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Dynamics Analysis of High-Rise Buildings on the Pile Foundation

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Abstract: This study investigates the critical role of soil types, foundations, and building frames in resisting external loads, with a particular focus on storey displacement as an indicator of structural safety under various loading conditions. In earthquake-prone regions, foundation failures are a leading cause of structural displacement, often resulting in significant human and economic losses. The interaction between deep foundations and the surrounding soil, known as Soil-Structure Interaction (SSI), plays a pivotal role in a structure's performance. Factors such as foundation geometry, soil properties, and load conditions significantly influence the stability and design of buildings. This research highlights the importance of considering SSI effects to enhance the structural resilience and safety of buildings, especially in areas susceptible to seismic activity.
Keywords: Single under-reamed friction pile, Isolated footing, Sub-structure, Storey displacement, Building frame etc.

I. INTRODUCTION

This study employs software for finite element analysis to examine the movement behavior of a four-story, single-bay structure resting on various soil types under dynamic loads. The impact of deep foundations—more especially, single under-reamed friction piles—with or without square footings on structural displacement is investigated in this work. Structural displacement brought on by foundation failure, especially in earthquake-prone areas, frequently results in a high death toll and substantial financial losses. The stability as well as design of structures are greatly influenced by the type of footing, foundation, and soil characteristics. When compared to foundations without footings, the analysis shows that those with a single under-reamed resistance pile and footings had less overall displacement [1].

A key factor in the changing behavior of structures is the Soil-Structure Interaction (SSI), which is the interaction among the foundation and the surrounding soil. According to the study, foundations in solitary under-reamed friction pile dramatically change the dynamic behavior of the foundation and enhance the overall structural reaction to dynamic loads. When surface soil is insufficient to sustain the structure due to strong vertical loads or poor soil conditions, deep foundations are frequently used. Numerous elements, including as soil characteristics, foundation geometry, which is and loading circumstances, affect how well these foundations work [1][2].

Figure 1. Pile Foundations

The movement of foundations that are deep under dynamic as well as static loads can be greatly impacted by SSI, a complicated process that involves the transmission of forces among the soil and the foundation. For constructions based on deep foundations to be safe and stable, it is essential to comprehend the behavior of soil elements, as civil engineering structures transfer loads through foundation components such as footings, rafts, and piles into the underlying soil. This paper offers a comprehensive analysis of both static and dynamic aspects of SSI, providing valuable insights into foundation behavior under loading conditions [5][6].

II. PROBLEM STATEMENTS

1) The stability and safety of structures, particularly in earthquake-prone areas, are heavily dependent on the foundation system and its interaction with the underlying soil.
2) Foundation failures during seismic events can lead to significant structural displacement, endangering lives and causing economic losses. While deep foundations, such as single under-reamed friction piles, are frequently employed in weak soil situations to support huge constructions, the effect of these foundations with or without square footings on structural displacement remains underexplored [6][7].
3) Soil-Structure Interaction (SSI) is a complicated phenomenon that affects how well deep foundations work, yet its dynamic impact on foundation behavior is not fully understood.
4) This study looks into the movement behavior of a four-story building in an effort to close the gap, single-bay frame supported by deep foundations, using finite element analysis.
5) The study aims to compare the dynamic response of single under-reamed friction piles with and without footings, analyzing how these configurations affect displacement under different soil conditions and loading scenarios.

III. LITERATURE RESEARCH

A. *Criteria for Selecting this Study*

The study on deep foundations and soil-structure interaction (SSI) has been selected based on the following criteria:

1) Relevance to Real-World Conditions: The study emphasizes the challenges of applying research findings to practical design, particularly in seismic-prone areas. It draws attention to the shortcomings of small-scale experiments and simplified models, which frequently fail to accurately depict real-world situations. This makes the research highly applicable to actual construction projects.
2) Focus on Soil-Structure Interaction (SSI): The study discusses the crucial function of SSI, a foundation design component that has a direct bearing on a structure's stability and safety. This element is particularly crucial in areas with soft soils or regions prone to seismic activity, providing valuable insights into the interplay between soil properties and foundation behavior.
3) Comprehensive Approach: By exploring a variety of factors such as soil type, foundation geometry, and loading conditions, the study takes a holistic approach to understanding deep foundations. It goes beyond traditional analyses by incorporating the effects of SSI, offering a more detailed evaluation of structural performance under external loads [8].
4) Impact on Earthquake-Prone Regions: The focus on seismic regions adds a layer of urgency and importance to the research. Foundation failures are a leading cause of building displacement during earthquakes, and this study provides insights on improving structural resilience and safety, a critical concern in seismic engineering.
5) Contribution to Structural Design Improvement: The research not only identifies potential risks (e.g., settlement and deformation in soft soils) but also offers strategies for improving foundation design. By emphasizing the importance of accurate soil behavior modeling, the study contributes to safer and more reliable building designs [9].

