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Influence of Soil-Structure Interaction on Seismic Behaviour of Mid-Rise Building using Non-Linear Time History Analysis.

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Abstract

Soil-Structure Interaction (SSI) plays an important role in how buildings respond to earthquakes, especially mid-rise structures supported on different soil conditions. This study examines the seismic behaviour of a G+10 reinforced concrete building resting on soft, medium, and hard soils. The building was analysed in SAP2000 under both fixed-base and flexible-base conditions to capture the effect of soil flexibility. For the flexible-base models, springs were used to represent the stiffness of each soil type. To ensure realistic seismic loading, ground motions were scaled using the One-Step Scaling method, and nonlinear time history analysis was carried out to observe the building's dynamic response. The results clearly show that buildings with flexible bases experience greater fundamental periods, base shear, overturning moments, lateral displacements, and storey drifts than fixed-base models. These effects are most noticeable on soft soil, where the increased flexibility amplifies the building's response. Medium and hard soils also influence the behaviour, but the changes are less severe. Maximum storey drift occurs in the middle floors, highlighting potential areas for damage. These findings stress the importance of considering SSI in seismic design to avoid underestimating the real demands on a structure and to improve earthquake resilience.

Keywords: RC Building, Soil Structure Interaction (SSI), Non-Linear Time History Analysis, Scaled Ground Motions, Stiffness, SAP-2000

1. Introduction

Modern structural design increasingly highlights the importance of dynamic analysis, especially in seismically active regions. Traditionally, many building models assume fixed-base conditions, where the foundation is treated as rigid and immune to soil effects. However, in reality, the behavior of a structure during an earthquake is strongly influenced by the flexibility of the surrounding soil. This interaction, known as Soil-Structure Interaction (SSI), can lead to substantial deviations in expected structural performance. SSI modifies the system's stiffness, damping, and mass participation, thereby altering critical response

characteristics such as Fundamental Period, base shear, displacement, and drift. Soft soil conditions typically amplify ground motions, causing significant increases in lateral displacements and deformation demands. However, even in medium and hard soils, SSI cannot be entirely neglected, as it still influences dynamic behaviour, although to a lesser extent. Ignoring these effects can result in an underestimation of seismic forces and potential misjudgement of structural safety margins. This study investigates a G+10 RC building modelled in SAP2000 under fixed and flexible base conditions across soft, medium, and hard soil types. By applying scaled ground motions through the One Step Scaling method, the project aims to understand how soil flexibility affects seismic performance. Key structural parameters such as Fundamental Period, base shear, overturning moment, displacement, and drift are compared to highlight the necessity of SSI consideration in performance-based seismic design. While the effects of SSI are most pronounced in soft soil, even medium and hard soils can affect how seismic forces are distributed and absorbed by a structure. This study focuses on comparing structural response, such as Fundamental Period, base shear, overturning moment, displacement, and drift between fixed and flexible base conditions for different soil types. The aim is to provide a clearer understanding of how SSI changes building behaviour during seismic loading and why it must be included in design procedures.

2. Previous Studies on Soil Structure Interaction

Azra Anna Razvi et al., investigated the seismic behaviour of a G+10 RC multi-storey building with plan irregularity under fixed and flexible base conditions using ETABS. To model the flexible base, Winkler springs were used by calculating spring stiffness from soil properties based on NIST guidelines. The results showed that considering soil-structure interaction (SSI) led to increased storey displacements, drift, and overturning moments, especially in soft soil conditions and seismic Zone III. Their study clearly indicated that the fixed-base assumption underestimates seismic demand, making SSI consideration essential even for mid-rise buildings [Azra Anna Razvi et al., 2018]

