International Journal of Computational and Experimental Science and ENgineering (IJCESEN)

Vol. 11-No.4 (2025) pp. 10283-10292
http://www.ijcesen.com

ISSN: 2149-9144

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Research Article

Assessment of Soil-Structure Interaction for Reinforced Concrete Buildings in Seismic-Prone Regions

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Article Info:

DOI: 10.22399/ijcesen.4759
Received : 01 November 2025
Revised : 29 December 2025
Accepted : 30 December 2025

Keywords

Base shear,
Building response,
Earthquake analysis,
Fixed-base condition,
Fundamental period,
Inter-story drift

Abstract:

Soil-structure interaction (SSI) testing is important for finding out how well reinforced concrete (RC) buildings handle earthquakes, especially in places where they happen often. A fixed-base condition is often used in traditional structural analysis, which ignores the role of soil flexibility and may result in erroneous estimates of structure response. This study compares fixed-base and flexible-base models to see how SSI affects multi-story RC constructions. The study uses empirical formulas and numerical simulations to assess stiffness fluctuations, interstory drift, and overall structural stability under seismic loads. The findings emphasize the importance of SSI in changing structural responses, resulting in an increase in basic period and displacement under flexible-base settings. The results underscore the need of include SSI effects in seismic design to increase accuracy and resilience.

1. Introduction

Most of the time, building foundations sit on the ground, which means they are flexible. A common way to judge a building, on the other hand, is to assume that its base is rigid (fixed). This is a false assumption, because the soil's local condition has a big impact on how the structure responds, as we saw during the 1985 Mexico City, Mexico earthquake or an 1989 Loma Prieta an earthquake. In light of recent large earthquakes that have destroyed buildings, the seismic interaction between soil and structure (SSI) in multi-story buildings is now very important[1] [2]. A number of new scientific methods are being developed to use SSI for research[3]. For people who are interested, Kausel et al. give a full account of SSI's early years[4]. The benefits of SSI on health are not agreed upon by experts or health professionals, though. While lowering the base shear might be good, it causes more inter-story drift and movement, which causes the P-Δ effect and forces the whole structure to become unstable. Additionally, some experts have found that the building's response changes when the base is flexible compared to when it is set. This makes the structure less stiff and the reaction range smaller[5]. It has also been looked at how SSI affects Systems with one degree of freedom (SDOF) or multiple degrees of freedom (MDOF). Other studies[6] [7] We saw some new dynamic features, such as the basic time getting longer and the base cuts getting smaller. There is less vibration in a flexible base structure when stress waves or the hysteretic action in the supporting component break it down. This is the major reason for these findings[8].

If the building is on loose earth, SSI might overstate the horizontal moves and interstory slips by a large amount[9]. as a result, the structures may not work as well when there are shocks. The effect of SSI may also play a part in the structure risk assessment[10]. More than that, Hokmabadi and Fatahi found that a building with a deep foundation enjoyed fewer story drifts than one with a surface foundation because it had fewer rocking parts[11]. Nguyen et al. said that the type and size of pile foundations could change how well midrise buildings in areas with soft soil held up during an earthquake because of SSI[12]. In addition, detailed 3D computer modelling was recently used to look

at how structural beating and earthquake soil–pile–structure interaction affect the behaviour of nearby buildings that are built on pile foundations[13]. It's important to note that the complicated problems that arise when dirt, piles, and structures combine led to pile foundations being made easier to plan for earthquakes[14]. So, a sensible way to define a curvilinear Winkler p-y element was suggested as a way to test the behaviour of the pile group.

It is easier for SSI to have an impact on soft soil than on middle or hard soil[15]. Because of nonlinearities in the material and geometry, seismic waves moving through the near-field are amplified more than those moving through the far-field[16]. Also, the surface rock seems have been a major role in determining how the damage was spread[17]. In order to understand earthquake recordings in buildings, Maria I. Todorovska talked about how structural and dirt vibrations affect each other[18]. Traditional ways of modelling the subgrade modulus, like Winkler's theory and the stiff method, were not very good at describing what was seen because they assume that the subgrade modulus stays the same throughout the mat. Changes in the value of the subgrade from the centre to the edges have shown increase in some new studies. These involve the Pasternak Subgrade technique or the Discrete Area method. Some people think that using a single modulus in subgrade should stop, and that structural and geological engineers should work together to find the exact value of Ks[19]. The slowing of the soil material is stronger in soft soil and thin buildings. FEMA 440 suggests a soil damping ratio that doesn't take material damping into account[20]. This half-power bandwidth method was used by Julio A. García to figure out the total soil damping. There are different methods that have been used for performing SSI, like finite element or finite boundary. But these methods take a lot of time, which is why structural engineers find it hard to use them for study and design. Discrete models, like cone models, give us useful data with a reasonable range of error[21]. It has also been shown in some tests that adding SSI lowers the reaction reduction due to soft soil[22]. From what has been written, it is not clear whether SSI has positive or negative effects. The basic period of the system gets longer because SSI makes it more flexible. Most of the time, when the period in the structure gets longer, the reaction patterns get smaller, which means the result is positive. However, when the structure's time period goes up, the earthquake wave period can also go up, especially in areas with soft soils. This makes the structure more likely to collapse when it resonates with waves with such long periods. Most seismic codes provide no significant guidance on the design of structures by incorporating the effect of SSI, e.g., the Indian (IS, 1893), Japanese (JSCE-15), New Zealand (NZS 1170-5), and European (EN, 1998-1 and 1988-5). The ASCE 7-16 only has a few rules. For example, it says that buildings with a high inelastic displacement capacity should have their base stress reduced.