B. *Method of Analysis*

1) The method of analysis for the given study involves a comprehensive approach using both experimental and numerical techniques.
2) First, soil properties, foundation geometry, and load conditions are systematically evaluated through field data collection and laboratory testing to recognize their impact on the relationship between soil and structure (SSI).
3) FEA, or finite element analysis, is used to model the response of foundations under various loading scenarios, particularly in seismic conditions.
4) Additionally, sensitivity analysis is conducted to determine how variations in soil type, foundation shape, and material properties affect displacement and stability.
5) The results are validated against real-world case studies to ensure practical relevance and accuracy [10].

C. *Comparison and Analysis:*

The comparison of key studies on deep foundations and soil-structure interaction (SSI) reveals several critical insights across diverse approaches and conditions:

1) Simplified SSI Models: A simplified SSI approach using a linearized p-y curve to simulate soil resistance in pile foundations, making the analysis more time-efficient compared to complex finite element models. This technique is valuable in seismic events, optimizing design resources without sacrificing accuracy.
2) Seismi Design Standards: A focus on pile foundation design in seismic zones, comparing Indian and European standards. The study emphasizes the impact of ground conditions (C and D types) on seismic loads, highlighting the importance of localized seismic design to ensure structural safety [11].
3) Limit State Design for Pile Foundations: Using a limit state design approach for tall buildings, balancing safety and performance by minimizing foundation deformation while maintaining stability under ultimate load conditions. This method ensures resilience in high-rise structures.
4) Pile Configuration and Seismic Zones: Different pile group configurations and aspect ratios influence the seismic performance of foundations in varying seismic zones, providing practical insights into designing efficient pile systems.
5) Dynamic SSI in Foundation Design: The critical role of SSI in dynamic conditions, such as earthquakes. Shah particularly highlights the influence of foundation geometry, soil properties, and seismic factors on deep foundation behavior, while Prajapati and Panchal emphasize the complex interactions between soil and foundation, affecting long-term performance.
6) SFSI and Structural Response: Noto et al. (2020) study the difference between fixed and compliant base models in soil-foundation-structure interaction (SFSI), showing how incorporating soil flexibility into the design can significantly alter the building's dynamic response, especially in seismic scenarios.
7) Foundation Optimization: On optimizing pile foundation systems using FEM, demonstrating how pile placement, number, length, and diameter can be adjusted based on soil conditions to reduce costs while ensuring structural integrity. This optimization improves load distribution and minimizes the need for excessive piles [11][12].

These studies collectively highlight the importance of integrating soil properties, seismic standards, SSI models, and foundation design optimizations to enhance the stability, safety, and cost-effectiveness of deep foundations under various load conditions.

D. Evaluation of methodologies used in the reviewed studies:

The methodologies employed in the reviewed studies on soil-structure interaction (SSI) and pile foundations showcase a range of innovative approaches aimed at enhancing structural safety and design efficiency.

1) Simplified Models: Advocate for a linearized p-y curve model, which simplifies the complex soil-structure interaction into a more manageable analysis while maintaining accuracy during seismic events. This approach emphasizes practicality in real-world applications.
2) Comparative Analysis: Employ a comparative study of seismic design codes from India and Europe, analyzing the effects of varying ground conditions on foundation capacity. This comparative methodology allows for a deeper understanding of how regional practices impact seismic resilience.
3) Finite Element Modeling (FEM): Utilize FEM to optimize pile foundations, focusing on varying soil conditions to reduce construction costs while ensuring structural integrity. This computational method enables precise modeling of complex interactions between soil and structures.
4) Limit State Design: Advocates for a limit state design framework, which balances safety with performance, allowing for a nuanced approach to foundation design that accommodates real-world loads [13].
5) Dynamic Analysis: The dynamic behavior of deep foundations under seismic loads, utilizing advanced modeling techniques to capture the intricate relationships between soil properties, foundation geometry, and loading conditions [13][14].

These diverse methodologies highlight the need for tailored approaches in foundation design, accounting for local soil conditions and specific structural requirements to enhance overall stability and safety.

E. Highlighting Trends, Advancements, and Challenges

Trends, Advancements, and Challenges in Soil-Structure Interaction and Pile Foundations:

Trends:

1) Simplified Modeling Approaches: There is a growing trend toward simplified modeling techniques, such as the linearized p-y curve approach, which enables faster analysis and reduces costs while maintaining accuracy in predicting soil-structure interaction during seismic events (Kurnia et al., 2021).

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2) Comparative Studies: Researchers increasingly compare international design codes and practices to optimize seismic design for pile foundations, as demonstrated by Krishna et al. (2020), facilitating improved understanding of how different codes address ground conditions.
3) Use of Finite Element Methods (FEM): The adoption of FEM for optimizing pile foundations is becoming common, allowing for precise modeling of complex soil conditions, which helps in designing more efficient foundation systems (Itankar and Kurzekar, 2020).
4) Focus on Dynamic Analysis: Recent studies emphasize the dynamic behavior of foundations under seismic loads, integrating both static and dynamic soil-structure interaction analyses to enhance structural safety (Shah, 2021; Prajapati and Panchal, 2019).

