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KINEMATIC INTERACTION EFFECTS ON DYNAMIC RESPONSE OF HIGH-RISE BUILDINGS WITH SUBSURFACE STRUCTURES

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ABSTRACT: High-rise buildings in urban areas face significant seismic challenges due to interactions between the structure, foundation, and surrounding soil. One key component is the kinematic aspect of Soil–Structure Interaction (SSI), which alters the seismic motion transmitted to the foundation, particularly for buildings with basements. This study investigates the effect of kinematic SSI on the seismic response of high-rise buildings with basement structures using linear time-history analysis. Two site classes based on soil stiffness—SD (medium soil) and SE (soft soil)—are analyzed to evaluate how kinematic interaction influences base shear and displacement. Results show that in site class SD, the reduction in response is minimal. However, in site class SE, where soil stiffness is lower, kinematic effects lead to substantial decreases in both base shear and displacement. Basement embedment depth also plays a role in modifying seismic input. These findings emphasize the importance of including kinematic interaction in seismic analysis to achieve safer, more efficient structural designs, especially in soft-soil conditions.

Keywords: Kinematic interaction, Base shear, Displacement, Soil site class

1. INTRODUCTION

High-rise buildings have become iconic features of modern urban landscapes, providing solutions to space limitations and fulfilling the demand for vertical development. However, the design and performance of such structures under seismic loading remain complex challenges due to the intricate interactions between the structure, the foundation, and the soil [1]. Accurate interaction modeling is vital for safe and economical structural design, making its integration in analysis essential [2]. Among these interactions, the phenomenon of kinematic interaction on soil-structure interaction (SSI) has garnered significant attention because this interaction has the potential to change the measured foundation motion values at the base of the foundation or foundation input motion (FIM) to deviate from the free field motion (FFM) or the natural response motion of the ground to seismic waves which then has an impact on the seismic demands imposed on the building [3].

The difference between FFM and FIM arises due to kinematic interaction. The presence of a rigid foundation on or within the soil leads to deviations in the base slab motion compared to free-field motion [4]. Kinematic interaction reduces the foundation motion relative to the free-field response due to the stiffness contrast between the foundation and the surrounding soil [5]. For shallow foundations, this deviation is primarily influenced by the averaging effect of the base slab motion. FFM associated with inclined or incoherent seismic waves is averaged across the base slab area due to kinematic constraints imposed by the rigid slab's movement [6]. Additionally, the embedment effect plays a significant role in kinematic interaction. Foundations embedded deeper into the soil tend to experience greater motion reductions than shallow ones. This is because the surrounding soil of embedded foundations provides additional damping and enhances lateral stiffness, ultimately reducing the amplitude of dynamic motion transmitted to the foundation [7]. Structural and foundation properties can significantly influence a structure's load and deformation behavior [8] .

The portion of a building located below the ground surface is commonly referred to as a basement. Basement structures in high-rise buildings serve not only as integral parts of the structural system but also play a critical role in modifying the kinematic response of the building. The presence of a basement increases the embedment depth, which can either attenuate or amplify seismic forces depending on the soil type, stiffness, and seismic wave characteristics [9].

Numerous studies have examined kinematic interaction and SSI in general; most have focused on shallow foundations or treated the effects of building mass and basement geometry separately. There remains a lack of comprehensive research that integrates the effects of kinematic interaction and soil classification. The main objective of this study is to evaluate the influence of kinematic soil–structure interaction on the seismic performance of high-rise buildings with basement structures, by analyzing variations in base shear and displacement across different soil classifications. These findings are expected to contribute to improved structural design practices, ensuring safety and optimal performance in real-world scenarios.

2. RESEARCH SIGNIFICANCE

This study emphasizes the importance of kinematic interaction in the seismic design of high-rise buildings with basements, an aspect already addressed in codes such as ASCE 7-16 and SNI 1726:2019, but still often overlooked in practical engineering applications. While this research fully follows existing code provisions, it highlights how applying the SSI-related clauses, particularly those involving kinematic interaction, can lead to more accurate, efficient, and reliable designs. Many practitioners still avoid implementing these provisions due to perceived complexity, yet this study shows that doing so can optimize material use and improve safety without unnecessary overdesign.