Based on what has been said so far, it seems that there aren't many studies on SSI. More research is needed on reinforced concrete buildings, which make up most planned and built structures[23]. Also, it's clear that we need to look into how SSI affects different structure reaction factors and how reliable different methods really are. dirt-Structure Interaction (SSI), which is the interaction between the structure, the base, and the dirt below, has a big effect on how well reinforced concrete (RC) buildings handle earthquakes. In seismically prone areas, ignoring SSI effects might lead to an erroneous evaluation of structural behavior, possibly jeopardizing safety and performance. Despite substantial seismic analysis research, there is still a crucial gap in quantifying the effects of SSI, especially for RC structures in high seismic zone (V) with changing soil conditions. Current design standards, notably IS 1893, provide little advice on adding SSI effects into seismic design, resulting in cautious or too simplified assumptions that fail to reflect the genuine dynamic response of buildings. Furthermore, traditional numerical modeling tools often fail to account for nonlinear soil behavior and its influence on structural response, prompting the development of sophisticated computational methodologies for a more realistic portrayal of SSI[24]. In this study, the impact of SSI in the seismic performance for RC frames with momentary resistance (MRF) in seismic zone V is looked into[25]. To analyze and quantify the effects of SSI, the study uses both numerical modeling and machine learning-based prediction tools. The study entails creating finite element models in SAP2000 for a 15-story RC frame, studying structural response under various soil conditions (hard, medium, and soft), and comparing the findings of fixed-base and SSI-integrated models. This study's results seek to give insights into structural design changes, retrofitting procedures, and risk assessment, therefore helping to the development of safer and more robust structures in earthquake-prone locations.

2. Modelling soil-structure interaction

The methodology for the study starts with a Literature Review, which aids in comprehending previous research, finding gaps, and outlining the technique for modeling a symmetrical RC multi-