F. Advancements

1) Integrated Design Approaches: The incorporation of limit state design principles in foundation design enhances safety by balancing performance under service loads and ultimate load conditions (Poulos, 2018).
2) Advancements in Computational Tools: The development of advanced computational tools and finite element modeling software facilitates the detailed analysis of soil-structure interactions, improving the accuracy of predictions and designs (Itankar and Kurzekar, 2020).
3) Enhanced Understanding of Soil Behavior: Recent research sheds light on the complex relationships between soil properties and foundation performance, helping to tailor designs to specific site conditions (Noto et al., 2020).

G. Challenges

1) Modeling Limitations: Many studies rely on simplified models that may not accurately capture real-world complexities, limiting their applicability in diverse site conditions (Prajapati and Panchal, 2019).
2) Data Sensitivity: The accuracy of numerical models is heavily dependent on the quality of input data, This can differ significantly depending on site-specific circumstances and modeling assumptions (Kurnia et al., 2021).
3) Seismic Design Variability: There is a challenge in addressing the variability of seismic conditions across different regions, necessitating tailored designs that can adapt to local geological and seismic characteristics (Krishna et al., 2020).
4) Cost Implications: While advanced modeling techniques and materials may offer enhanced performance, they can also lead to increased costs, making it essential to balance innovation with budget constraints (Itankar and Kurzekar, 2020).

These trends, advancements, and challenges highlight the evolving landscape of soil-structure interaction research, emphasizing the need for ongoing innovation and adaptation in foundation design methodologies to ensure safety and resilience in construction.

IV. METHODOLOGY

A. Implications in study

The analysis of pile foundation design has significant implications for improving structural safety and optimizing construction practices, especially in seismic zone. Understanding the role of ground conditions, pile length, spacing, and configuration helps engineers design foundations that can resist vertical and lateral loads, ensuring stability for high-rise structures. The findings highlight that weak soil strata demand the use of pile foundations, often preferred over raft systems for economic and structural reasons. Furthermore, advancements in modeling methods, such as simplified Soil-Structure Interaction (SSI) analysis, reduce the time and cost of designing pile foundations, making them more accessible for diverse construction needs [15].

B. Methodology for Research Directions

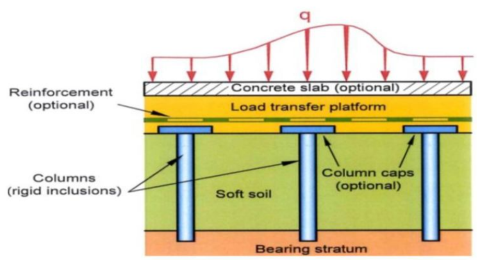

Figure 2. Soil-structure interaction in deep foundations

When surface soils are unable to sustain a structure's weight, deep foundations are necessary. These foundations extend into deeper soil layers to provide necessary support. The interaction between soil and foundation is influenced by various factors, including soil type, loading conditions, and the foundation's geometry. Understanding soil behavior is crucial for the stability and safety of deep foundations. Soft and compressible soils, for instance, can lead to increased settlement and deformation, affecting the foundation's performance. The shape, diameter, and length of deep foundations also play a significant role in their behavior and response to loads [16]. Prior studies on the relationship between soil and structure frequently had drawbacks, such as their reliance on small-scale experiments or simplistic models that might not accurately represent actual situations. Furthermore, location factors and modeling assumptions might affect the precision of the input information, which is crucial for the numerical models utilized in these investigations. These limitations highlight the challenges in applying research findings to practical design and construction, underscoring the need for more comprehensive studies and accurate modeling to better understand and manage soil behavior in deep foundations.

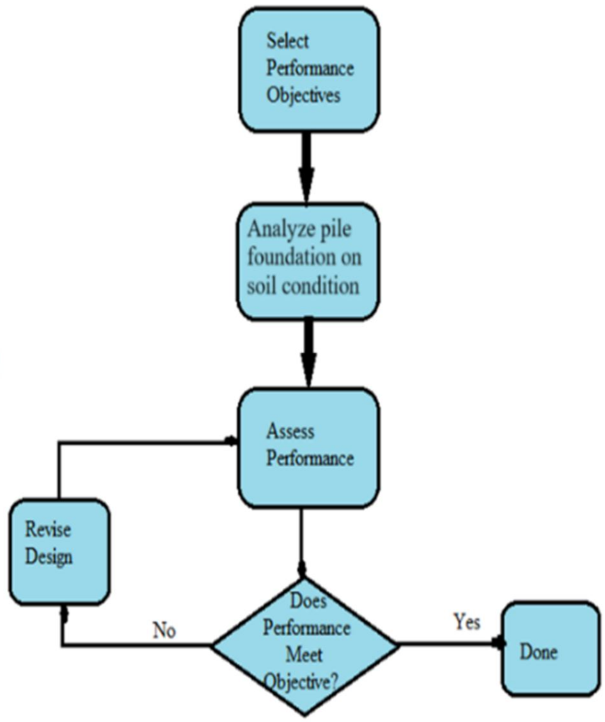

Figure 3. Flow chart of analysis of pile foundation for high rise structure

The distribution between stress and strains, in addition to the foundation's deflection and settlement, are commonly used to describe the behavior of the basis and the soil around it. The study can be used to optimize the foundation's design to satisfy the necessary performance standards and assess the foundation's stability and safety under the applied loads.

