Effect of Soil Structure Interaction on High Rise RCC Building

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Abstract - The foundation, the surrounding and underlying soil, and the building itself form interconnected systems that collectively determine a structure's response to seismic activity. Evaluating the interplay between soil and structure is crucial in understanding their combined reaction to specific ground movements. In literature, the terms "soil-structure interaction" (SSI) and "soil-foundation-structure interaction" (SFSI) are often used interchangeably to describe this phenomenon. Despite the potential impact of SSI, structural engineers sometimes overlook its influence, assuming it has no detrimental effects on the structure. However, this assumption may not always hold true. Recognizing the foundation's critical role in the structure, this project adopts the term "SSI." For analytical purposes, we consider a B+S+24 R.C.C. building to compare the influence of SSI. Furthermore, we investigate two distinct soil types—soft soil and hard soil—by measuring their stiffness using techniques developed by Richart and Lysmer. Our analysis examines the advantages and disadvantages of soil-structure interaction. We conduct initial static analyses of the building, evaluating factors such as bending moment, shear force, and axial force for comparison. Subsequently, we contrast the impact on beams and columns with and without SSI. Dynamic response spectrum analysis is then applied to assess the building's behavior, including story drift, lateral displacement, base shear, and time period, with and without considering SSI. Our findings underscore the paramount importance of accounting for SSI, or soil-foundation-soil interaction, in structural assessments."

Key Words: *Soil structure interaction, framed structure, Behavior of foundation, ETABS, Response spectrum analysis*

1. INTRODUCTION

The term "soil-structure interaction" encompasses a range of processes that influence the response of soil to the presence of structures and vice versa, affecting how structures respond to the flexible soil beneath their foundations. Illustrated in Figure 1, a complete soil-foundation-structure system comprises a superstructure frame, its foundation, and the supporting soil. Differential settlement, stemming from variations in soil characteristics across different areas beneath the structure, can impact both axial forces and moments within structural members.

The majority of civil structures include at least one component directly in contact with the ground. When external forces, such as earthquakes, act upon these systems, ground displacements and structure displacements become interdependent. Soil-structure interaction (SSI) describes the reciprocal influence between soil response and structural movements.

The degree of load redistribution within structural components is determined by the structural rigidity and the soil's capacity for settling under load. Consequently, numerous studies in the literature have investigated the impact of this factor. Traditional structural design methods often overlook the effects of SSI. While it may be reasonable to disregard SSI in light constructions on relatively hard soil, such as low-rise buildings and basic solid retaining walls, massive structures like skyscrapers, nuclear power stations, and highways situated on softer soils are significantly affected by SSI.

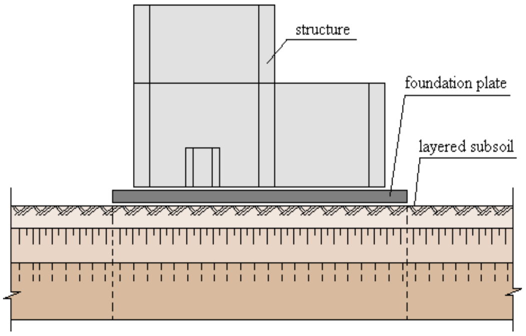


Fig -1: Interaction between structure, foundation plate and soil

Yassine Razzouk et. al. (2023) aimed to investigate the impact of soil-structure interaction (SSI) on the seismic behavior of reinforced concrete buildings. A sophisticated numerical model for soil-structure interaction (SSI) was developed and validated using ABAQUS software. The seismic response of a twelve-story building was analyzed on four different types of soil (rock, dense soil, stiff soil, and soft soil) using a Normalized Response Spectra based on the Moroccan para seismic regulation RPS 2011. The study compared the global lateral displacement, interstory drift, and period for both column and shear wall bracing systems. The results revealed significant differences in seismic responses between shear wall bracing and column bracing in soil-structure systems, highlighting the considerable influence of SSI on the seismic behavior of buildings. [1]

M.E. Hossain1, A. Sakib, M. Hasan (2022) aimed to identify the influence of soil-structure interaction (SSI) subjected to seismic forces with fixed and flexible base conditions in multistory buildings through numerical simulations. A finite element-based software program called ETABS was employed to model G+9 storey building frames. Dynamic analysis was conducted using the response spectrum method. The Winkler technique was utilized to incorporate soil flexibility through a spring model. The study compared the responses of structures with flexible and fixed bases, considering various structural components such as tale drift, story displacement, and natural period. It was observed that tale displacement, tale drift, and the natural period were smaller in fixed-base structures compared to flexible-base structures. Structures designed without considering the impacts of soil-structure interaction (SSI) may be less resilient during earthquakes. Therefore, it is imperative to account for these effects and select an appropriate foundation system during the construction of a building. [2]

Srijit Bandyopadhyay et. al. (2021) studied the effect of structure soil structure interaction of the two adjacent Reinforced Concrete (RC) three storied structures, located in highest seismic zone of India are studied. One structure was installed on a lead rubber bearing base isolator, while the other was a conventional reinforced concrete (RC) framed construction. Seismic sensors were installed in both buildings, and their actual seismic responses were recorded between 2006 and 2007. As expected, the base-isolated structure exhibited a frequency 2.6 times lower than that of the conventional structure, and its response was also 4–5 times lower. However, the response of the base-isolated building indicated structure-soil structure interaction, as it reflected the frequency of the surrounding structure. In a numerical simulation, two nearby structures were considered along with comprehensive soil modeling, and the numerical results were validated using actual earthquake data. Additionally, the responses of both buildings to a stronger earthquake in the same region, with a peak ground acceleration (PGA) of 0.26 g, were examined. The response acceleration of the base-isolated building was approximately 4.1 times slower than that of the conventional building. Furthermore, due to the nonlinear deformation of the isolator, resulting in varying effective stiffness for different displacements during cyclic motion, the floor spectra of the roof of the base-isolated structure exhibited multiple peaks. It was also demonstrated that as peak ground acceleration increased, the frequency of the base-isolated building decreased [3]

Wesam Al Agha et. al. (2021) considered SSI using the direct method (i.e. FEM soil medium) and studied the effect of changing soil type (soft soils and hard soils) on the performance of the tall building under consideration. The structure, consisting of 16 floors and employing a twin wall-framed design to withstand seismic loads, was analyzed using Abaqus software (Simulia's Abaqus 6.14). The boundaries of the soil media were modeled using semi-infinite elements from the Abaqus solid element library. El-Centro acceleration time-history data were utilized as the seismic loading input. The analysis revealed notable differences between hard and soft soil types, particularly in terms of base shear values and displacements. It was concluded that when soil-structure interaction is considered, displacement values should be increased. In comparing displacement values between hard and soft soil, the values in hard soil closely resembled those from the fixed-base scenario. Base shear values decreased with soil-structure interaction between soft and hard soil, but base shear values in hard soil were nearly equivalent to those in the fixed-base scenario. This study highlights the importance of considering soil-structure interaction, especially in soft soil conditions, and suggests extending the analysis timeframe to accurately capture the effects of soil-structure interaction. [4]

