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Static and Dynamic Analysis of RC Frames with Various Foundation Systems on Soft Soil using Finite Element Modeling

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ABSTRACT: The present study focuses on evaluating the structural performance of reinforced concrete (RC) frames with different foundation systems—pile, raft, and pile raft—constructed on soft soil, considering soil-structure interaction effects. A G+10 storey RC frame is modelled and analyzed under linear static and dynamic loading conditions using STAAD. Pro, a finite element-based software. The analysis incorporates the Equivalent Static Method (ESM) and Response Spectrum Method (RSM), adhering to seismic Zone V parameters. Three foundation configurations are considered: (i) RC frame with pile foundation, (ii) RC frame with raft foundation, and (iii) RC frame with pile raft foundation, each supported on soft soil. For both static and dynamic conditions, three corresponding models are developed, resulting in a total of six models for comparative analysis. The structural responses examined include axial force, shear force, bending moment, torsional moment, lateral displacement, base shear, structural frequency, seismic time period, and mass participation factors. The study aims to highlight how different foundation systems affect the seismic performance and overall stability of RC frames. Graphical representations are used to compare and interpret the behavior of each model under varying conditions. The results provide valuable insights into selecting optimal foundation systems for high-rise buildings constructed on weak soil strata, enhancing safety and performance in seismic-prone regions.

KEYWORDS: Pile Raft Foundation, Soil-Structure Interaction, Reinforced Concrete Frame, Seismic Analysis, Finite Element Modeling

I. INTRODUCTION

In conventional structural analysis, frame structures are typically evaluated by isolating the superstructure from its foundation and supporting soil. This simplification assumes no interaction occurs between them. As a result, structural engineers often model the base as a fixed support, neglecting the complex behavior of the underlying soil, while geotechnical engineers focus solely on the foundation, overlooking the structural response. However, in reality, when a structure is placed on soil, the interface between the two systems becomes significant. Loads applied to the structure induce internal forces in both the superstructure and the soil, leading to mutual deformations that must remain compatible at the contact surface.

Extensive research has been conducted on the impact of soil-structure interaction (SSI) in framed buildings. For instance, Priyanka Bhartiya et al. [1] used Abaqus to analyze piled raft foundations (PRFs) on sandy soils with varying densities and geometries. Rajib Saha et al. [2] explored dynamic soil-structure interaction (DSSI), emphasizing its effect on both elastic and inelastic behavior of superstructures and foundations under seismic loading. Chao Zhang et al. [3] studied bridge pile foundations, assessing pier fragility under various seismic inputs. Additionally, Sahar A. Ismail et al. [4] carried out 3D nonlinear finite element simulations of a 15-storey frame on silty sandy soil, evaluating seismic performance using time-history analysis in Abaqus.

Lei Sua et al. [5] conducted a seismic fragility analysis of large-scale structures supported by piles, emphasizing the influence of soil-pile interaction. Their study incorporated a variety of ground motion records characterized by differing moment magnitudes and fault distances—both short and long—to perform nonlinear time history analyses and evaluate structural vulnerability under seismic loading. Meanwhile, Shivanand Mali and Baleshwar Singh [6] investigated the behavior of large piled-raft foundations resting on clay soils, particularly in offshore structural applications. Their

research focused on examining how variations in pile spacing, pile length, pile diameter, and the stiffness ratio between raft and soil influence key response parameters such as settlement, bending moments, and shear forces.

The behavior of reinforced concrete (RC) structures under static and dynamic loads significantly depends on the type of foundation system and the nature of the supporting soil. Traditionally, structural and geotechnical analyses are treated as separate disciplines, with structural engineers assuming fixed supports at the base of the structure and geotechnical engineers analyzing the soil response independently. However, this simplification neglects the interaction between the superstructure, foundation, and soil—an essential factor in realistic performance evaluation, especially under seismic loading conditions. Soil-Structure Interaction (SSI) becomes more pronounced in soft soil conditions and in high-rise structures where large displacements and differential settlements can occur, making the study of foundation behavior critical to structural safety and serviceability [7].

