

Effect of Soil-Structure Interaction on the Seismic Response of a 15-Story RC Building

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Abstract - The conventional seismic analysis of reinforced concrete buildings generally assumes that the foundation is perfectly fixed, thereby neglecting the influence of soil flexibility on structural behaviour. In reality, the supporting soil and the structure interact during earthquake excitation, and Soil-Structure Interaction (SSI) can significantly modify dynamic characteristics and seismic response. This study investigates a fifteen-storey reinforced concrete building using Autodesk Robot Structural Analysis Professional. Four support conditions are considered: fixed base and SSI models representing hard, medium, and soft soil using translational Winkler springs. Modal analysis and response spectrum analysis are performed in accordance with IS 1893 (Part 1):2016. Fundamental natural period, base shear, story displacement, roof displacement, inter-story drift, and story shear are compared. The fundamental period increases from 2.65 s for the fixed-base model to 3.38 s for the soft-soil model, while base shear decreases from 2517.74 kN to 2104.17 kN. Roof displacement increases from 4.2 cm to 5.5 cm. The results demonstrate that decreasing soil stiffness produces longer natural periods and larger deformation demand but lower force demand, emphasizing the importance of SSI in realistic seismic assessment.

Keywords - soil-structure interaction; reinforced concrete building; Winkler spring; response spectrum analysis; seismic response; Autodesk Robot Structural Analysis

I. INTRODUCTION

Earthquakes are among the most destructive natural hazards, and the seismic response of a building depends not only on its mass, stiffness and damping but also on the properties of the supporting soil [1]. Conventional structural analysis commonly assumes a perfectly fixed foundation. This simplifies analysis but neglects soil deformation and the coupled response of the soil-foundation-structure system [2]. Soil-Structure Interaction becomes particularly important for medium- and high-rise buildings on medium or soft soils. Soil flexibility can increase the natural period, modify seismic force distribution, and increase lateral displacement and inter-story drift [3], [5]-[7]. The Winkler spring idealization is widely used because it provides a computationally efficient representation of soil flexibility using independent elastic springs beneath foundation nodes [11], [13].

The present investigation develops four analytical models of a regular reinforced concrete building: a fixed-base model and three SSI models representing hard, medium and soft soil. The objective is to quantify how soil flexibility changes the

principal seismic response parameters within one consistent numerical framework.

II. LITERATURE REVIEW

SSI research has evolved from simplified fixed-base assumptions toward coupled numerical representations of soil and structure. Reviews have shown that the influence of SSI depends on soil stiffness, foundation dimensions, building height, structural stiffness, earthquake characteristics and mass distribution [2], [6]. SSI may be beneficial for some force-based measures while being detrimental for deformation-sensitive response, so its effect cannot be characterized as universally beneficial or detrimental [7].

Winkler-based studies have demonstrated the practicality of representing soil flexibility with translational springs. Wani et al. investigated a G+10 RC building and reported that fundamental period, base shear and story drift were among the parameters most affected by SSI [18]. Patel and Adhikari examined RC frame buildings of different heights and concluded that SSI should be considered in structural analysis and design [19]. Other studies using direct finite-element soil modelling have reported increased drift and changes in spectral response when SSI is included [20], [21].

The literature also shows that foundation type, soil condition and modelling approach can substantially influence computed seismic response [15]-[17], [22]-[28]. The present study focuses specifically on a fifteen-storey RC building and compares fixed-base, hard-soil, medium-soil and soft-soil conditions using the Winkler approach in Autodesk Robot Structural Analysis Professional.

III. RESEARCH METHODOLOGY

3.1 Building Configuration

A regular fifteen-storey reinforced concrete building was selected. The structure has a symmetric 5 x 5 column grid with twenty-five column locations and reinforced concrete beams, columns and slabs. The foundation system is represented by isolated footings. Autodesk Robot Structural Analysis Professional was used for three-dimensional modelling and seismic analysis.

TABLE I. BUILDING DETAILS

Parameter	Value
Building type	Reinforced concrete moment resisting frame
Number of stories	G + 15
Total floors	16
Plan configuration	Regular
Number of columns	25
Column grid	5 x 5

Column size	600 mm x 600 mm
Beam type	Reinforced concrete
Slab type	Reinforced concrete
Foundation	Isolated footing
Structural software	Autodesk Robot Structural Analysis Professional

3.2 Material and Loading

Concrete grade M30 and reinforcement steel grade Fe500 were used. The concrete Poisson ratio was 0.20, concrete density was 25 kN/m³, steel modulus of elasticity was 200 GPa and steel density was 78.5 kN/m³. Dead load was generated from structural self-weight, live load was assigned according to IS 875 (Part 2), and earthquake loading was applied using the response spectrum method.

3.3 Soil-Structure Interaction Modelling

Soil flexibility was represented by the Winkler spring model. Independent translational elastic springs were attached at foundation nodes. Only UX, UY and UZ springs were considered; rotational soil springs and explicit soil damping were outside the scope of the analysis.

