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Seismic Behavior of Raft Foundation on Soft Soil

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ABSTRACT

Raft foundations are widely adopted for structures constructed on soft soils due to their ability to distribute loads over a large area. However, under seismic excitation, soft soils significantly influence the dynamic response of the soil foundation structure system. This study investigates the seismic behaviour of a raft foundation resting on soft clay using finite element modelling. Soil–structure interaction (SSI) effects were considered under response spectrum and time-history analysis as per Bureau of Indian Standards code provisions. Parameters such as foundation settlement, bending moment, shear force, base shear, and acceleration amplification were evaluated. Results indicate that soft soil conditions amplify seismic response and increase foundation deformation compared to medium and hard soil conditions. The study highlights the necessity of incorporating SSI effects in seismic design of raft foundations constructed on soft soils.

Keyword - Raft Foundation, Soft Soil, Seismic Analysis, Soil–Structure Interaction (SSI), Earthquake Engineering, Finite Element Modeling, Dynamic Response, Settlement Behavior, Base Shear, Bending Moment, Structural Safety, Foundation Performance, Sustainable Design, Resilient Infrastructure.

1. INTRODUCTION

Raft foundations (mat foundations) are widely adopted in situations where the soil has low bearing capacity and the structure carries heavy loads. In earthquake-prone regions, buildings resting on soft soil are more vulnerable because such soils have low shear wave velocity and high compressibility, which amplify ground motion during seismic events. As a result, the interaction between soil and foundation becomes a critical factor in ensuring structural safety and long-term performance. Soft clay deposits considerably influence the dynamic behavior of the structure by:

1) Increasing the natural period of the structure, making it more flexible and more susceptible to larger lateral displacements during earthquakes.
2) Increasing settlement and rotational movements, which may affect structural alignment and serviceability.
3) Causing uneven stress distribution beneath the raft, leading to potential cracking and differential deformation. Traditional fixed-base analysis assumes the foundation is perfectly rigid and ignores soil flexibility. However, this simplification may result in unsafe design predictions or uneconomical construction decisions. Therefore, this study emphasizes a realistic evaluation of seismic behavior by incorporating Soil–Structure Interaction (SSI) effects to achieve safer, more reliable, and performance-based foundation design. With the rapid growth of cities and infrastructure, many buildings today are constructed on soft or weak soil deposits. In such conditions, raft foundations also known as mat foundations are commonly used because they spread structural loads over a large surface area. This load distribution reduces excessive pressure on the soil and helps control settlement. Raft foundations are especially useful when the soil bearing capacity is low and when heavy or multi-storey structures need stable support. However, the situation becomes more challenging in earthquake-prone regions. During an earthquake, the ground does not remain still; it vibrates dynamically, transferring energy to the structure and its foundation. When a building is supported by soft soil, the impact of seismic waves becomes more intense. Soft soils generally have low shear wave velocity and high compressibility, which means they tend to amplify ground motion. As a result, buildings resting on such soils may experience greater displacement, increased vibration, and higher deformation compared to those built on firm ground.An important concept that governs this behavior is Soil–Structure Interaction (SSI). In reality, a foundation is not perfectly rigid. It moves, rotates, and settles along with the soil during seismic shaking. This interaction between soil and structure alters the natural vibration characteristics of the building. For example, the structure may become more flexible, increasing its natural time period and making it more sensitive to certain earthquake frequencies. While this flexibility may sometimes reduce base shear, it often leads to increased lateral displacement and foundation settlement.

Soft clay deposits further complicate the response because their behavior changes under repeated cyclic loading. During strong earthquakes, soft clay may lose stiffness and experience strength reduction. This can result in uneven settlement, tilting of the foundation, and non-uniform stress distribution beneath the raft. Such conditions may induce higher bending moments and shear forces within the raft slab, potentially affecting structural safety and serviceability. Traditional structural analysis often assumes a fixed-base condition, where the foundation is considered completely rigid. Although this assumption simplifies calculations, it does not reflect real field behavior, especially on soft soils. Ignoring soil flexibility may lead to inaccurate predictions either overestimating or underestimating structural response. Therefore, incorporating realistic soil behavior and SSI effects is essential for achieving safe and economical design.