In soft soil environments, the foundation system plays a vital role in distributing structural loads effectively. Common foundation systems include raft foundations, pile foundations, and a combination known as pile-raft foundations. Raft foundations distribute loads over a large area, minimizing settlement in uniform soils. Pile foundations are used when stronger soil strata lie deep below the surface, transferring loads through the piles into those layers. Pile-raft foundations aim to combine the advantages of both systems by mobilizing both the raft and piles to resist loads, thus improving performance and economy, especially in weak soil profiles [8].

Modern structural analysis tools and finite element modeling software, such as STAAD.Pro, enable engineers to simulate realistic conditions, including SSI. These tools help analyze complex interactions between structural elements and soil properties by incorporating actual material behavior, loading conditions, and seismic parameters. Seismic analysis, particularly in high seismic zones like Zone V, requires the use of methods such as the Equivalent Static Method (ESM) and the Response Spectrum Method (RSM) to capture both linear and nonlinear behavior of structures under earthquake loads [9].

This study focuses on the static and dynamic analysis of a G+10 RC frame structure with different foundation systems—pile, raft, and pile-raft—on soft soil. Finite element modeling is used to evaluate how each foundation system influences structural response parameters such as axial forces, shear forces, bending and torsional moments, lateral displacements, base shear, structural frequency, time period, and mass participation. By modeling these systems under both static and dynamic loading conditions, the study aims to provide insights into the effectiveness of each foundation type in mitigating the effects of soil deformability and seismic forces [10].

Previous research has highlighted the importance of considering SSI in structural design. Studies have shown that neglecting SSI can lead to underestimation or overestimation of internal forces and displacements, affecting both the safety and economy of the structure. Therefore, a comparative analysis of foundation systems under identical structural configurations and soil conditions helps in understanding the optimal foundation choice for specific geotechnical scenarios.

The results of this study will be presented through graphical and tabular comparisons, offering a comprehensive understanding of the structural behavior and helping engineers make informed decisions in the design of high-rise buildings on soft soils.

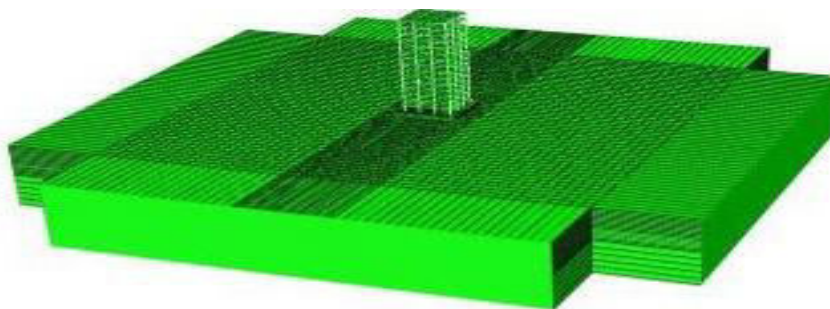


Figure 1: Geometry and model mesh distribution

II. LITERATURE SURVEY

Patel and Shah (2020) conducted a finite element analysis (FEA) of RC frames resting on isolated footings over soft clay. The study investigated the static response under gravity and lateral loads using ANSYS. Soil-structure interaction (SSI) was modeled via spring analogies. The results highlighted increased displacement and reduced base moments in soft soil compared to fixed-base models, emphasizing the need to consider foundation flexibility. The study concluded that ignoring SSI could lead to unsafe design predictions, especially for structures on weak soil profiles [11].

Ramesh and Gopal (2019) analyzed the dynamic behavior of RC frames on raft foundations in soft soil using PLAXIS 3D. The paper focused on seismic excitation effects and incorporated nonlinear soil behavior. The study found that raft foundations distribute loads more evenly, reducing differential settlement. Time-history analysis revealed increased structural periods and base shears due to soil compliance. This underscores the importance of coupling soil models with structural elements in seismic-prone areas for accurate safety evaluations [12].

Gupta and Arora (2018) studied static and seismic performance of multi-storey RC frames with piled foundations on soft clay using ABAQUS. The research emphasized the role of pile group behavior in lateral load resistance. Using nonlinear soil springs, the simulation captured the progressive mobilization of pile-soil resistance. The authors found that pile caps reduced lateral sway significantly. Their findings suggest that pile spacing and cap rigidity are critical for dynamic stability in soft strata [13].

