Seismic Performance Assessment of RC Buildings Considering Combined Effects of Soil Structure Interaction and Soil Liquefaction

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Abstract - *Conventional seismic analysis of reinforced concrete (RC) buildings generally assumes a fixed base and ignores the flexibility of the supporting soil and the degradation of soil properties during liquefaction. In reality, the soil, foundation, and superstructure interact during earthquake loading, and this interaction can significantly modify the structural response. The present study evaluates the seismic performance of a G+30 RC building by considering Soil Structure Interaction (SSI) and soil liquefaction. Four analytical models were developed in ETABS 2021: (i) fixed-base model, (ii) SSI model with raft foundation, (iii) SSI model with pile foundation, and (iv) SSI with soil liquefaction model using reduced spring stiffness. Response Spectrum Analysis was carried out in accordance with IS 1893 (Part 1): 2016 for Seismic Zone III and soft soil conditions. The results indicate that SSI increases the fundamental time period, lateral displacement, and inter-storey drift, while base shear decreases compared with the fixed-base model. The combined SSI and liquefaction model produced the highest displacement and drift because of the reduction in soil stiffness. The study demonstrates that neglecting SSI and liquefaction may lead to an unrealistic assessment of seismic demand, particularly for high-rise buildings on soft soils. Incorporating both effects provides a more reliable basis for earthquake-resistant design and performance evaluation.*

Key Words: Soil Structure Interaction, Soil Liquefaction, ETABS, Response Spectrum Analysis, RC Building, Pile Foundation, Raft Foundation, Seismic Performance

1. INTRODUCTION

The seismic performance of reinforced concrete (RC) buildings is influenced not only by the structural system but also by the behaviour of the supporting soil and foundation. Conventional seismic analysis generally assumes a fixed-base condition, neglecting the effects of Soil Structure Interaction (SSI), which may lead to inaccurate prediction of structural response, particularly for high-rise buildings constructed on soft soils [1], [2], [12].

Soil Structure Interaction represents the dynamic interaction between the soil, foundation, and superstructure during earthquake loading. The flexibility of the supporting soil modifies the overall stiffness and damping of the structural system, resulting in changes in the natural time period, base shear, storey displacement, and inter-storey drift [6], [8], [10]. These effects become more significant for tall buildings and pile-supported foundations.

In addition to SSI, soil liquefaction is another critical factor affecting seismic performance. During strong earthquakes, saturated loose sandy soils may lose their strength and stiffness due to the development of excess pore water pressure, leading to excessive settlement, foundation instability, and increased structural deformation [2]. Although several studies have investigated SSI and liquefaction independently, research addressing their combined influence on high-rise RC buildings is still limited [6][11].

Therefore, this study evaluates the seismic performance of a G+30 reinforced concrete building by considering four analytical models: fixed-base, raft foundation with SSI, pile foundation with SSI, and SSI with soil liquefaction. The models are analysed using ETABS 2021 through Response Spectrum Analysis in accordance with IS 1893 (Part 1): 2016. The seismic response is assessed by comparing the fundamental time period, base shear, storey displacement, and inter-storey drift to understand the influence of soil flexibility and liquefaction on structural behaviour.

1.2 LITERATURE REVIEW

Azra Hanna Razvi J.B. et al. (2018) compared fixed base and flexible base (Winkler spring) models of an asymmetrical G+10 RC building in ETABS across two seismic zones, finding that SSI increased storey displacement and drift while leaving the base overturning moment nearly unchanged, and cautioned that ignoring SSI underestimates drift and displacement.

Rahul Raghunath Kharade & M. V. Nagendra (2020) studied a G+12 RC frame on clayey soil with a raft foundation on soil springs, reporting 4 10% higher lateral displacement, 5 10% higher storey drift, and a slightly longer time period under SSI, with base shear largely unchanged.

Konstantinos Kassas et al. (2022) showed that a neighbouring building on liquefiable soil worsens displacement, base shear, and settlement compared with an isolated building, so ignoring building to building SSI on liquefiable ground can underestimate seismic demand.

Faisal Mehraj Wani et al. (2022) modelled a G+10 RC building on a mat foundation using Winkler springs, pseudo coupled springs, and finite elements, finding SSI increases natural period and storey drift while generally reducing base shear, more so on softer soils.

Waleed Dawoud et al. (2024) used fully nonlinear 3D finite element analysis (Plaxis 3D) on a 25 storey building with a piled raft foundation, finding SSI lengthened the fundamental period by about 12%, increased displacement and drift, and reduced base shear to 27 33% of the fixed base value, with pile length optimisation offering diminishing returns beyond about 40% of the reference length.

