

Influence of Soil–Structure Interaction on Seismic Response of Vertically Irregular Reinforced Concrete Frames

Dipak B. Gaidhane^{1*}, Shrutika S. Sanghai²

Abstract

The present study focuses on the behavior of RC frames by performing Equivalent Static and Linear Dynamic Analysis. A reinforced concrete frame having a G+10 story was considered. The investigation on the behavior of the RC frame is carried out by using dynamic analysis, that is, the Response Spectrum method. The modeling of the RC frame is carried out by using a finite element-based computer program, that is, STAAD.Pro. The investigation is carried out by considering Strength Irregularity with Soil–Structure Interaction is considered. In strength irregularity, the parameters such Normal Model, the Model with soft story, the Model with floating column, and the Model with variation in story height are considered. By considering all these parameters total of 4 models for Static and Dynamic Conditions were created, all models were analyzed for the Seismic zone III. The Response of each RC frame with respect to others will be checked for Axial force, Shear Force, twisting moment, Bending Moment, Lateral displacement, and Base Shear. The behavior of each RC frame with respect to others is described with the help of figures.

Keywords: Horizontal and vertical irregularity, re-entrant corners, diaphragm flexibility, fragility assessment, hillside buildings, progressive collapse

INTRODUCTION

Seismic design of structures has evolved significantly, with increasing recognition of soil–structure interaction (SSI) as a critical factor influencing dynamic responses. SSI accounts for the interplay between a structure and its underlying soil, altering natural frequencies, damping, and seismic demands. This review compiles findings effects of SSI on RC frames, tall buildings, subway stations, and mitigation strategies like tuned mass dampers (TMDs), base isolation, and inter-story isolation. The

studies utilize nonlinear finite element modeling, shaking table tests, and probabilistic fragility analyses to explore seismic performance across various soil types and structural configurations.

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Jishuai Wang et al. [1] conducted probabilistic seismic fragility assessments on clusters of typical 3-, 6-, 9-, and 12-story RC frames on medium-stiff clay soil, using nonlinear high-fidelity FE models in OpenSees, incorporating structure–soil–structure interaction (SSSI) with and without pounding, compared to fixed-base and SSI cases. Incremental dynamic analysis (IDA) and Latin hypercube sampling (LHS) account for uncertainties in structural properties and 40 ground motions. Results show SSSI reduces exceedance probabilities for

immediate occupancy (IO), life safety (LS), and collapse prevention (CP) states in no-pounding scenarios (up to 12% median capacity increase), making fixed-base/SSI assumptions conservative. For pounding (3- and 12-story pair), SSSI minimally affects median capacities but elevates LS/CP probabilities at low intensities while reducing them at high intensities.

Sitong Fang et al. [2] evaluate the seismic performance of inter-story isolation systems in super high-rise buildings (e.g., 411-m case study) under SSI, using a lumped parameter sway-rocking (SR) model to derive dynamic characteristics like natural frequencies and displacement transfer ratios. Parametric analyses examine soil shear wave velocity (V_s) and damping ratios (5%–25%) (Figure 1).

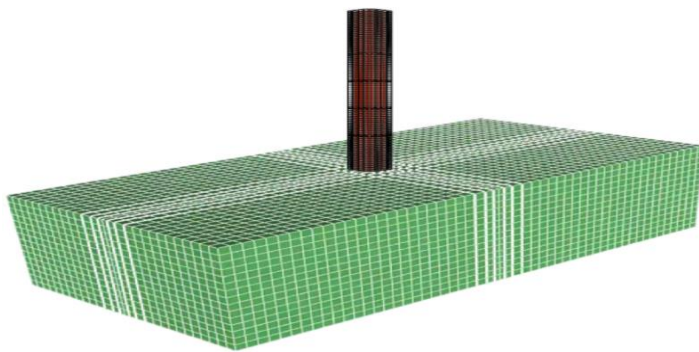


Figure 1. 3D visualization of SSI [2].

Findings show inter-story isolation effectively reduces displacements and Park-Ang damage indices, but high-damping systems increase displacement/damage on low- V_s soils; non-isolated structures see damping ratio increases with decreasing V_s , while isolated ones exhibit.

Key Findings

SPFSI induces foundation rocking and inelastic pile rotations (correlated with compressive loads), increasing yield/ultimate drifts but reducing global ductility ($\mu_c = \Delta u / \Delta y$) by up to 12% for frames and 39% for wall-frames, especially in softer soils and taller/wider configurations. Recommends adjusting seismic response reduction factors and further experimental studies.

It decreases at higher damping. Recommendations emphasize optimizing designs for SSI effects.