TABLE II. SOIL SPRING STIFFNESS

Soil type	Kx (kN/m)	Ky (kN/m)	Kz (kN/m)
Hard soil	216000	720000	216000
Medium soil	108000	360000	108000
Soft soil	54000	180000	54000

3.4 Analytical Models and Seismic Analysis

TABLE III. SUPPORT CONDITIONS USED IN THE ANALYTICAL MODELS

Model	Kz	Kx	Ky	Rotational condition
Fixed base	Fixed	Fixed	Fixed	Fixed
Hard soil	216000 kN/m	216000 kN/m	720000 kN/m	No rotational spring
Medium soil	108000 kN/m	108000 kN/m	360000 kN/m	No rotational spring
Soft soil	54000 kN/m	54000 kN/m	180000 kN/m	No rotational spring

Twenty-five modes were considered in each model. The cumulative modal mass participation exceeded 90% in both principal horizontal directions. The seismic analysis used Zone V, zone factor 0.36, importance factor 1.0, response reduction factor 5.0, X and Y horizontal directions, CQC modal combination and dynamic response spectrum analysis.

TABLE IV. SEISMIC ANALYSIS PARAMETERS

Parameter	Adopted value
Design code	IS 1893:2016
Seismic zone	Zone V
Zone factor	0.36
Importance factor, I	1.0
Response reduction factor, R	5.0
Structural occupancy	Residential or commercial building
Analysis type	Dynamic seismic response spectrum
Horizontal directions	X and Y
Modal combination	CQC
Number of modes	25

IV. RESULTS AND DISCUSSION

4.1 Modal Analysis

The fixed-base model has a fundamental period of 2.65 s. Introducing elastic soil springs progressively lengthens the fundamental period as the supporting soil becomes more flexible. The selected modal properties also show that cumulative translational modal mass participation exceeds 90% within the included modes for all four models.

TABLE V. SELECTED MODAL PROPERTIES OF THE FIXED-BASE MODEL

Mode	Frequency (Hz)	Period (s)	Cumulative mass Ux (%)	Cumulative mass Uy (%)
1	0.38	2.65	38.47	40.96
2	0.38	2.65	79.44	79.44
3	0.44	2.28	79.44	79.44
5	1.15	0.87	89.74	89.74
7	2.02	0.49	91.74	91.31
11	2.94	0.34	95.25	95.25
25	6.30	0.16	97.67	97.70

TABLE VI. SELECTED MODAL PROPERTIES OF THE HARD-SOIL MODEL

Mode	Frequency (Hz)	Period (s)	Cumulative mass Ux (%)	Cumulative mass Uy (%)
1	0.33	3.05	40.53	44.86
2	0.33	3.05	85.39	85.39
3	0.39	2.56	85.39	85.39
5	1.03	0.97	95.13	95.13
7	1.84	0.54	96.04	96.53
11	2.70	0.37	98.41	98.41
25	5.84	0.17	99.15	99.15

TABLE VII. SELECTED MODAL PROPERTIES OF THE MEDIUM-SOIL MODEL

Mode	Frequency (Hz)	Period (s)	Cumulative mass Ux (%)	Cumulative mass Uy (%)
1	0.32	3.16	40.63	44.55
2	0.32	3.16	85.17	85.17
3	0.39	2.58	85.17	85.17
5	1.02	0.98	95.36	95.36
7	1.83	0.55	96.26	96.69
11	2.68	0.37	98.55	98.55
25	5.45	0.18	99.25	99.25

TABLE VIII. SELECTED MODAL PROPERTIES OF THE SOFT-SOIL MODEL

Mode	Frequency (Hz)	Period (s)	Cumulative mass Ux (%)	Cumulative mass Uy (%)
1	0.30	3.38	40.38	44.39
2	0.30	3.38	84.77	84.77
3	0.38	2.62	84.77	84.77
5	0.99	1.01	95.77	95.77
7	1.82	0.55	96.65	96.95
11	2.61	0.38	98.63	97.94
25	5.05	0.20	99.40	99.40

4.2 Fundamental Natural Period

TABLE IX. COMPARISON OF FUNDAMENTAL PERIOD

Model	Frequency (Hz)	Period (s)	Increase relative to fixed base (%)
Fixed base	0.38	2.65	—
Hard soil	0.33	3.05	15.09
Medium soil	0.32	3.16	19.25
Soft soil	0.30	3.38	27.55

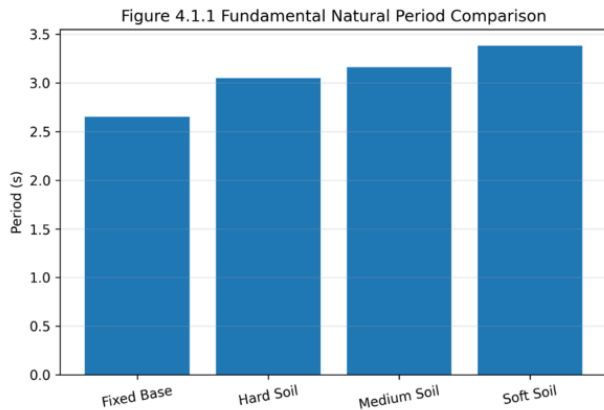


Fig. 417. Comparison of the fundamental natural period for the four analytical models.

The fixed-base model produces the shortest fundamental period because it has the highest effective stiffness. The period increases from 2.65 s to 3.05 s, 3.16 s and 3.38 s for hard, medium and soft soil, respectively. The maximum increase is 27.55% for soft soil.