Deepashree R et. al. (2020) studied 6 models of G+13 multi-storey symmetrical RC building with storey height 3m is modelled using ETABS which was assumed to be located in Hard-soil, Medium-soil and Soft-soil of zone-IV was subjected to response spectrum analysis. The structure was initially analyzed without considering soil-structure interaction (SSI), and its behavior was compared to the scenario where SSI effects were incorporated using spring elements. Various systematic characteristics were examined and compared, including natural period, storey stiffness, overturning moment, base shear, storey displacement, storey drift, and storey shear. The analysis revealed that soft soil conditions are more critical, and the structure responds more significantly when SSI effects are considered. Therefore, it is imperative to account for these impacts when designing a structure, especially in regions with soft soil conditions. [5]

Hossein Tahghighi and Ali Mohammadi (2020) aimed to investigate whether the seismic performance and vulnerability of reinforced concrete (RC) structures were affected by soil–structure interaction (SSI). The OpenSees finite-element framework was utilized to construct and model a series of reinforced concrete (RC) frames situated on three distinct types of soil. The interaction between the soil and the foundation was simulated using a nonlinear Winkler-based approach. Seismic behavior and fragility of RC buildings were evaluated in relation to rigid and flexible base assumptions through nonlinear static analysis and incremental dynamic analysis. Numerical results demonstrated the significant impact of soil-structure interaction (SSI) on altering the fragility and performance of structures with rigid bases. Furthermore, a straightforward method was proposed to derive vulnerability values for structures with flexible bases by adjusting the basic mode spectral acceleration. Pushover analysis and incremental dynamic analysis were employed to investigate the effects of SSI inclusion on the seismic performance and fragilities of RC buildings. Foundation flexibility was modeled using the Beam on Nonlinear Winkler Foundation (BNWF) approach, assuming a range of soil conditions from soft to hard. The findings underscored the crucial role of seismic SSI in altering structural demands and emphasized the potential inaccuracies in performance and fragility assessment if SSI effects are disregarded. Additionally, it was concluded that foundation flexibility has minimal impact on the period and response modification factors of RC moment-resisting frames (MRFs), suggesting that it can be disregarded in their assessment. Moreover, the results highlighted a significant enhancement in the performance level of midrise frames when positioned on soft soil sites, further emphasizing the importance of considering SSI effects in seismic design and assessment. [6]

Purva M. Kulkarni, Dr. Y.M. Ghugal (2019) attempted to understand the influence of soil flexibility in soil structure interaction (SSI) on building frames resting on piled raft foundation. Finite element-based program ETABS was employed for building frame modeling. G+10 story frames were subjected to earthquakes on various homogenous and stratified soil types, with and without soil-structure interaction (SSI). The study compared fixed bases with buildings supported by piled raft foundations. IS 1893:2002 Response Spectra was utilized for dynamic analysis, and the Winkler technique (spring model) was used to incorporate soil flexibility. The analysis investigated the impact of SSI on various structural characteristics, including natural time period, lateral displacement, and roof displacement. It was observed that time duration and displacement increased significantly with the inclusion of SSI. The study concluded that the foundation and soil types played a major role in the impact of SSI on structural behavior. [7]

Taha A. Ansari, Sagar Jamle (2019) attempted to understand the effect interaction of soil and structure on building with underground storey. Nonlinear static analysis was utilized to compare the seismic response of ten-story buildings with fixed bases and subsurface stories. Factors such as pushover curves, performance points, and hinge formation were taken into account. The study examined differences in seismic analysis parameters between linear and nonlinear static analyses, considering the impact of soil-structure interaction (SSI) for medium stiff ML soil and low stiff CH soil. It was concluded that, for both ML and CH soil types, design storey shear forces were lower for a typical ten-story building with an underground storey when SSI effects were considered compared to a fixed-base building. Demand capacity curves for underground storey buildings indicated that the building's performance point remained nearly the same. Furthermore, additional hinges were observed in the fixed foundation building for the underground structure, particularly near the building's ends. [8]

Ajit C. Suryawanshi, V. M. Bogar (2019) considered RCC structures along with and without soil structure interaction on sloping ground to compare the displacement, story shear, story drift and base shear of buildings. Buildings situated on sloping terrain were evaluated based on predetermined criteria, with and without considering soil-structure interaction (SSI). Response spectrum analysis was employed to assess the performance of these structures. To achieve this objective, ETABS 2016 was utilized to model G+19 structures both with and without soil-structure interaction. The analysis of the G+19 building models incorporated soil-structure interaction and was conducted from various perspectives. The study concluded that, compared to conventional fixed-base (NSSI) models, the story displacement of building models with SSI was greater. This effect was particularly pronounced in soft soil conditions. Notably, the highest story displacement was observed in building models situated on a 30° slope, regardless of soil type and the presence of soil stabilization. Furthermore, it was observed that in models with conventional fixed bases, the base shear value increased with the model's number, whereas in models with SSI, the base shear value decreased. [9]

1.1 Nonlinear Behavior of Soils

Following the initial loading, soil exhibits nonlinear behavior due to its flexible nature. Engineers have long struggled to accurately model this behavior mathematically due to its complexity, which is further compounded by its time-dependent nature. This nonlinearity is the primary source of uncertainty in predicting the static behavior of the soil foundation-superstructure system post-construction.

Physically, when an external load is applied to the soil mass, soil particles tend to reorganize themselves to minimize potential energy and achieve stability. Initially, the strain transferred to the soil mass is elastic up to a certain stress threshold. Depending on the magnitude of the applied load, it may progress into the plastic range. Subsequently, there is visco-plastic deformation caused by viscous inter-granular activity, leading to strain accumulation over time.