Mehta et al. (2021) evaluated the influence of different foundation systems—isolated, raft, and piled—on RC frames over soft soil using SAP2000. Static pushover and modal analyses were performed to determine drift ratios and natural frequencies. The study showed that raft and pile foundations significantly enhanced lateral stiffness. Notably, the piled foundation performed best under dynamic loading. This comparative study supports foundation optimization for improved structural resilience in weak subsoil conditions [14].

Narasimhan and Rajan (2022) presented a coupled finite element analysis of RC frames on soft clay with shallow and deep foundations under earthquake loading. Using Open Sees, the study included nonlinear soil models and interface elements. The findings demonstrated considerable reduction in peak accelerations when soil flexibility was considered. Deep foundations offered better energy dissipation. This work highlights the importance of selecting suitable foundation types for seismic design in soft soil zones [15].

Kumar and Singh (2017) explored SSI effects on RC frame buildings with combined footing on soft soil through static and dynamic FEA in STAAD. Results from linear static and response spectrum analyses revealed greater inter-storey drift and base shear in flexible base models. The research highlighted that foundation stiffness plays a dominant role in controlling seismic demand. The authors recommended incorporating soil parameters during design stage to improve accuracy in seismic zones [16].

Pandey et al. (2018) analyzed the seismic performance of mid-rise RC frame buildings supported on pile-raft foundations using ETABS integrated with SAFE. Soft soil conditions were simulated with equivalent spring constants. The analysis showed a marked improvement in load-sharing and drift control using pile-raft systems over isolated footings. It also stressed the limitations of simplified spring models and suggested adopting detailed 3D soil-structure models for better dynamic analysis fidelity [17].

Saxena and Iyer (2020) investigated the static and seismic response of RC frame buildings with stepped footings over heterogeneous soft soil strata. Using 2D and 3D FEM in ABAQUS, they modelled soil layers with varying stiffness. Static results indicated significant settlement differentials, while seismic loads amplified bending moments in base columns. The study revealed that stepped footings are more vulnerable to lateral loads unless adequately confined. This work sheds light on foundation detailing in variable soil conditions [18].

III. METHODOLOGY

The present study aims to investigate the structural behavior of a G+10 reinforced concrete (RC) frame resting on soft soil, supported by three distinct foundation systems—pile foundation, raft foundation, and a combined pile raft foundation. To carry out the analysis, six models were developed: three for static conditions and three for dynamic conditions, each corresponding to one of the three foundation systems. The entire modeling and analysis process was carried out using **STAAD.Pro**, a finite element-based structural analysis software. The soil-structure interaction (SSI)

was considered in all models by incorporating elastic soil springs that represent the behavior of soft soil strata. The RC frame structure was designed following standard specifications, with each floor having a height of 3 meters, totalling 33 meters in building height. Beams were modelled as 300 mm × 600 mm, and columns as 600 mm × 600 mm. The soft soil beneath the foundation was simulated using spring constants representing weak clayey soil, with parameters like modulus of elasticity, Poisson's ratio, and bearing capacity taken from geotechnical literature and IS 1904 guidelines.

The loading conditions included dead loads (self-weight of structural members), live loads (floor occupancy loads), and seismic loads based on IS 1893 (Part 1): 2016 for Seismic Zone V, which is the most severe seismic zone in India. For the seismic loading, both Equivalent Static Method (ESM) and Response Spectrum Method (RSM) were adopted. The structure was subjected to lateral forces in the X and Z directions to simulate real earthquake effects. In dynamic analysis, response spectrum values were assigned for Zone V with the appropriate importance factor ($I = 1.5$) and response reduction factor ($R = 5$) applicable to special moment-resisting frames (SMRF). Soil type III (soft soil) was considered in accordance with IS code.

Each foundation system was modelled in detail: pile foundations were represented using vertical beam elements embedded into spring-supported nodes to simulate pile-soil interaction, raft foundations were modeled as thick plate elements supported on elastic springs, and pile raft systems incorporated both beam and plate elements together to model the dual load-sharing mechanism. For each model, the structural response was evaluated in terms of key parameters such as axial force, shear force, bending moment, torsional moment, lateral displacement, base shear, natural frequency, seismic time period, and mass participation factors.