4.3 Base Shear

TABLE X. COMPARISON OF SEISMIC BASE SHEAR

Model	Base shear (kN)	Reduction relative to fixed base (%)
Fixed base	2517.74	—
Hard soil	2286.06	9.20
Medium soil	2217.60	11.92
Soft soil	2104.17	16.43

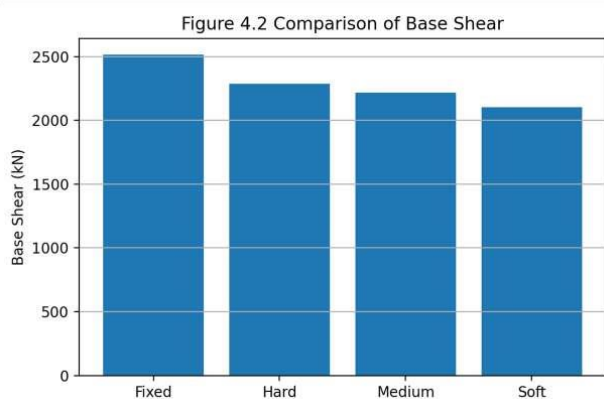


Fig. 418. Comparison of the seismic base shear for the four analytical models.

Base shear decreases progressively as the supporting soil becomes more flexible. The reductions for hard, medium and soft soil are 9.20%, 11.92% and 16.43%, respectively. The

reduction is associated with period lengthening and changes in spectral acceleration, modal response and support flexibility. Lower base shear should not be interpreted automatically as improved seismic performance because the SSI models also experience larger displacement.

4.4 Story Displacement

TABLE XI. STORY DISPLACEMENT COMPARISON

Story	Fixed base (cm)	Hard soil (cm)	Medium soil (cm)	Soft soil (cm)
1	0.2	0.8	0.8	0.9
2	0.6	1.2	1.3	1.4
3	1.0	1.6	1.7	1.8
4	1.3	2.0	2.1	2.2
5	1.7	2.4	2.4	2.5
6	2.1	2.7	2.8	2.9
7	2.4	3.0	3.1	3.2
8	2.7	3.3	3.4	3.6
9	3.0	3.6	3.7	3.9
10	3.2	3.8	4.0	4.2
11	3.5	4.1	4.2	4.5
12	3.7	4.3	4.4	4.7
13	3.9	4.5	4.6	4.9
14	4.0	4.6	4.8	5.2
15	4.2	4.8	5.0	5.3
16	4.2	4.9	5.1	5.5

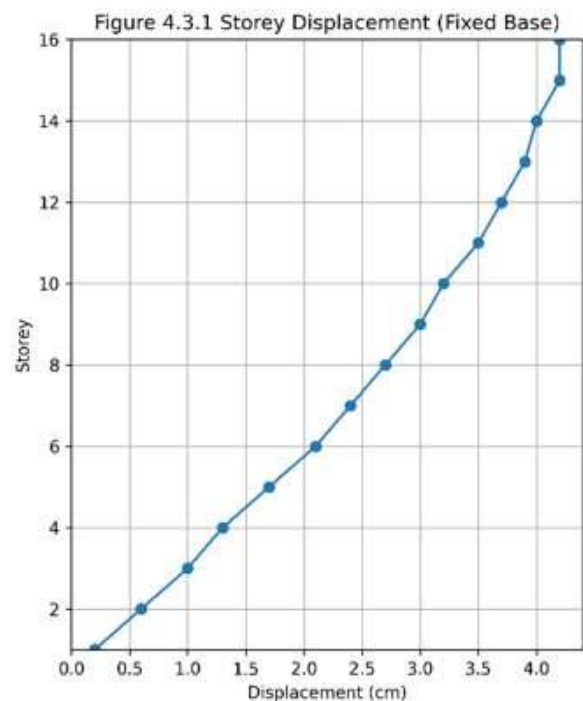


Fig. 419. Story displacement profile of the fixed-base model.

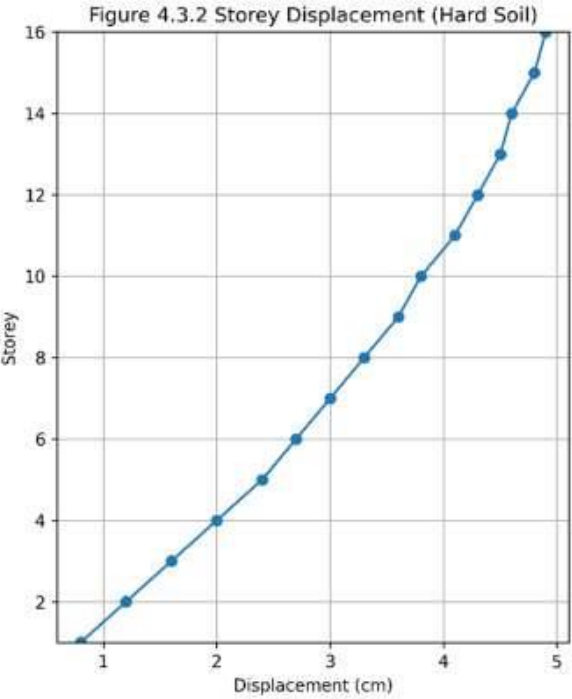


Fig. 420. Story displacement profile of the hard-soil SSI model.