Yangzhou Wu et al. [3] develop an iterative static analysis method to efficiently compute effective frequencies and modes dominating seismic responses of aboveground structures in 3D SSI systems, bypassing full modal analysis of soil-dominated modes. Parametric studies examine the impacts of site shear wave velocity and adjacent underground structures (e.g., tunnels) on these frequencies (Figure 2).

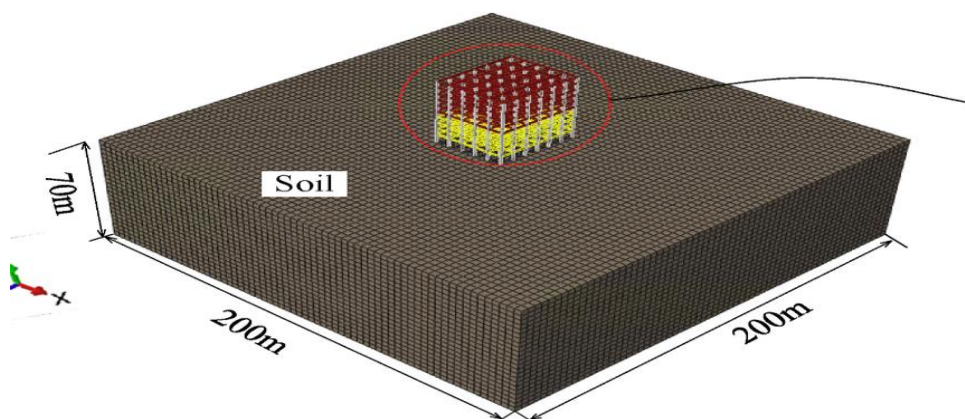


Figure 2. Finite element model of a frame structure–foundation–soil system [3].

A response spectrum method (RSM) incorporating these effective parameters is proposed for seismic design, with numerical examples (e.g., 5–15 story buildings) validating its accuracy (errors <3%) against time–history analyses under artificial and real earthquakes.

Nishant Sharma et al. [4] examine the impact of soil–pile foundation–structure interaction (SPFSI) on the inelastic response and ductility capacity of 3 to 12-story RC frame and wall-frame buildings using nonlinear finite element pushover analyses in ABAQUS. Models incorporate pile inelasticity, soil nonlinearity (via Drucker–Prager), and varying sand densities (loose to dense) (Figure 3).

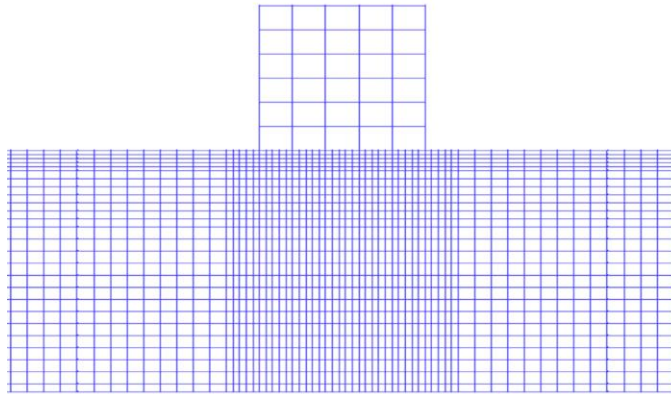


Figure 3. Adopted non-uniform optimized meshing [4].

Gholamreza Keyvani Hafshejani et al. [5] examine the seismic response of two adjacent irregular RC structures (6- and 10-story) at varying embedment depths (0–3 m) and distances (2–10 m) using 3D Abaqus simulations incorporating SSI (Figure 4).

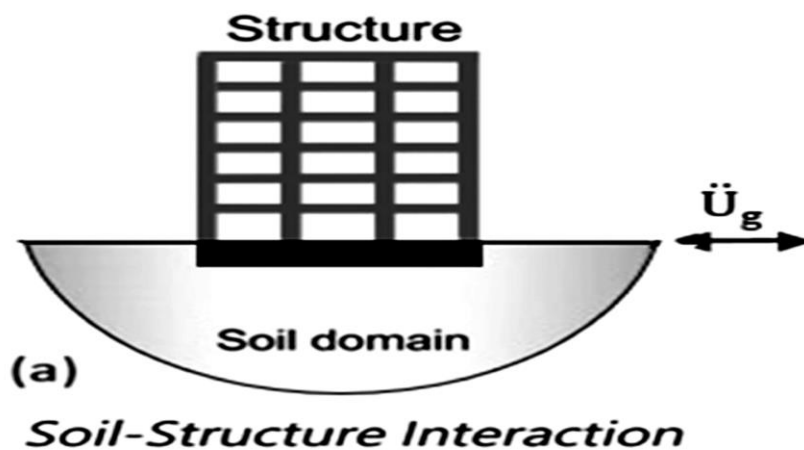


Figure 4. Illustration of the substructure method for SSI analysis [5].

