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Investigating the role of nonlinear dynamic interaction of soil structure on the seismic response of structures

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Abstract

The examination of nonlinear dynamic soil-structure interaction (SSI) within the seismic responses domain uncovers noteworthy implications for the structural behavior. SSI impacts, encompassing lateral torsional coupling and alterations in base shear, hold a crucial role in transforming the seismic response of structures, particularly in the presence of extreme seismic occurrences. Studies underscore the significance of genuinely integrating SSI considerations into the structural design processes to precisely forecast parameters like natural period, modal mass contribution, lateral displacement, and base shear forces. The inclusion of SSI in the analyses holds the potential to induce modifications in the structure's performance, underscoring the essential need to account for the soil's flexibility and its interplay with the foundation. The incorporation of SSI considerations can markedly influence the foundation shear of structures, with the extent of these impacts contingent upon variables such as pile length, diameter, and soil characteristics. Dynamic models delineating soil-structure interaction are imperative for accurately assessing the behavior of structures upheld by pile foundations and comprehending the energy transmission mechanisms within the soil. The study investigates the influence of soil-structure interaction on seismic responses of multi-storey buildings, comparing the Winkler method and soil continuum method through time-history analysis in SAP2000 software, highlighting structural behavior changes and uncertainties under SSI conditions.

Keywords: Dynamic interaction, seismic response, soil properties, resilience.

1- Introduction

During severe seismic events, the structural response is greatly influenced not only by the behavior of the superstructure but also by the characteristics and conductivity of the soil surrounding the substructure. In the conventional process of structural design, it is commonly assumed that the foundation footing is fully restrained, indicating that it is in a state of equilibrium. However, this assumption is inadequate as it fails to consider the plasticity effect brought about by the interaction between the structure and the soil. The debate within the engineering community continues regarding whether soil-structure interaction (SSI) yields advantageous or detrimental outcomes on the seismic performance of structures. The influence of soil-structure interaction (SSI) is pivotal in shaping the dynamic response of structures under seismic loading conditions. Conventional methods of structural design frequently overlook the influence of SSI, presuming a stiff foundation without acknowledging the flexibility it imparts. Neglecting the impacts of SSI can result in inaccurate forecasts concerning how structures will react to seismic events. The response of the soil surrounding the substructure can substantially impact the overall behavior of a building when subjected to seismic forces. By integrating SSI into structural analyses, engineers can cultivate a more profound comprehension of the intricate interplay between the superstructure and the underlying soil, thereby enhancing the precision and authenticity of seismic design outcomes. The inclusion of SSI into design procedures, through the contemplation of the dynamic interaction between the structure and the supporting soil, holds the potential to enhance the structural performance and resilience of buildings during seismic occurrences. The primary objective of this investigation is to scrutinize the influence of SSI on the seismic response of a multi-story building. A thorough case study has been carried out to explore the nonlinear dynamic characteristics of the building under various soil bearing capacities. The results are elucidated in relation to fundamental period, base shear forces, and floor drift magnitude, furnishing valuable insights into the impact of SSI on the seismic response of the structure. The quantification of Seismic Soil-Structure Interaction (SSSI) effects remains a challenging research area compared to Seismic Structure Interaction (SSI) due to its complexities. Studies have shown that SSI can enhance structural flexibility, reducing base shear while increasing lateral displacement, leading to potential P-Δ effects from inter-storey drift during seismic events[15][16]. Reversal of stresses during earthquakes can change tension to compression in structural components, causing large distortions and yielding, resulting in significant storey drift that may compromise the safety of occupants.[17] Research in this area explores the responses of different reinforced concrete buildings under various ground motions, analyzing parameters such as time period, base shear, lateral displacement, and inter-storey drift ratio under fixed and flexible base conditions.[18]

2- Literature review

Soil-structure interaction (SSI) is a critical factor that significantly affects the dynamic response of buildings when experiencing seismic events, thus playing a central role in the field of structural engineering. The integration of SSI in structural design is highlighted as an important aspect in the discussed academic paper. Traditional design approaches often ignore the benefits of considering soil-structure interaction, usually by assuming rigid foundation conditions. To correct this limitation, the purpose of this research is to investigate the effects of SSI on a multi-story structure using Finite Element Method (FEM) software. This research addresses two main strategies for combining SSI: the Winkler method (uncoupled) and the pseudo-coupled approach. By performing a comparative evaluation of these methods, the aim of this study is to gain insight into the nonlinear dynamic behavior of the building under different soil bearing capacities. Special attention is paid to the analysis of the fundamental period, base shear forces and floor drift to evaluate how SSI affects the seismic performance of the building. The case study findings provide valuable insights into the complex relationship between soil properties and structural response and provide a better understanding of the complexities inherent in this interaction.