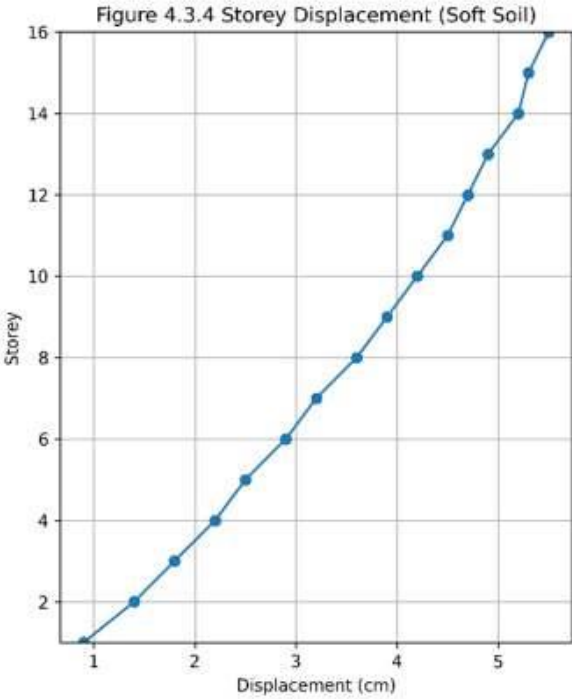


Fig. 422. Story displacement profile of the soft-soil SSI model.

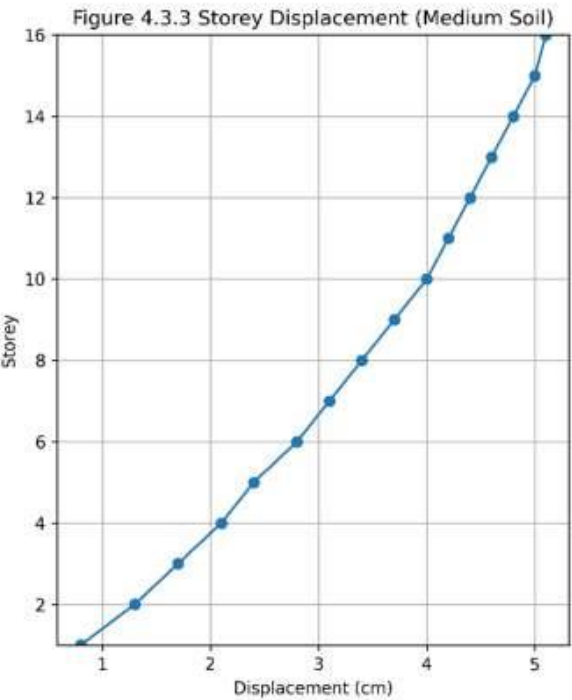


Fig. 421. Story displacement profile of the medium-soil SSI model.

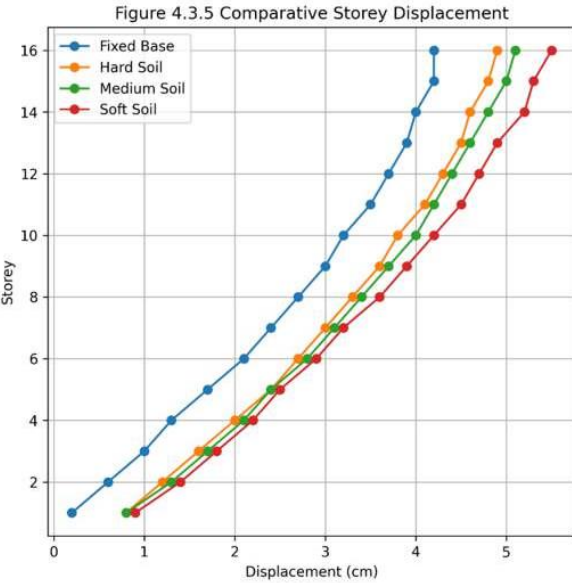


Fig. 423. Comparative story displacement profiles for all analytical models.

The displacement curves shift to the right as soil stiffness decreases. The fixed-base model has the lowest displacement, followed by the hard-, medium- and soft-soil models. The soft-soil model increases from 0.9 cm at the first story to 5.5 cm at the roof.

4.5 Roof Displacement

TABLE XII. COMPARISON OF ROOF DISPLACEMENT

Model	Roof displacement (cm)	Increase relative to fixed base (%)
Fixed base	4.2	—
Hard soil	4.9	16.67
Medium soil	5.1	21.43
Soft soil	5.5	30.95

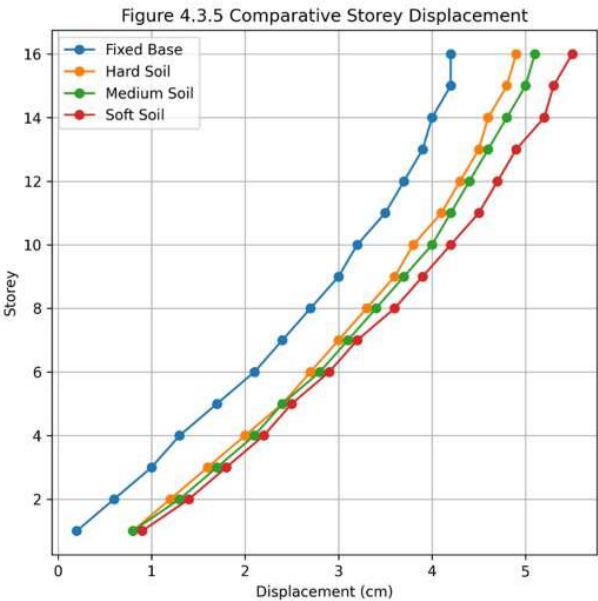


Fig. 424. Comparison of roof displacement for the four analytical models.