Certainly, several factors influence the behavior of soil:

a) Heterogeneous Distribution: Soil properties such as composition, density, and moisture content can vary widely across a given area, leading to heterogeneous behavior in response to external loads.

b) Anisotropy: Soil may exhibit different properties or behaviors depending on the direction of stress or loading due to factors such as sedimentation patterns or geological features.

c) Geometric Differences (Large Displacements): Large displacements, such as those caused by excavation or construction activities, can significantly alter the soil's behavior, leading to nonlinear responses and potential instability.

d) Nonlinear Behavior Between Interfaces: Interfaces between different soil layers or between soil and structural elements can exhibit nonlinear behavior under stress, impacting the overall behavior of the soil-structure system.

e) Cracks: The presence of cracks in soil due to factors like shrinkage, settlement, or differential loading can influence soil behavior by altering its strength, stiffness, and permeability.

f) Underground Water Consolidation: Changes in groundwater levels and water flow patterns can affect soil behavior through processes such as consolidation, swelling, or erosion, leading to changes in soil volume and strength.

These factors, among others, contribute to the complex and varied behavior of soil, highlighting the importance of considering them in engineering analyses and designs involving soil-structure interaction.

1.2 Effect of soil structure interaction on structural response

It has been a longstanding belief in the engineering community that the interaction between soil and structure can enhance a structure's seismic response. Many design guidelines have historically suggested that the effects of soil-structure interaction (SSI) can be neglected in seismic analysis of buildings. This misconception stems from the idea that SSI can improve safety margins by reducing a structure's overall seismic response. Most design codes utilize a simplified design spectrum that accelerates in a certain manner before monotonically decreasing over time. In conventional structural design, the substructure is typically treated as inflexible. However, considering soil-structure interaction makes the substructure more flexible or less rigid. Consequently, the structure becomes more flexible and exhibits a longer natural period compared to a similar structure with fixed supports. Additionally, considering the SSI effect results in an increase in the system's effective damping ratio. The smooth idealization of the design spectrum, combined with the rise in effective damping ratio and natural period due to SSI, suggests a reduced seismic response. This led to the misconception that SSI could be conveniently disregarded for conservative design.

Neglecting SSI allows designers to simplify their analysis and overlook the complexities associated with soil-structure interaction, which can be advantageous for certain types of structures on relatively hard soils. However, this assumption does not hold true in all cases. In reality, SSI can have adverse effects on structural response, and ignoring SSI in analysis may pose risks for foundation and superstructure designs. Therefore, it is important to carefully consider the effects of SSI in structural analysis and design, particularly for structures on softer soils or in regions with high seismic activity.

1.3 Objectives of investigation

1. To check the stability of structure with seismic load in different seismic zones (IV &V)

2. To understand the effect of soil structure interaction for soft and medium soil.

3. To find the effect of SSI on structure.

4. To suggest the suitable methodology to include the effect of soil structure interaction.

2. METHODOLOGY

For the current project, seismic analysis is being conducted on a reinforced concrete moment-resistant high-rise building frame, specifically a B+S+24 storey structure. The aim of this study is to examine the impact of soil-structure interaction (SSI) on tall buildings. The structure in question stands at a height of 83.1 meters above ground level. Each of the 24 storeys is situated 3 meters above ground level, with a stilt height of 3.9 meters. This configuration is crucial for understanding how SSI influences the seismic behavior of tall buildings, as the interaction between the building's foundation and the underlying soil becomes increasingly significant with height.

Two types of buildings considered in the study, which are

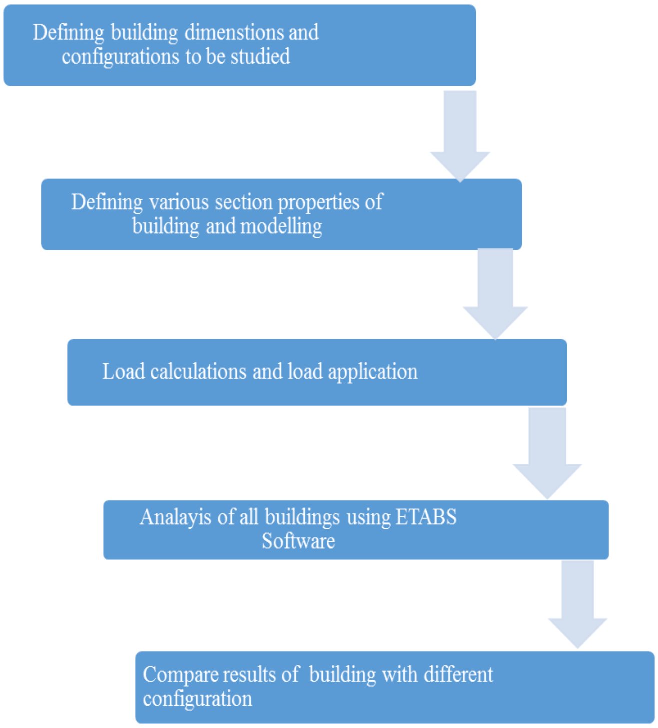
1) Buildings without fixed base (soft and hard)

2) Buildings with flexible base with SSI

In order to facilitate modeling, the ETABS software has been utilized to simulate a 26-story case study building.

The entire building is represented by a three-dimensional reinforced concrete (R.C.C.) frame model. The R.C.C. frame model utilizes 3-D beam elements with 6 degrees of freedom at each node to accurately model beams and columns. The slab is treated as a fairly stiff membrane in its own plane to provide diaphragm action for transferring horizontal loads to columns and shear walls. The frame of the building is modeled using the 3D R.C.C. beam element, with beams and columns incorporated in the modeling process. The columns are constructed using M35 grade concrete and Fe 500 grade steel, while the beams and slab are made using M30 grade concrete and Fe 500 grade steel, in accordance with design specifications.

R.C.C. shell elements are employed in modeling the shear walls. These shell elements consist of monolayer membranes with varying thicknesses and eccentricities, providing resistance to membrane forces, bending, and shearing. Membrane elements are used to simulate floor slabs, which are considered stiff diaphragms. Seismic barriers are simulated using 3D quadrilateral shell elements, with each shell element assigned M35 grade material properties. This comprehensive modeling approach allows for accurate representation of the building's structural components and their behavior under seismic loading conditions.



2.1 Buildings with fixed base

The coordinate points, which denote the locations of the columns in relation to the base plan arrangement of the building, are crucial for analysis. In a fixed base condition, all points are constrained with displacements in the x, y, and z directions (ux, uy, uz), as well as rotations about the x, y, and z axes (rx, ry, rz). This means that both linear and rotational displacements are restricted. In the structural model, the first floor is designated as the master storey, and subsequent levels are modeled accordingly. Each storey is represented by appropriate beams, columns, slabs, and shear walls, ensuring a comprehensive representation of the entire structure. The three-dimensional perspective of the towering building can be visualized in Figure 2, illustrating the arrangement of beams, columns, slabs, and shear walls in the structural model. This perspective provides a clear understanding of the building's geometry and structural components.