The research paper delves into the utilization of soil-structure interaction (SSI) in buildings, including those with basements, in the context of seismic events. Previous research has underscored the significance of incorporating SSI in the structural evaluation and design process. It has been noted that SSI can have a notable impact on the dynamic response of buildings, particularly those with deep basements when subjected to seismic forces. Disregarding the influence of SSI could result in inaccurate forecasts of structural behaviors and jeopardize the overall safety of buildings. A range of research endeavors have employed diverse modeling techniques to represent the intricate interplay between structures and soils. Nonlinear hysteresis models, like normal and perfectly elastic plastic friction soil springs, have been utilized to effectively replicate soil behaviors. The integration of variable-depth ground motions across the subsurface layers in the analysis mirrors the realistic response of soils during seismic occurrences.

The review of existing literature underscores the necessity for thorough analyses that account for the impacts of SSI to bolster the seismic resilience of buildings, particularly those featuring basements.

The nonlinear dynamic interaction of soil-structure significantly influences the seismic response of structures. Soil-structure interaction (SSI) can either amplify or mitigate the seismic effects on buildings[1][2][3][4]. Neglecting SSI in structural design can lead to inaccurate seismic assessments[5]. Studies show that SSI can alter building responses during earthquakes, especially for structures with significant basement depths. Incorporating SSI in seismic analyses can reveal inconclusive effects, with some cases showing increased base shears and inter-story drifts, while others exhibit the opposite results. Different damping schemes, like friction-type and two-step viscous dampers, can efficiently regulate the seismic response of structures under SSI conditions. Overall, the consideration of SSI is crucial in seismic design to accurately predict and mitigate the seismic response of structures.

3- Modeling and Validation

3-1Winkler Model

According to the Winkler model, the foundation's deformations resulting from the application of a load are restricted to the specific regions where the load is applied. An essential challenge associated with the Winkler model lies in determining the stiffness of elastic springs that serve as a representation of the soil situated beneath the foundation. Gazetas, in a related study, provided formulas for computing the stiffness of soil springs in both the horizontal direction (longitudinal Kx and lateral Ky) and the vertical direction (Kz). These expressions offer valuable insights into how to calculate the stiffness values required for the accurate simulation of soil behavior in foundation analysis.

$$k_x = k_y \frac{-0.2GL}{(0.75-\nu)}[1.0-\{\frac{B}{L}\}] \quad (1)$$

$$k_y = \frac{GL}{(2-\nu)}[0.2+2.50-\{\frac{B}{L}\}^{0.85}] \quad (2)$$

$$k_z = \frac{GL}{(2-\nu)}[0.2+2.50-\{\frac{B}{L}\}^{0.75}] \quad (3)$$

Where G is the shear modulus of soil, E is the modulus of elasticity of soil, ν is the Poisson's ratio of soil. L and B are the length and width of the foundation, respectively.

3-2 Soil Continuum Model

Numerous research studies have highlighted the crucial significance of Soil-Structure Interaction (SSI) in the assessment of how structural elements respond to seismic events. The consideration of SSI is deemed imperative in accurately forecasting the actual structural behavior, particularly when subjected to dynamic or seismic loads. It is essential to incorporate SSI in the analytical process [6]. The analysis of SSI involves subjecting the soil to excitations generated by seismic events. Initially, these excitations are absorbed by the foundation system before being transmitted to the structural system. The fundamental equation of motion governing the entire three-dimensional volume under the influence of seismic activity can be succinctly expressed as follows. This equation encapsulates the intricate interplay between the soil, foundation, and structural components when responding to seismic forces, thereby underscoring the critical role of SSI in ensuring the structural integrity and stability of buildings and infrastructure during seismic events.