Roof displacement increases by 16.67%, 21.43% and 30.95% for the hard-, medium- and soft-soil models relative to the fixed-base condition. This indicates that lower force demand caused by SSI is accompanied by increased deformation demand.

4.6 Inter-Story Drift

TABLE XIII. INTER-STORY DRIFT COMPARISON

Story	Fixed base (cm)	Hard soil (cm)	Medium soil (cm)	Soft soil (cm)
1	0.2	0.5	0.5	0.5
2	0.3	0.3	0.3	0.3
3	0.3	0.3	0.3	0.3
4	0.3	0.3	0.3	0.3
5	0.3	0.2	0.3	0.3
6	0.2	0.2	0.2	0.3
7	0.2	0.2	0.2	0.2
8	0.2	0.2	0.2	0.2
9	0.2	0.2	0.2	0.2
10	0.2	0.2	0.2	0.2
11	0.2	0.2	0.2	0.2
12	0.2	0.2	0.2	0.2
13	0.1	0.1	0.1	0.2
14	0.1	0.1	0.1	0.1
15	0.1	0.1	0.1	0.1
16	0.1	0.1	0.1	0.1

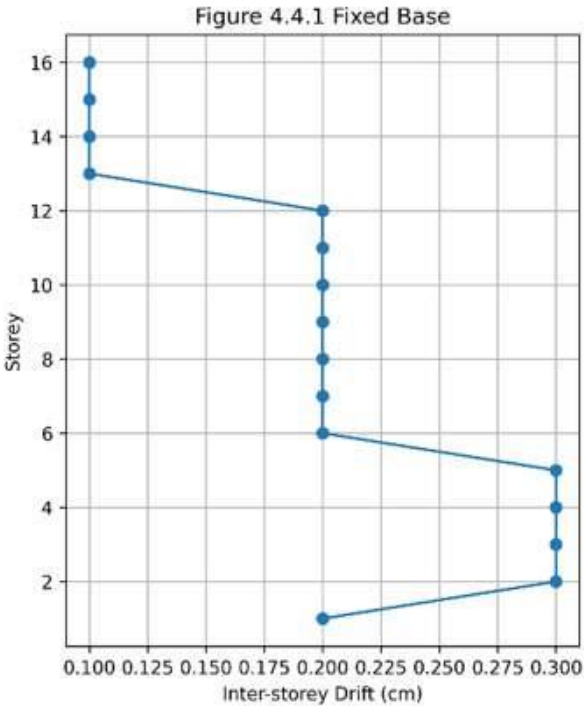


Fig. 425. Inter-story drift profile of the fixed-base model.

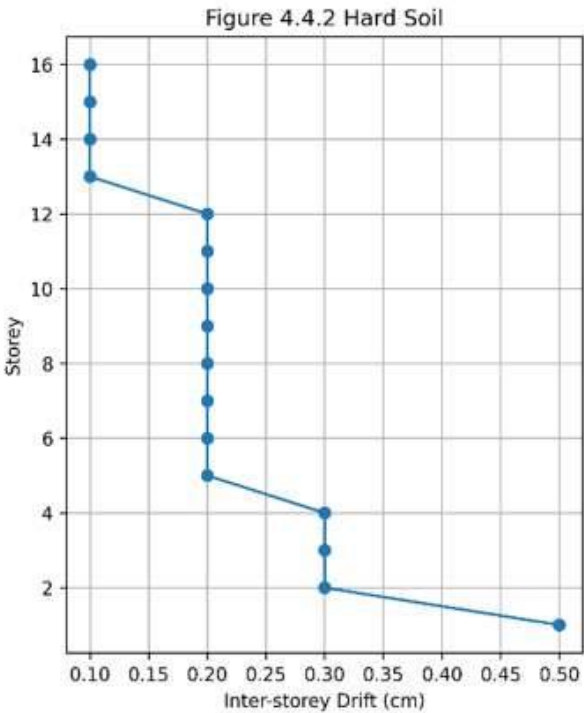


Fig. 426. Inter-story drift profile of the hard-soil SSI model.

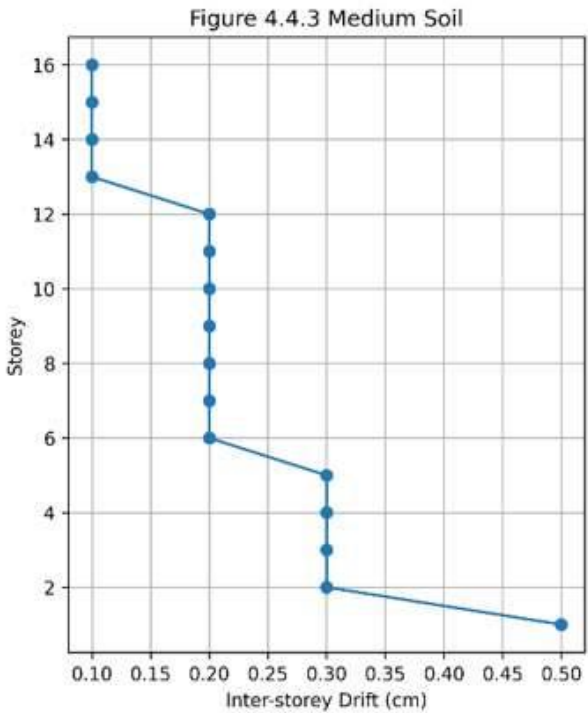


Fig. 427. Inter-story drift profile of the medium-soil SSI model.