Nonlinear dynamic analyses under the El Centro earthquake reveal that increasing distance reduces displacements, accelerations, and stresses, while greater depths amplify responses due to soil stiffening; maximum SSI effects occur at minimum distance and surface level (84.4% increase), with depth variations mitigating effects (31.2%–19.2% reduction). Results emphasize considering embedment in SSI for urban designs [6–10].

PROBLEM DESCRIPTION

A reinforced concrete (G+10) Story Frame Structures are considered for the present study with different strength irregularities. A set total of 04 models for static and dynamic condition are model for Normal symmetric, model with soft story, model with Floating column and model with different story

height are considered in present study and structural analysis and design is performed using STAAD.Pro. All the Structures were modeled for Seismic Zone-III. The details of geometric properties, design parameters, and sectional properties of Frame Structures are given in Tables 1–3 and Figures 5–14 [9–15].

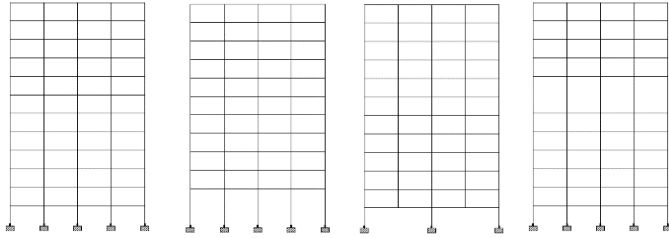


Figure 5. Frame models with a fixed base are present study.

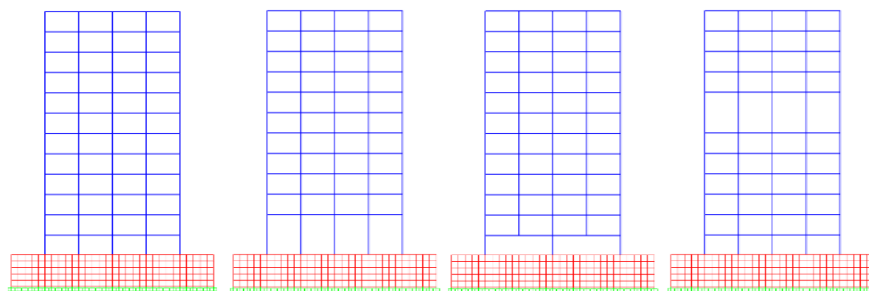


Figure 6. Frame models with soil structure interaction for the present study.

Table 1. Design seismic parameters.

S.N.	Design Parameter	Value
1	Seismic zone	III
2	Zone factor	0.16
3	Response reduction factor	3
4	Importance factor	1.5
5	Soil type	II
6	Soil for SSI	Clay
6	Frame type	OMRF

Table 2. Design material properties.

S.N.	Design Parameter	Value
1	Unit weight of concrete	25.00 kN/m ³ .
2	Unit weight of walls	20 kN/m ³ .
3	Characteristic strength of concrete	20 N/mm ² .
4	Characteristic strength of steel	500 N/mm ² .
5	Damping ratio	5%.

Table 3. Design structural parameters.

S.N.	Design Parameter	Value (mm)
1	Beam	300 × 600
2	Column (1–8 floor)	750 × 750
3	Column (9–14 floor)	600 × 600
4	Column (15–20 floor)	450 × 450
5	Slab thickness	200
6	Ext. wall thickness	230