$$[M]\{\ddot{u}(t)\}+[C]\{\dot{u}(t)\}+[K]\{u(t)\}=[M]\{y_a(t)\} \quad (4)$$

The mass, damping, and stiffness matrices for the entire system, denoted as M, C, and K respectively, represent the physical properties of the system in structural dynamics analysis. The acceleration, velocity, and relative displacement vectors of the system nodes are denoted as a, v, and u respectively, reflecting the dynamic response of the structural elements. Additionally, the input ground acceleration vector denoted as ag represents the external excitation applied to the system due to seismic or other loading conditions. The solution of the governing equation for the system is highly intricate, involving a complex interplay of various vectors and matrices that describe the behavior of the soil-structure interaction system. This complexity renders the equations mathematically abstruse and poses a significant challenge for conventional solution methods. To tackle this complexity, engineers often turn to sophisticated tools such as finite element analysis software, like SAP2000, which is specifically designed to handle such intricate structural dynamics problems in the time domain. In SAP2000, the nonlinear dynamic analysis of structures can be effectively carried out using direct integration techniques, such as the Hilber-Hughes-Taylor (HHT) method. The HHT method, also known as the alpha-method, is widely utilized in the field of structural dynamics for numerical integration due to its efficiency and accuracy in capturing the transient response of structures subjected to dynamic loads. This numerical method, being a one-step implicit scheme, is particularly well-suited for solving transient dynamic problems where both inertial and damping effects are significant. By employing advanced numerical techniques like the HHT method within software tools like SAP2000, engineers can effectively simulate and analyze the dynamic behavior of complex structural systems under various loading conditions. This integration of sophisticated computational tools with theoretical principles enhances the capability of engineers to predict and optimize the dynamic performance of structures, leading to safer and more resilient civil infrastructure designs.[7]

3-3 Validation

A 10-storey residential building design measuring 20.0 m × 12.0 m, as illustrated in Figure 1, has been chosen for the validation problem under consideration. Farqaleet [8] also utilized a similar model for analysis. The height of each storey is 3.1 m, and the building has four bays in the X-direction, each 5.0 m wide, and three bays in the Y-direction, each 4.0 m wide. The dimensions of the beam sections are 0.23 m × 0.45 m, while the columns have different sizes of 0.50 m × 0.50 m. The structural analysis assumes loading conditions, concrete properties, and steel properties in accordance with Indian standards. Following the creation of the structural model, a nonlinear time history analysis is conducted using the Elcentro time history input with fixed-based conditions. The obtained analysis results are compared and validated against the findings presented by Farqaleet [8]. It is observed that there is a slight variance of 1.52% in the calculated time period and 4.71% in the displacement of the roof structure. This validation process helps ensure the accuracy and reliability of the structural model and analysis results, providing valuable insights for further research and design improvements in the field of building engineering and earthquake-resistant structures. The comparison of results between different studies aids in enhancing the understanding of structural behavior under seismic loads and validates the computational models used in such analyses. By adhering to established standards and methodologies, the study contributes to the ongoing advancement of seismic design practices and the development of resilient structures capable of withstanding dynamic loading conditions effectively.

4-Results and Discussion

In the conducted study, the analysis focused on three multi-story reinforced concrete (RC) buildings of varying heights: six (G+6), eight (G+8), and ten (G+10) stories. These buildings were subjected to dynamic analysis considering two scenarios: with a flexible base and without considering the Soil-Structure Interaction (SSI) effects in a fixed base condition. The architectural layout of an RC building, resembling a structure found in the MNNIT Allahabad campus, has dimensions measuring 45.5 meters by 10.8 meters, depicted in Figure 2 for reference. To streamline the analysis, standard dimensions for beams and columns were assumed, with beams set at 400 mm by 400 mm and columns at 500 mm by 500 mm. Each story in the building has a uniform height of 3.0 meters. The distribution of dead and live loads followed the guidelines outlined in the relevant IS code [9]. The choice of materials adhered to specifications from the IS code for concrete (M20 grade) and steel bars (Fe415 grade) [10][11].