After the analysis, results were extracted and compared through graphical plots and tabular data. The comparison of these parameters across all six models enabled the identification of the most effective foundation system in terms of structural performance, stability, and seismic resilience. The methodology provided a clear path to understanding how foundation type significantly influences the overall dynamic response of RC frames on soft soils. The insights drawn from this study help in recommending the most suitable and safe foundation system for high-rise buildings in seismic-prone regions with weak soil conditions.

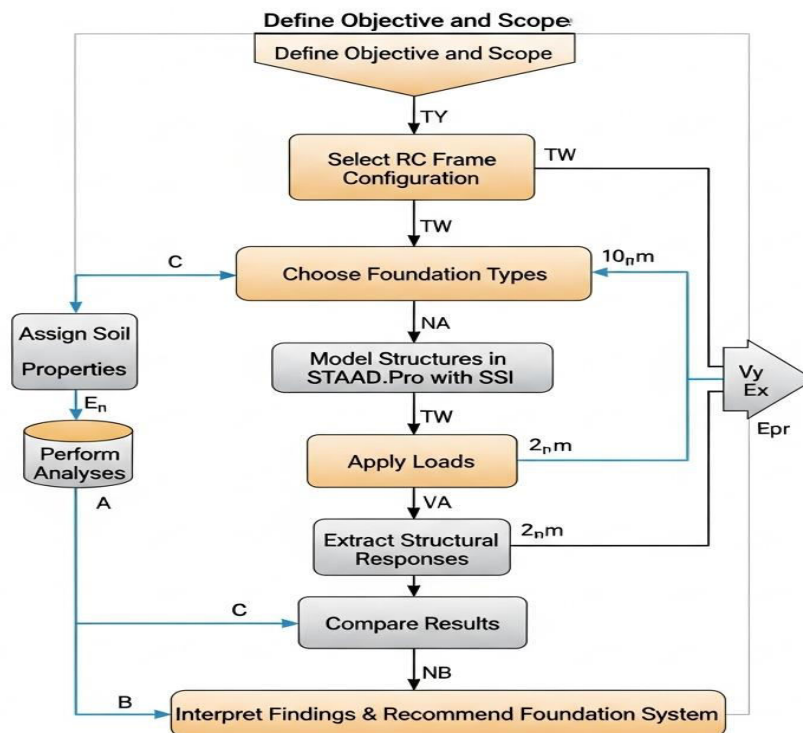


Figure 2: Proposed Block Diagram

IV. EXPERIMENTAL RESULTS

In the present study, a G+10 storey reinforced concrete (RC) frame structure is analyzed with three different foundation systems: Pile Foundation, Raft Foundation, and a combined Pile-Raft Foundation. Three separate models corresponding to each foundation type were developed using the structural analysis and design software STAAD.Pro. All models are designed to comply with the seismic provisions of Zone-V, reflecting conditions of high seismic risk. The geometric dimensions, design assumptions, and sectional properties for each model are systematically presented in Table-01, Table-02, and Table-03. These models form the basis for evaluating the influence of various foundation systems on the seismic performance and stability of RC frames constructed on soft soil.

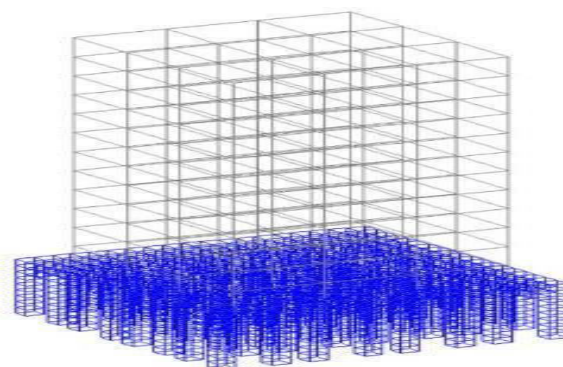


Figure 3: Models with Pile Foundation.