2.2 Building on Raft foundation

To replicate the effects of Soil-Structure Interaction (SSI) in clayey soil, thick reinforced concrete (R.C.C.) shell elements are employed in the raft foundation model. These elements are designed to accurately capture the behavior of the foundation under the influence of soil interaction. The model of the structure with the raft foundation is depicted in Figure 3.

Table 1 presents the assumed and computed parameters of the soil, which are crucial for accurately modeling the interaction between the structure and the underlying clayey soil. These parameters are determined based on empirical data and analysis methods such as the Richart and Lysmer models. In accordance with these models, spring stiffness values are established for various modes of deformation, including twist, rocking, and horizontal motion. These stiffness values are essential for defining the behavior of the soil-structure system under different loading conditions. Quad shell elements are utilized to mesh the entire region encompassing the foundation and surrounding soil. Additionally, soil springs are applied to represent the interaction between the structure and the underlying soil, ensuring an accurate simulation of Soil-Structure Interaction effects in the analysis.

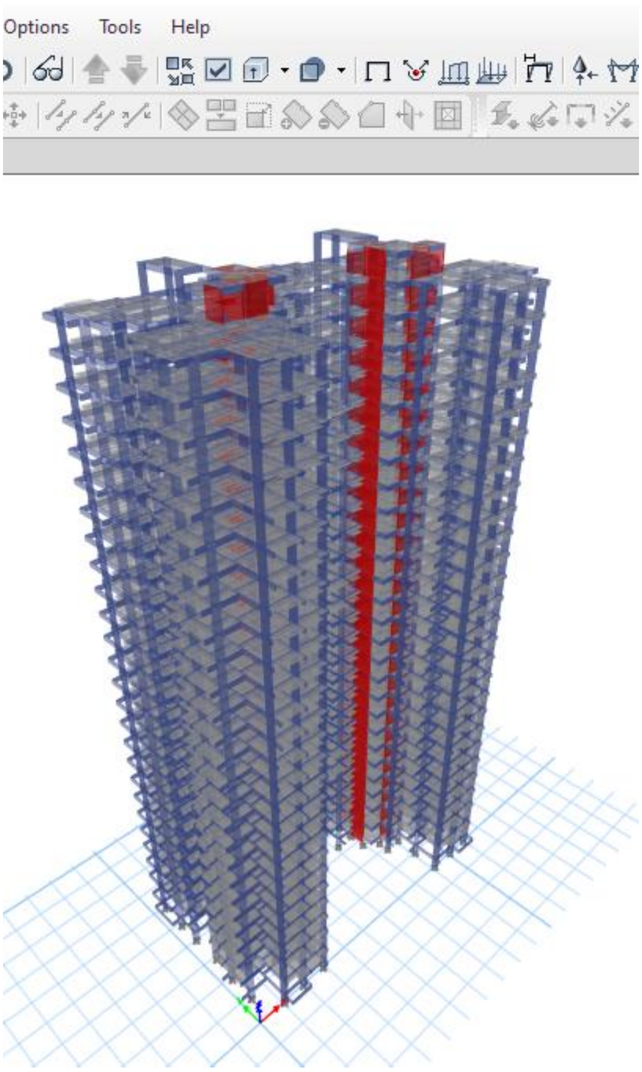


Fig. 2: 3D rendering view of building with fixed base in ETABS

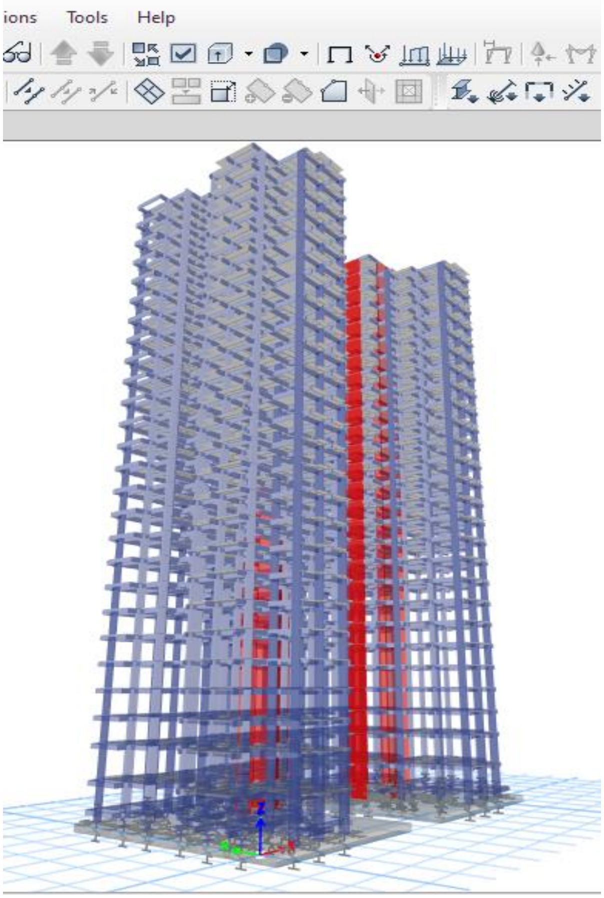


Fig. 3: 3D rendering view of building with raft foundation and applied soil springs in ETABS

Table 1: Soil Spring Values as Per Richart and Lysmer

Direction	Spring Values	Equivalent Radius
Vertical	$K_z = \frac{4Gr_z}{(1-\theta)}$	$r_z = \sqrt{\frac{LB}{\pi}}$
Horizontal	$K_x = K_y = \frac{32(1-\theta)Gr_x}{(7-8\theta)}$	$r_x = \sqrt{\frac{LB}{\pi}}$
Rocking	$K\omega_x = \frac{8Gr_{\varphi x}^3}{3(1-\theta)}$	$r_{\omega x} = \sqrt[4]{\frac{LB^3}{3\pi}}$
	$K\omega_y = \frac{8Gr_{\varphi y}^3}{3(1-\theta)}$	$r_{\omega y} = \sqrt[4]{\frac{LB^3}{3\pi}}$
Twisting	$K\omega_z = \frac{16Gr_{\varphi z}^3}{3}$	$r_{\omega z} = \sqrt[4]{\frac{LB^3+BL^3}{6\pi}}$

3. RESULTS AND DISCUSSIONS

The value of axial force in columns does not change much with soil structure interaction for hard soil as compared to fixed base scenario, but it does decrease marginally for soft soil case for earthquake zones IV and V, according to our examination of all the models using response spectrum analysis. It is discovered that, in comparison to the fixed base case for earthquake zones IV and V, the values of bending moment in the stilt beam group rise by 20–35% for soft soil with soil structure interaction but do not vary much for hard soil. It is discovered that, in comparison to fixed bases for seismic zone IV, values of lateral displacement (mm) with floor level in the X direction do not change significantly for hard soil but increased slightly, by about 70–80%, for soft soil with soil structure interaction. I discovered that, for seismic zone IV, the values of the time period of a building with mode no drop by about 1-2% when compared to a fixed basis, but the values do not vary depending on the kind of soil. It is discovered that, in comparison to a fixed base, values of Story Drift with floor level in the X direction rose slightly, by around 40–60%, for soft soil with soil structure interaction but did not vary much for hard soil. It is found out that, base shear in X direction for seismic zone IV is same in both cases as there is no increase in seismic weight of the building.