3. METHODOLOGY

This study utilizes a planned (dummy) structure as a case study, featuring a dual system consisting of a special moment-resisting frame and a special concentrically braced frame, in accordance with [10]. The structural layout consists of 8 spans in both the X and Y directions, as shown in Fig. 1. The span length in the X direction is 5 meters per span, while in the Y direction, it is 6 meters per span. The element profiles used include HB 400 for columns and bracing, HB 300 for the main beams in the X direction, HB 350 for the main beams in the Y direction, and HB 200 for secondary beams. Detailed specifications of the steel structure properties are presented in Table 1.

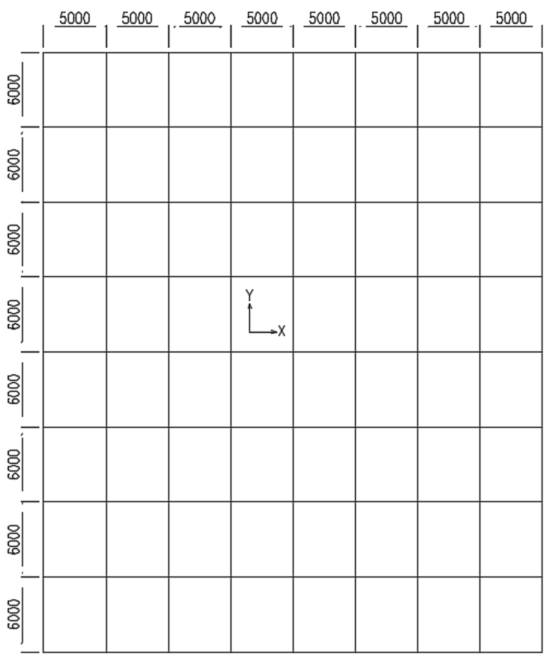

Fig. 1 Layout structures

Table 1. Properties Of Steel Structure

Element	*r* (kg/m^3)	*A* (cm^2)	*Ix* (cm^4)	*E* (MPa)
Column, Brace	7850	218.70	66600	200000
Main Beam X	7850	119.80	20400	200000
Main Beam Y	7850	173.90	40300	200000
Sec. Beam	7850	63.53	4720	200000

Where r denotes the material density, A is the cross-sectional area, Ix is the moment of inertia, and E is the elastic modulus of steel. The superstructure is predominantly composed of steel structures with 20 stories and a total height of 84 meters, with 5% damping ratio, as illustrated in Fig. 2. Meanwhile, the basement structure incorporates reinforced concrete walls with a thickness of 250 mm, concrete strength of 35 MPa, and reinforcing steel grade 420B. The structure is assumed to behave linearly elastically to isolate and study the effects of kinematic interaction under seismic loading, without introducing complexities from material nonlinearity. Analysis using the finite element method modeled using the CSI ETABS 2019 software with a fixed-base boundary condition.

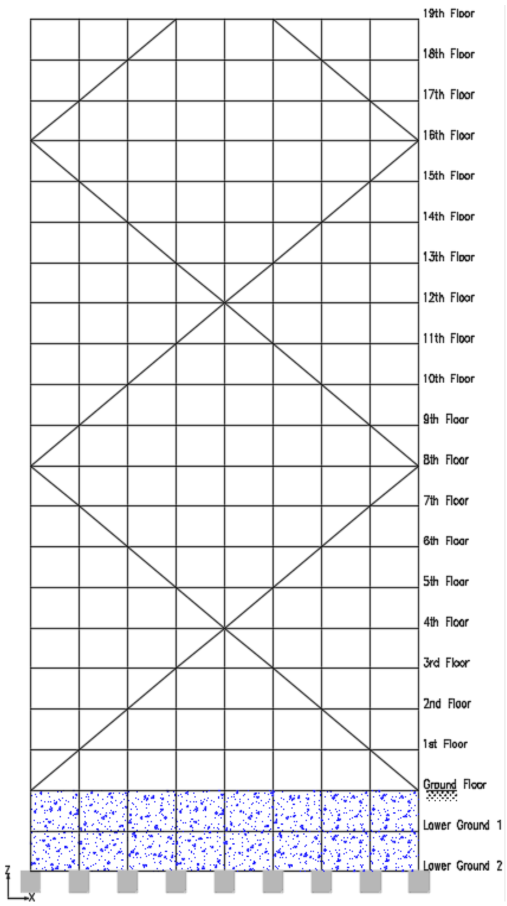

Fig. 2 Section Structure

Soil data were collected from two different locations within the Riau Province area, as shown in Fig. 3 and 4. These two sites were selected to provide variation in soil site classification, serving as a reference for defining seismic design criteria for the structure. The properties of the soils from both locations, presented in Table 2, were derived through correlations with N-SPT values, which indicate the strength and density of the soil at each site. This approach ensures that the seismic design model can reflect more realistic ground conditions.