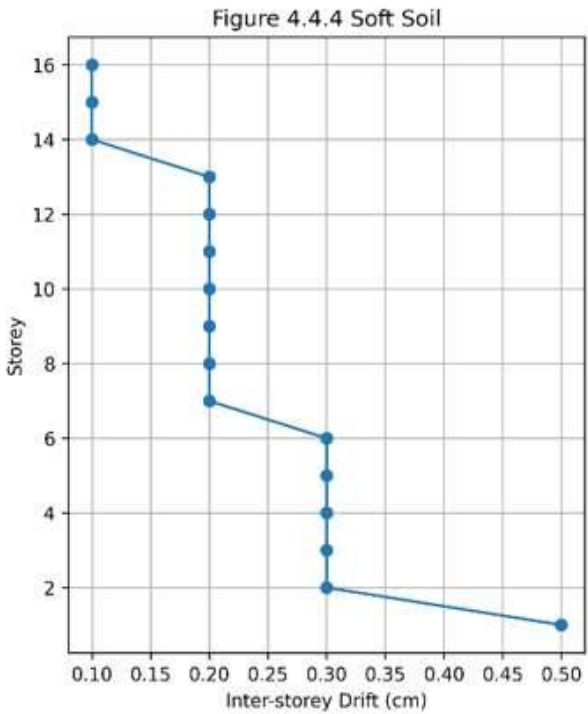


Fig. 428. Inter-story drift profile of the soft-soil SSI model.

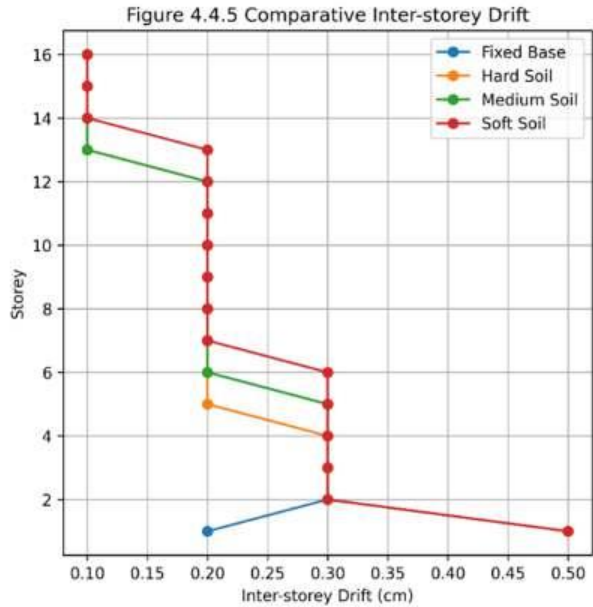


Fig. 429. Comparative inter-story drift profiles of the four analytical models.

The drift profiles show that SSI has its greatest influence in the lower portion of the structure. The reported values are rounded to the nearest 0.1 cm; therefore, small differences may be concealed by rounding. The drift ratio is represented by $\theta_i = \Delta_i/h_i$, where Δ_i is the relative displacement between adjacent floors and h_i is the corresponding story height. A definitive codal compliance statement requires unrounded output and the adopted story height.

4.7 Story Shear

TABLE XIV. STORY SHEAR COMPARISON

Story	Fixed base (kN)	Hard soil (kN)	Medium soil (kN)	Soft soil (kN)
1	2517.77	2286.08	2217.61	2104.17
2	2465.63	2203.36	2131.89	2013.11
3	2365.89	2107.48	2035.24	1914.51
4	2259.99	2016.76	1944.79	1823.25
5	2156.42	1930.41	1860.03	1739.80
6	2058.08	1845.71	1778.57	1662.87
7	1961.94	1757.62	1695.40	1587.80
8	1859.82	1663.18	1607.47	1511.20
9	1751.47	1563.38	1515.42	1432.52
10	1636.54	1457.65	1417.80	1348.88
11	1514.20	1344.54	1312.06	1255.81
12	1383.16	1219.71	1193.32	1146.64
13	1230.24	1071.45	1050.51	1010.65
14	1037.11	885.96	870.45	837.08
15	783.09	648.01	637.83	613.13
16	430.77	342.72	337.79	325.03

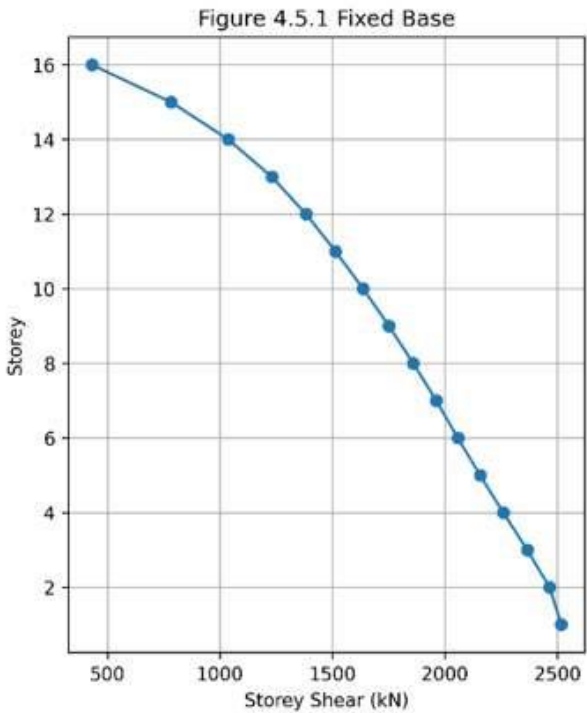


Fig. 430. Story shear distribution for the fixed-base model.