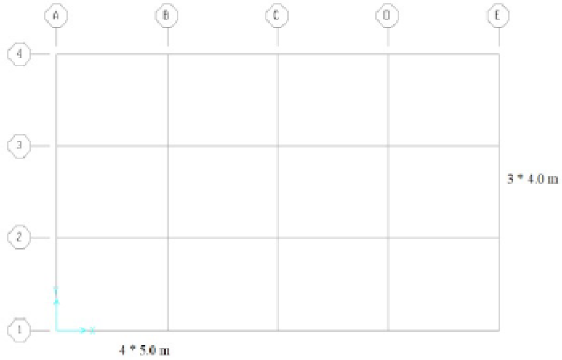

Fig. 1. Plan of the building [8] for validation

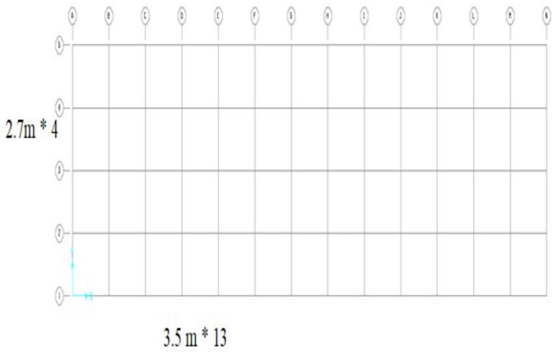

Fig. 2. Plan of the building for present study

In the scenario with a flexible base, two distinct methods were employed to model the soil behavior: the Winkler approach and the soil continuum approach. In the Winkler model, the soil was represented as a series of springs, while in the soil continuum model, a 3D continuous elastic solid was created using finite element meshing techniques. The depth of the soil layer considered extended beyond twice the width of the building (2B), with the perimeter of the model not exceeding three times the width of the building (3B) to ensure accurate representation. Here, 'B' denotes the width of the building in its shorter dimension. The soil meshing utilized solid elements, specifically eight-noded isoparametric elements, to capture the soil's behavior effectively. On the other hand, shell elements, which are uniform throughout, were employed for meshing the structural components of the buildings, ensuring consistency and accuracy in the analysis [12].

4-1 Convergence Study

A convergence analysis is carried out on the G+6 building under fixed base conditions to determine the optimal size of elements necessary for minimizing errors in the calculated outcomes. The convergence is observed in Figure 3 at a mesh size of 200 mm, with subsequent changes in roof displacement value amounting to approximately 0.1%. Consequently, the mesh size of 200 mm is selected for discretizing the models of reinforced concrete (RC) buildings under study.

4-2 Dynamic Analysis

The dynamic analysis and design of the response spectrum for soft soil conditions, in accordance with IS code [8], utilize the ground motion data from the 1979 Imperial (El-Centro) earthquake. Figure 4 displays the ground motion data for the Imperial earthquake over a duration of 28 seconds. Subsequently, time history analysis is carried out under fixed and flexible base conditions using this data.

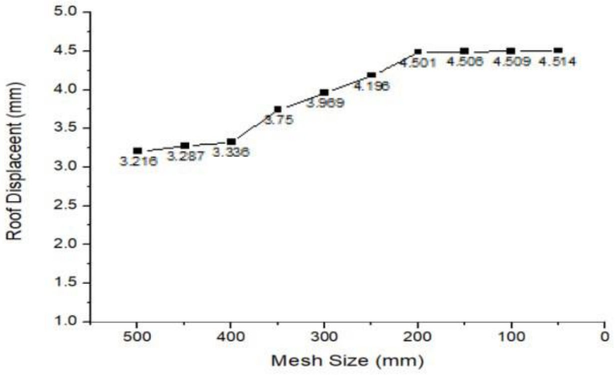

Fig. 3. Convergence study

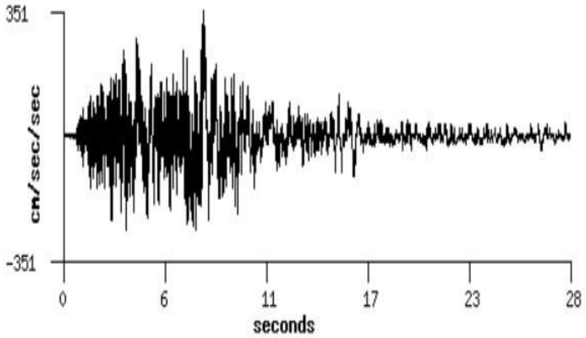

Fig. 4. Ground motion of 1979 Imperial [12]

The assessment of lateral loads in structures is significantly influenced by the time period, which is contingent upon both mass and stiffness characteristics. The behavior of buildings subjected to lateral loads can be effectively examined by considering the time period. Nonetheless, pinpointing the precise time period can pose challenges due to various factors at play. The study illustrates the variation of time periods across different mode numbers for the structures analyzed, as depicted in Figures 5, 6, and 7. Notably, the time period exhibits a gradual decrease for the initial three modes, followed by a sudden shift in its value, as these first three modes of vibration hold paramount importance as they are primarily responsible for structural damage. In structures with more stories like G+10, the time period tends to be longer due to the increased mass resulting from additional floors, which in turn leads to a reduction in overall stiffness. Consequently, as building height escalates, the time period also increases in correspondence. Particularly in the context of Site-Specific Earthquake (SSI) conditions, the time period is notably higher as the base's flexibility diminishes the structural stiffness, thereby elongating the vibration period during seismic events.

