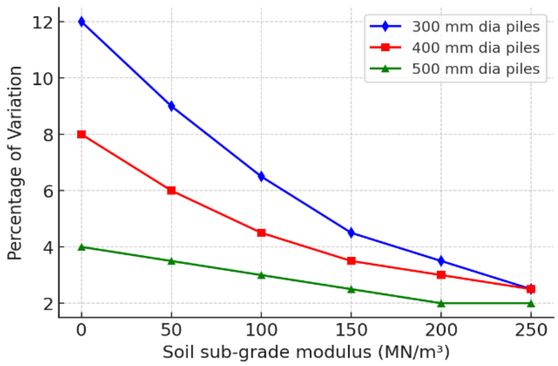

Fig 3.10 Variation of Axial Force in column 1D (End bay)

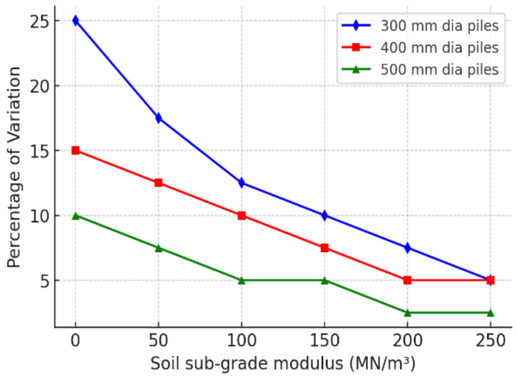

Fig 3.11 Variation of Moments in column 2C (Intermediate Bay, moment at base of column)

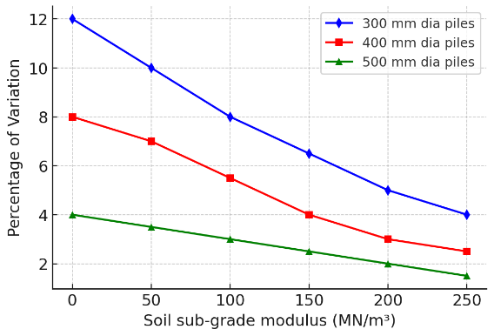

Fig 3.12 Variation of Axial Force in column 2C (Intermediate Bay)

ANALYSIS OF RESULTS

The structural system was analysed for both interaction and non-interaction scenarios, comparing the results across different soil types, pile diameters, and pile orientations.

4.1 Moments in Columns (Piles in Series with Lateral Load Considered)

The interaction analysis generally shows reduced moments compared to the non-interaction analysis for both end bay (Bay 1) and intermediate bay (Bay 2).

- **Moments in Column 1A (End Bay, Base of Column)**: Variation ranged from 31.4% (300 mm piles, soft soil) to 2.26% (500 mm piles, hard soil).
- **Moments in Column 1B (End Bay, Base of Column)**: Variation ranged from 31.22% (300 mm piles, soft soil) to 2.68% (500 mm piles, hard soil).
- **Moments in Column 1C (End Bay, Base of Column)**: Variation ranged from 29.35% (300 mm piles, soft soil) to 2.34% (500 mm piles, hard soil).
- **Moments in Column 1D (End Bay, Base of Column)**: Variation ranged from 30.45% (300 mm piles, soft soil) to 2.38% (500 mm piles, hard soil).
- **Moments in Column 2A (Intermediate Bay, Base of Column)**: Variation ranged from 29.36% (300 mm piles, soft soil) to 2.41% (500 mm piles, hard soil).
- **Moments in Column 2B (Intermediate Bay, Base of Column)**: Variation ranged from 30.08% (300 mm piles, soft soil) to 3.05% (500 mm piles, hard soil).
- **Moments in Column 2C (Intermediate Bay, Base of Column)**: Variation ranged from 26.82% (300 mm piles, soft soil) to 2.3% (500 mm piles, hard soil).
- **Moments in Column 2D (Intermediate Bay, Base of Column)**: Variation ranged from 28.85% (300 mm piles, soft soil) to 2.59% (500 mm piles, hard soil).

4.2 Moments in Beams (Piles in Series with Lateral Load Considered)

Interaction analysis indicates higher moments compared to non-interaction analysis for both end bay (Bay 1) and intermediate bay (Bay 2).

- **Moments in Beam 1A-1B (End Bay, Intermediate Support)**: Variation ranged from 8.24% (300 mm piles, soft soil) to 0.35% (500 mm piles, hard soil).

- **Moments in Beam 1B-1C (End Bay, Right Intermediate Support)**: Variation ranged from 24.04% (300 mm piles, soft soil) to 2.16% (500 mm piles, hard soil).
- **Moments in Beam 1C-1D (End Bay, End Support)**: Variation ranged from 27.39% (300 mm piles, soft soil) to 2.44% (500 mm piles, hard soil).
- **Moments in Beam 2A-2B (Intermediate Bay, Intermediate Support)**: Variation ranged from 21.84% (300 mm piles, soft soil) to 2.41% (500 mm piles, hard soil).
- **Moments in Beam 2B-2C (Intermediate Bay, Right Intermediate Support)**: Variation ranged from 18.11% (300 mm piles, soft soil) to 1.56% (500 mm piles, hard soil).
- **Moments in Beam 2C-2D (Intermediate Bay, End Support)**: Variation ranged from 24.68% (300 mm piles, soft soil) to 2.51% (500 mm piles, hard soil).