Table 2. Properties Of Soil

Soil Properties	Values	
	SD (Fig 3)	SE (Fig 4)
N-SPT	17.55	2.53
Shear Wave Velocity (m/s)	252.05	137.65
Shear Modulus (MPa)	105.60	30.05
Modulus Elasticity (kN/m^2)	27100	10312.50
Poisson Ratio (υ)	0.20	0.25
Unit Weigth (kN/m^3)	18.60	14

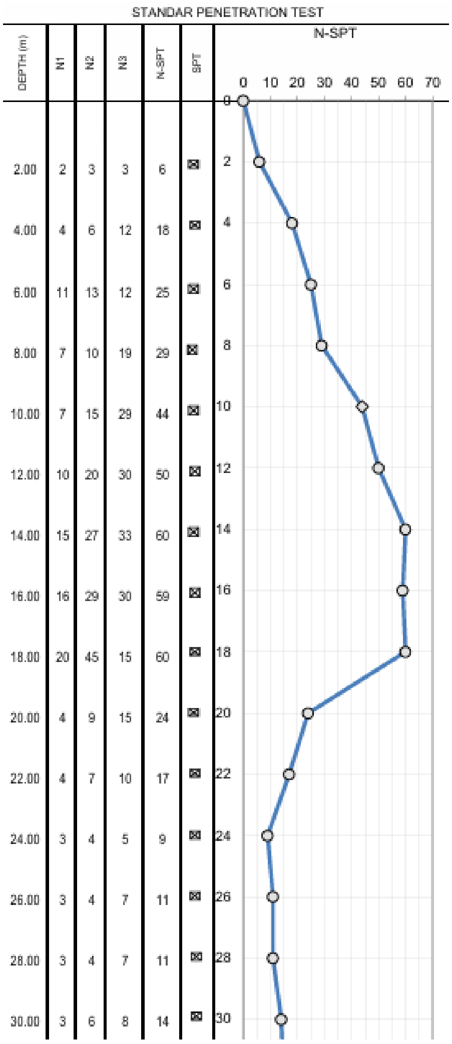

Fig. 3 Soil investigation data (Site Class: SD)

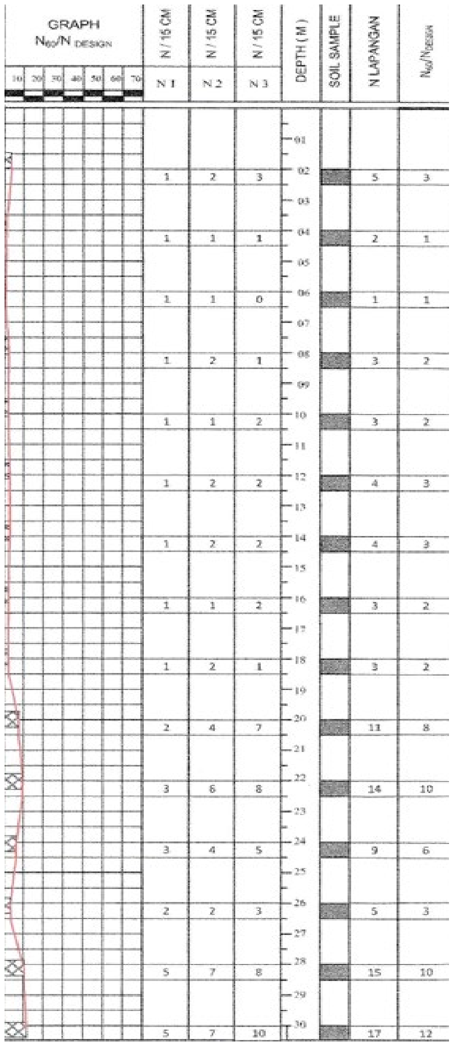

Fig. 4 Soil investigation data (Site Class: SE)

3.1 Earthquake Data

Earthquake data chosen from the PEER ground motion data website managed by the Pacific Earthquake Engineering Research Center (PEER). The selection of earthquake data was based on several criteria: earthquake magnitude, site classification, and distance to the earthquake source [11]. The earthquake magnitude was chosen in the range of 7.2 to 7.7 because it is included in the strong earthquake category [12]. In addition, the distance from the earthquake source to the recording station location was also a major consideration, with the selected distance being in the range of 80 to 100 km from the recording station. Earthquake data that met these criteria are presented in Table 3. Time history graphs of earthquake data for the SD and SE site classes are shown in Fig. 5 and 6, respectively.

