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Investigation of Dynamic Soil-Structure Interaction on the Seismic Response of Reinforced Concrete Multi-Storey Buildings

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Abstract - *This study evaluates the dynamic seismic response of a G + 7 story reinforced concrete (RC) moment-resisting frame modeled in ETABS V22.5. Standard structural design practices frequently assume a rigid, fixed base; however, actual foundation behavior depends on the mechanical properties of supporting soil media. To quantify these effects, two dynamic soil-structure interaction (SSI) scenarios soft clay and dense clay are compared against a conventional fixed-base structural model. The structural models were evaluated under time-history excitation using the 1940 El Centro ground motion record. Soil flexibility was incorporated using equivalent Winkler Spring supports beneath isolated column foundations. The analytical results demonstrate that omitting soil flexibility leads to significant underestimations of lateral displacement, inter-story drift, fundamental vibration periods, and story force distributions. Notably, roof lateral displacement increased by over 640%, and base shear demand in the X-direction expanded by 67.8% when soft clay SSI was integrated relative to the rigid fixed-base assumption. These findings highlight the importance of incorporating SSI into performance-based seismic design, particularly for structures founded on highly compressible soils.*

Keywords: Soil-Structure Interaction (SSI), ETABS, Reinforced Concrete Frame, Time-History Analysis, Base Shear, Inter-story Drift, Winkler Springs.

1. INTRODUCTION

The dynamic behaviour of multi-storey structural systems during seismic events is governed by the structural stiffness and mass distribution as well as the mechanical properties of the underlying soil [1, 14]. Conventional structural engineering methodologies assume a rigid base connection, treating the foundation as fixed and immovable [3, 7]. While this assumption simplifies structural analysis, it fails to reflect physical performance for structures founded on flexible or compressible soil strata [2, 6]. Dynamic Soil-Structure Interaction describes the continuous coupling between structural oscillations and foundation soil deformation under time-varying seismic wave excitation [5, 13]. During earthquake shaking, kinetic energy propagates from the surrounding earth through the foundation into the superstructure. As the ground deforms under these stress fields, the dynamic character of the combined soil-structure system changes typically resulting in reduced overall system stiffness, elongated natural vibration periods, altered force distributions, and increased overall displacements [4, 15].

Seismic soil-structure interaction encompasses two primary mechanisms [2, 5]:

1. Kinematic Interaction: Occurs due to the stiffness contrast between rigid foundation elements and the surrounding natural soil medium. As seismic shear waves travel upward through the soil mass, the presence of a stiff foundation alters wave propagation, resulting in modified base accelerations termed Foundation Input Motion (FIM).
2. Inertial Interaction: Arises from dynamic inertial forces generated by the vibrating superstructure. These lateral shears and overturning moments generate secondary dynamic stresses in the supporting soil, producing localized soil deformations that increase overall structural flexibility.

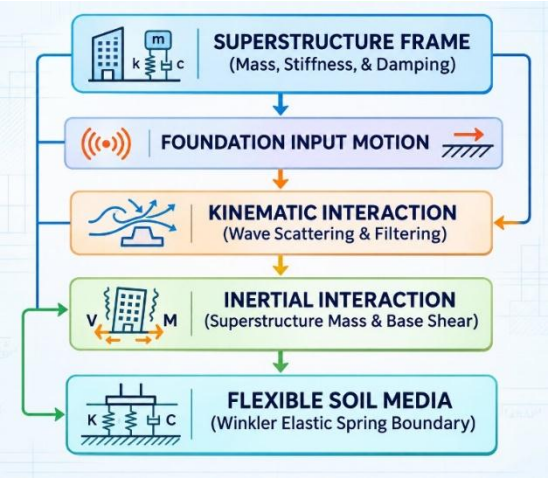


Fig. 1. Soil-Structure Interaction Effect Block Diagram

In urban areas such as Pune, India (located in Seismic Zone III per IS 1893:2016), multi-storey development frequently encounters deep clay deposits, weathered basaltic formations, and expansive black cotton soils [7, 8].