4.3 Axial Force in Columns (Piles in Series with Lateral Load Considered)

The interaction analysis for axial forces in columns with piles arranged in series under lateral loads showed that axial forces were generally higher in the end bay (Bay 1) and lower in the intermediate bay (Bay 2) compared to the non-interaction analysis. Specifically, in the end bay, Column 1A exhibited axial force variations ranging from 14.92% with 300 mm piles in soft soil to 1.57% with 500 mm piles in hard soil. Column 1B showed variations between 5.16% and 0.87%, Column 1C between 8.06% and 1.37%, and Column 1D between 12.44% and 1.3%. In the intermediate bay, Column 2A had variations from 9.57% to 2.03%, Column 2B from 14.41% to 2.23%, Column 2C from 12.16% to 1.67%, and Column 2D from 6.8% to 1.33%, depending on the pile diameter and soil type.

4.4 Moments in Columns (Piles in Parallel with Lateral Load Considered)

The interaction analysis for columns subjected to lateral loads generally showed lower moments compared to the non-interaction analysis for both the end bay (Bay 1) and intermediate bay (Bay 2). In the end bay, Column 1A at the bottom experienced moment variations ranging from 47.1% for 300 mm piles in soft soil to 5.7% for 500 mm piles in hard soil, while Column 1B saw variations from 44.45% to 5.9%, Column 1C from 42.78% to 5.57%, and Column 1D from 36.74% to 5.86%. In the intermediate bay, Column 2A exhibited moment variations between 47.12% and 5.71%, Column 2B varied from 44.45% to 6.14%, Column 2C from 41.77% to 5.41%, and Column 2D showed variations ranging from 44.45% to 5.98%, depending on the pile diameter and soil type.

4.5 Moments in Beams (Piles in Parallel with Lateral Load Considered)

The interaction analysis for beams subjected to lateral loads generally revealed higher moments compared to the non-interaction analysis for both the end bay (Bay 1) and intermediate bay (Bay 2). Specifically, moments in Beam 1A-1B at the intermediate support in the end bay varied between 16.97% for 300 mm piles in soft soil and 1.91% for 500 mm piles in hard soil. Similarly, beam 1B-1C at the right intermediate support showed variations from 33.91% to 4.31%, while Beam 1C-1D at the end support had variations ranging from 37.19% to 4.57%. In the intermediate bay, beam 2A-2B at the intermediate support exhibited variations between 34.86% and 4.62%, Beam 2B-2C at the right intermediate support varied from 25.57% to 3.34%, and Beam 2C-2D at the end support showed variations ranging from 32.38% to 4.29%, depending on the pile diameter and soil type.

4.6 Axial Force in Columns (Piles in Parallel with Lateral Load Considered)

In the interaction analysis, axial forces in the end bay columns (Bay 1) were generally higher, while those in the intermediate bay columns (Bay 2) were lower compared to the non-interaction analysis. Specifically, Column 1A in the end bay showed a maximum variation of 21.37% with 300 mm piles in soft soil, and a minimum of 1.42% with 500 mm piles in hard soil. Similar trends were observed across other columns in the end bay, with Column 1B showing variations ranging from 5.51% to 0.91%, Column 1C from 8.80% to 1.34%, and Column 1D from 13.56% to 1.80%. In the intermediate bay, Column 2A exhibited variations between 11.31% and 1.80%, Column 2B between 19.67% and 2.2%, Column 2C between 15.81% and

1.7%, and Column 2D between 7.84% and 1.63%, depending on the pile diameter and soil type.

Summary and Conclusions

This study presents an interaction analysis of a framed structure supported by pile foundations, conducted using ETABS software. The structure analyzed is a symmetrical three-story reinforced cement concrete frame with three bays by two bays, each with a 5m span and a height of 3.5m. Loading conditions are based on IS standards.

A non-interaction analysis of the same structure was also conducted using ETABS for comparison purposes. The analysis examined various factors: different soil types (characterized by varying modulus of subgrade reaction), different pile diameters, and different orientations of piles. Key parameters considered in the study include variations in column moments, beam moments, and axial forces in the columns.

- The percentage variation in axial forces, column moments, and beam moments is greater when piles are aligned parallel to the direction of the lateral load compared to when they are arranged in series with the lateral load.
- Column moments in the interaction analysis are consistently lower than in the non-interaction analysis. The highest percentage variation occurs with soft soil and 300mm diameter piles, while the lowest variation is observed with hard soil and 500mm diameter piles.
- Beam moments in the interaction analysis are higher than in the non-interaction analysis, with the highest variation occurring for soft soil and 300mm diameter piles.
- Axial forces in the end bay (Bay 1) are higher in the interaction analysis compared to the non-interaction analysis, while axial forces in the intermediate bay (Bay 2) are lower in the interaction analysis. The greatest percentage variation is found for soft soil and 300mm diameter piles in both bays.

Overall, the study concludes that factors such as pile orientation, pile diameter, and soil type significantly influence the variations in bending moments and axial forces in the superstructure. Specifically, pile arrangements aligned parallel to the direction of the lateral load result in the highest variations compared to series arrangements.

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