Table 3. Earthquake data were chosen for analysis

Earthquake (Eve.)	Mag.	Dist. (km)	Vs30 (m/s)	Site Class
Manjil (Iran) 1990	7.37	93.62	289.69	SD
Chichi (Taiwan) 1999	7.62	88.89	124.27	SE

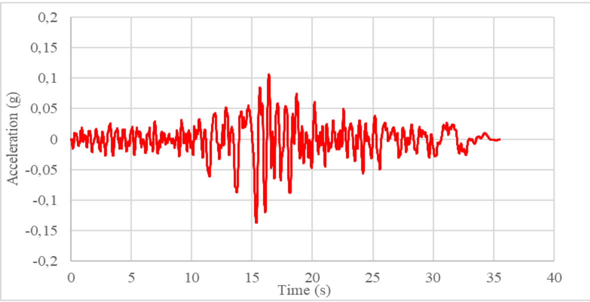

Fig. 5 Ground motion Manjil (Iran) 1990

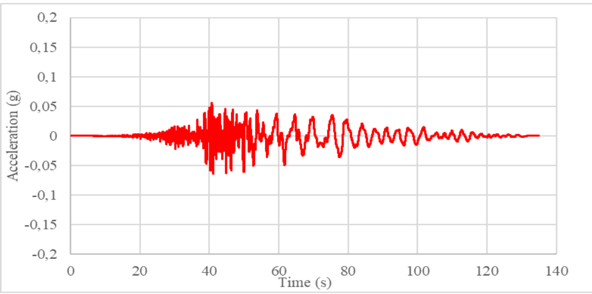

Fig. 6 Ground motion Chichi (Taiwan) 1999

3.2 Equation Of Kinematic Interaction

This section provides an in-depth discussion of two simplified procedures available for accounting for the effects of kinematic interaction in structural analysis, particularly in the context of seismic loading. These procedures adopt a semi-empirical approach based on the guidelines outlined in [13]. This approach is designed to offer practical insights into how kinematic interaction influences foundation motions, as illustrated in the following Eq. (1) and Eq. (2).

$$U_{FIM} = RF \ x \ U_{FFM} \quad (1)$$

$$RF = RRS_{bsa} \ x \ RRS_e \geq 0.7 \quad (2)$$

Where RF is the reduction factor, a coefficient calculated from the components of kinematic interaction. RRS_{bsa} denotes the reduction coefficient for free-field motion due to base slab averaging, while RRS_e represents the reduction coefficient for free-field motion caused by the embedment effect. The maximum reduction value must not be less than 0.7.

According to ASCE 7-16, there are two fundamental effects of kinematic interaction:

3.2.1 Base slab averaging effects

The base slab averaging effect is calculated using Eq. (3) to assess the extent to which this phenomenon contributes to the reduction of foundation input motion compared to free field motion.

$$RRS_{bsa} = 0.25 + 0.75 \text{ x } \left\{\frac{1}{bo^2}\left[1 - (\exp(-2bo^2)) x \ B_{bsa}\right]\right\}^{1/2} \quad (3)$$

$$bo = 0.0023 \left(\frac{be}{T}\right) \quad (4)$$

$$B_{bsa} = 1 + bo^2 + bo^4 + \frac{bo^6}{2} + \frac{bo^8}{2} + \frac{bo^{10}}{12} \quad (5)$$

be is the equivalent value of the square root of the foundation footprint area, with a minimum allowable value of 80 meters. B_{bsa} refers to the Bessel function used to calculate the base slab averaging effect. bo is a parameter related to the effective foundation, while T represents the structural period, set at a minimum of 0.2 seconds.