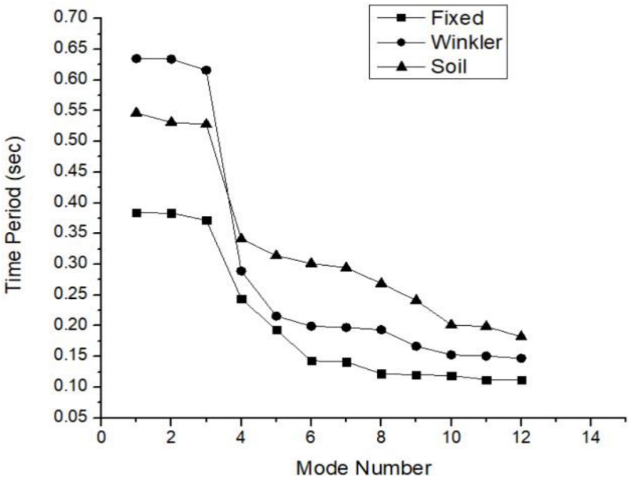

Fig. 5. Time period vs. mode number for G+6

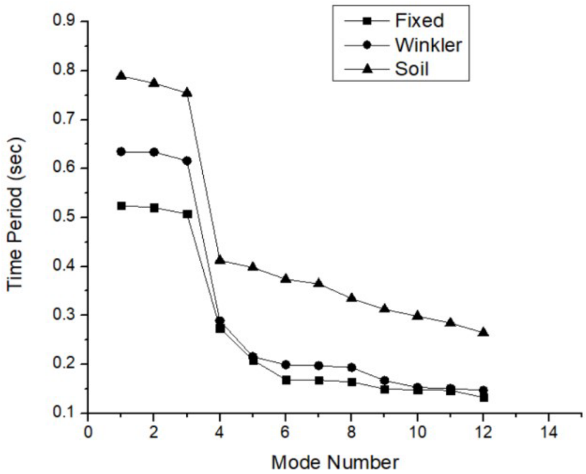

Fig. 6. Time period vs. mode number for G+8

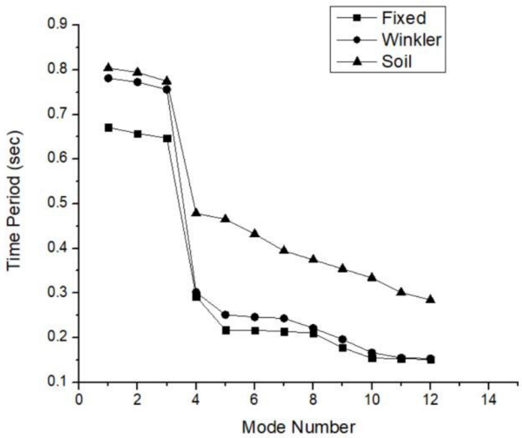

Fig. 7. Time period vs. mode number for G+10

The information provided pertains to a specific mode, detailing the extent to which the system mass is involved in that particular mode. This involvement is quantified through the calculation of Eigen values based on the time period. A mode characterized by a significant effective mass typically plays a crucial role in influencing the response of the systems under consideration. As stipulated by IS code [14], it is recommended to determine the number of modes to be taken into account in a manner that ensures that the collective modal mass participation exceeds 90%. Tables 1, 2, and 3 offer insights into the requisite number of modes for achieving 90% mass participation and the corresponding percentage of mass involvement. The findings indicate that the number of modes necessary for 90% mass participation remains relatively consistent in fixed and Winkler conditions. However, in the soil condition, a higher number of modes are needed compared to the other two conditions. This is attributed to the heightened significance of modal effects in the soil continuum approach, which is crucial for accurately evaluating the structural response. Notably, mass participation reaches its peak in G+10 structures due to the greater seismic weight contribution in high-rise buildings compared to their low-rise counterparts with similar building layouts.

Table-1. Modes and mass participation for G+6

Fixed		Winkler		Soil	
No. of Mode	Mass Participa -tion (%)	No. of Mode	Mass Participa -tion (%)	No. of Mode	Mass Participa -tion (%)
06	91.29	06	94.40	08	94.89

Table-2. Modes and mass participation for G+8

Fixed		Winkler		Soil	
No. of Mode	Mass Participa -tion (%)	No. of Mode	Mass Participa -tion (%)	No. of Mode	Mass Participa -tion (%)
07	91.95	08	94.73	10	95.01

Table-3. Modes and mass participation for G+10

Fixed		Winkler		Soil	
No. of Mode	Mass Participa -tion (%)	No. of Mode	Mass Participa -tion (%)	No. of Mode	Mass Participa -tion (%)
10	92.14	10	94.76	12	95.62