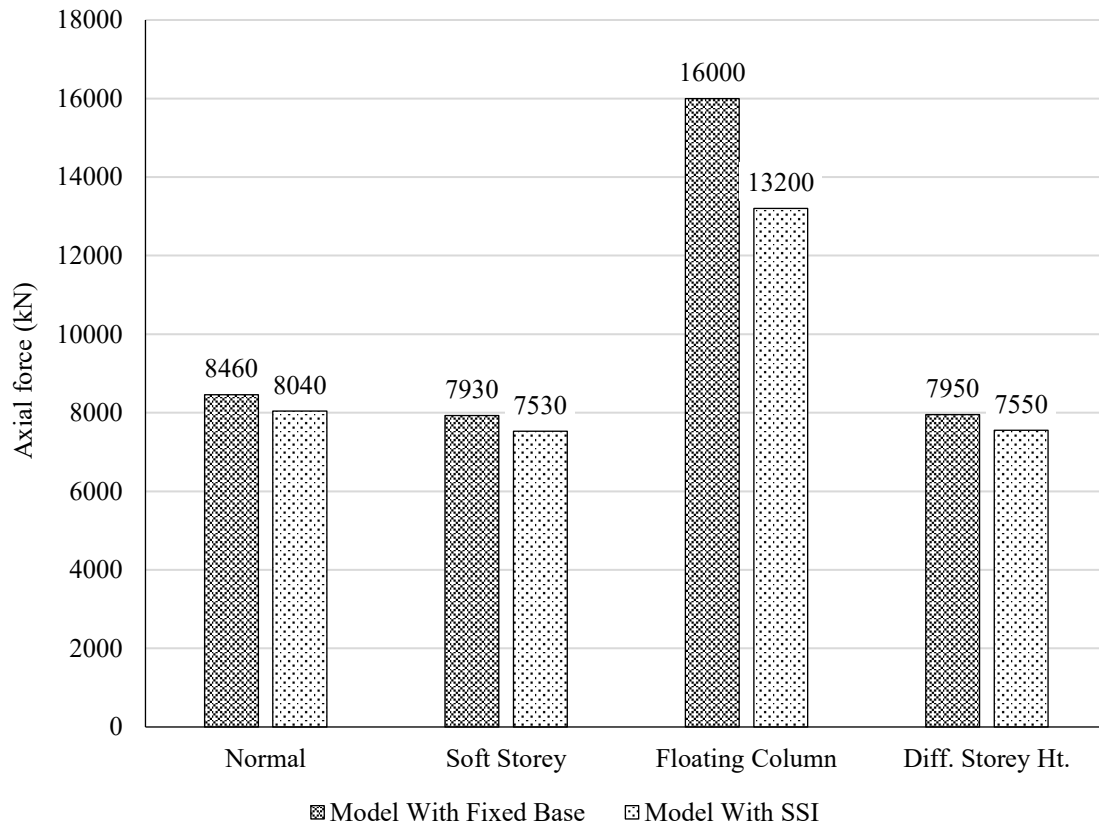


Figure 7. Maximum axial forces (Fx).

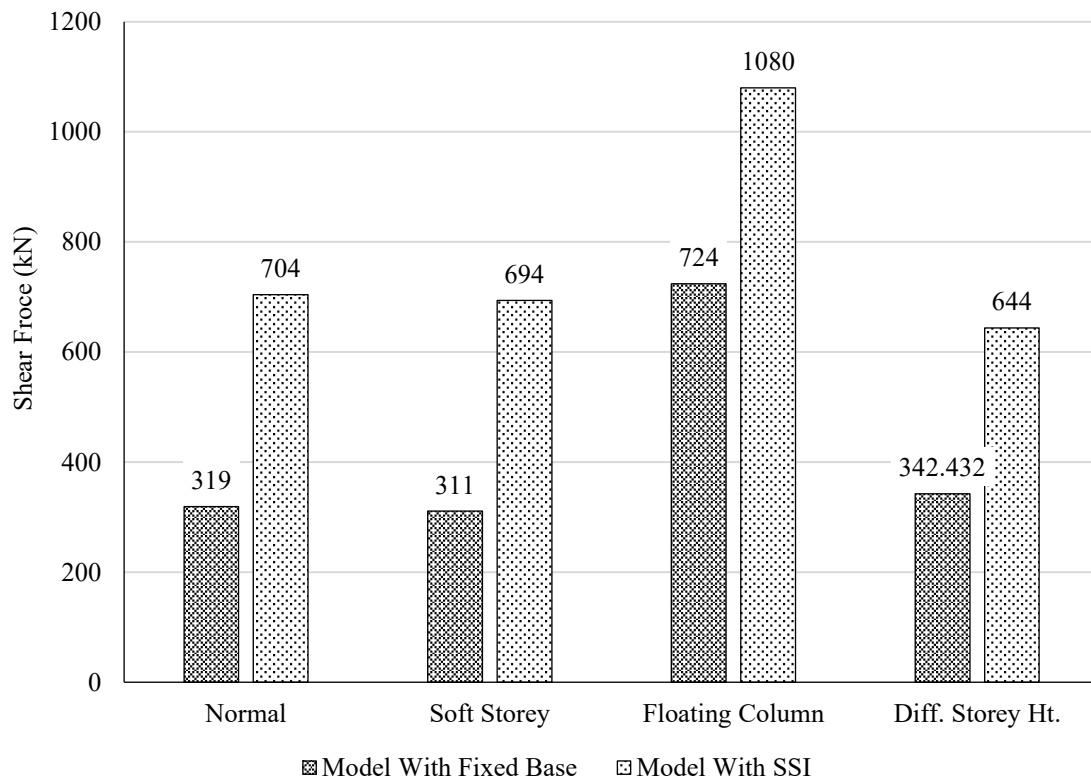


Figure 8. Maximum shear forces (Fy).