storey structure. The modeling technique is divided into two basic approaches: model with fixed base condition and model with soil-structure interaction (SSI). Setting up and giving structure characteristics is what the Model at Fixed Base Condition method is all about, as well as ensuring that material properties, member dimensions, and boundary conditions are correctly configured. Next, loads and load combinations are assigned, taking into account gravity loads, lateral loads, and seismic loads in accordance with applicable norms and standards. The structure is next examined under a Fixed-Base Condition, assuming that the structure's base is solidly supported, and internal forces such as column forces are computed. The structural parameters, loads, and load combinations for the Model with Soil-Structure Interaction (SSI) are initially assigned in the same manner as for the fixed-base model. Rather than assuming a rigid base, the column forces produced from the fixed-base analysis are utilized to determine the stiffness values of the supporting soil using empirical equations. These computed stiffness values are then assigned to the column bases, taking into account the SSI effect, the model is looked at again to learn more about how soil flexibility affects how structures respond.Finally, the findings are assessed by comparing the two models, with an emphasis on critical factors such as storey displacement, drift, and other significant response characteristics. This comparison approach aids in determining the impact in soil-structure interaction on structure behaviour, which is important for building better and more effective buildings in places prone to earthquakes. Please let me know if you want any revisions or further information!In this study, a 15-story concrete moment-resisting building frame with four spans at each direction was used as a model. The frame was 45 meters high and 20 meters wide. This building frame is an example of a typical mid-rise moment-resisting building. These building features are typical of typical buildings in megacities in terms of their structure and how they are put together. They were chosen to look into the effect of SSI. A 15-story RC building with a symmetrical plan that is 20 m x 20 m will be modelled and analysed via SAP(2000) (finite element analysis software). There will be hard, middle and soft ground around the building. It will be in zone V. It is looked at both as well as without SSI affects on the structure. These models show a lot of typical low- to mid-rise buildings in big towns in countries like India that are more likely to have earthquakes. The building in question has G+14 stories and a plan that is 20.00 × 20.00 m². Inside, there are five bays going both X and Y. There are 300 mm by 600 mm frames and 230 mm by 600 mm beams that make up the structure. The slab is 150 mm thick, and the height from floor to floor stays at 3 m. The outside wall is 230 mm thick, and the inside wall is 150 mm thick. M25 grade material and Fe 500 grading steel were used to build the building. The live load that was thought about was 2 kN/m², and the floor finish load was 1 kN/m². The patio floor finish load was also 2 kN/m². The building is in earthquake zone V, which has a 1 for value and a 0.05 for calming. The unit weights for RCC are 25 kN/m³ and for brick they are 19 kN/m³. The structure to be analyzed with and without SSI effects in Hard soil, Medium soil & Soft soil of zone V. The provided classification of models is based on soil type and seismic zone, structured into three main categories: Hard Soil, Medium Soil, and Soft Soil, with each category further divided into seismic zone V. This structured classification appears to be aimed at analyzing Soil-Structure Interaction (SSI) effects under varying seismic conditions, helping in understanding the behavior of structures on different soil types across high-seismic zones. The image represents a structural grid layout typically used in architectural or engineering design, showing a rectangular plan divided into a 5x5 grid. The vertical columns are labeled A to E from left to right, while the horizontal rows are labeled 1 to 5 from bottom to top. Each square in the grid indicates an intersection point between a column grid line and a row grid line, representing potential nodes where columns, beams, or other structural elements may be placed. The red-shaded zone shows the main footprint of the building enclosed by the grid boundaries. The thick blue lines represent the primary grid lines for reference, and the grid intersections (nodes) stand at the potential location for structural elements. The total number of grid spaces is 25 (5 rows × 5 columns) constituting the modular planning system. Such a grid architectural arrangement is structurally easy to plan, ensuring the correct placement of structural elements and improved coordination between architectural and engineering disciplines. The image displays a three-dimensional model for structural analysis of a high-rise, focusing upon the main framework and load transfer within. The elements shown in blue correspond to beams and columns arranged to form a moment-resisting frame system against lateral loads such as wind and earthquake forces. Inside this structure are shown red planes that represent diaphragm or slab elements transferring lateral loads to the vertical members. The green supports signify the foundation connections at the base of the structure, which are basically fixed/pinned. The grid identifiers along the base help in locating and

referencing particular structural members during modeling and documentation. Having a slight tapering outward, the building seems to allow enhanced architectural expression or structural optimization. Such models are commonly created in various structural analysis software, including ETABS or SAP2000, to analyze the model's structural performance under gravity and or lateral loads. The visualization aids in verifying member connectivity, load paths, and overall stability of the structural system. The image shows a 3D structural analysis model of a multi-story building, likely created using software such as ETABS, SAP2000, or STAAD.Pro. The model consists of a regular grid system forming the vertical and horizontal framing of the structure. The blue lines represent beams and columns forming the skeleton of the building, while the red lines and detailing at the base suggest foundation or base isolation systems, possibly showing spring or damper elements (common in seismic analysis). The grid system aligns with the earlier 5x5 layout, extended vertically across multiple floors, indicating a high-rise or mid-rise building design. The black circular elements at the base appear to be symbolic of isolators or foundation pads. This model is used to simulate and analyze the behavior of the building under various loads such as gravity, wind, and seismic forces. Such a visual model aids engineers in verifying stability, load distribution, and dynamic performance.This image presents an elevation view of a structural frame model, typically used in finite element analysis for tall buildings. The vertical orange members represent columns, while the horizontal green members are beams, forming a regular grid layout. The black dots mark joint connections where structural elements intersect. The base includes light blue horizontal members and black joint points, indicating the foundation level or a base slab. Additionally, the presence of pink-colored elements at the base could represent structural supports such as shear walls, base isolators, or ground beams. Grid labels at the top help identify column lines for referencing. The structure appears to be symmetrical, with uniform spacing between members, indicating a regular and balanced design. This simplified representation is likely used to evaluate axial, bending, and shear behavior of the frame system under different loading conditions in software like ETABS or SAP2000.The image represents a 3D finite element model of a multi-story building structure, likely analyzed for seismic or wind performance. The structural frame comprises vertical columns (orange), horizontal beams (green), and diagonal braces, forming a braced frame system for lateral stability. The model rests on a base that appears to include isolators or damping elements (black springs), suggesting a base isolation system for seismic protection. The turquoise blue platform represents the foundation mat or base slab, while the color-coded elements help differentiate between structural components (columns, beams, braces, and foundation supports). This model shows detailed meshing and connectivity, likely generated using advanced structural analysis software such as ETABS or SAP2000. The bracing system indicates enhanced resistance to lateral forces, and the isolators reduce seismic energy transmission to the superstructure. This level of modeling supports performance-based design and ensures safety and serviceability under critical loading conditions, especially in earthquake-prone areas.