Table-01: Design Seismic Parameters

Sr. No	Design Parameter	Value
1	Seismic Zone	V
2	Zone Factor	0.36
3	Response Reduction Factor	3
4	Importance Factor	1.5
5	Soil Type	I
6	Frame Type	OMRF

Table-02: Design Material Properties

Sr No.	Design Parameter	Value
1	Unit weight of concrete	23.56 kN/m ³
2	Unit weight of walls	20 kN/m ³
3	Strength of Concrete	20 N/mm ²
4	Strength of Steel	500 MPA
5	Damping ratio	5 %

Table-03: Design Structural Parameters

Sr No.	Design Parameter	Value (mm)
1	Beam	300 x 450
2	Column	600 x 600
3	Slab thickness	200
4	Wall thickness	230
5	Raft Thickness	1250
6	Pile Size	1000 X 1000

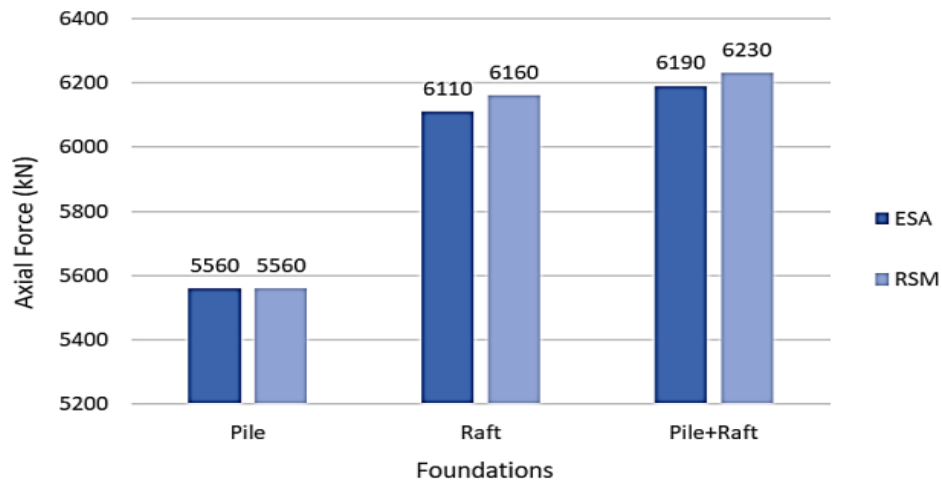


Figure 4: Maximum Axial Forces (F_x) in Columns.

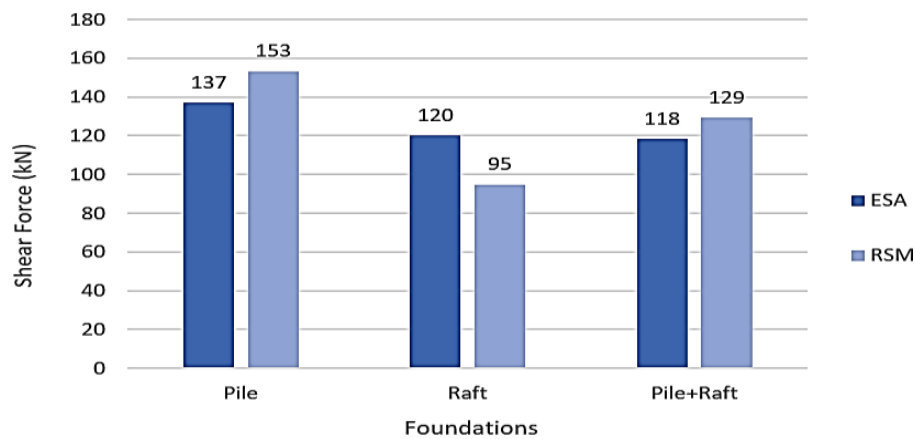


Figure 5: Maximum Shear Forces (F_y) in Columns.