Kemal Edip et al., conducted a detailed SSI study on mid-rise RC buildings using ANSYS, modeling soil with elastic, Drucker–Prager, and BISO nonlinear material models. They found that nonlinear modeling of soil significantly altered structural response, increasing displacements and affecting force-displacement relationships. The research highlighted that relying on simple elastic models may misrepresent the actual behavior of structures during earthquakes, particularly in soft soils. Their work emphasizes the need for advanced soil models in seismic design for more reliable results. [Kemal Edip et al.,2023]

Baban Bapir et al., presented a comprehensive review of dynamic soil-structure interaction effects, covering modeling techniques, code provisions, and real-world observations. They discussed that while SSI may reduce base shear by increasing flexibility, recent studies and earthquake evidence reveal it can also increase drift, ductility demand, and foundation settlement in soft soils. The review urged that fixed-base assumptions can be unsafe for soft sites and mid- to high-rise buildings. The study advocates for realistic SSI modeling and updates in design codes to ensure safer seismic designs. [Baban Bapir et al., 2023]

Ghahari et al., carried out a detailed investigation into nonlinear time-history analysis of soil-structure systems while incorporating frequency-dependent impedance functions. Their study highlights the practical limitations of the traditional substructure approach in capturing complex SSI behavior, especially under nonlinear structural response. To address this, they implemented and verified the Hybrid Time-Frequency Domain (HTFD) method, which successfully represents frequency-dependent impedance in the time domain without causing numerical instability. Using OpenSees, they demonstrated how HTFD could be applied to both single and multi-degree-of-freedom systems. Their results showed that traditional SSI simplifications—such as fixed-base assumptions or frequency-independent impedance—can produce inaccurate responses under seismic loading, particularly when frequency content shifts across the spectrum. This research is highly relevant to realistic modeling of mid- to high-rise buildings on soft soils under dynamic loads [Ghahari,et al., 2011]

O M O Ramadan, when buildings are designed, assuming they sit on a completely rigid base can be misleading, especially during an earthquake. This study shows that the interaction between the soil and the structure is crucial, particularly for shorter, stiffer buildings on softer ground. Ignoring this interaction often leads to overestimating the earthquake's impact, which can result in building a structure that is much stronger, and therefore more expensive, than it needs to be. In some cases, the calculated forces on a building could be overestimated by as much as three or four times. [O M O Ramadan, 2012]

3. Selection of Ground Motions and Their Scale Factors

Earthquake ground motion records were downloaded from the Pacific Earthquake Engineering Research Center (PEER) Ground Motion Database, using criteria like Magnitude M > 6.5, Fault Mechanism: Reverse and Strike Slip, PGA > 0.2g, and the selected ground motions are shown in Table 1.

To maintain uniformity across all seismic inputs, the One Step Scaling method was employed to scale the ground motion records as shown in equation (1). This method works by aligning the spectral acceleration of each record with a standard reference value of 1g at the structure's fundamental period. By doing this, all records are adjusted to the same intensity level, allowing for consistent and realistic assessment of structural performance [Vamvatsikos, D., & Cornell, C. A.]. This approach ensures that the applied ground motions are compatible with the dynamic characteristics of the building. The scale factor used for this adjustment is calculated using the following expression, and it is mentioned in Table 2.

$$\text{Scale Factor} = \frac{1}{\text{Spectrual Acceleeration of Ground Motion at } T_1} \quad (1)$$

Table 1 Selected Ground Motions

Selected Ground Motions					
RSN	Event	Year	Magnitude	Fault	PGA
126	Gazli, USSR	1976	6.80	Reverse	0.864
139	Tabas, Iran	1978	7.35	Reverse	0.409
496	Nahanni, Canada	1985	6.76	Reverse	0.519
848	Landers	1992	7.28	Strike Slip	0.417
952	Northridge	1994	6.76	Reverse	0.620
1158	Kocaeli, Turkey	1999	7.51	Strike Slip	0.321
1633	Manjil, Iran	1990	7.37	Strike Slip	0.497