3. Seismic response demands

In this Fig 6, the X-axis shows how much the 16 floors of a building moved in different types of soil, regardless of soil-structure interaction (SSI). Displacement gradually decreases from the top storey (storey 1) to the base (storey 16) under all conditions. The maximum displacement is observed in soft soil without SSI, reaching approximately 92 mm at the top. When SSI is considered, displacement in soft soil decreases to around 78 mm. For medium soil, the top storey displacement is about 66 mm without SSI and reduces to 59 mm with SSI. In the case of hard soil, displacement is comparatively lower, with values around 48 mm without SSI and further reducing to 43 mm with SSI. This trend shows that softer soils result in higher lateral displacements and that incorporating SSI helps to reduce these displacements across all soil types. The influence of SSI is more prominent in softer soils, improving overall structural stability. In the Fig 7, you can see how much the storeys of a 16-story building moved in the Y direction (in millimetres) when the soil was different, regardless of soil-structure interaction (SSI). Displacement decreases progressively from the top (storey 1) to the bottom (storey 16) in all cases. The highest displacement is observed in soft soil without SSI, reaching about 91 mm at the top storey. When SSI is considered in soft soil, the top displacement reduces to approximately 76 mm. Medium soil shows a displacement of around 66 mm without SSI and 58 mm with SSI at the top level. In hard soil conditions, displacement is lower, with about 47 mm without SSI and 42 mm with SSI at the top. The pattern indicates that softer soil leads to higher lateral movement, while the incorporation of SSI consistently reduces displacement. This emphasizes that SSI has a significant impact on reducing

structural movement, particularly in flexible soil conditions like soft soil.The figure 8 represents the storey drift in the X direction (in mm) across 16 storeys under various soil conditions, with and without soil-structure interaction (SSI). Storey drift increases from the base up to around the 8th or 9th storey and then slightly decreases towards the top, showing a typical parabolic pattern. The maximum drift occurs in soft soil without SSI, peaking at approximately 1.91 mm near the 9th storey. When SSI is included in soft soil, the peak drift reduces slightly to around 1.75 mm. For medium soil, the peak drift is about 1.69 mm without SSI and 1.59 mm with SSI. Hard soil shows the lowest drift values, with a peak of around 1.46 mm without SSI and 1.34 mm with SSI. Overall, the trend indicates that softer soils contribute to higher drift values, and the inclusion of SSI helps in reducing the drift, improving the lateral stability of the structure.

Fig 9 shows A 15-story building was built on hard, medium, or soft soils, regardless of Soil-Structure Interaction (SSI). The graph shows how the floors moved in the Y direction (in millimetres). The storey drift increases gradually from the base up to around the 9th storey and then decreases slightly toward the top. The highest displacement is observed around storey 9 for all cases. at storey 9, the peak values are approximately: soft soil with SSI at 1.95 mm, soft soil without SSI at 1.85 mm, medium soil with SSI at 1.65 mm, medium soil without SSI at 1.55 mm, hard soil without SSI at 1.6 mm, and hard soil with SSI at 1.5 mm. These values indicate that SSI increases storey drift in soft and medium soils, whereas it slightly reduces drift in hard soil conditions. The results highlight the need to consider SSI in seismic design, especially for structures on soft soil, due to the amplified displacements.Above Fig 10 Based on 15 stories of buildings on three types of soil (hard, medium, and soft), the graph shows base shear at the X direction (in kN), regardless of Soil-Structure Interaction (SSI). In all cases, there is a general trend in less base stress from below to the top floor. at storey 1 (base), the base shear values are approximately: hard soil without SSI at 8200 kN, hard soil with SSI at 4100 kN, medium soil without SSI at 6100 kN, medium soil with SSI at 5100 kN, soft soil without SSI at 7400 kN, and soft soil with SSI at 8500 kN, which is the highest among all. SSI significantly reduces base shear in hard and medium soils, but increases it in soft soil, reflecting higher flexibility and energy absorption demands. This highlights that SSI effects are more pronounced in soft soils, necessitating careful consideration during seismic design to ensure structural safety and stability.