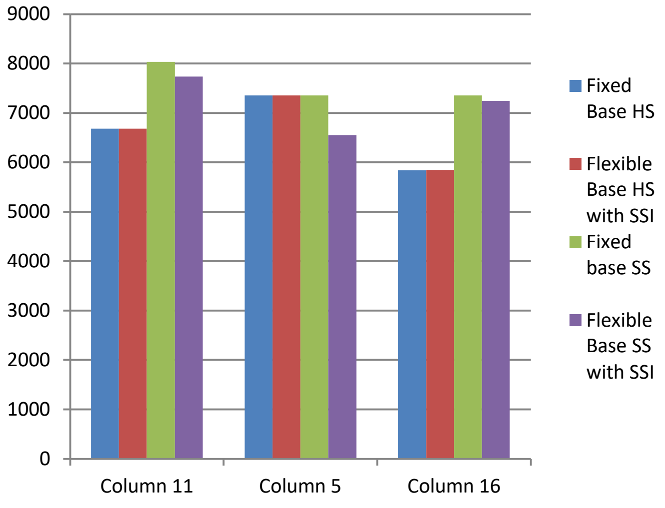


Chart-1: Variation of maximum axial force in column C8, C23 and C37 for zone IV

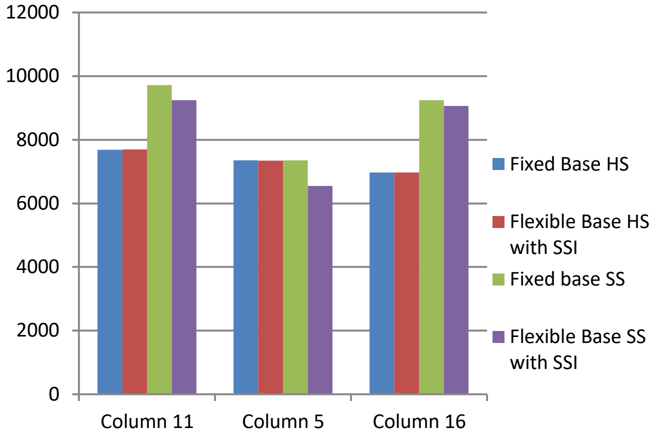


Chart-2: Variation of maximum axial force in column C8, C23 and C37 for zone V

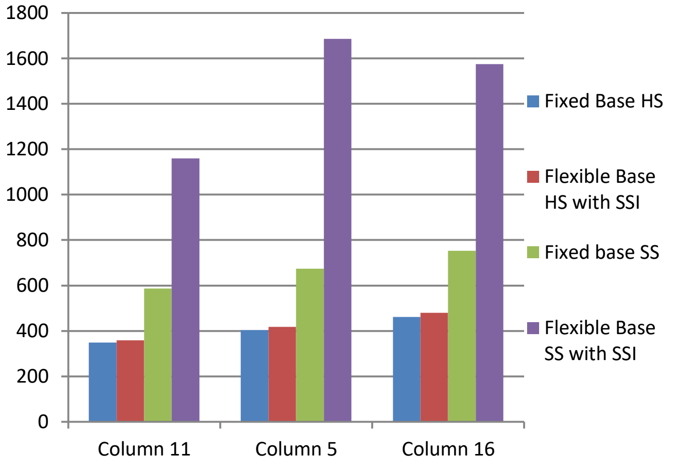


Chart-3: Variation of maximum B.M. in column C8, C23 and C37 for zone IV

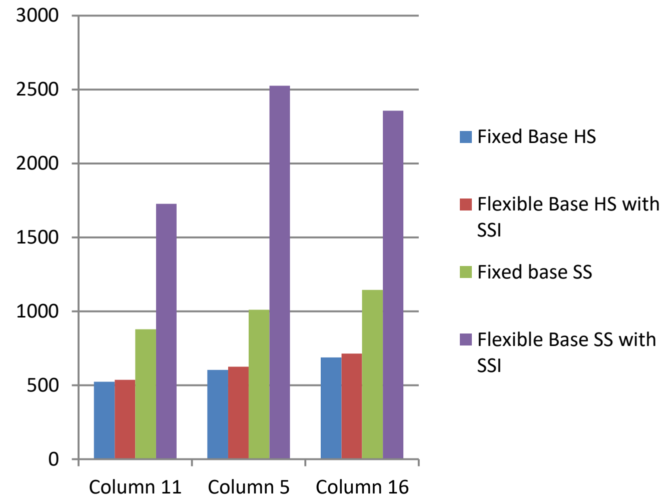


Chart-4: Variation of maximum B.M. in column C8, C23 and C37 for zone V

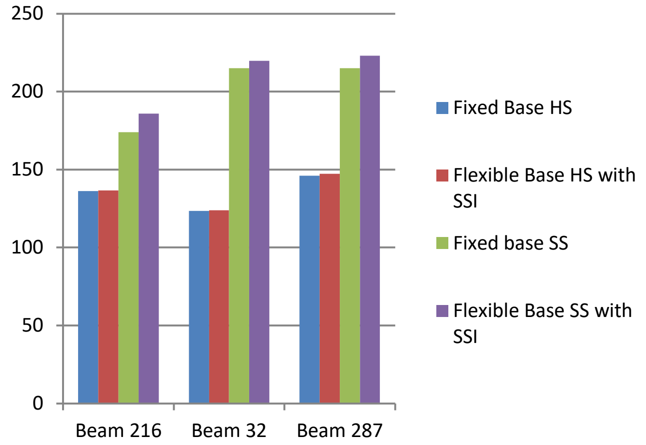


Chart-5: Variation of maximum S.F. in stilt beam B52, B47 and B35 for zone IV

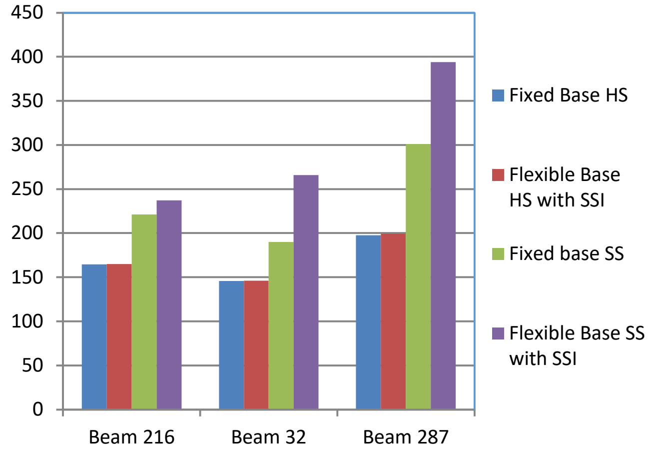


Chart-6: Variation of maximum S.F. in stilt beam B52, B47 and B35 for zone V