Table 2 Scale Factor of Ground Motions

Scale Factors				
RSN	Fixed Base	Flexible Base		
	All Types of Soil	Soft Soil	Medium Soil	Hard Soil
126	42.46	43.44	43.59	43.46
139	82.18	92.50	88.81	86.43
496	109.78	126.39	119.74	115.87
848	102.62	110.45	107.62	105.87
952	147.82	140.61	141.01	142.74
1158	33.19	38.69	36.55	35.28
1633	27.10	28.51	27.88	27.52

4. Methodology

4.1 Mathematical Modelling

This study focuses on the Soil Structure Interaction of a G+10 RC building using CSI-SAP2000 software. The structure is modelled as a bay frame system comprising a Special Moment Resisting Frame (SMRF) with fixed and flexible supports at the base. The building consists of a uniform story height of 3 m from the plinth to the terrace floor, while the base to plinth height is 2 m. The materials used for the members include concrete of grade M40 and

M30 for columns and beams, respectively. While the rebars of grade Fe500 and Fe415 are used for longitudinal and transverse reinforcement, respectively, for both beams and columns. Beam Size is 300X450 mm and Column Sizes from base to story 4 is 350X750 mm, from story 5 to story 7 is 350X650 mm, and from story 8 to story 10 is 350X550 mm as shown in fig.1 (a) and 1 (b)

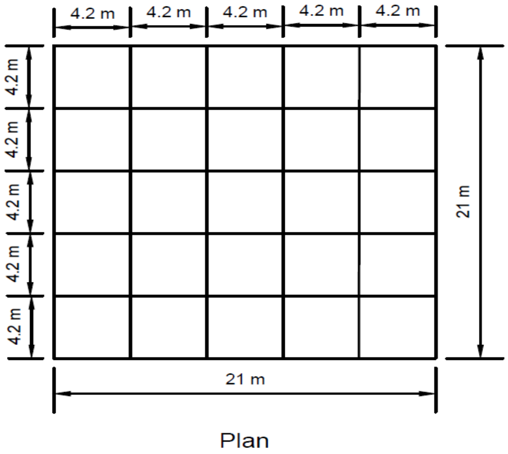

Fig. 1 (a)

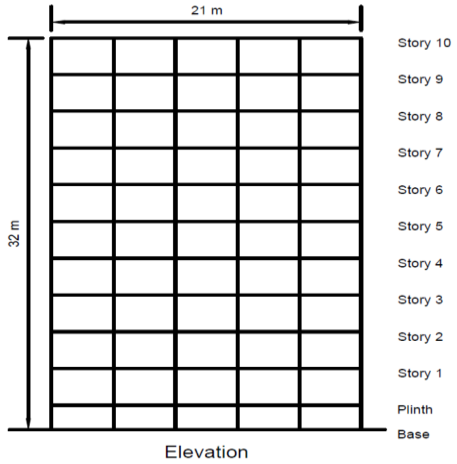

Fig. 1 (b)

Figure 1: (a) Plan and (b) Elevation

The structural model represents a ten-storey reinforced concrete building situated in Seismic Zone IV, as per the specifications of IS 1893:2016 [Bureau of Indian Standards, 2016] For seismic analysis, the design parameters include a zone factor (Z) of 0.24, an importance factor (I) of 1.5 due to its commercial function, and a response reduction factor (R) of 5. Rigid diaphragm action is assumed at all floor levels to ensure even distribution of lateral loads. The building is subjected to gravity and seismic loads, with all load definitions and combinations applied in accordance with relevant Indian Standard codes. The building is situated in Seismic Zone IV and categorized for commercial use, with floor slabs assumed to act as rigid diaphragms.