The Fig 11 displays the base stress in the Y direction (in kN) for 15-story buildings that were constructed on hard, medium, or soft soils, as well as with Soil-Structure Interaction (SSI). A consistent decrease in base shear from the bottom to the top storey is observed in all cases. at the first storey, the approximate base shear values are: soft soil with SSI at 8200 kN, soft soil without SSI at 7900 kN, medium soil without SSI at 6100 kN, medium soil with SSI at 5200 kN, hard soil without SSI at 4000 kN, and hard soil with SSI at 3800 kN. These values show that SSIs increase base shear in soft soil but decrease it in medium and hard soils. It further shows that these effects are severe in soft soils, where flexibility and dynamic interaction play a crucial role in structural response. Hence, careful consideration must be given to SSI during seismic design, more so on soft ground.

4. Conclusions

In seismic-prone areas, the soil-structure interaction (SSI) analysis for reinforced concrete (RC) buildings plays an important part in the adequate assessment of structural safety and performance during earthquakes. The study points out the major role soil conditions play in influencing the dynamic response of buildings, particularly in seismically active areas. When SSI is considered in the analysis, it becomes apparent that the seismic force response of the building is highly dependent on soil properties, which include, among others, stiffness, damping, and soil types. This often alters the behavior of the structure when compared to fixed foundation analyses. Under soil-structure interactions, there can be an increase in displacements, alteration of natural frequencies of the structure, and modification of seismic forces transmitted to the building side, which would be crucial in determining the stability and performance of the structure during the seismic event. It was observed that soft soils cause seismic waves to amplify so as to increase displacement and cause damage, while stiffer soils try to reduce this effect. Furthermore, the SSI effect must be keenly modeled with proper foundation models and dynamic analysis respectively.