Although Zone III denotes moderate seismic hazard, local soil conditions can amplify seismic ground motions [1, 16]. Assessing structural safety under strong motion scenarios such as the 1940 El Centro earthquake provides insight into how varying soil stiffness influences building resilience [6, 13]. Recent analytical advancements and machine learning approaches further emphasize the necessity of explicitly accounting for subsoil flexibility in performance-based structural design [1, 15, 16].

2. ANALYTICAL METHODOLOGY AND STRUCTURAL MODELING

2.1 STRUCTURAL FRAME DESCRIPTION

An 8-storey (G + 7) reinforced concrete moment-resisting frame was constructed in ETABS V22.5. The building features a total height of 31.5 m with uniform floor-to-floor heights of 3.0 m, except for the first level (parking/ground tier) which has a height of 4.65 m. Concrete of grade M30 is specified for all structural members [3, 9].

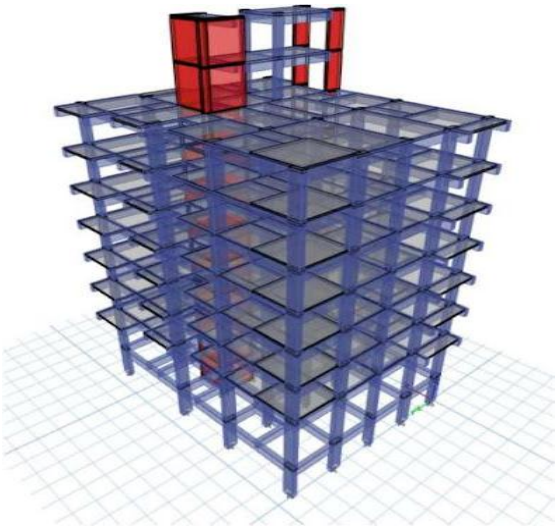


Fig. 2. Soil-Structure Interaction Model in ETABS

Table 1: Geometric and Sectional Properties of Structural Frame Elements

Structural Component	Finite Element Type	Cross-Sectional Dimensions	Material Specification
Beam 1	1D Frame Element	0.30 m × 0.65 m	Concrete M30
Beam 2	1D Frame Element	0.23 m × 0.60 m	Concrete M30
Column 1	1D Frame Element	0.30 m × 0.80 m	Concrete M30
Column 2	1D Frame Element	0.30 m × 0.75 m	Concrete M30
Column 3	1D Frame Element	0.23 m × 0.60 m	Concrete M30
Floor Slab	2D Shell Element	0.15 m thickness	Concrete M30

2.2 APPLIED STRUCTURAL LOADS

Structural loading protocols complied with standard Indian code provisions [10]:

- Dead Load (DL): Self-weight calculated automatically based on concrete density (25 kN/m^3) with a unit self-weight multiplier.
- Imposed Live Load (LL): 2.0 kN/m^2 as per IS 875 (Part 2).
- Floor Finish & Ceiling Plaster: 1.5 kN/m^2 per IS 875 (Part 1).
- Masonry Wall Infill Load: Evaluated assuming a brick unit weight of 20.0 kN/m^3 applied along peripheral and internal beam spans.

2.3 SUBSOIL BOUNDARY CONDITIONS AND SPRING FORMULATION

Soil flexibility at isolated column footings was represented using elastic Winkler Spring models. Translational spring stiffness values along three orthogonal axes (U_x, U_y, U_z) were applied to support joint nodes.

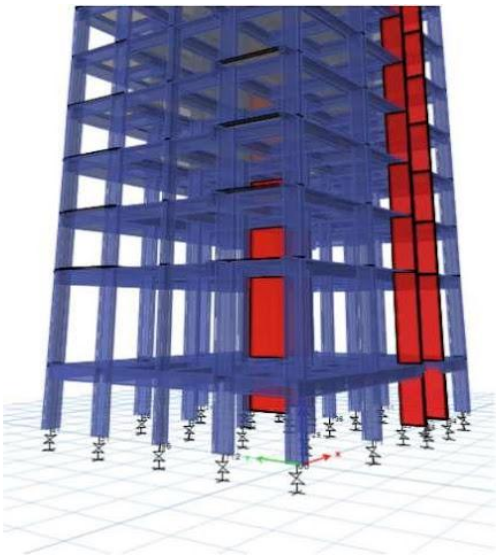


Fig. 3. Visualization of Soil-Structure Interaction Springs in a Multi-Storey ETABS Model