To replicate the interaction between the structure and varying soil conditions, flexible base behaviour was introduced by assigning spring supports in both horizontal and vertical directions at the base of all columns. These springs were calibrated to represent the stiffness characteristics of soft, medium, and hard soils, respectively. The structural model considered both material and geometric nonlinearity to ensure a realistic simulation of the building's performance. Material nonlinearity was modelled using a lumped plasticity approach, wherein plastic hinges were defined at the ends of beams and columns as per ASCE 41-17 Tables 10-7, 10-8 to 10-9 [American Society of Civil Engineering, 2017], allowing localized inelastic deformations. Geometric nonlinearity was addressed by incorporating P-Delta effects, which consider the influence of lateral displacements on axial forces. This dual approach to modelling ensures the system captures both deformation capacity and stability effects under seismic action.

4.2 Spring Stiffness Calculations

To realistically capture soil-structure interaction (SSI) effects under seismic loading, the foundation of the structure was modelled using discrete spring supports. Springs were provided in the X, Y, and Z directions to simulate the flexibility of soil beneath the columns. The stiffness of each spring was determined based on the modulus of subgrade reaction for each soil type and calculated using the relation and which is taken from ASCE 41-17, as shown in Table 3 [American Society of Civil Engineering, 2017]

Table 3 Elastic Solutions for Static Stiffness of Rigid Footing at the Ground Surface

Degree Of Freedom	Stiffness of Foundation Soil
Translation along X axis	$Kx = \frac{GB}{2-v}\left[3.4\left(\frac{L}{B}\right)^{0.65} + 1.2\right]$
Translation along Y axis	$Ky = \frac{GB}{2-v}\left[3.4\left(\frac{L}{B}\right)^{0.65} + 0.4\left(\frac{L}{B}\right) + 0.8\right]$
Translation along Z axis	$Kz = \frac{GB}{1-v}\left[1.55\left(\frac{L}{B}\right)^{0.75} + 0.8\right]$
Rocking about X axis	$Kxx = \frac{GB^3}{1-v}\left[0.4\left(\frac{L}{B}\right) + 0.1\right]$
Rocking about Y axis	$Kyy = \frac{GB^3}{1-v}\left[0.47\left(\frac{L}{B}\right)^{2.4} + 0.034\right]$
Rotation about Z axis	$Kzz = GB^3\left[0.53\left(\frac{L}{B}\right)^{2.45} + 0.51\right]$

Where, G is Soil Shear Modulus in $\mathrm{N/mm^2}$, v is Poisson's ratio, L is the length of the footing, B is the breadth of the footing, and these footing sizes are obtained from forces coming from columns. And for the values above, terms of different soil types like Soft, Medium and Hard as mentioned in Table 4, while G is calculated as $\mathrm{G} = \frac{\mathrm{E}}{2*(1+\mathrm{v})}$ where E is Young's Modulus in $\mathrm{N/mm^2}$ and all this taken from ASCE 41-17

Table 4 Calculated Values of E, v, and G

	Soft Soil	Medium Soil	Hard Soil
E	25	50	80
v	0.5	0.25	0.25
G	8.33	20	32

5. Results and Discussion

The study focuses on the Fixed Base vs Flexible Base of an RC building under the Non-linear time history response by using the One Step scaling method. To understand this, results of various structural parameters are taken into account, which include: 1. Fundamental Period 2. Base Shear 3. Overturning Moment 4. Displacement 5. Drift. Using these results, a detailed discussion can be put forth regarding the effects of various scaling methods.

5.1 Results

We performed a non-linear time history analysis on the structure to calculate key parameters like fundamental period, base shear, overturning moment, displacement, and drift. This analysis used seven ground motion records processed with the One Step scaling method. Due to the large volume of results generated, the findings from two representative earthquakes are detailed in this report. In displacement and drift graphs, short forms are used like SS stands for Soft Soil, MS stands for Medium Soil, and HS Stands for Hard Soil.