One of the disadvantages of fixed soil-structure evaluation is that it ignores the effects on time-dependent soil behavior, like creep and reorganization, which can have a big impact on the foundation's behavior over time. To properly assess the behavior of the foundation or the surrounding soil, more time-dependent work could be required. An effective method for assessing how foundations behave under static stresses and improving their design is the static interactions between soil and structure analysis. Nonetheless, the analysis's assumptions and simplifications must to be thoroughly examined and supported by the site's characteristics and the design guidelines [17].

When it comes to foundation design, soil-structure interaction, or SSI, is crucial, particularly in assessing how structures and underlying soils interact under various loads. The goal of this study is to evaluate SSI's impact on deep foundations through dynamic and static analyses. By defining the boundaries of the research, it focuses on examining the interaction effects using state-of-the-art modeling techniques.

Dynamic SSI analysis simulates how structures and soils respond to seismic and other transient loads, while static SSI evaluates the foundation's behavior under permanent or slowly varying loads. Methods for simulating soil response include finite element models that consider soil properties, foundation geometry, and load conditions. Factors like soil stiffness, foundation type, and loading influence SSI behavior.

Accurate SSI analysis is vital for ensuring deep foundation safety and performance, leading to optimized design practices that mitigate settlement risks, enhance structural stability, and ensure better long-term functionality under diverse load scenarios [18].

C. Implementation of work

In the dissertation work that was presented, STAAD Pro software was used to examine a regular rectangle plan of an elevated structure (G+20) with an aspect ratio of L/B=4. Analysis was done on the building plan in seismic zone IV. The nodal pressures at the building's base were calculated. End-bearing piles were taken into account. Pile caps were used to unite several pile groups—three, four, and five piles—in a square and triangular pattern. Indian codes are taken into consideration when designing the structural layout of piles along with pile caps in seismic zones. The quantity of asphalt and steel is the basis for the comparative cost analysis of the piling foundation.

Data Used: According to Indian standard codes, various types of data are employed, including zone factor, units weights, designer loads, load combinations, etc. Tables 1 through 2 provide the data used in the investigation.

Table1 : Factors in the Seismic Zone

Seismic Zone	Zone Factor (Z)
II	0.10
III	0.16
IV	0.24
V	0.36

Zone IV (Zone Factor = 0.24) as a moderate-to-severe seismic zone, is used for conservative design and this research.

Table 2 : Design loads and unit weights

Remarks	Loads / Unit Weights
Unit weight of concrete	24 kN/m³
Unit weight of brick	19 kN/m³
Floor dead load	4 kN/m²
Floor live load	4 kN/m²
Seismic floor load	6 kN/m²
Roof live load	2 kN/m²
Unit weight of soil	18 kN/m³
Grade of concrete	M30
Grade of steel	Fe415

D. Load Calculations : for Zone IV

1) Parameters (as per code IS 1893:2016):
- Importance factor I=1.0 (general buildings)
- Response Reduction Factor R=3.0 (OMRF system)
- Soil Type: Medium → Sa/g=2.5 (Ground motion spectrum)(as per IS 1893 (Part 1): 2016)
- Building Height h=63 m, Base dimension = 40 m
- Fundamental natural period T (for moment resisting RC frame):

$$T=0.075\times h^{0.75}=0.075\times(63)^{0.75}\approx 1.92\text{sec}$$

2) Base Shear Vb :

$$V_b=\frac{ZIS_a}{2Rg}\times W$$

Z=0.24, I=1, R=3, Sa/g=2.5, W=Seismic weight of building

3) Seismic Weight W :

For each floor:

- Dead Load:

  Slab + finishes = 4 kN/m²

Walls (230 mm thick, 3 m height): 0.23×3×19=13.11 kN/m per running meter (apportioned over area)

Live Load (as per IS 1893: reduce 50% for seismic calc) = 0.5 × 4 = 2 kN/m²

Total load per floor (approx.): 4+2+wall=4 + 2 + wall =7–9 kN/m²

Floor area = 20×40=800m²

W_{floor}=800×8=6400kN

Total W for 21 floors (G + 20):

W=21×6400=134400Kn

$V_b = \frac{0.24 \times 1 \times 2.5}{2 \times 3} \times 134400$ =0.1×134400=13440Kn

4) Vertical Load Calculations :

Dead Load (DL)

- Slab + finishes: 4 kN/m²
- Beams: 0.45×0.45×24=4.86 kN/m
- Columns: 0.75×0.75×3×24=40.5 kN per storey height
- Walls: 230 mm thick, 3 m high
- Total DL summed floor-wise for STAAD

Live Load (LL)

- Floors: 4 kN/m²
- Roof: 2 kN/m²

5) Load Combinations (IS 456 & IS 1893)

- 1.5(DL + LL)
- 1.2(DL + LL ± EL)
- 1.5(DL ± EL)
- 0.9DL ± 1.5EL

6) Pile Load Calculation

From STAAD outputs (support reactions), pile loads for each group (3, 4, 5 piles) are calculated:

- Reaction/pile = Total base reaction ÷ number of piles
- Pile design based on end-bearing:

$$Q_{ult} = A_p \cdot q_p + A_s \cdot f_s$$

But in most cases, ultimate capacity,

$$Q_{safe} = \frac{Q_{ult}}{FOS}$$

Pile group analysis considers spacing, group effect, and interaction.