3.2.2 Embedment effects

The embedment effect helps reduce the amplitude of dynamic motion transmitted to the structure due to the depth of foundation embedment within the soil. This effect is calculated using Eq. (6).

$$RRS_e = 0.25 + 0.75 \text{ x} \cos\left(\frac{2\pi e}{T v_s}\right) \quad (6)$$

e represents the depth of structural embedment. The deeper the structure is embedded in the soil, the greater the reduction value it produces. Certain conditions must be met when determining the embedment depth, including a maximum depth (e) limited to 6 meters, and the foundation footprint must cover at least 75% of the building's total area.

4. RESULT AND DISCUSSION

The distribution of structural mass on each floor of the building is presented in Table 4. This information plays a crucial role in understanding how mass influences the dynamic response of the structure, particularly in the context of seismic load analysis. Furthermore, the mass distribution serves as one of the key parameters in dynamic simulation calculations, as it is closely related to the base shear forces, and deformation mechanisms that occur during seismic loading.

Table 4. Structural mass of each floor

Story	Mass X (Ton)	Mass Y (Ton)
Story 19	916.40	916.40
Story18	1193.97	1193.97
Story17	1193.97	1193.97
Story16	1193.97	1193.97
Story15	1193.97	1193.97
Story14	1193.97	1193.97
Story13	1193.97	1193.97
Story12	1193.97	1193.97
Story11	1193.97	1193.97
Story10	1193.97	1193.97
Story9	1193.97	1193.97
Story8	1193.97	1193.97
Story7	1193.97	1193.97
Story6	1193.97	1193.97
Story5	1193.97	1193.97
Story4	1193.97	1193.97
Story3	1193.97	1193.97
Story2	1193.97	1193.97
Story1	1193.97	1193.97
Ground Surface	1409.88	1409.88
Lower Ground 1	1466.28	1466.28
Lower Ground 2	3610.36	3610.36

4.1 Base Shear Result

Base shear is a critical parameter in seismic analysis, representing the total lateral force exerted on a structure due to earthquake loading . The magnitude of this force is influenced by several key factors, including the structure's mass, stiffness, and the dynamic properties of the underlying soil [14]. Understanding the behavior of base shear is essential for evaluating structural performance and ensuring the safety and stability of buildings subjected to seismic forces.

This section examines the structural response to lateral forces induced by kinematic interaction, with particular emphasis on variations in soil classification. As presented in Table 5, kinematic interaction is more pronounced in structures built on soft soils or site class SE compared to those found on medium soils or site class SD. This phenomenon aligns with the findings of [15]. Highlighting the significant role of soil flexibility in amplifying seismic demands. Furthermore, incorporating soil-structure interaction (SSI) into the analysis demonstrates beneficial effects by reducing structural demand requirements when compared to models that disregard this interaction. These observations are consistent with previous research conducted by [16], reinforcing the importance of considering SSI effects in seismic design to achieve more realistic and efficient structural performance.

Table 5. Force acting at the base of the structure

Structural Model	Base Shear (kN)	
	X	Y
SD Without Kinematic	1638.50	1524.44
SD With Kinematic	1505.08	1285.76
SE Without Kinematic	5752.95	7305.72
SE With Kinematic	2312.25	2403.19

The comparison of base shear results for all models is presented in Fig. 7 for the X-direction, while Fig. 8 illustrates the base shear in the Y-direction.