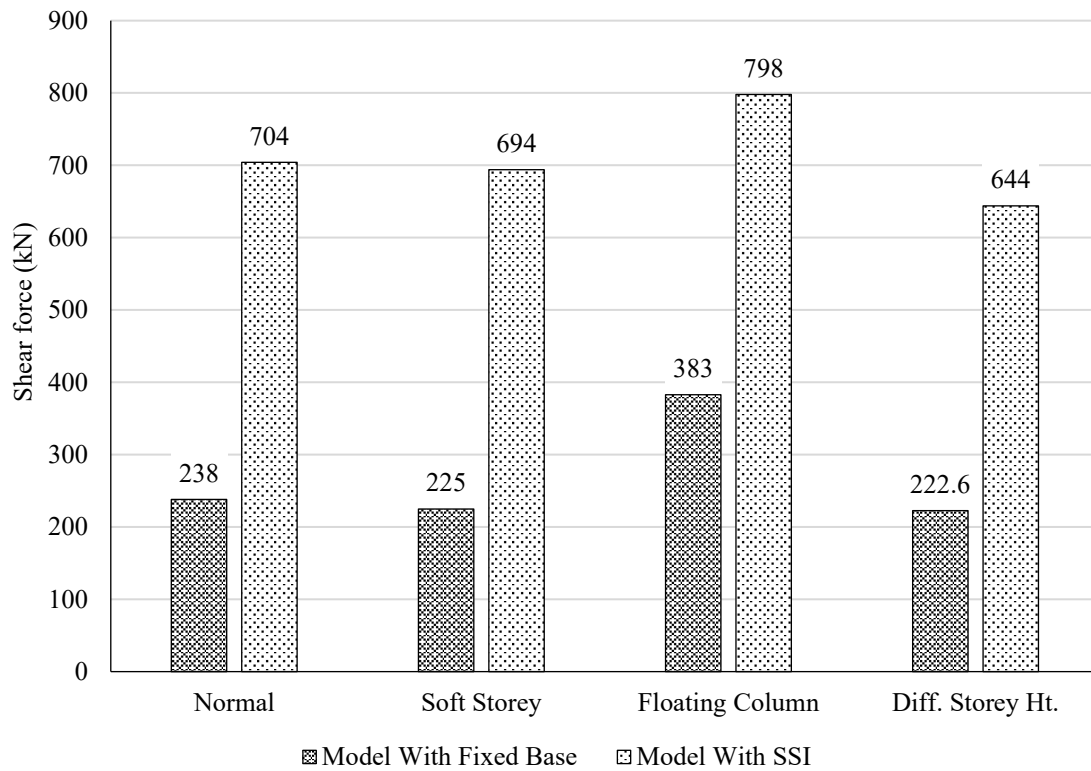


Figure 9. Maximum shear forces (FZ).