7) Modelling Parameters

- Material: M30 concrete, Fe415 steel
- Column: 0.75 m × 0.75 m
- Beam: 0.45 m × 0.45 m
- Storey height: 3 m
- Grid spacing: 5 m × 5 m
- Plan: 20 × 80 m (aspect ratios = 4)

8) Earthquake load directions
- EQ in 1 direction → X-direction (longitudinal direction)
- EQ in 2 direction → Z-direction (transverse direction)

Rectangular buildings (e.g., 20 × 40 m, 20 × 80 m):
- X-direction likely represents the shorter span (20 m).
- Z-direction likely represents the longer span (40 m, 60 m, or 80 m).
  So,
- EQ in X-direction → May cause more rigid frame action (less displacement)
- EQ in Z-direction → May cause larger displacement due to flexibility.

High-rise buildings on pile foundations under seismic conditions, the type of analysis performed to account for earthquake effects is Response Spectrum Analysis (RSA).

In this study, both earthquake (dynamic) and non-earthquake (static) loads were considered to evaluate structural performance. Non-earthquake loads included dead load, live load, and floor/roof loads, which act vertically and remain constant over time. In contrast, earthquake loads were applied laterally in X and Z directions as per IS 1893:2003, simulating ground motion effects. The analysis revealed that vertical loads primarily governed the foundation design, while lateral seismic forces influenced displacement behavior. Though seismic loads were lower in magnitude compared to vertical loads, their impact on structural stability, particularly under different pile configurations, was significant in seismic zone.

E. Theoretical Framework

1) A structure with a ground floor and twenty stories, each three meters high, was regarded as having a standard rectangular layout, measuring 20.0 m by 80.0 m. The building's plan is located in India's seismic zone IV.

2) The superstructure was examined using the design and computation program StaadPro. At the base of every building, the support reactions as well as moments derived from the computer software analysis were gathered.

3) End bearing piles with a length of 25.0 meters were taken into consideration when designing the pile foundation using the data that was acquired.

4) Three distinct plié group geometry styles—utilizing three, four, as well as five piles inside of a group—were implemented.

The dimensions of the beam and column were 0.45 m and 0.75 m, respectively, making them square in shape. For both the X and Y directions, the center-to-center spacing between columns was measured at 5.0 meters.