The vertical subgrade stiffness (k_z) was evaluated using the Winkler relation [12]:

$$k_z = k_s \times A \quad (1)$$

Where:

- k_s = Modulus of subgrade reaction of soil (kN/m^3).
- A = Required footing contact area (m^2), defined by $A = \frac{F_z}{q_{safe}}$.
- F_z = Unfactored axial column load in the vertical Z-direction (kN).
- q_{safe} = Safe Bearing Capacity (SBC) of the soil strata (kN/m^2).

Horizontal translational stiffness components (k_x, k_y) were set to $0.30 \times k_z$. Rotational degrees of freedom (R_x, R_y, R_z) were assumed unconstrained at individual isolated footings.

Table 2: Geotechnical and Spring Stiffness Parameters

Geotechnical Base Condition	Modulus of Subgrade Reaction (k_s)	Safe Bearing Capacity (q_{safe})	Horizontal-to-Vertical Stiffness Ratio (k_x/k_z)
Fixed Base (Rigid)	∞ (Infinite)	∞ (Rigid Support)	N/A (Fully Restrained)
Soft Clay Base	3,500 kN/m^3	50 kN/m^2	0.30
Dense Clay Base	40,000 kN/m^3	210 kN/m^2	0.30

2.4 SEISMIC EXCITATION AND TIME-HISTORY ANALYSIS

Dynamic time-history analysis was conducted by applying ground accelerations from the 1940 El Centro earthquake record (Imperial Valley event) simultaneously along both horizontal global axes (U_x and U_y) [6, 13].

3. RESULTS AND PERFORMANCE ANALYSIS

3.1 PEAK HORIZONTAL BASE SHEAR RESPONSE

Base shear represents the cumulative lateral dynamic inertial force resisted at the foundation level during seismic excitation.

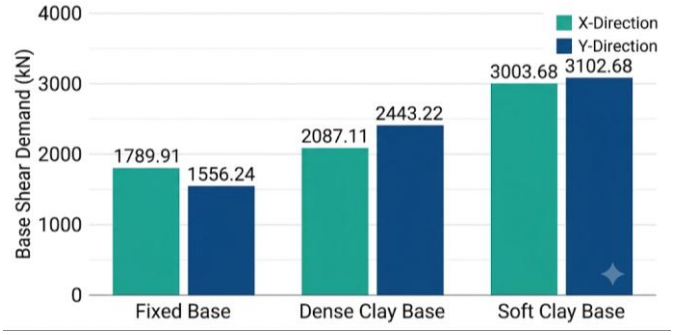


Fig. 4. Base Shear Demand Comparison

Key Findings:

- The soft clay flexible base model produced the highest peak base shear demand, expanding by 67.8% in the X-direction and 99.4% in the Y-direction compared to the fixed-base model.
- The fixed-base assumption underestimates peak lateral force demands because it ignores dynamic base motion and interaction effects.
- Dense clay exhibited intermediate load amplification, reflecting its higher subgrade stiffness.

Table 3: Summary of Maximum Horizontal Base Shear Demand

Foundation Support Model	Peak Base Shear X-Direction (kN)	Peak Base Shear Y-Direction (kN)	Percentage Variation Relative to Fixed Base (X/Y)
Fixed Base	+1,789.91	-1,556.24	Reference (0.0%)
Dense Clay Base	+2,087.11	-2,443.22	+16.6% (X) /+57.0% (Y)
Soft Clay Base	+3,003.68	-3,102.68	+67.8% (X) /+99.4% (Y)

3.2 LATERAL DISPLACEMENT PERFORMANCE AT ROOF LEVEL

Roof level displacement was extracted at corner Joint 41 to measure overall structural flexibility and sway.