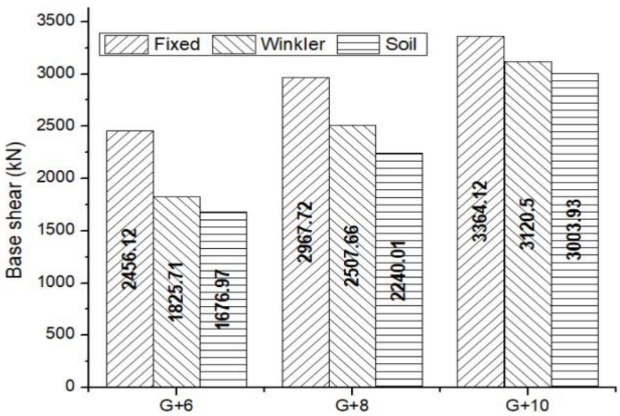

Fig. 8. Base shear of buildings

4-2-1 Base Shear

Base shear represents the maximum horizontal force experienced at the foundation of a multi-storey structure as a result of seismic forces. In the visual representation provided in Figure 8, the comparison of base shear values across buildings with varying foundation conditions is illustrated. Analysis of the data indicates that the base shear is significantly higher for a structure with ten storeys above ground level due to the increased contribution of seismic mass. Conversely, buildings with a base subjected to soil-structure interaction (SSI) exhibit lower base shear values as the flexibility of the foundation resists strong seismic excitations, resulting in reduced acceleration levels.

4-2-2 Lateral Displacement

Lateral displacement represents the magnitude of displacement experienced by a storey due to lateral forces such as earthquake and wind loads. This parameter plays a critical role in the context of seismic pounding effects during seismic events, requiring appropriate spacing between adjacent structures. A higher displacement indicates a less rigid structure, thereby influencing its overall stiffness. The lateral displacement patterns of buildings under various base conditions are illustrated in Figures 9, 10, and 11. Analysis of the results reveals that lateral displacement tends to be more pronounced in the case of Site Specific Earthquake (SSI) conditions. This is primarily attributed to the increased flexibility of buildings under SSI scenarios, leading to extensive lateral displacement, which may not be advantageous for the structural integrity. As per the guidelines outlined in the IS code [14], the maximum allowable displacement at the top storey is limited to H/500, where H denotes the total building height in meters. For buildings with G+6, G+8, and G+10 storeys, the maximum top storey displacements are recorded at 36.0 mm, 48.0 mm, and 60.0 mm, respectively. These findings demonstrate compliance with the specified permissible limits, ensuring structural safety and integrity.