Tallah Naoui (2024) modelled an 18.4 m slender RC minaret in SAP2000 under fixed base, rigid raft, and flexible spring conditions, finding top displacement ranged from 2.35 cm (rigid raft) to 8.23 cm (flexible spring), concluding that foundation flexibility assumptions strongly govern the predicted seismic response of slender structures.

B. Bapir et al. (2023) reviewed SSI modelling approaches (Winkler springs, lumped parameter models, BNWF, and full continuum models), concluding that SSI generally increases natural period and inter storey drift while reducing base shear, and identified layered soils, structure to structure pounding, and irregular geometry as continuing research gaps.

K. Yang et al. (2024) used ABAQUS to study 10 , 20 , and 30 storey RC frame shear wall buildings on sand and loess soil under long period ground motion, finding SSI increases sway and drift while lowering shear force and natural frequency, and warned that code based shear reductions for soil flexibility may be unsafe under long period shaking.

Sandhya, V. and Shubhalakshmi, B. S. (2025) analysed a G+10 reinforced concrete building with regular and irregular configurations supported on raft foundations using the Winkler spring model in ETABS. Response Spectrum Analysis showed that SSI reduced base shear but increased the natural period, lateral displacement, storey drift, and column moments. The study concluded that irregular buildings on soft soil are more sensitive to SSI effects.

N. Sharma et al. (2025) used nonlinear static pushover analysis on RC frame and wall frame systems on piles, finding soil pile foundation structure interaction reduces ductility by up to 39% for wall frame systems and 12% for frame systems through rocking and inelastic pile group behaviour.

T. S. Gulve et al. (2025) analysed a ten storey vertically irregular RC moment resisting frame on a raft foundation using Winkler spring and elastic continuum SSI models across hard, medium, and soft soils, finding SSI effects on period, displacement, and drift are more pronounced in vertically irregular structures than conventional fixed base analysis assumes.

Saad, G. et al. (2025) developed an equivalent Winkler spring model for mat foundations resting on clay using three-dimensional finite element analysis. The study showed that soil spring stiffness varies across the foundation due to stress redistribution and soil plasticity. Variable spring stiffness provided more accurate predictions of settlement and bending moments than conventional uniform spring models.

K. Varsha et al. (2025) compared fixed base and flexible base G+5, G+7, and G+10 RC buildings under response spectrum analysis, finding the largest time period increase (49.6%) and a base shear reduction of over 22% for the G+10 building, alongside a 74 79% rise in roof displacement across all heights, concluding taller buildings are more sensitive to soil flexibility.

1.3 OBJECTIVES

The main objective of this study is to evaluate the seismic performance of RC buildings by considering the combined effects of Soil–Structure Interaction and soil liquefaction. The specific objectives are:

- To model soil flexibility using spring-based SSI representation.
- To simulate liquefaction through soil stiffness degradation.
- To compare the seismic response under fixed-base, SSI, and SSI with liquefaction conditions.
- To assess the influence of raft and pile foundations on seismic performance.
- To provide recommendations for realistic seismic analysis and design.

2. METHODOLOGY

A numerical modelling approach was adopted using ETABS 2021. A three-dimensional G+30 RC building was modelled with beams, columns, slabs, and shear walls. The building has a plan size of 40 m × 40 m and a total height of 90 m. M40 concrete and Fe550 reinforcement steel were used. Seismic analysis was performed according to IS 1893 (Part 1): 2016 for Zone III, soft soil, R = 5, and 5% damping.

Four analytical models were considered:

- Model 1: Fixed-base building.
- Model 2: SSI model with raft foundation.
- Model 3: SSI model with pile foundation.

- Model 4: SSI with soil liquefaction using reduced spring stiffness.

The raft foundation was modelled as a reinforced concrete raft resting on Winkler springs. The pile foundation was represented through winkler spring stiffness derived from geotechnical parameters. Liquefaction was incorporated by reducing the stiffness of the soil springs to simulate the loss of soil rigidity during earthquake shaking. Response Spectrum Analysis was then carried out for all models.

Table -1: Structural details

Storey Details	G+30
Plan Size	As Per Plan
Height of Building	90 m
Columns	From Ground to 14th Floor 650 mm x650 mm
	From storey 15th to 24th 550 mm x 550 mm
	From storey 25th to 30th 500 mm x 500 mm
Floor to Floor Height	3.0 m
Shear wall thickness	230 mm
Beam Size	230mm x 750 mm Sizes used as per structural framing requirements
Grade of concrete	M40
Grade of steel	Fe 550
Density of RCC	25 kN/m^3

2.1 Model 1: Fixed-base building.

The reinforced concrete G+30 building was modelled in ETABS 2021 assuming a perfectly fixed support condition at the foundation level. Soil flexibility was neglected, and all translational and rotational degrees of freedom at the base were restrained. This model served as the reference for comparison

2.2 Model 2:SSI with raft foundation

The fixed supports were replaced with six-degree-of-freedom Winkler spring elements representing the stiffness of the supporting soil. The raft foundation was modelled as a reinforced concrete shell element, while translational and rotational spring stiffness values were calculated using the winkler subgrade modulus approach to simulate soil flexibility.