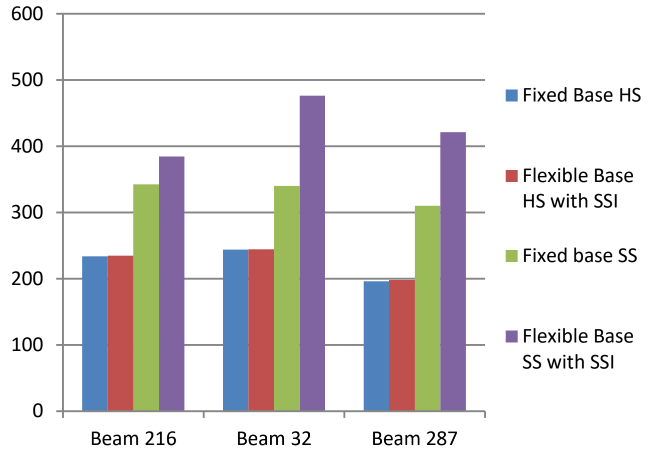


Chart-7: Variation of maximum B.M. in stilt beam B52, B47 and B35 for zone IV

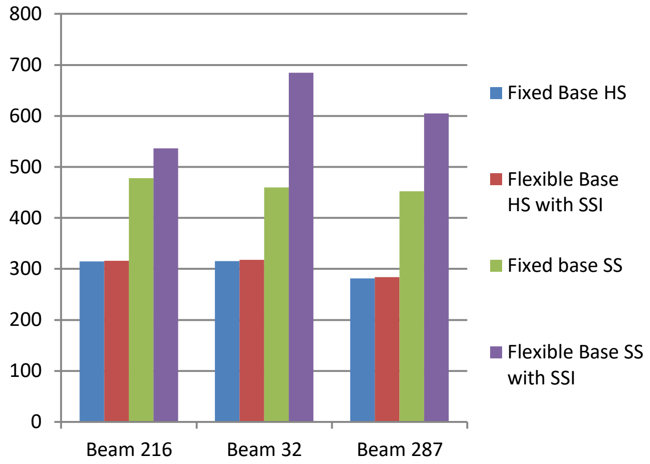


Chart-8: Variation of maximum B.M. in stilt beam B52, B47 and B35 for zone V

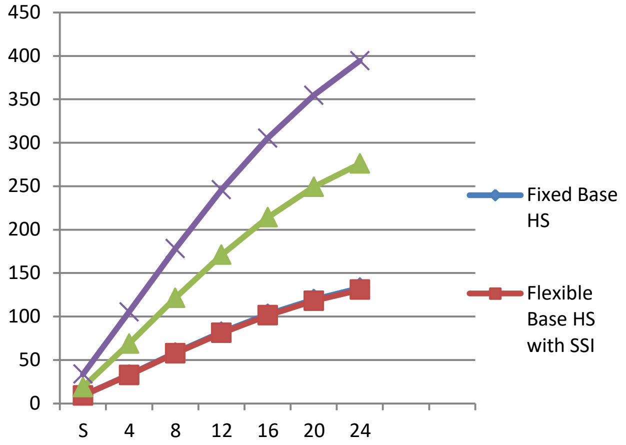


Chart-9: Variation of lateral displacement (mm) with floor level in X direction for zone IV

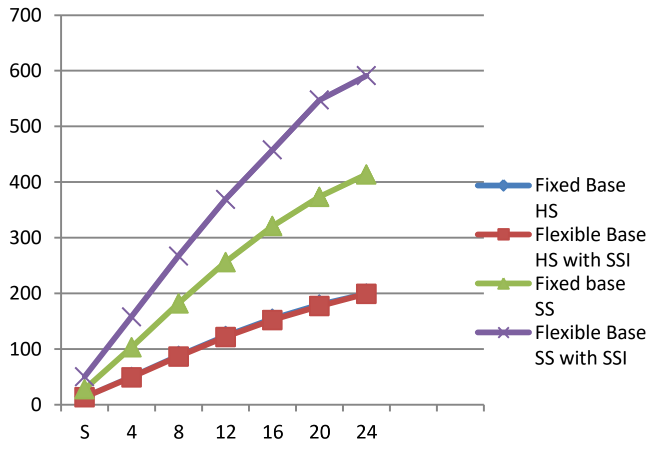


Chart-10: Variation of lateral displacement (mm) with floor level in X direction for zone V

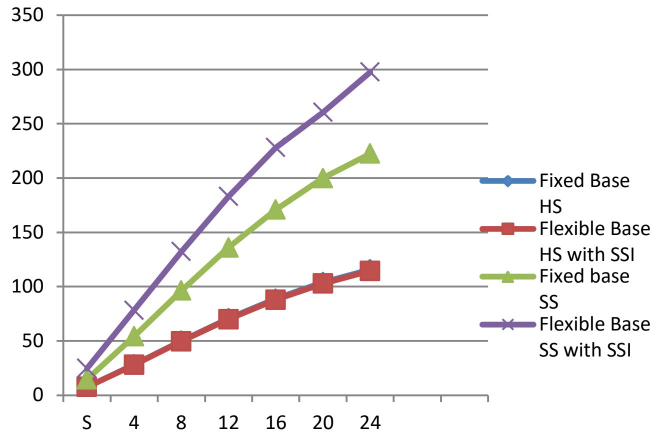


Chart-11: Variation of lateral displacement (mm) with floor level in Y direction for zone IV