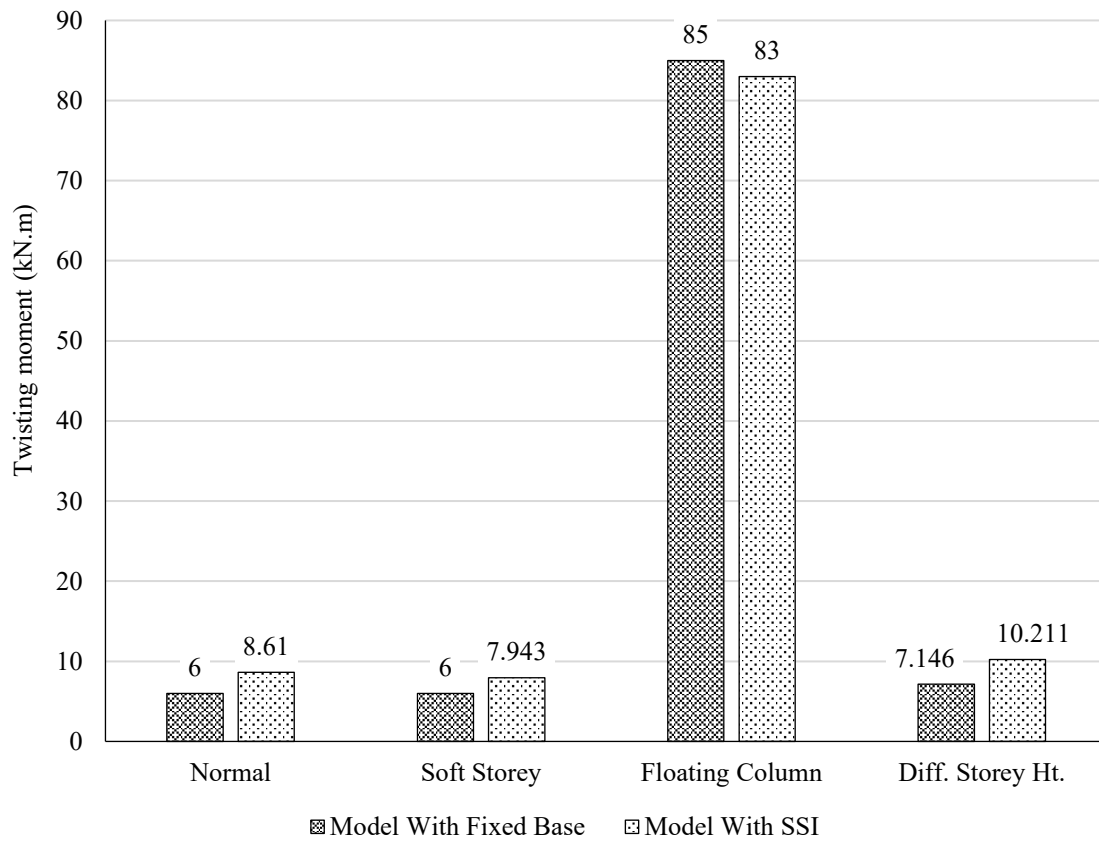


Figure 10. Maximum twisting moment (Mx).

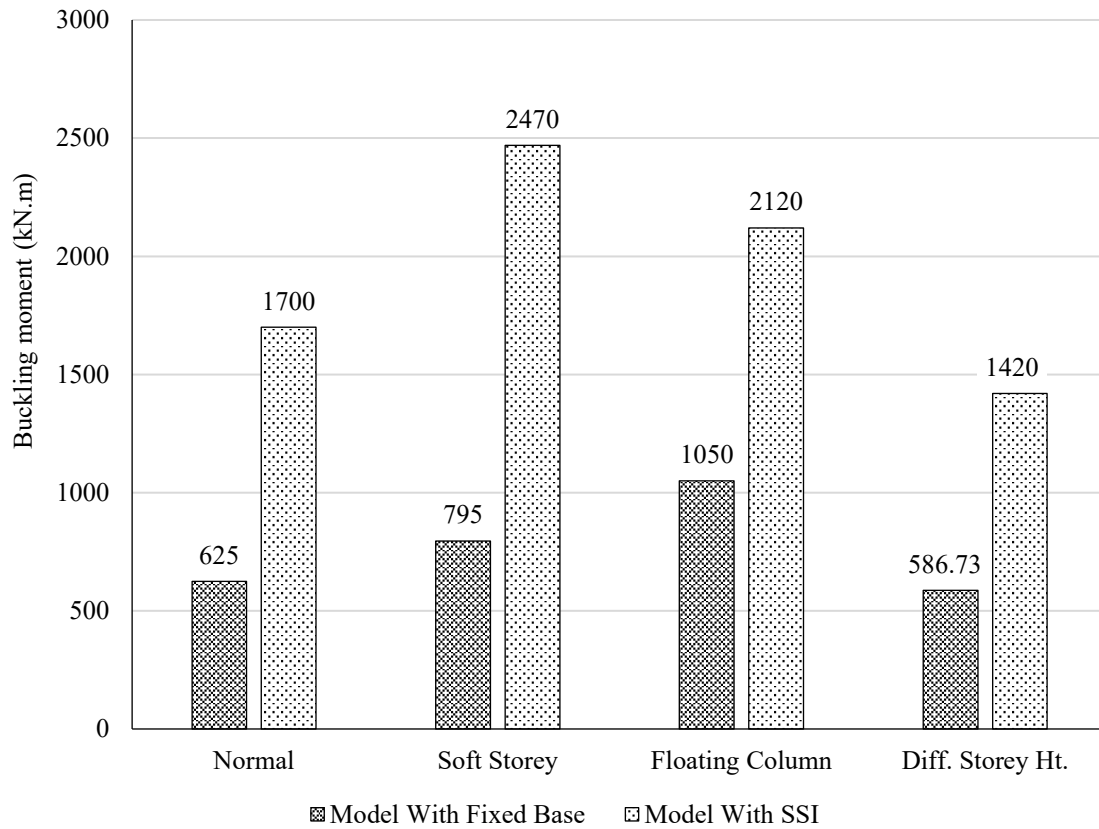


Figure 11. Maximum buckling moment (My).