2.3 Model 3 SSI with pile foundation

The building was modelled on a pile supported foundation. The pile group was represented using winkler spring stiffness, derived for the stiffness of individual piles. This model accounts for the dynamic behaviour of the pile soil foundation system under seismic loading.

2.4 Model 4 SSI with Soil Liquefaction Pile foundation

To simulate liquefaction effects, the soil spring stiffness was reduced based on degraded soil properties obtained from the geotechnical investigation. The liquefied soil condition was incorporated by assigning spring and the settlement value is calculated by Tokimatsu and seed 1987. This model represents the combined influence of Soil Structure Interaction and soil liquefaction on the seismic response of the building.

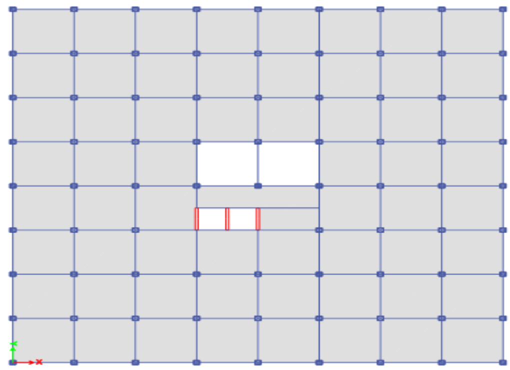


Fig no. 1 ETABS PLAN

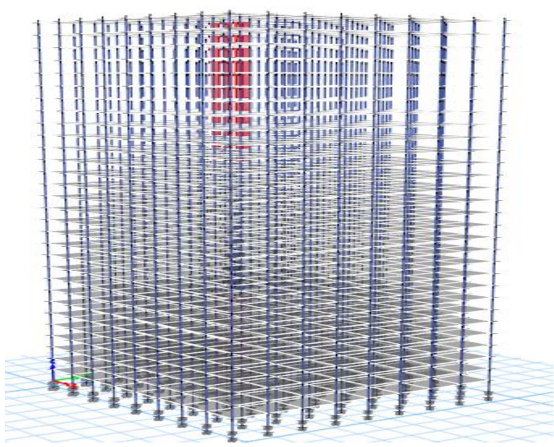


Fig no.2 3D View of ETABS

3. RESULT

Response Spectrum Analysis was carried out for four analytical models: Fixed Base (Model 1), Raft Foundation with SSI (Model 2), Pile Foundation with SSI (Model 3), and SSI with Soil Liquefaction (Model 4). The seismic response was evaluated in terms of modal mass participation, fundamental time period, base shear, storey displacement, and inter-storey drift.

The fixed-base model exhibited the highest overall structural stiffness and served as the reference model. Incorporating Soil–Structure Interaction through the raft foundation (Model 2) increased the fundamental time period by approximately 17.1%, indicating a reduction in structural stiffness. Consequently, roof displacement increased by 45.3% in the X-direction and 48.4% in the Y-direction, while the maximum storey drift increased by 39.2% and 44.8%, respectively.

The pile foundation SSI model (Model 3) showed improved seismic performance compared with the raft foundation model. The increased stiffness of the pile-supported foundation reduced the fundamental time period by 7.4%, roof displacement by 29.7% (X) and 32.8% (Y), and maximum storey drift by 34.2% (X) and 33.1% (Y), demonstrating better control of lateral deformation.

The SSI model considering soil liquefaction (Model 4) produced the largest fundamental time period (3.853 s), indicating the maximum reduction in foundation stiffness. The base shear increased by approximately 3.6% compared with the fixed-base model because of the modified dynamic characteristics of the liquefied soil. All analytical models satisfied the modal mass participation and storey drift requirements specified in IS 1893 (Part 1): 2016, confirming the adequacy of the adopted modelling approach.