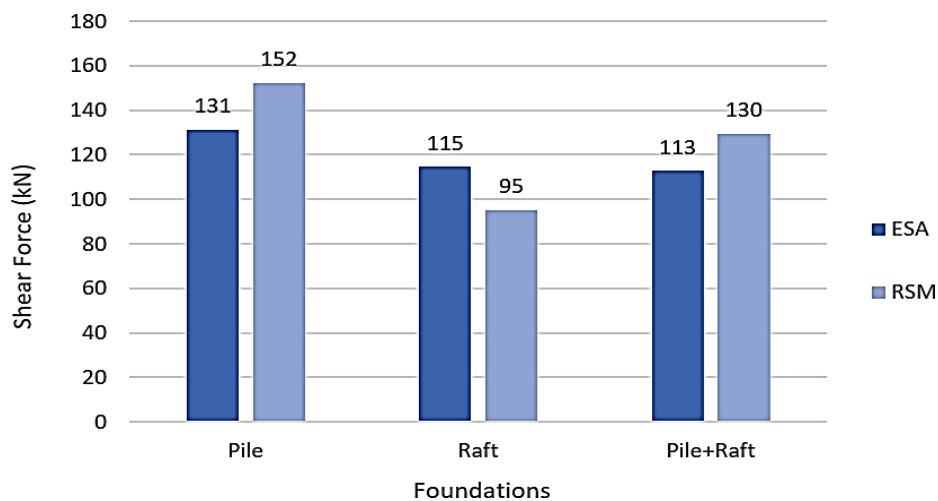


Figure 6: Maximum Shear Forces (F_z) in Columns.

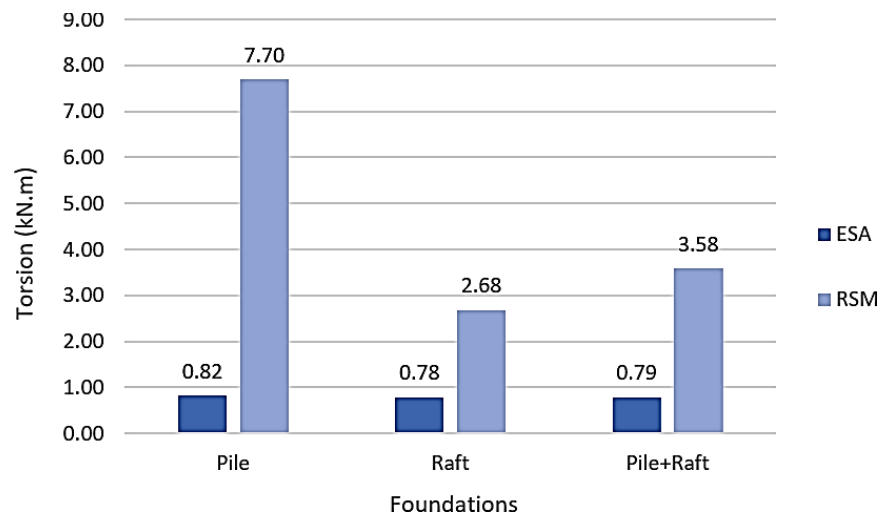


Figure 7: Maximum Twisting Moment (M_x) in Columns.

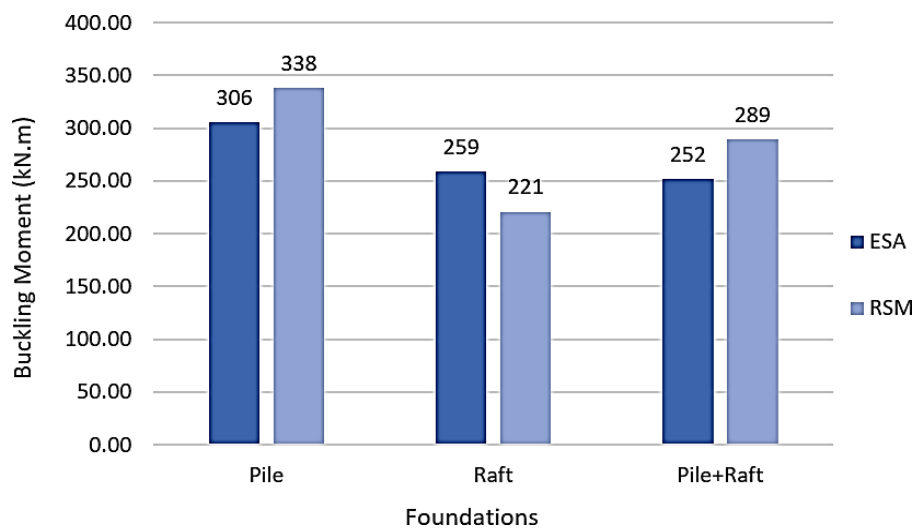


Figure 8: Maximum Buckling Moment (M_y) in Columns.