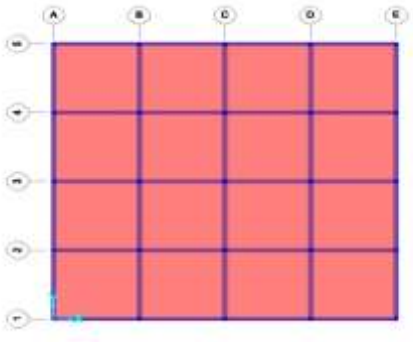

Figure 1: *Plan view of building*

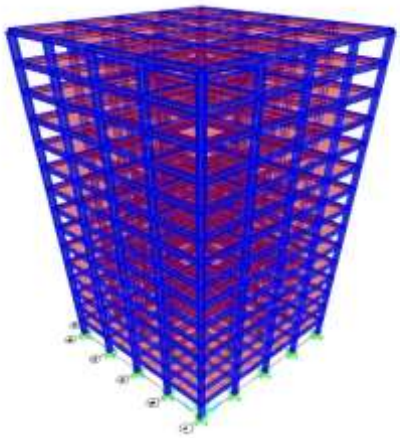

Figure 2: *3D structure with fixed base*

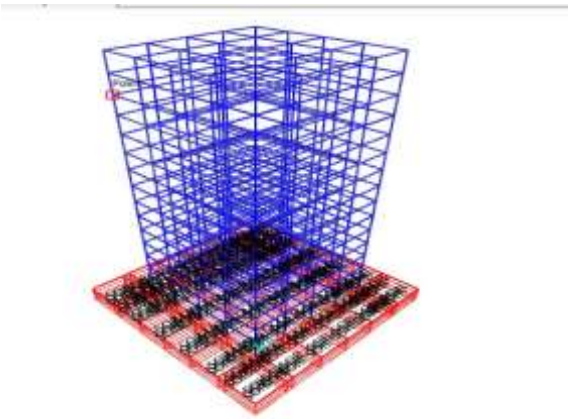

Figure 3: *3D view with SSI*

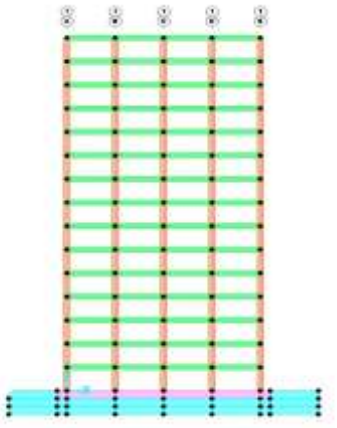

Figure 4: *Front view with SSI*

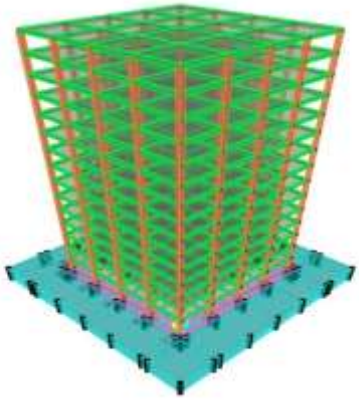

Figure 5: *3D view with SSI rendered view*

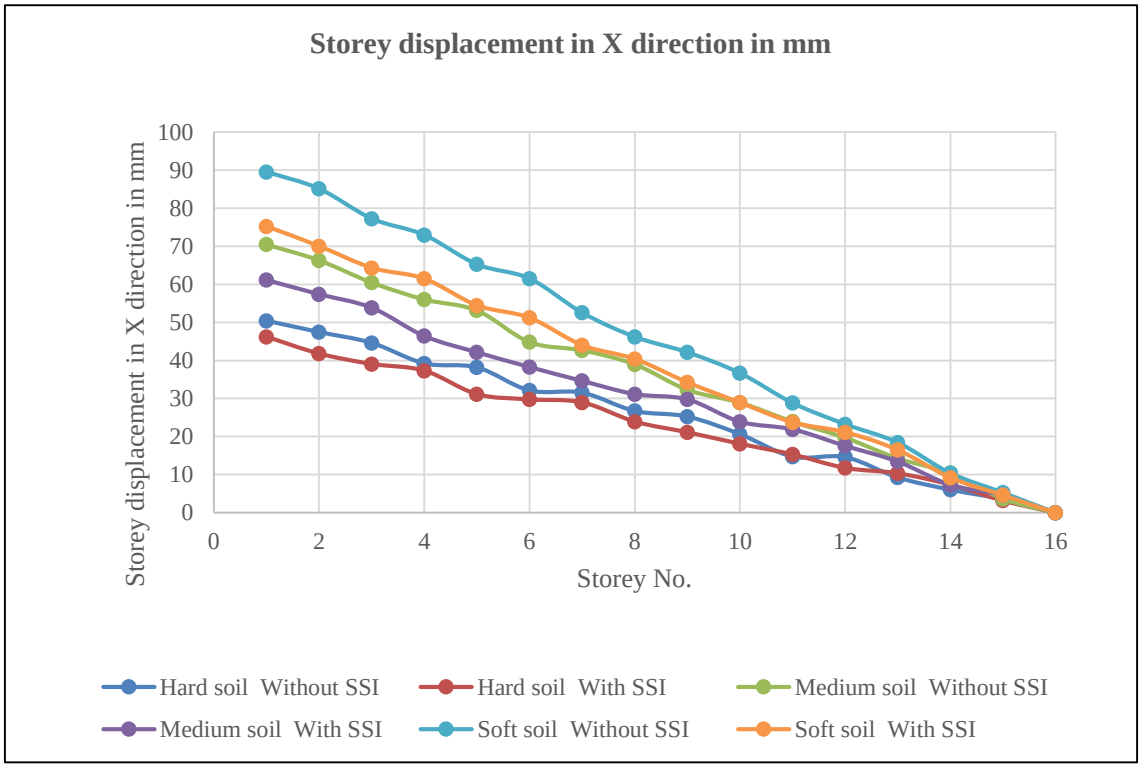