Chart no.1 Base Shear in X and Y direction

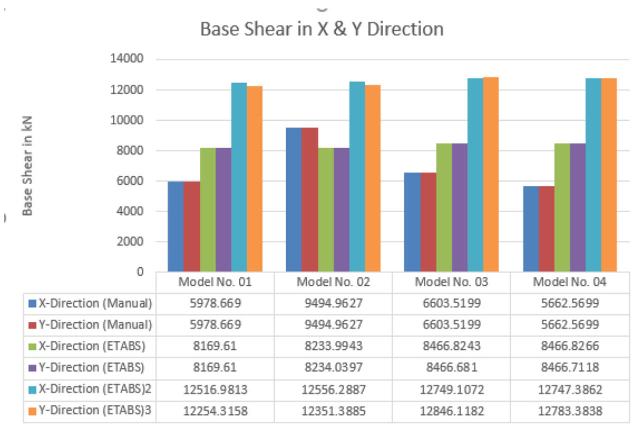


Chart no.2 Storey Displacement in X and Y direction

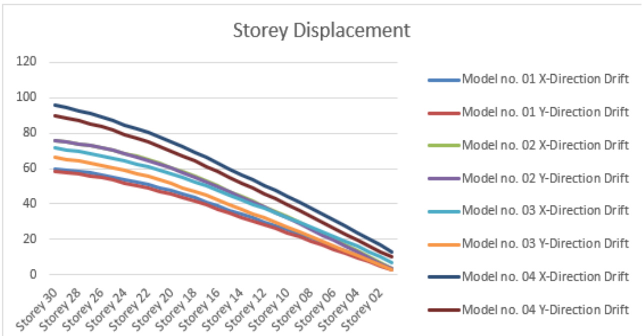


Chart no.3 Storey Drift in X and Y direction

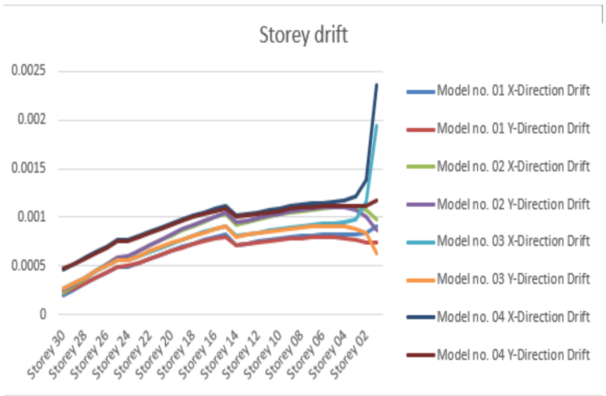
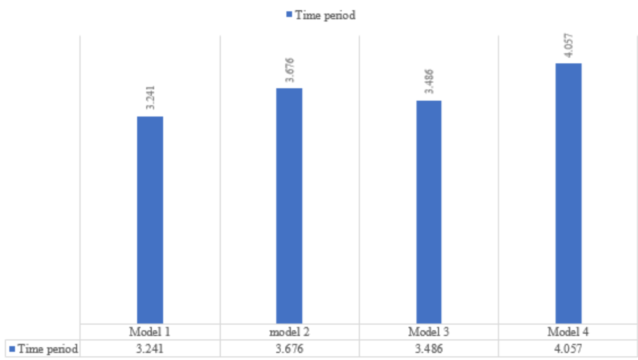


Chart no.4 Base Shear in X and Y direction



Parameter	Model 01Fixed Base	Model 02 SSI (Raft)	Model 03 SSI (Pile)	Model 04 SSI + Soil Liquefaction
Modal Mass Participation (UX)	0.7716	0.6776	0.7232	0.7433
Modal Mass Participation (UY)	0.7564	0.6658	0.7216	0.7460
Modal Mass Participation (RZ)	0.7798	0.6760	0.7278	0.7605
Fundamental Time Period (s)	3.251	3.808	3.527	3.853
Base Shear X (kN)	8169.61	8233.99	8466.82	8466.83
Base Shear Y (kN)	8169.62	8234.04	8466.68	8466.71
Roof Displacement X (mm)	62.123	90.274	63.478	76.928
Roof Displacement Y (mm)	60.293	89.446	60.088	73.511
Maximum	0.00089	0.00124	0.00081	0.000936

Storey Drift X	1	0	6	
Maximum Storey Drift Y	0.000852	0.001234	0.000825	0.000938

4. CONCLUSIONS

The present study demonstrates that Soil–Structure Interaction (SSI) significantly influences the seismic behaviour of high-rise reinforced concrete buildings. Compared with the fixed-base model, the raft foundation SSI model increased the natural time period, roof displacement, and storey drift due to reduced foundation stiffness.

Among the analysed foundation systems, the pile foundation with SSI exhibited the most favourable seismic performance by reducing lateral displacement and inter-storey drift while maintaining adequate structural stiffness. The inclusion of soil liquefaction further modified the dynamic characteristics of the building by increasing the natural time period and altering the seismic response.

The results confirm that the assumption of a perfectly fixed base may not accurately represent the behaviour of buildings founded on deformable soils. Therefore, incorporating realistic soil flexibility, foundation modelling, and liquefaction effects in seismic analysis leads to a more reliable assessment of structural performance and supports safer and more economical design of medium- and high-rise RC buildings.

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