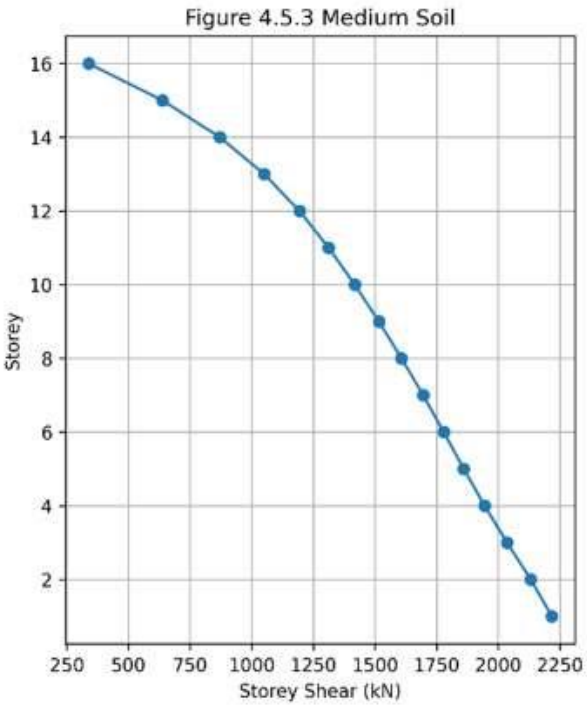


Fig. 432. Story shear distribution for the medium-soil SSI model.

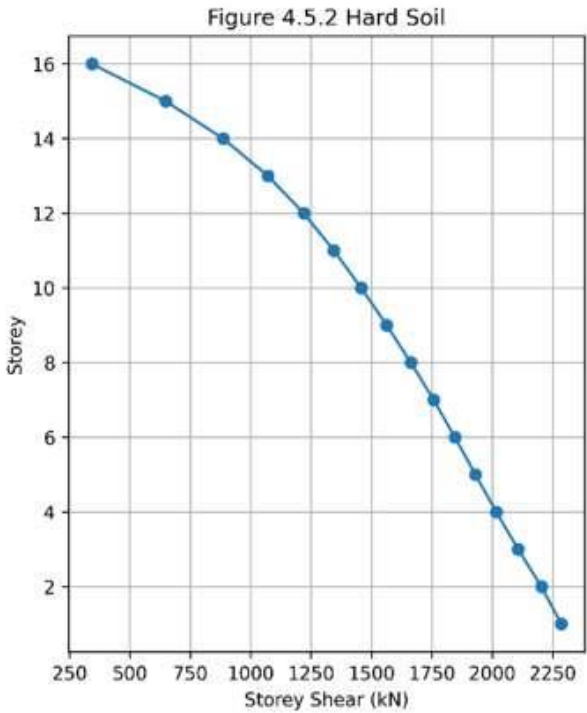


Fig. 431. Story shear distribution for the hard-soil SSI model.

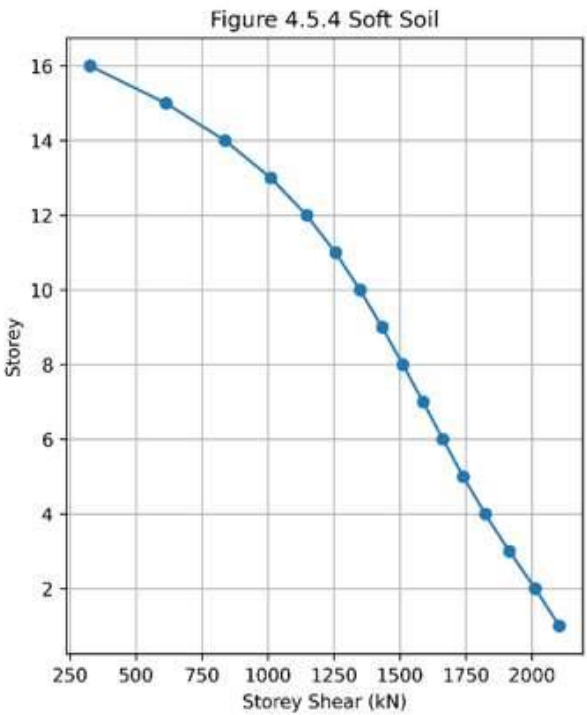


Fig. 433. Story shear distribution for the soft-soil SSI model.

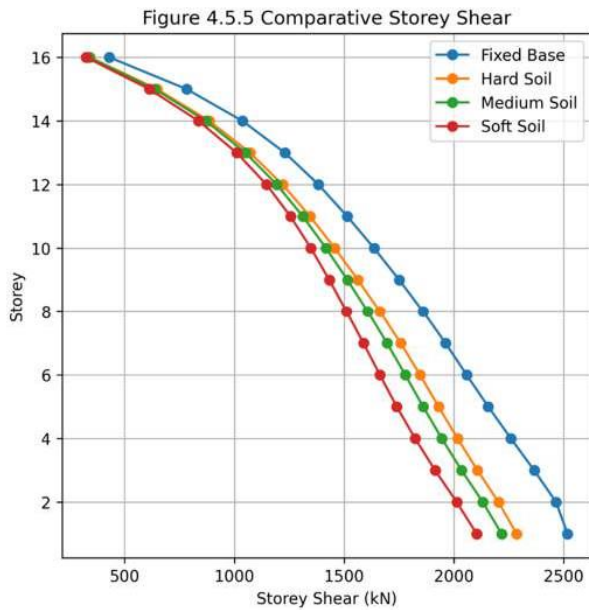


Fig. 434. Comparative story shear distribution for all analytical models.