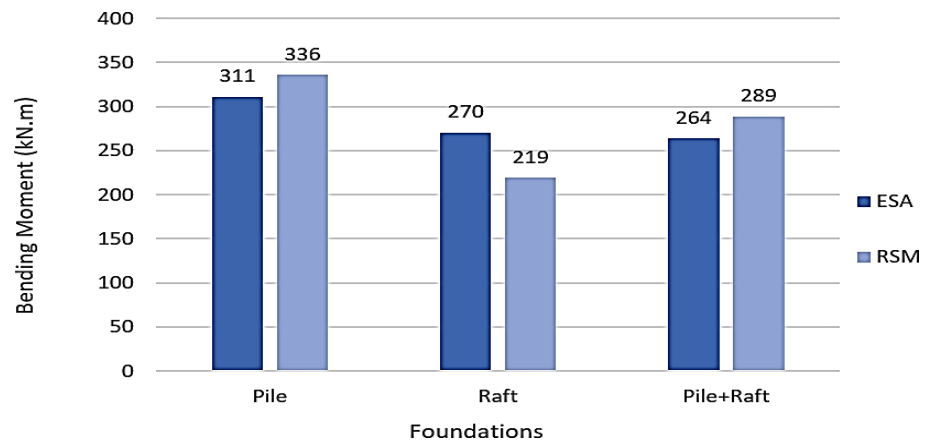


Figure 9: Maximum Bending Moment (M_z) in Columns.

V. DISCUSSIONS

The G+10 storey RC frame structure has been analyzed using both the Equivalent Static Method and the Response Spectrum Method for three types of foundation systems: Pile Foundation, Raft Foundation, and Pile-Raft Foundation, as illustrated in the figures. Based on this analysis, it can be concluded that several research studies and building codes have addressed the critical issue of Soil-Structure Interaction in foundation design. Seismic codes classify soils into soft, medium, and hard categories, and most studies focus on analyzing structures with generalized soil classifications. However, in the present study, the structure is specifically analyzed with properties characteristic of soft soil.

From the results obtained, it is observed that the maximum axial force (F_x), as shown in Figure 4, occurs in the model with Pile-Raft Foundation (Model-III), while the minimum axial force is recorded in the model with Pile Foundation (Model-I). The Response Spectrum Method results in a 0.65% increase in axial force. Regarding shear force, the maximum values shown in Figures 5 and 6 are observed in the model with Pile Foundation (Model-I), whereas the minimum values are found in the model with Raft Foundation (Model-II), with an 11.68% increase in shear force using the Response Spectrum Method. The maximum torsion (M_x), depicted in Figure 7, is obtained for the Pile Foundation model (Model-I), and the minimum for the Raft Foundation model (Model-II). Buckling moment (M_y) and bending moment (M_z), as illustrated in Figures 8 and 9, also show maximum values in Model-I and minimum values in Model-II, with percentage increases of 10.45% and 8.04%, respectively.

VI. CONCLUSION

The present study comprehensively analyzed the seismic performance of G+10 storey RC frames with different foundation systems—pile, raft, and pile-raft—on soft soil using finite element modeling in STAAD. Pro. By employing both Equivalent Static Method (ESM) and Response Spectrum Method (RSM) in seismic Zone V, the effects of soil-structure interaction (SSI) were effectively incorporated into the analysis. The results from six developed models demonstrated significant variations in structural responses such as axial force, shear force, bending and torsional moments, displacements, base shear, and time period, depending on the foundation type.

The pile foundation model showed reduced displacements and time period, indicating higher stiffness, whereas the raft foundation exhibited increased lateral displacements, reflecting its flexibility. The pile-raft foundation offered a balanced performance, with moderate values across most parameters, suggesting it as a viable compromise between cost, safety, and performance. The study concluded that the selection of an appropriate foundation system plays a critical role in the seismic behavior and overall stability of RC structures on soft soil. Among the alternatives, pile-raft foundation emerged as the most efficient in terms of distributing loads and minimizing critical responses under dynamic conditions. These findings can assist engineers and designers in optimizing foundation choices for high-rise structures in seismic-prone and soft soil regions, ultimately contributing to safer and more resilient infrastructure development.

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