Table 4: Peak Lateral Roof Displacement Response

Base Boundary Condition	Max Lateral Displacement X (mm)	Max Lateral Displacement Y (mm)	Amplification Ratio Relative to Fixed Base
Fixed Base	10.85 mm	12.43 mm	1.00 × (Baseline)
Dense Clay Base	38.47 mm	37.53 mm	3.55 × (X)/3.02 × (Y)
Soft Clay Base	80.67 mm	80.94 mm	7.43 × (X)/6.51 × (Y)

Key Findings:

- Soft soil flexibility increased lateral displacements to 80.67 mm in X and 80.94 mm in Y, representing a > 640% increase over rigid fixed-base predictions.
- Fixed-base models significantly underestimate roof displacements, which could lead to inadequate seismic separation distances and increased risk of structural pounding.

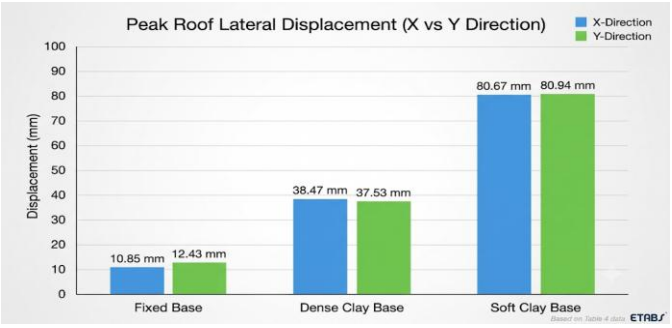


Fig. 5. Maximum Roof Lateral Displacement

3.3 DYNAMIC MODAL CHARACTERISTICS AND TIME PERIOD

Modal analysis was performed to evaluate fundamental vibration periods across models.

Table 5: Fundamental Natural Period Comparison

Foundation Condition	Fundamental Natural Period (seconds)	Period Extension Percentage
Fixed Base Model	0.857 s	Reference (0.0%)
Dense Clay Base Model	1.176 s	+37.2%
Soft Clay Base Model	1.351 s	+57.6%

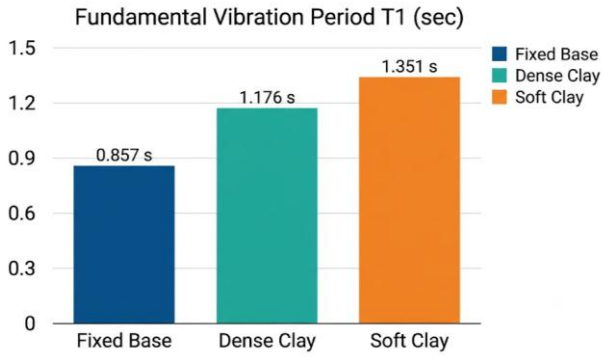


Fig. 6. Fundamental Vibration Period

Key Findings:

- Incorporating foundation flexibility lengthens the structure's fundamental natural period.
- The period increased from 0.857 s (fixed) to 1.351 s (soft clay), shifting structural response along the seismic acceleration response spectrum.

3.4 INTERNAL STOREY BENDING MOMENTS AND SHEAR FORCES

Storey force distributions along representative Column C09 were extracted to evaluate how soil flexibility influences internal member demands.

Table 6(a): Storey-wise Bending Moment Distribution

Building Level / Storey	Fixed Base Moment (kNm)	Soft Clay Moment (kNm)	Dense Clay Moment (kNm)
Terrace Level	28.60	75.40	50.80
Sixth Floor	23.40	66.80	45.20
Fifth Floor	27.10	74.70	50.60
Fourth Floor	30.80	84.10	57.30
Third Floor	35.00	96.50	66.30
Second Floor	49.00	127.30	90.60
First Floor	27.50	116.60	80.20
Ground Level	64.02	62.51	45.30

Table 6(b): Storey-wise Shear Force Distribution

Building Level / Storey	Fixed Base Shear (kN)	Soft Clay Shear (kN)	Dense Clay Shear (kN)
Terrace Level	20.20	60.50	41.50
Sixth Floor	17.60	49.80	34.00
Fifth Floor	20.50	58.10	39.70
Fourth Floor	22.70	65.80	44.90
Third Floor	24.70	75.20	51.40
Second Floor	29.10	91.10	63.20
First Floor	8.70	49.80	32.60
Ground Level	23.90	23.70	14.80

Key Findings:

- In the fixed-base model, internal forces concentrated at the ground base (64.02 kN·m) and decreased monotonically upward.
- Soft clay boundary conditions shifted maximum internal moment (127.30 kN·m) and shear (91.10 kN) demands upward to the 2nd and 3rd story levels.
- This upward force redistribution is caused by higher-mode mid-height sway oscillations permitted by base rotation and translation.