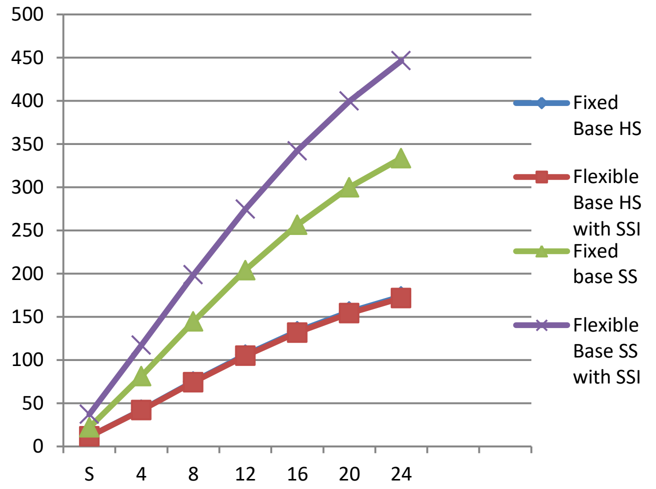


Chart-12: Variation of lateral displacement (mm) with floor level in Y direction for zone V

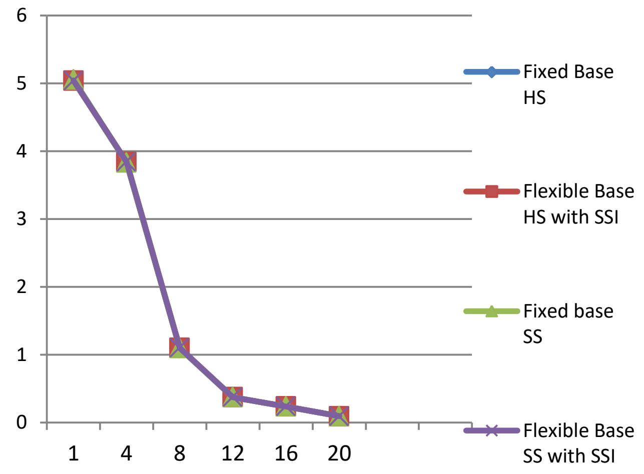


Chart-13 Variation of time period of building with mode shape no for zone IV and V