Story shear is maximum at the lowest story and decreases toward the roof. The SSI models develop lower shear than the fixed-base model at all levels. The soft-soil model gives the lowest values, with first-story shear of 2104.17 kN, approximately 16.43% below the fixed-base value. The overall distribution shape remains similar across the four models, indicating that SSI changes magnitude more than the general vertical pattern.

4.8 Integrated Effect of Soil Stiffness

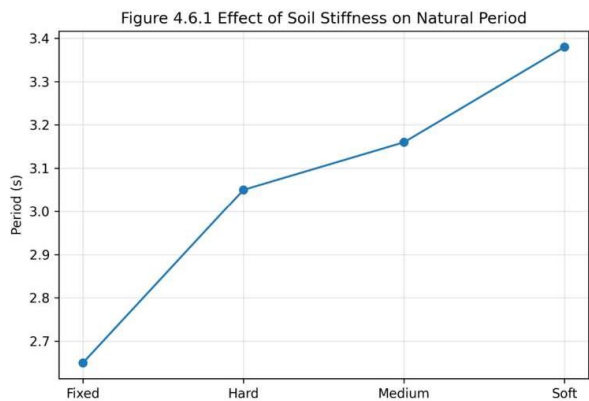


Fig. 435. Effect of soil stiffness on the fundamental natural period.

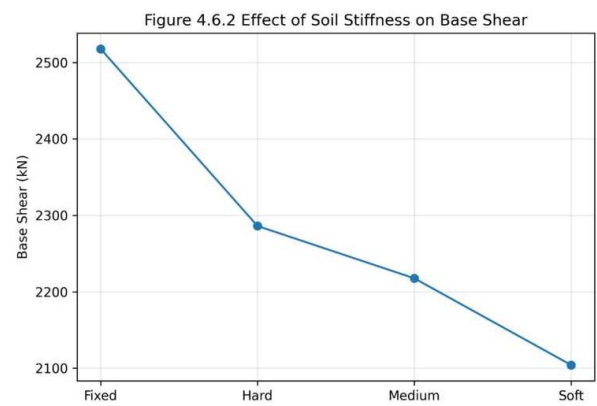


Fig. 436. Effect of soil stiffness on seismic base shear.

TABLE XV. OVERALL RESPONSE COMPARISON

Model	Period (s)	Base shear (kN)	Roof displacement (cm)	Maximum reported drift (cm)
Fixed base	2.65	2517.74	4.2	0.3
Hard soil	3.05	2286.06	4.9	0.5
Medium soil	3.16	2217.60	5.1	0.5
Soft soil	3.38	2104.17	5.5	0.5

TABLE XVI. PERCENTAGE VARIATION RELATIVE TO THE FIXED-BASE MODEL

Model	Period change (%)	Base shear change (%)	Roof displacement change (%)
Hard soil	+15.09	-9.20	+16.67
Medium soil	+19.25	-11.92	+21.43
Soft soil	+27.55	-16.43	+30.95

The results reveal a consistent relationship between soil stiffness and structural response: decreasing soil stiffness increases the fundamental period and absolute floor and roof displacement, while reducing base shear and story shear. Thus, the fixed-base assumption produces the greatest force demand but the lowest displacement demand, whereas the soft-soil model produces the lowest force demand and greatest displacement demand.

V. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The study demonstrates that Soil-Structure Interaction materially changes the computed seismic response of the fifteen-storey RC building. The principal findings are: (1) the fundamental period increases from 2.65 s for the fixed-base model to 3.38 s for soft soil, a 27.55% increase; (2) base shear decreases from 2517.74 kN to 2104.17 kN, a 16.43% reduction; (3) roof displacement increases from 4.2 cm to 5.5 cm, a 30.95% increase; (4) SSI increases displacement demand at all levels, with the largest influence near the lower stories; and (5) story shear decreases as soil stiffness decreases while retaining a broadly similar distribution shape.

5.2 Engineering Implications

The results indicate that a lower seismic force demand does not necessarily imply lower overall performance demand. Soil flexibility can reduce force response while increasing

deformation response. Therefore, fixed-base analysis may not adequately represent deformation-sensitive response for buildings founded on deformable soils. The Winkler model provides a practical first-level representation of this effect, although it does not capture all aspects of soil continuity, nonlinear behaviour, radiation damping or rotational soil stiffness.

5.3 Recommendations for Future Work

Future investigations may employ nonlinear soil constitutive models, continuum finite-element soil domains, frequency-dependent impedance functions, foundation rocking and rotational stiffness, explicit soil damping, and time-history analysis. Further work should also verify story drift using unrounded analysis output and clearly separate the effects of support stiffness from any changes in the code response-spectrum soil category.

ACKNOWLEDGMENT

The author gratefully acknowledges the guidance of Dr. D. K. Singh, Department of Civil Engineering, Cambridge Institute of Technology, Ranchi, and the support of the Department of Civil Engineering during this research.

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