3.5 INTER-STOREY DRIFT PROFILES

Inter-storey drift indicates relative lateral displacement between consecutive floor diaphragms.

Table 7: Inter-Storey Drift Magnitudes across Elevation

Storey Level	Fixed Base Drift (mm)	Soft Clay Drift (mm)	Dense Clay Drift (mm)	Soft Clay vs Fixed Increase (%)
Ground Tier	0.925	8.360	5.810	+803.8%
First Tier	1.790	6.840	4.630	+282.1%
Second Tier	1.350	5.020	3.150	+271.9%
Third Tier	1.170	4.450	2.690	+280.3%
Fourth Tier	0.850	4.080	2.380	+380.0%
Fifth Tier	0.880	3.710	2.090	+321.6%
Sixth Tier	0.710	3.370	1.800	+374.6%
Terrace Tier	0.570	3.070	1.570	+438.6%

Key Findings:

- Peak inter-storey drift occurred at the ground level in flexible-base models (8.36 mm for soft clay and 5.81 mm for dense clay) due to soil yield and support displacement.
- The fixed-base model underestimated ground level drift by over 800%, highlighting the limitations of rigid base assumptions for soft soil sites.

4. CONCLUSIONS, LIMITATIONS AND FUTURE RESEARCH

The key takeaways from the research are as follows:

- Underestimation of Lateral Sway: Fixed-base assumptions underpredict lateral displacements and inter-story drifts on soft soils, increasing the risk of structural pounding and architectural damage.
- Dynamic Period Lengthening: Incorporating soil flexibility increases the fundamental natural period of the building (e.g., from 0.857 s to 1.351 s in soft clay), altering its response to seismic excitation.
- Upward Force Redistribution: Flexible base models shift maximum bending moment and shear demands from the ground foundation up to intermediate levels (2nd and 3rd stories).
- Impact on Base Shear: Soft soils can amplify overall lateral force demand, with base shear increasing by 67.8% (X-direction) and 99.4% (Y-direction) relative to fixed-base models.
- Design Implications: Unyielding fixed-base assumptions can lead to unsafe designs for structures on soft soils. Practical seismic engineering should incorporate soil flexibility parameters to ensure structural resilience.

Based on the structural and geotechnical methodology presented in the study, the research has the following key limitations. Foundation flexibility is modelled using linear elastic Winkler Spring boundary conditions. This approach omits complex dynamic soil phenomena, including non-linear soil yielding, soil hysteresis, dynamic radiation damping, foundation uplift, gap formation, and soil-footing sliding interfaces. The study does not evaluate structural performance across a broader suite of real and synthetic ground motion records with varying frequency contents,

peak ground accelerations, and duration profiles. Soil flexibility is applied through discrete joint springs beneath individual footings rather than a full 3D continuum finite element mesh. Consequently, dynamic shear wave scattering, continuous stress distribution through soil strata, and inter-footing interaction are simplified. The investigation focuses on an 8-storey (G+7) regular reinforced concrete moment-resisting frame supported on isolated column footings. The results cannot be directly extended to irregular building configurations, dual/shear wall structural systems, or alternative foundation types such as mat/raft foundations or deep pile foundations. Geotechnical conditions are limited to two idealized clay strata (soft clay and dense clay) using constant subgrade reaction moduli. Dynamic strain-dependent modulus degradation and cyclic degradation of subsoil parameters under repeated earthquake loading are not incorporated.

Future studies should incorporate full geometric and material nonlinearities, including soil yield, foundation uplift, gap formation, and sliding interfaces [2, 5]. Replacing linear Winkler springs with continuum finite element formulations (e.g., PLAXIS 3D or ABAQUS) will better capture stress distribution and shear coupling between footings [1, 14]. Future investigations should evaluate structural performance across a broader suite of real and synthetic ground motion records across varied seismic zones and soil profiles [13, 15].

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