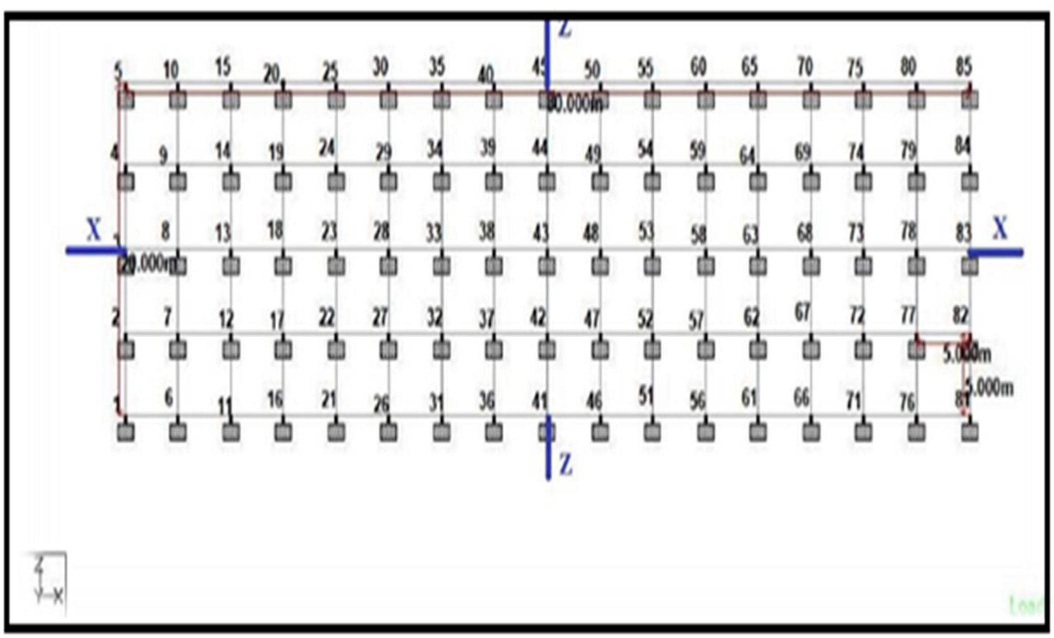

Figure 4. Plan View of Building

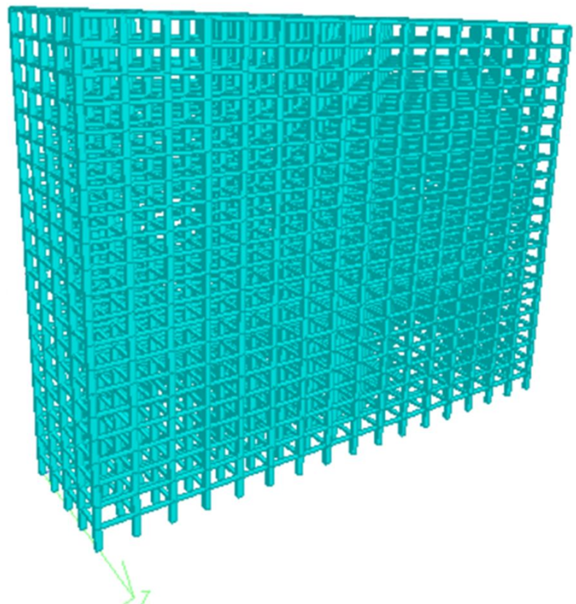

Figure 5. Isometric View of Building

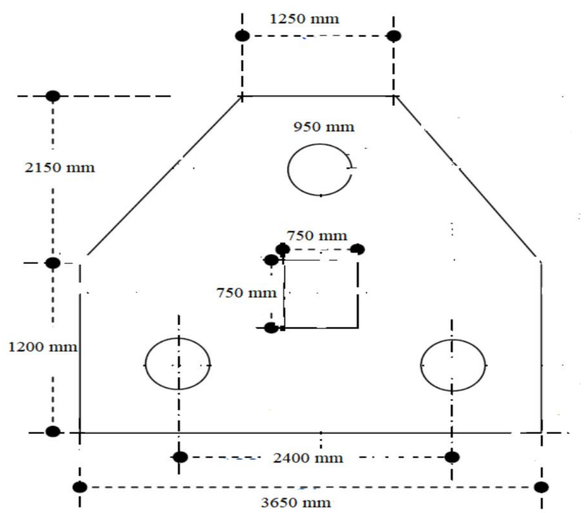

Figure 6. Triangular Pile Cap Adopted for Three Piles in Group

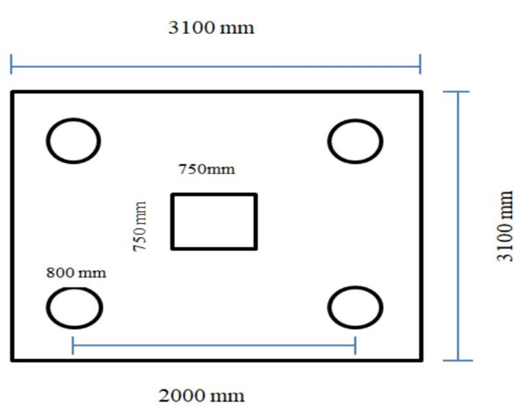

Figure 7. Square Pile Cap Adopted for Four Piles in Group

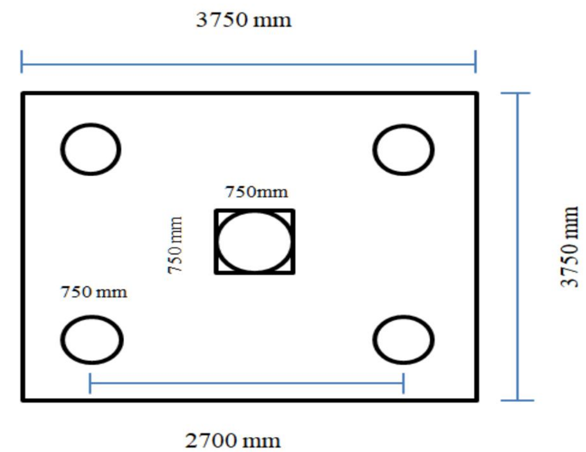

Figure 8. Square Pile Cap Adopted Five Piles in Group

V. RESULTS AND DISCUSSIONS

A. *Support Reactions Obtained At the Base of the Buildings*

For the aspect ratios of a structure under seismic zone, the fluctuation of moments and forces along the X and Z axes was observed to follow the same pattern. The variation patterns of nodal moments and forces along the X axis for buildings under the fourth seismic zone are shown in Figures 9 to 11.