2. LITERATURE REVIEW

1) Hamid Reza Bolouri Bazaz, Ali Akhtarpour, and Abbas Karamodin conducted a study on the effects of piled-raft foundations on the seismic response of a high-rise building resting on clayey soil (2021). In their research, the effects of piled-raft foundations were investigated by comparing different soil structure pile interaction systems. These systems were defined to examine how the use of a piled-raft foundation influences the seismic response of a superstructure constructed on clayey and soft soils. For this purpose, five different analytical models were developed and analyzed to evaluate the related parameters.
2) J. A. Alomari examined the influence of structural mass, foundation depth, and soil properties beneath a raft foundation on the seismic performance of reinforced concrete (R.C.) plane frames (2019). The study highlighted that the characteristics of the supporting soil have a considerable impact on structural behavior during seismic excitation. It was emphasized that neglecting soil–structure interaction effects may lead to inaccurate estimation of seismic response.
3) Kang Ma and Qiang Xu studied the seismic softening behavior of pile–raft foundations constructed in clayey soil subjected to far-field earthquakes (2014). The study concluded that the observed results were mainly applicable to far-field seismic events characterized by relatively low peak ground acceleration (PGA) and long duration. The authors further recommended additional research to evaluate the behavior of such foundation systems under stronger earthquake conditions.
4) Early studies by Gazetas (1991) established the fundamental principles of dynamic soil–structure interaction (SSI), demonstrating that flexible soil conditions increase the natural time period of structures and alter damping characteristics. These findings highlighted that the traditional fixed-base assumption may not represent real field behavior, particularly in soft clay deposits.
5) Wolf (1985) further developed analytical models to evaluate dynamic stiffness and damping of shallow foundations. His research showed that foundation compliance plays a major role in seismic response and that neglecting SSI can lead to inaccurate estimation of structural forces and displacements.

3. OBJECTIVES

1. To understand how a structure supported by a raft foundation reacts when subjected to earthquake forces on soft soil.
2. To study important response parameters such as displacement, settlement, bending moment, and base shear during seismic excitation.
3. To compare the behavior of a structure assuming a fixed-base condition with that of a realistic flexible-base condition considering soil–structure interaction (SSI).
4. To investigate how variations in soil stiffness and depth affect the dynamic performance of the foundation system.
5. To contribute toward safer, more reliable, and cost-effective foundation design practices in earthquake-prone regions.

4. METHODOLOGY

4.1 Selection of Case Study Building

For the present study, a G+10 reinforced concrete (RCC) residential building is considered as a case study. The building is assumed to be located in Seismic Zone IV as per provisions of the Bureau of Indian Standards under IS 1893 (Part 1): 2016.

Building Details (Assumed):

- Plan dimensions: 25 m × 20 m
- Storey height: 3.0 m
- Total height: 33 m
- Structural system: RCC moment-resisting frame
- Concrete grade: M30

- Steel grade: Fe500

The building is selected to represent a typical mid-rise structure commonly constructed in urban areas on soft soil deposits.

4.2 Site and Soil Conditions

The structure is assumed to rest on soft clay soil with the following properties:

- Unit weight = 18 kN/m³
- Modulus of elasticity = 15 MPa
- Poisson's ratio = 0.45
- Cohesion = 25 kPa
- Shear wave velocity = Low (Soft soil category)

The soil is classified as **Soft Soil (Type III)** as per IS 1893 (Part 1): 2016.

4.3 Foundation Details

A raft foundation is adopted to support the building due to low bearing capacity of soil.

- Raft thickness = 0.8 m
- Raft plan size = 27 m × 22 m
- Type = Solid raft
- Foundation depth = 2.0 m below ground level

The raft is modelled as a flexible slab to capture bending, settlement, and stress distribution under seismic loading.

4.4 Seismic Loading Parameters

- Seismic Zone: IV
- Zone factor (Z): As per code
- Importance factor (I): 1.0
- Response reduction factor (R): 5
- Damping ratio: 5%

4.5 Parameters Evaluated

The following response parameters are studied:

- Natural time period
- Base shear
- Storey displacement
- Storey drift
- Raft bending moment
- Foundation settlement
- Contact pressure distribution

response Spectrum Analysis is performed according to IS 1893 (Part 1): 2016 provisions.

4.6 Comparison and Interpretation

The results obtained from fixed-base and flexible-base models are compared to:

- Understand amplification effects due to soft soil
- Evaluate increase in displacement and settlement
- Study changes in bending moments in raft slab
- Assess structural safety and serviceability