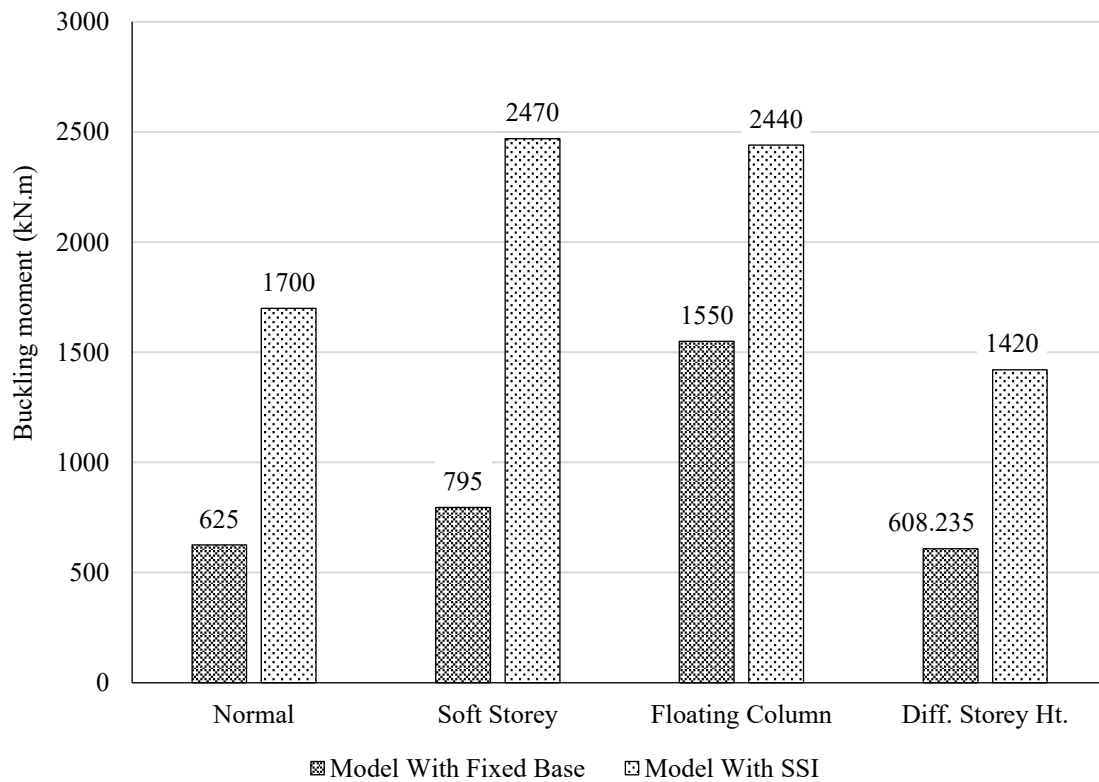


Figure 12. Maximum bending moment (Mz).

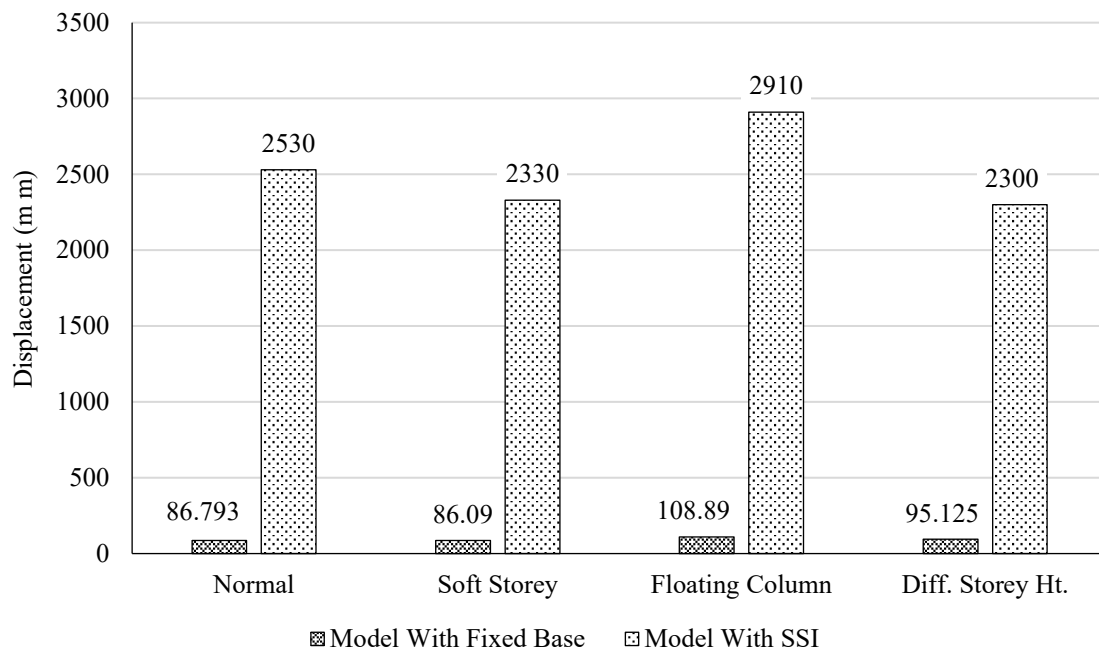


Figure 13. Resultant displacement.