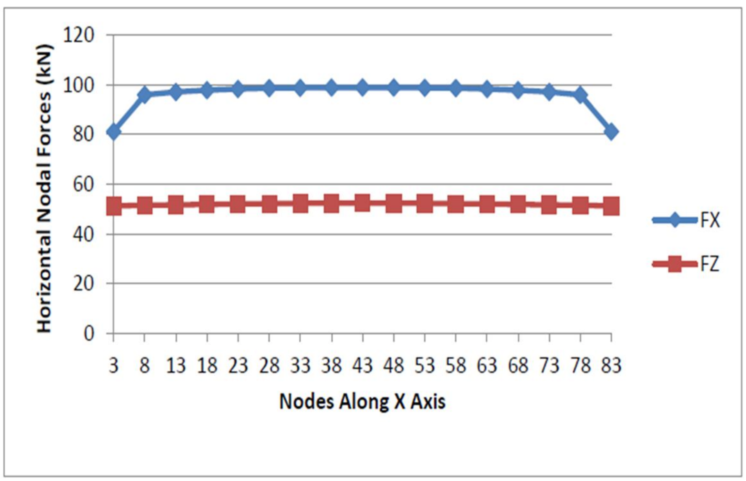

Figure 9. Variations of FX and FZ along X Axis for Nodes 3 to 83

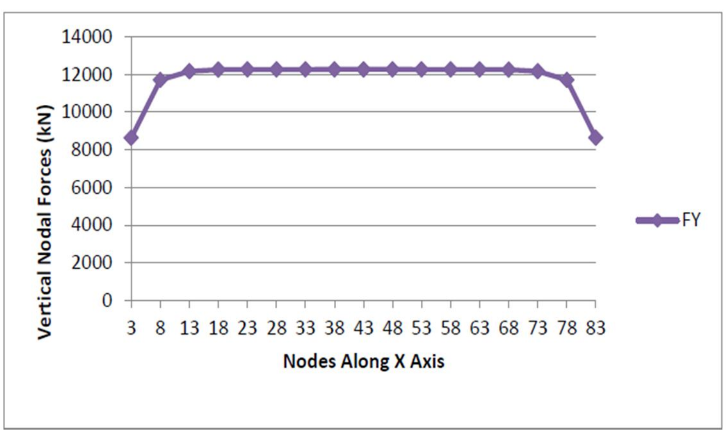

Figure 10. Variation of FY along X Axis for Nodes 3 to 83

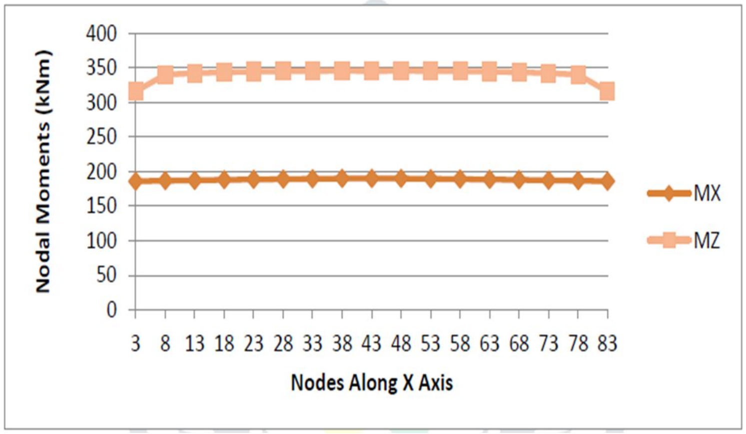

Figure 11. Variations of MX and MZ along X Axis for Nodes 3 to 83

B. Determining the amount of concrete and steel needed for construction

The amount of steel and concrete needed for the piling foundations was estimated. The most appropriate and cost-effective pile group shape was identified by comparing the amounts of concrete and steel needed for various pile group arrangements. The entire amount of steel and concrete needed for the building plan is shown in a bar chart in Figure 12.

Table 3: Concrete and Steel Required for Building

Number of Piles	Concrete (m^3)	Steel (tons)
3	5289.75	293.87
4	4571.22	344.17
5	4944.30	355.32

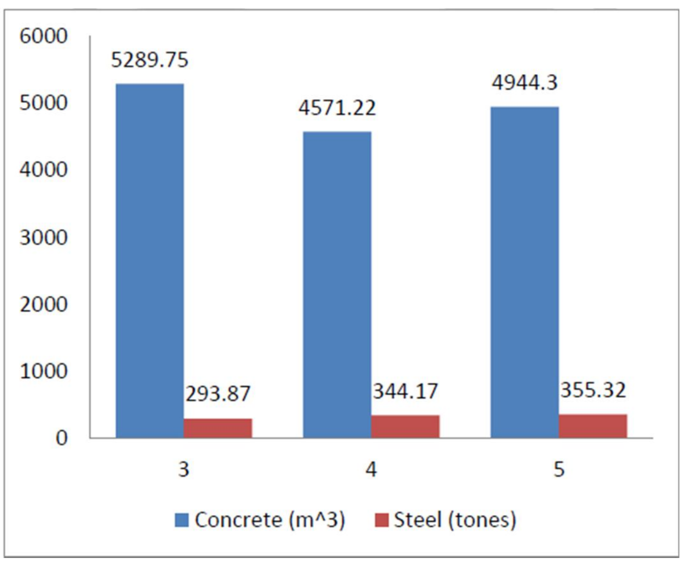

Figure 12. Concrete and Steel Required for Building

Lateral forces are negligible in comparison to vertical forces, according to an investigation of 12 buildings having different aspect ratios within seismic zone. The greatest and minimum vertical loads at the base of a 63.0 m building stayed constant across aspect ratio. The study showed that, for buildings located in seismic zones, the change of momentum and moments in the X and Z axes mirrored a similar pattern. According to the support reactions, the design is governed by vertical loads.