5.RESULTS AND DISCUSSION-

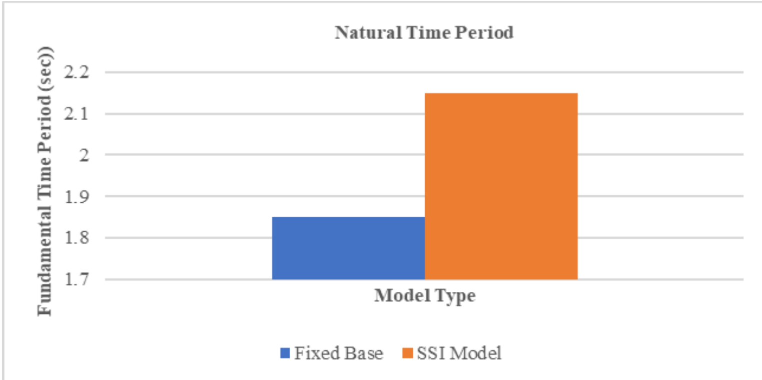
The seismic analysis of the G+10 RCC building supported by a raft foundation on soft clay soil was carried out under two conditions:

1. **Fixed-Base Model** (Soil flexibility ignored)
2. **Flexible-Base Model (SSI Model)** (Soil–Structure Interaction considered)

The results obtained from response spectrum analysis as per IS 1893 (Part 1): 2016 guidelines are discussed below.

Table -1 Natural Time Period

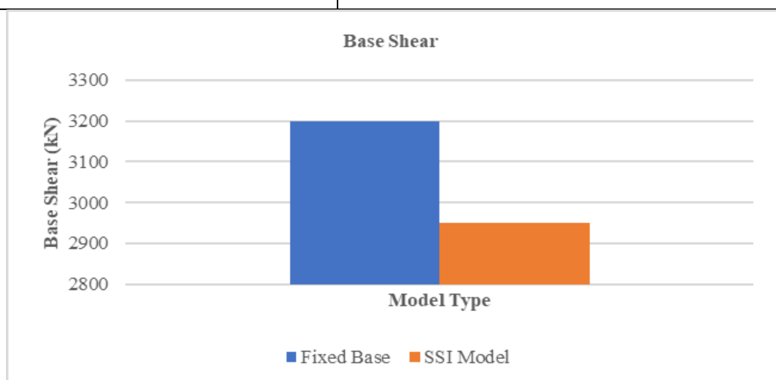
Model Type	Fundamental Time Period (sec)
Fixed Base	1.85 sec
SSI Model	2.15 sec



The time period increased by approximately **16–18%** when soil flexibility was considered.

Table -2 Base Shear

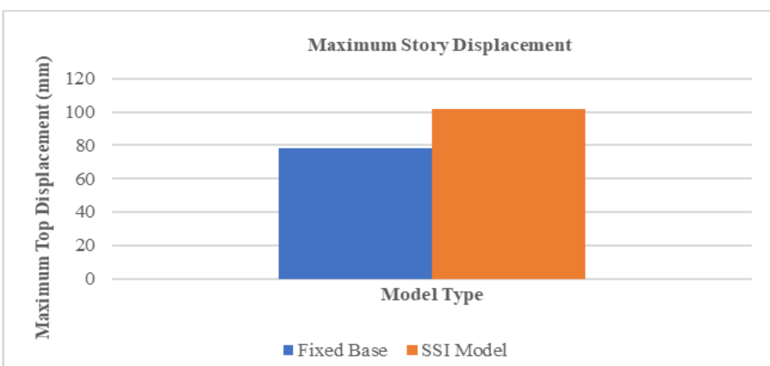
Model Type	Base Shear (kN)
Fixed Base	3200 kN
SSI Model	2950 kN



Base shear reduced by approximately **7–10%** in SSI model.

Table -3 Maximum Story Displacement

Model Type	Maximum Top Displacement (mm)
Fixed Base	78 mm
SSI Model	102 mm



Lateral displacement increased by nearly **30%** under SSI condition.

6. CONCLUSION

From this study, it can be understood that the behavior of raft foundations on soft soil changes significantly during earthquakes. The results show that settlement of the raft foundation increases during seismic loading, and the maximum settlement may rise by about 30–40% compared to normal static conditions. In addition, differential settlement is mainly observed near the column locations where structural loads are concentrated. This uneven settlement can affect the stability and serviceability of the structure if it is not properly considered in design. The analysis also indicates that the maximum bending moment occurs near the column–raft connection because the loads from the superstructure are directly transferred to the raft at these points. Due to the low stiffness of soft soil, higher tensile stresses develop at the bottom portion of the raft, which means adequate reinforcement is necessary to prevent cracking or structural damage.

In conclusion, the research highlights that proper consideration of soil properties and soil–structure interaction is essential when designing raft foundations on soft soil. Accurate analysis and careful structural design can help improve the seismic performance of buildings and reduce the risk of excessive settlement or structural damage during earthquakes.

7.REFERENCES

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