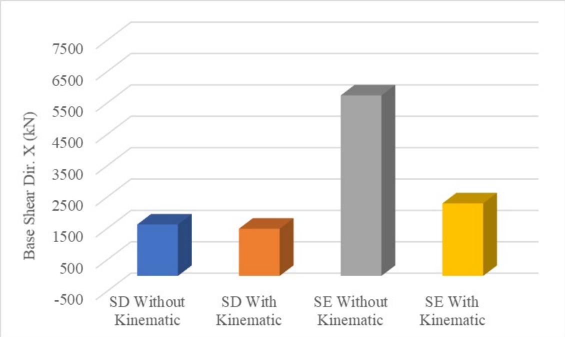

Fig. 7 Comparison base shear in X direction

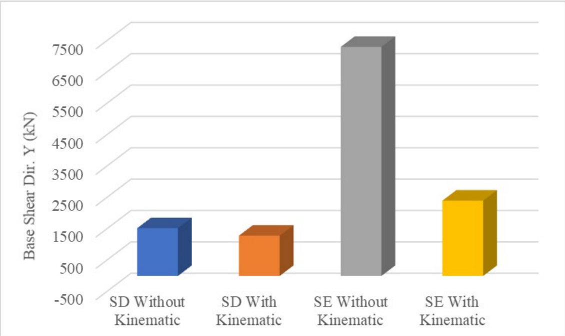

Fig. 8 Comparison base shear in Y direction

The reduction in base shear observed in the model with kinematic interaction is attributed to differences in the applied ground motion. In the model without kinematic interaction, the structure is subjected to free-field motion, which does not account for the presence of the foundation and is applied in full to the base. In contrast, the model with kinematic interaction uses a foundation input motion (FIM) that has been reduced due to two primary effects: base slab averaging and embedment effect. These effects lower the acceleration applied at the base of the structure, even though the support condition remains fixed. As a result of the reduced input motion, the dynamic response of the structure is also lower, leading to a smaller base shear. This demonstrates that considering kinematic interaction in seismic analysis yields a more realistic estimate of structural response compared to conventional approaches that assume unmodified free-field motion as input.

4.2 Displacement Result

The extent of displacement is directly influenced by the forces acting upon the structure, including lateral forces such as base shear [17]. This relationship is well established in the principles of structural mechanics, where key factors such as stiffness, mass, and structural configuration significantly govern the overall displacement behavior.

Beyond these fundamental aspects, additional factors such as SSI, material properties, and mass distribution also play a crucial role in determining the degree of deformation experienced by the structure [18]. Understanding these influences is essential for optimizing structural performance and ensuring long-term stability.

This section presents a comprehensive analysis of displacement to assess the effects of lateral forces induced by kinematic interaction and variations in soil conditions. The objective is to quantify how different soil classes influence internal force distribution and deformation patterns within the structure. The results of the displacement analysis are illustrated in Fig. 9 and 10, offering deeper insights into the role of kinematic interaction in modifying structural response under seismic loading. These findings provide valuable implications for improving structural design methodologies, emphasizing the necessity of incorporating SSI effects to enhance the accuracy, safety, and efficiency of earthquake-resistant structures.

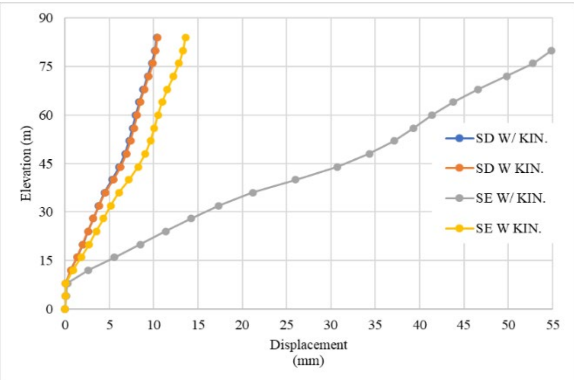

Fig. 9 Comparison displacement in X direction

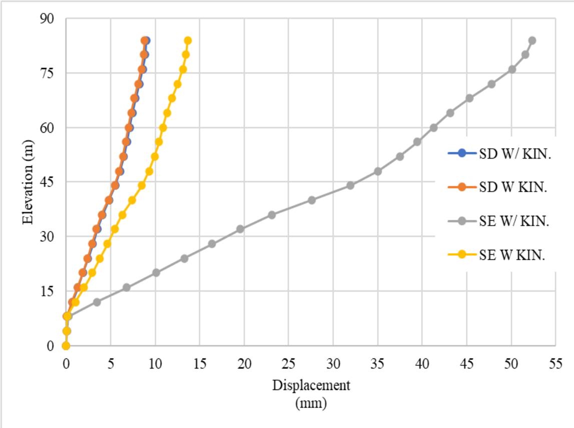

Fig. 10 Comparison displacement in Y direction

The displacement analysis presented in this study was conducted using output data generated by CSI ETABS 2019. Displacements in both X and Y directions were extracted from the program's dynamic time-history analysis results. The software calculates story displacements at each story level based on structural input parameters, applied seismic forces, and time-history ground motion records. The measurement of displacement follows the fundamental principle defined by the equation $X = F/K$, where X is displacement, F is the applied lateral force (such as base shear), and K is the stiffness of the structural system [19].