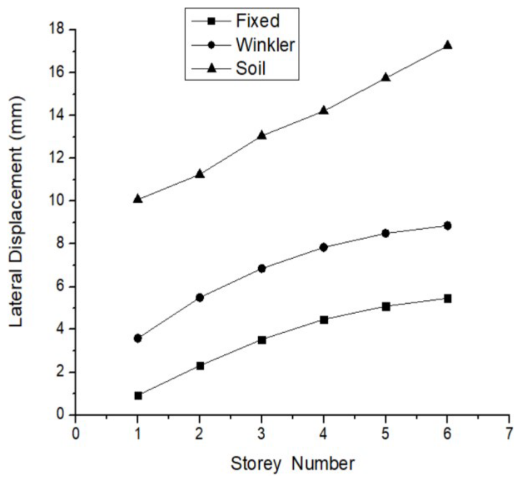

Fig. 9. Lateral displacement of G+6

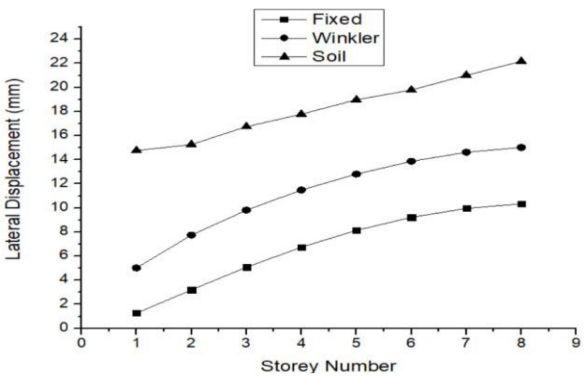

Fig. 10. Lateral displacement of G+8

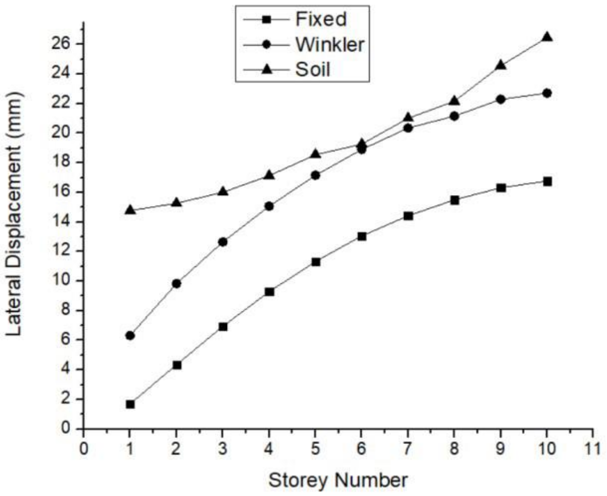

Fig. 11. Lateral displacement of G+10

4-2-3 Storey Drift

The inter-storey lateral displacement refers to the movement of one storey in relation to another storey located below it. According to the Indian Standard (IS) code, the lateral force designed for a structure should ensure that the storey drift within any floor does not surpass 0.004 times the height of the storey. The tabulated data in Tables 4, 5, and 6 provides information on the storey drift of buildings under various base conditions, all of which fall within the permissible limits set by the standards. When comparing the Winkler model to the soil model, it is observed that the former tends to yield larger storey drift values. This occurrence can be attributed to the higher modal effect resulting from 90% mass participation in the soil model. For all buildings, the maximum allowable storey drift is specified at 12.0 mm, emphasizing the critical importance of adhering to this limitation. It is imperative that the storey drift remains within the permissible threshold to ensure that nonstructural components like partition walls and pipe systems can adequately accommodate the deflection imposed on them during seismic events. As such, strict adherence to the specified storey drift limits is essential for the overall seismic performance and safety of the structure. Additionally, the consideration of modal effects is crucial in accurately predicting and mitigating storey drift, particularly in high-mass participation scenarios. The interplay between structural design, soil characteristics, and modal behavior underscores the complexity of assessing and managing storey drift in buildings subjected to lateral forces. Furthermore, the interaction between the structure and its foundation plays a significant role in determining the magnitude of storey drift, necessitating a comprehensive understanding of the dynamic response of the building system.

Table-4.Storey Drift in G+6

Storey	Storey Drift (mm)		
	Fixed	Winkler	Soil
1st - 2nd	1.385	1.901	1.180
2nd - 3rd	1.228	1.194	1.800
3rd - 4th	0.937	0.989	1.160
4th - 5th	0.621	0.652	1.540
5th - 6th	0.369	0.367	1.511

Table-5. Storey Drift in G+8

Storey	Storey Drift (mm)		
	Fixed	Winkler	Soil
1st - 2nd	1.385	1.901	1.180
2nd - 3rd	1.228	1.194	1.800
3rd - 4th	0.937	0.989	1.160
4th - 5th	0.621	0.652	1.540
5th - 6th	0.369	0.367	1.511

Table-6. Storey Drift in G+10

Fixed		Winkler		Soil	
No. of Mode	Mass Participa -tion (%)	No. of Mode	Mass Participa -tion (%)	No. of Mode	Mass Participa -tion (%)
10	92.14	10	94.76	12	95.62

4-2-4 Inter-storey Drift Ratio

Inter-story drift ratio (IDR) plays a crucial role in evaluating the structural response during performance-based seismic analysis, particularly in the context of tall buildings. IDR specifically refers to the proportional horizontal displacement between consecutive floors divided by the height of a single floor. An IDR exceeding 0.06 signifies severe damage potential, while values surpassing 0.025 indicate a level of destruction that could pose significant risks to human safety. When IDR values reach beyond 0.10, there is a heightened likelihood of structural collapse. Detailed graphical representations in Figures 12, 13, and 14 illustrate how IDR changes across different building stories. The inter-storey drift ratio patterns observed in the fixed base model and Winkler model markedly differ from those in the soil model due to the latter's increased lateral displacement resulting from a more pliant foundation in SSI structures. Notably, the IDR measurement for a G+10 building surpasses the critical 0.10 threshold, necessitating the implementation of shear walls to avert potential building failures. It is imperative to address IDR values diligently in structural assessments to ensure the safety and stability of high-rise constructions. The consideration of IDR is pivotal in informing design decisions and retrofitting strategies for buildings susceptible to seismic forces. Comprehensive analyses of IDR variations aid in identifying vulnerabilities and implementing mitigation measures to enhance structural resilience. Furthermore, the integration of IDR assessments into seismic design codes and standards is essential for promoting the overall safety and performance of tall buildings.