Figure 6: *Storey displacement in x direction in mm*

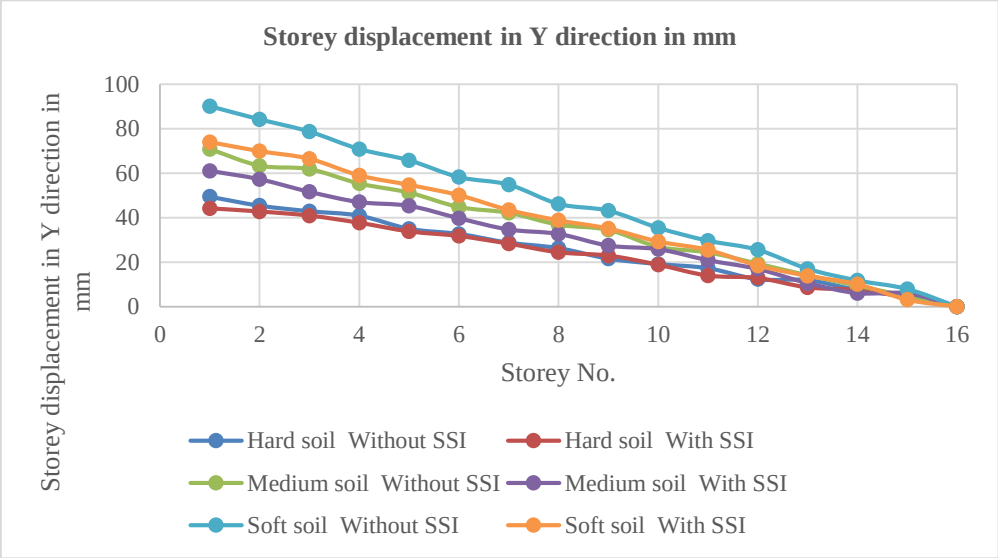

Figure 7: *Storey displacement in y direction in mm*

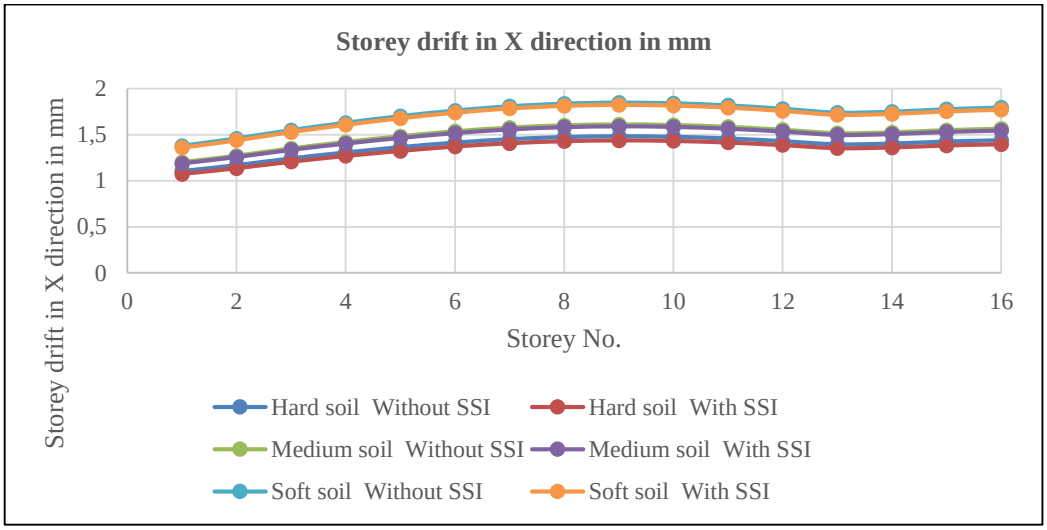

Figure 8: *Storey drift in x direction in mm*

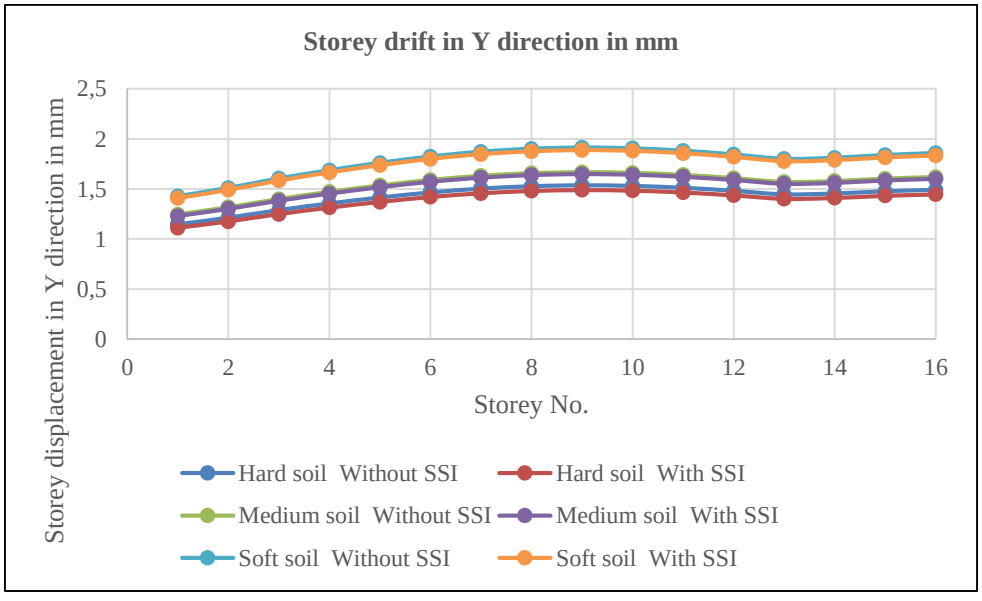

Figure 9: *Storey drift in y direction in mm*

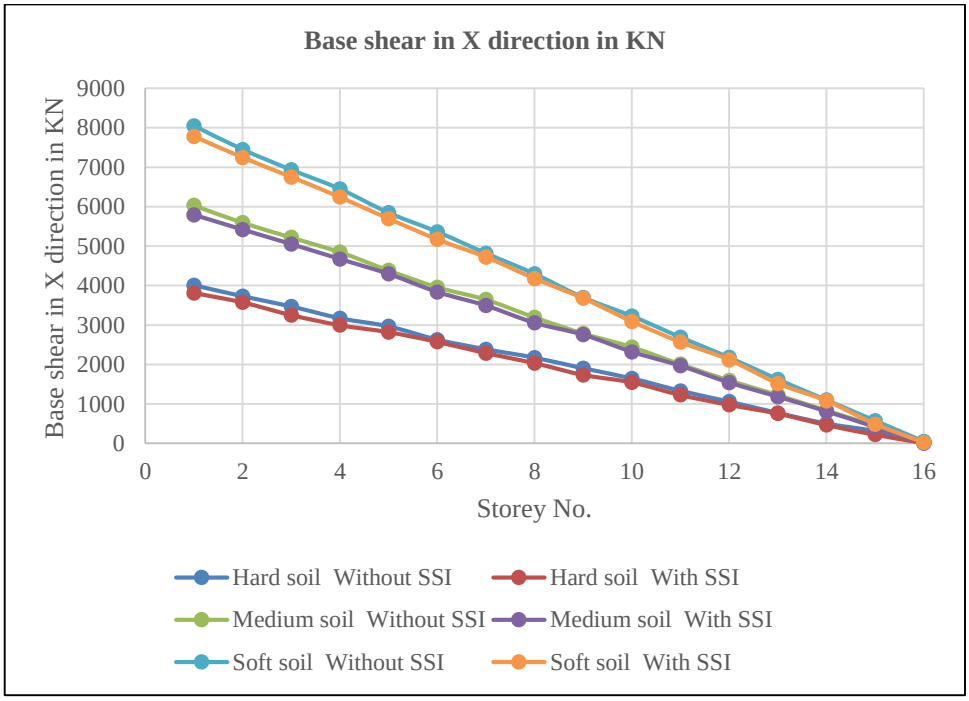

Figure 10: *Base Sharar in x direction in KN*

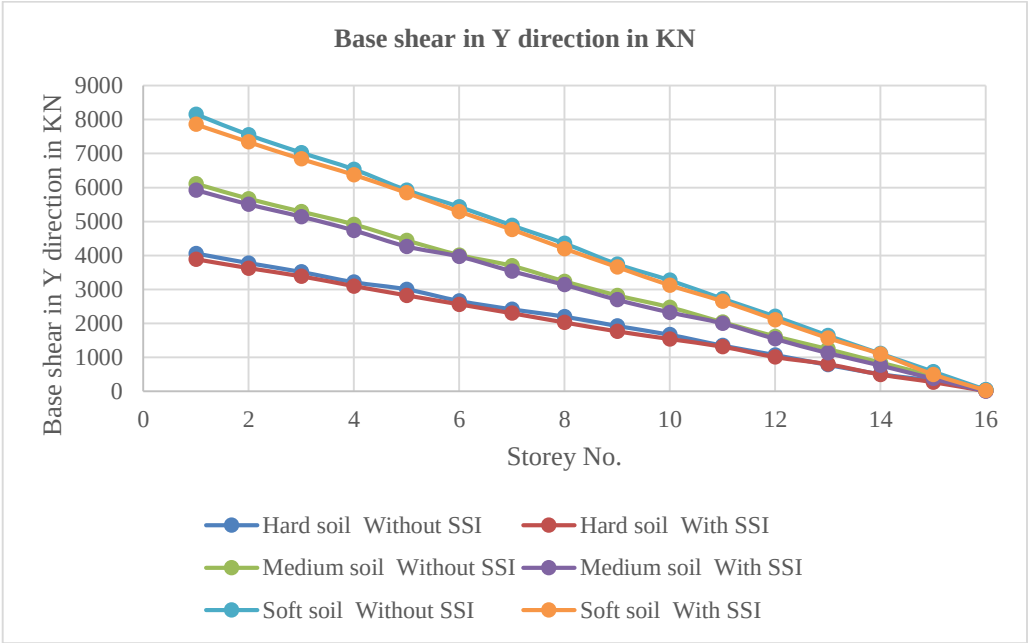

Figure 11: *Base Sharar in y direction in KN*

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
- **Acknowledgement:** The authors declare that they have nobody or no-company to acknowledge.
- **Author contributions:** The authors declare that they have equal right on this paper.
- **Funding information:** The authors declare that there is no funding to be acknowledged.
- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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