This study analyzed the seismic performance and material requirements of a 20-storey building with varying plan dimensions and pile group configurations (3, 4, and 5 piles) across seismic zone using STAAD.Pro. The seismic zone factors and load combinations followed IS 1893:2003 standards. The results showed that concrete usage was highest in the 3-pile group (5289.75 m³) and lowest in the 4-pile group (4571.22 m³), while steel usage increased with more piles, reaching 355.32 tons for the 5-pile configuration. Earthquake loads caused more significant structural demands compared to non-seismic loads, influencing both foundation design and material consumption. The study highlights the trade-offs between material optimization and seismic safety, offering insights for cost-effective, earthquake-resilient structural design.

VI. CONCLUSION

The study on the seismic performance of buildings with aspect ratio and pile foundation configurations provided valuable insights into structural behavior. The results indicated that lateral forces in seismic zone are significantly lower compared to vertical forces, making vertical loads the primary governing factor in foundation design. Despite variations in aspect ratios, the maximum and minimum vertical forces remained nearly constant for a building height of 63.0 m.

Among the three, four, and five-pile foundation groups, the four-pile arrangement was identified as the most economical option. The material consumption analysis showed that the quantity of steel and concrete required increased in proportion to the plan size of the building. The findings suggest that optimizing pile foundation design can lead to cost-effective and structurally efficient solutions. The study emphasizes the importance of selecting an appropriate pile group configuration to achieve an optimal balance between structural stability and material economy.

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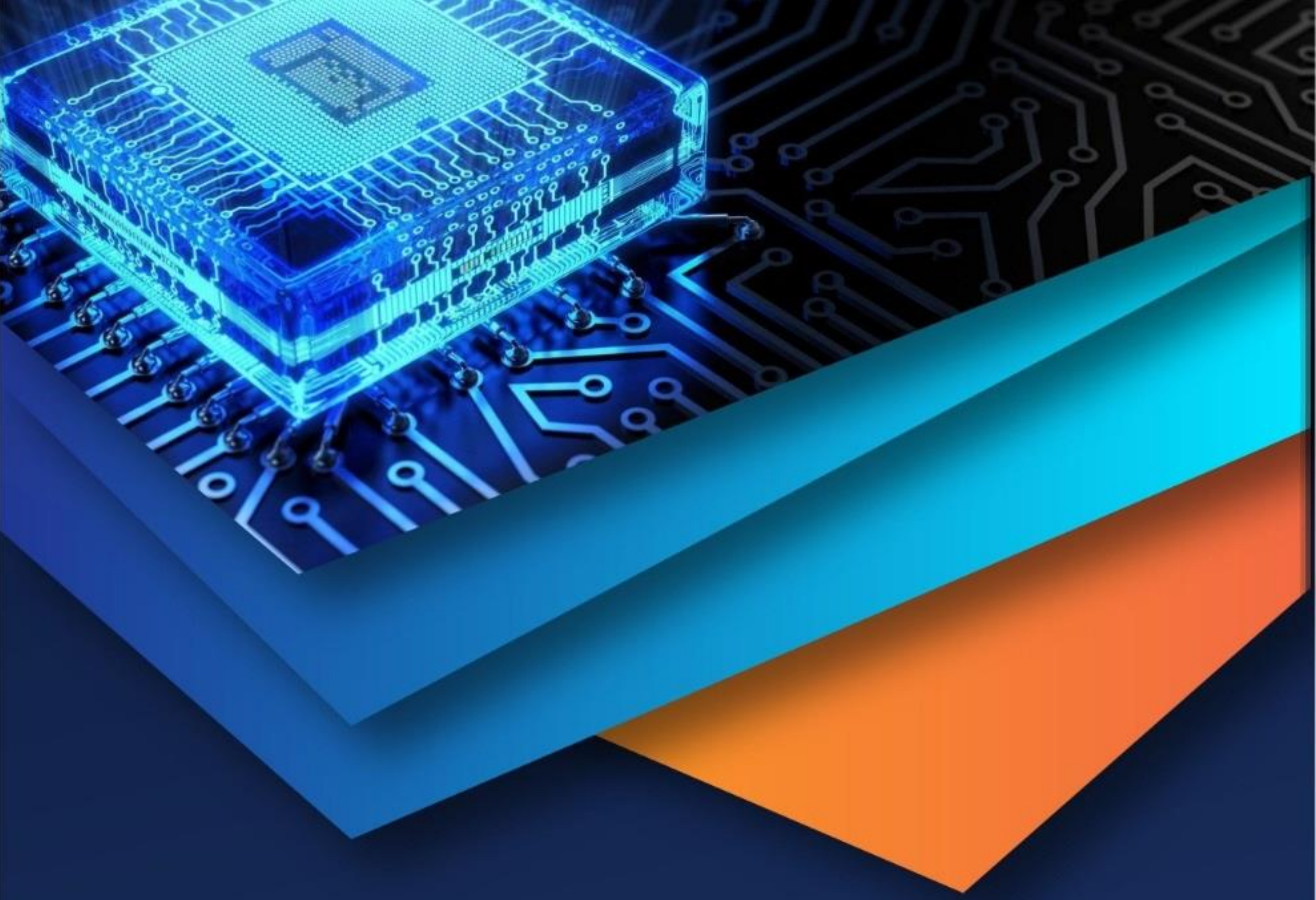

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