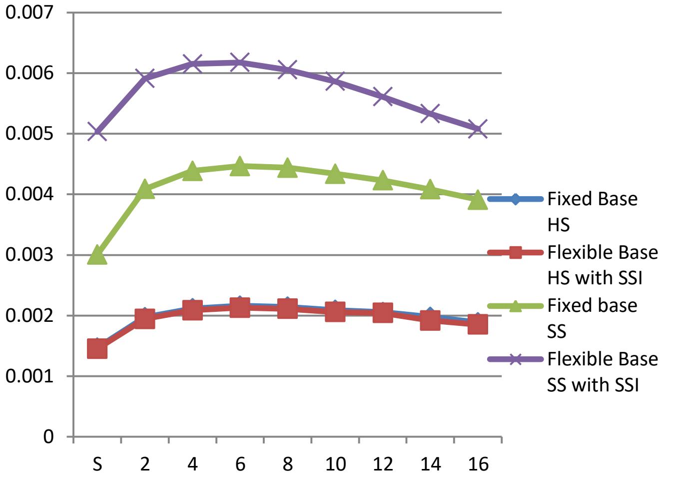


Chart-14 Variation of Story Drift with floor level in X direction for zone IV

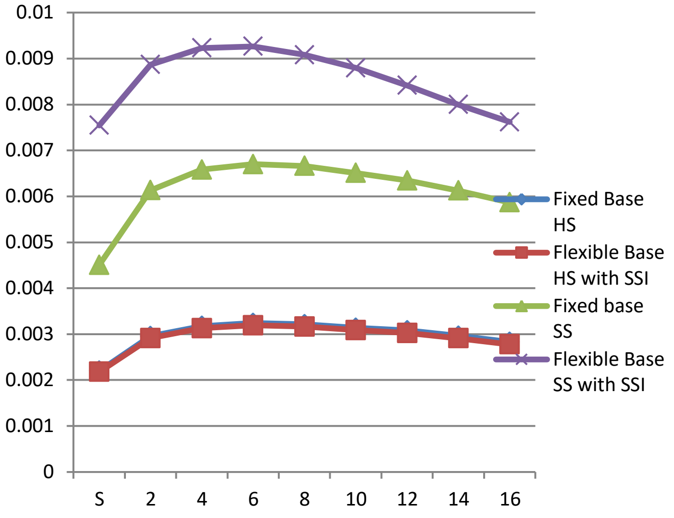


Chart-15 Variation of Story Drift with floor level in X direction for zone V

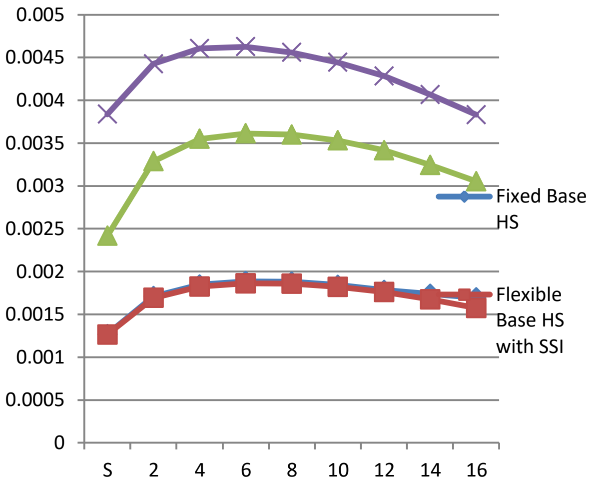


Chart-16 Variation of Story Drift with floor level in Y direction for zone IV

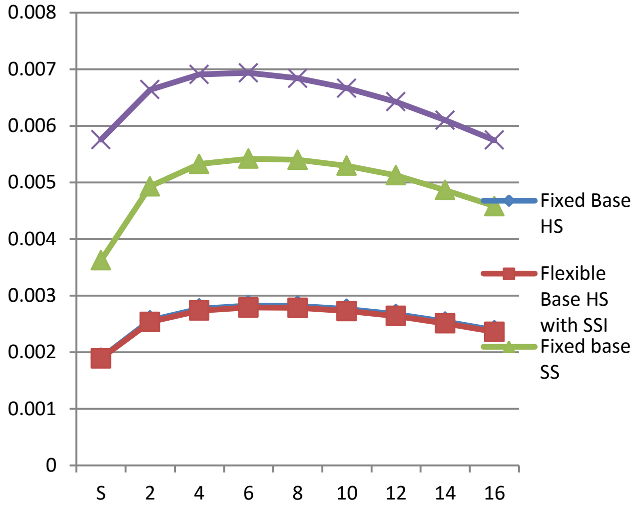


Chart-17 Variation of Story Drift with floor level in Y direction for zone V

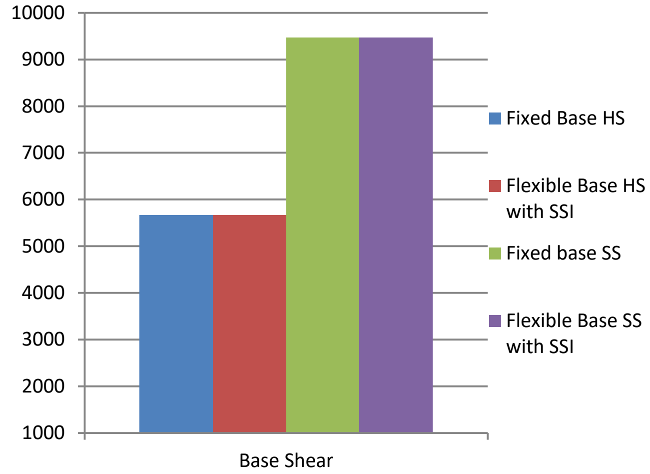


Chart-18 Variation of base shear (kN) of buildings in X direction for zone IV

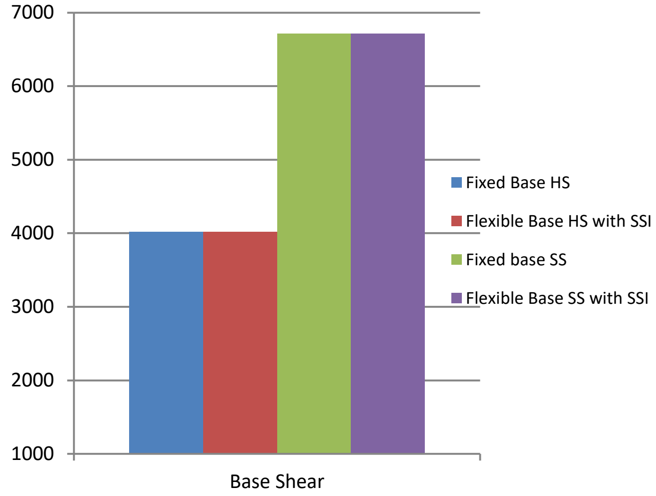


Chart-19 Variation of base shear (kN) of buildings in X direction for zone V

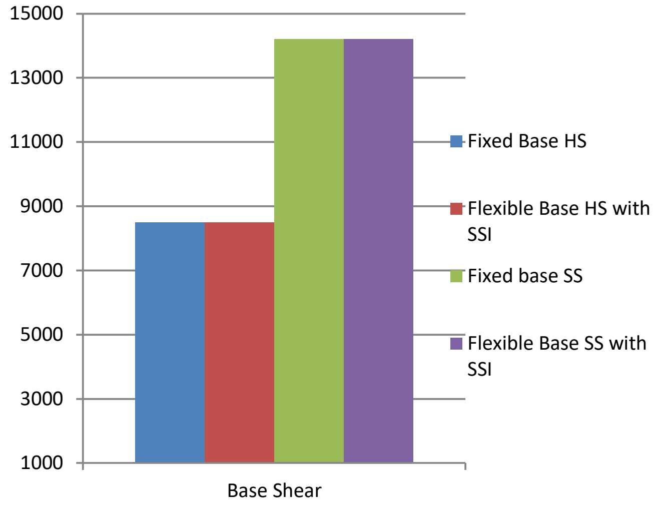


Chart-20 Variation of base shear (kN) of buildings in Y direction for zone IV

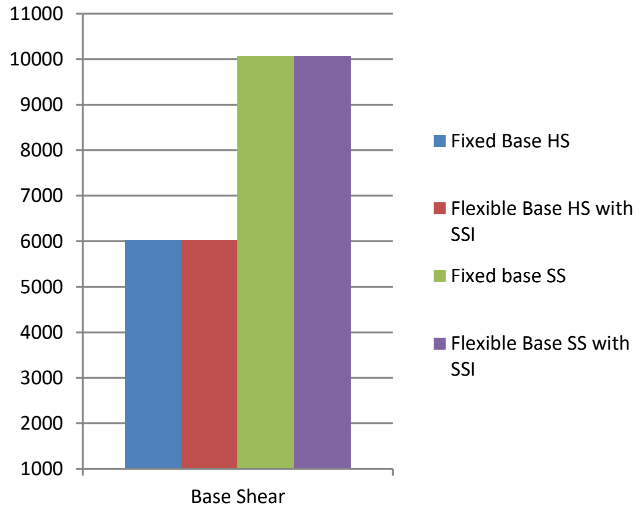


Chart-21 Variation of base shear (kN) of buildings in Y direction for zone V

4. CONCLUSIONS

For hard soil, the influence of Soil-Structure Interaction (SSI) on axial force and bending moment in the column group is negligible and not significant. However, for soft soil, there is a considerable increase of 100–130% in bending moment for both seismic zones IV and V, highlighting the importance of considering SSI in design for structures built on soft soil. Similarly, the variation in shear force and bending moment in the stilt beam group caused by SSI is insignificant for hard soil. However, for soft soil, there is a notable increase of 20-30% in shear force and 30-45% in bending moment for both seismic zones IV and V. This underscores the necessity of incorporating seismic safety engineering (SSI) when constructing on soft soil due to the significant fluctuations observed. In terms of storey drift, the middle storeys experience the greatest drift in both scenarios, with a parabolic difference in storey drift. While there is little change in story drift when SSI is considered for hard soil, there is a noticeable increase of around 30-60% in storey drift for soft soil. Additionally, the highest stories exhibit the greatest variation in lateral displacement, with a notable increase observed when SSI is considered for soft soil.

Despite these variations, the seismic weight of the building remains the same in both seismic zones, regardless of whether SSI is considered or not. The base shear for the scenario with soil-structure interaction is nearly identical to that of the fixed base case. However, the natural time period is somewhat shorter when constructing with soil-structure interaction compared to the fixed base scenario. Overall, buildings situated on soft soil demonstrate a significant increase in response for both fixed base and SSI cases compared to hard soil. The flexibility introduced in the base contributes to the significant rise in skyscraper reaction when considering SSI. Therefore, it is recommended to apply SSI while designing high-rise structures, particularly when constructed on soft soil, to ensure adequate seismic performance.

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