In buildings constructed on medium soil, classified as site class SD, the reduction in displacement is generally minimal due to the moderate stiffness of the supporting soil, which does not significantly alter the force transmission mechanism. In contrast, structures founded on soft soil, categorized as site class SE, experience a more substantial reduction in displacement. This occurs because the increased flexibility of soft soils results in more excellent energy dissipation and a more pronounced decrease in lateral force transmission [20]. Consequently, a strong correlation between lateral force reduction and displacement behavior can be observed.

This phenomenon plays a crucial role in optimizing structural design, particularly in seismic-prone regions where excessive displacement can compromise structural integrity. The findings suggest that incorporating SSI effects into design methodologies leads to a more efficient and realistic assessment of structural performance, reducing the need for overly conservative design assumptions. By refining analytical models to include kinematic interaction, engineers can develop more accurate and cost-effective structural solutions that enhance both safety and resilience in earthquake-resistant buildings.

4.3 Relative Reduction

Table 6 and Table 7, respectively, show the relative comparison of displacement and base shear for the model structures built on medium and soft soils, which are presented to provide a complete picture of the structure response to variations in soil conditions and kinematic interactions. These data help to evaluate the structure response comprehensively.

Table 6. Relative reduction of displacement and base shear for SD site class

Maximum Value	Displacement (mm)	Base Shear (kN)
Dynamic analysis ignoring kinematic	10.34	1638.51
Dynamic analysis considering kinematic	10.23	1505.09
Relative reduction (%)	1.05	8.14

Table 7. Relative reduction of displacement and base shear for SE site class

Maximum Value	Displacement (mm)	Base Shear (kN)
Dynamic analysis ignoring kinematic	56.14	7305.72
Dynamic analysis considering kinematic	13.60	2403.20
Relative reduction (%)	75.77	67.11

Based on the data in the tables above, the effect of kinematic interaction on the reduction of displacement and base shear varies significantly depending on the type of soil supporting the structure. For structures built on medium soil (SD site class), the relative reductions in displacement and base shear are 1.05% and 8.14%, respectively. These relatively small values indicate that the presence of kinematic interaction has only a limited influence on structural response in medium-stiff soils, where the energy transmission from seismic waves is less distorted.

In contrast, for buildings constructed on soft soils (SE site class), a much greater reduction is observed. The displacement is reduced by as much as 75.77%, while base shear decreases by 67.11%. These significant differences highlight the critical role of kinematic interaction in modifying structural response under seismic loading, particularly in low-stiffness soils where wave scattering and foundation-soil impedance mismatches become more pronounced. This clearly demonstrates that ignoring such interactions in soft soil conditions could result in overestimating seismic demands, leading to unnecessarily conservative design choices.

Therefore, this analysis emphasizes the necessity of incorporating soil-structure interaction, especially kinematic effects, into seismic design practices. By doing so, engineers can achieve a more accurate understanding of the actual demands imposed on a structure, enabling the development of safer, more resilient, and cost-effective buildings that can perform reliably under seismic events while avoiding excessive material use or overdesign.

5. CONCLUSIONS

This study aimed to evaluate the influence of kinematic soil–structure interaction (SSI) on the seismic response of high-rise buildings with basement structures under two site classes: SD (medium soil) and SE (soft soil). The findings highlight the significant impact of kinematic interaction on key response parameters, particularly base shear and maximum displacement. This effect is far more pronounced in buildings on soft soils, due to their lower stiffness, which alters the transmission of seismic energy and amplifies structural response.

The results show that in site class SD, the reductions in maximum displacement and base shear are minimal—1.05% and 8.14%, respectively. In contrast, for site class SE, these reductions increase substantially to 75.77% for displacement and 67.11% for base shear. These differences emphasize the critical role of soil stiffness in influencing SSI effects, underlining the need to consider this interaction in seismic design, especially for buildings founded on soft soils.

While the inclusion of kinematic SSI introduces analytical complexity, it contributes to more efficient, accurate, and cost-effective designs by capturing realistic structural behavior. This approach also helps prevent overly conservative assumptions, reduces material usage, and enhances safety and performance.

Future studies are encouraged to incorporate nonlinear material and soil behavior to complement the linear elastic approach used here. A broader parametric study—including variations in basement depth, foundation footprint, and structural period—would further clarify SSI sensitivity and support the development of improved seismic design practices for high-rise buildings with basement systems.

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