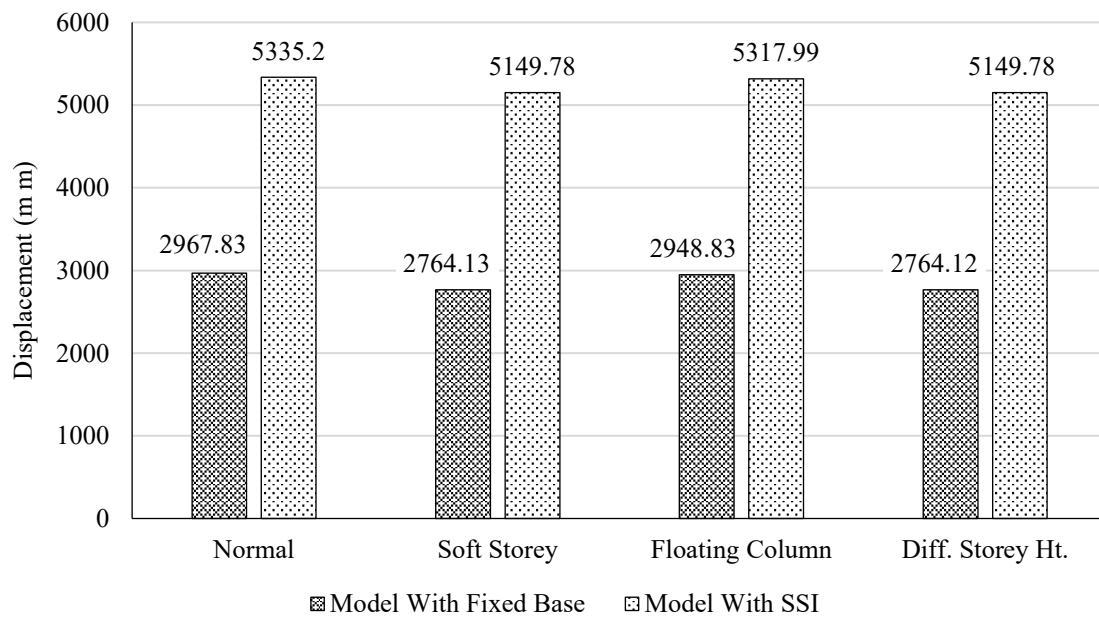


Figure 14. Maximum base shear.

DISCUSSION THROUGH FIGURES

- It is observed from Figure 7 that the maximum axial force of 16,000 kN is obtained for the model with a floating column with fixed base, while the minimum axial force of 7530 kN is obtained for the soft story model with SSI [16].
- The decrease in axial force for the model with a fixed base compared to the model with SSI is 17.5%.
- It is observed from Figures 8, 9 that the maximum shear force of 1080 KN is obtained for the floating column model with SSI, while the minimum shear force of 311 kN is obtained for the soft story model with a fixed base [17].

- The Increase in Shear force for the model with a fixed base compared to the model with SSI is 49.17%.
- It is observed from Figure 10 that the maximum twisting moment of 85 kN.m is obtained for the model with a floating column with fixed base, while the minimum twisting moment of 6 kN.m is obtained for model soft-story model with fixed base [18].
- The decrease in Twisting Moment for the model with a fixed base to the model with SSI is 2.35%.
- It is observed from Figures 11 & 12 that the maximum bending moment (M_y , M_z) is obtained for the floating column model of 2470 kN.m while the minimum bending moment (M_y , M_z) is obtained for the model with a different story height with fixed base is 586 kN.m.
- The Increase in Buckling and Bending Moment for the model with a fixed base to the model with SSI is 210.69%.
- It is observed from Figure 13 that, in contrast, the Soft Story and Double Story Building models exhibit lower forces but higher displacements, reflecting their flexibility and potential vulnerability to collapse if not properly designed.
- It is observed from Figure 14 maximum base shear is obtained for the model floating column with SSI 5317.99 kN, while the minimum base shear is obtained for the model with soft story with a fixed base 2764.12 kN.
- The Increase in Base Shear for the model with a fixed base to the model with SSI is 80.34%.

CONCLUSIONS

The analysis reveals that the Floating Column model experiences the highest forces and moments (axial, shear, twisting, buckling, bending, and base shear) and significant displacement, making it the most stressed configuration due to stress concentrations and amplified dynamic responses, particularly under seismic loading. In contrast, the Soft Story and Double Story Building models exhibit lower forces but higher displacements, reflecting their flexibility and potential vulnerability to collapse if not properly designed. The Normal model serves as a robust baseline with moderate forces and minimal displacement, while SSI models show increased displacements but reduced forces due to soil energy absorption compared to fixed-base models.

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