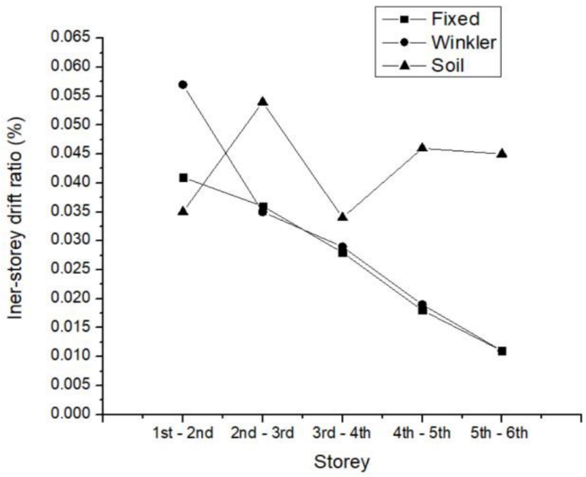

Fig. 12. Inter-storey drift ratio of G+6

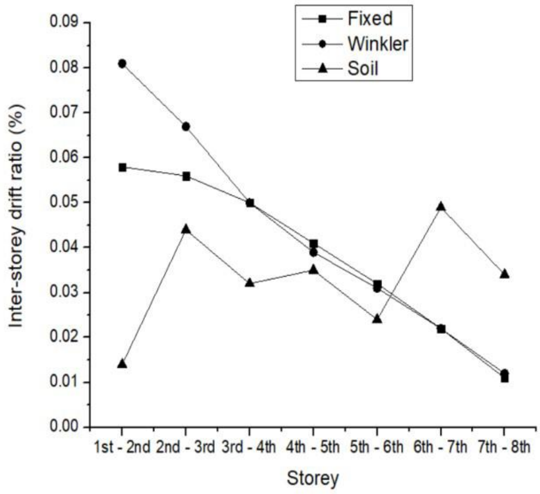

Fig. 13. Inter-storey drift ratio of G+8

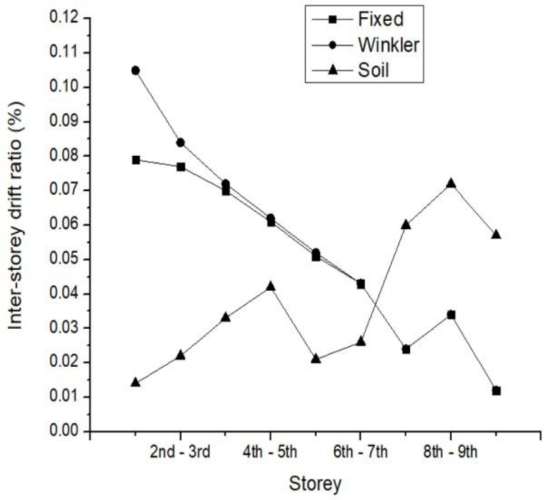

Fig. 14. Inter-storey drift ratio of G+10

5-Conclusions

The SSI models, such as the Winkler and soil models, play a crucial role in prolonging the duration of vibration and lateral displacement while decreasing the base shear in comparison to the fixed base model. Moreover, the behavior of the interstorey drift ratio in the fixed base model is closely akin to that exhibited by the Winkler model. The current research findings lead to several significant conclusions. Initially, it is evident that the fundamental time period of the flexible base exceeds that of the fixed base by 28% (Winkler) and 44% (Soil) in G+6, by 20% (Winkler) and 42% (Soil) in G+8, and by 17% (Winkler) and 20% (Soil) in G+10. Secondly, the base shear of the flexible base is notably reduced compared to that of the fixed base, showcasing decreases of 25% (Winkler) and 31% (Soil) in G+6, 13% (Winkler) and 24% (Soil) in G+8, and 07% (Winkler) and 15% (Soil) in G+10. Furthermore, the roof displacement of the flexible base exhibits a significant increase over the fixed base, with increments of 62% (Winkler) and 216% (Soil) in G+6, 42% (Winkler) and 114% (Soil) in G+8, and 35% (Winkler) and 57% (Soil) in G+10. These outcomes provide valuable insights for evaluating the effects of SSI on structural response. Nevertheless, it is imperative to undertake further analysis utilizing a more extensive dataset of ground motions before incorporating these findings into design recommendations.

6- Future works

It is possible to investigate the effects of soil-structure interaction (SSI) on the seismic behavior of multi-story buildings through further exploration of additional analysis techniques and parameters to enhance the understanding of structural responses under SSI conditions. Analyzed different ground motion data from different seismic events and regions. To evaluate the applicability of the results and to consider the variability in soil conditions and seismic hazards, and to examine the effect of different soil types, building materials, and structural arrangements on seismic performance under SSI conditions, to provide a more detailed insight into the interactions of these variables, financial and practical implications. evaluated the feasibility of integrating SSI considerations into the design and construction of multi-story buildings to determine the cost-effectiveness and feasibility of incorporating SSI practices into real-world engineering projects.

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