5.1.1 Fundamental Period

The results of the Fundamental Period under different conditions are shown in Table 5

Table 5 Fundamental Period of Structure on Different Conditions

Conditions	Fundamental Period
Fixed Base, all Soil Type	2.256
Flexile Base Soft Soil	2.382
Flexile Base Medium Soil	2.336
Flexile Base Hard Soil	2.307

5.1.2 Base Shear

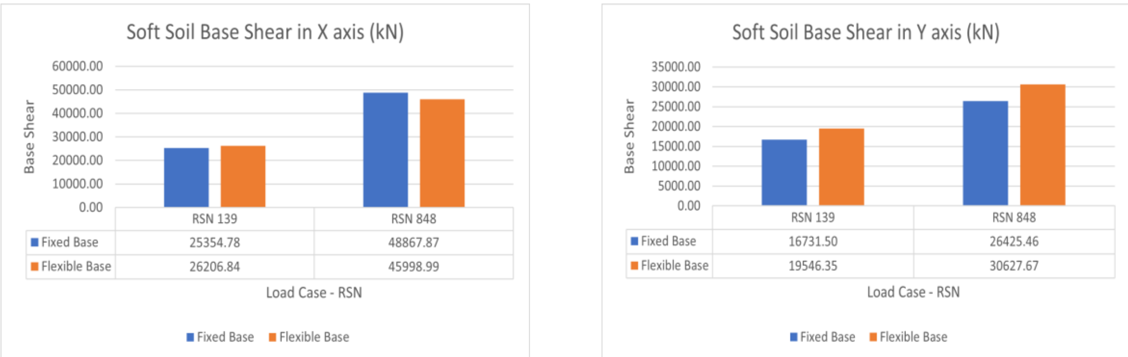

Fig. 2 (a)　　**Fig. 2 (b)**

Fig. 2: Soft Soil Base Shear - (a) in X axis (b) in Y axis of RSN 139 and RSN 848

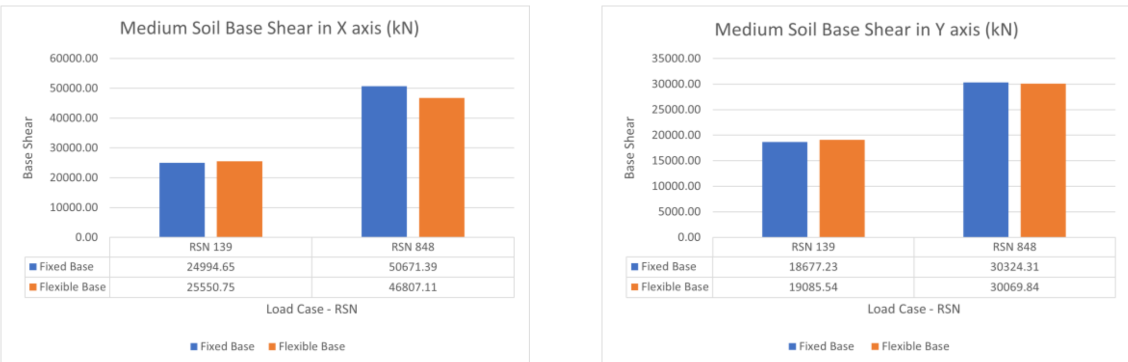

Fig. 3 (a)　　**Fig. 3 (b)**

Fig. 3: Medium Soil Base Shear - (a) in X axis (b) in Y axis of RSN 139 and RSN 848

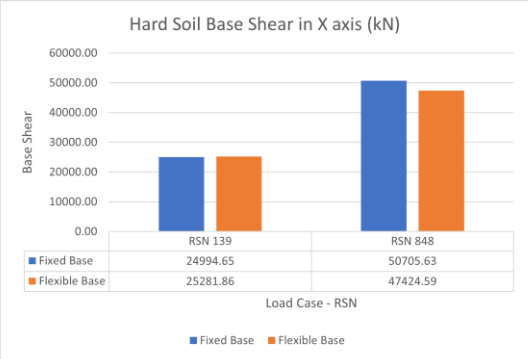

Fig. 4 (a)

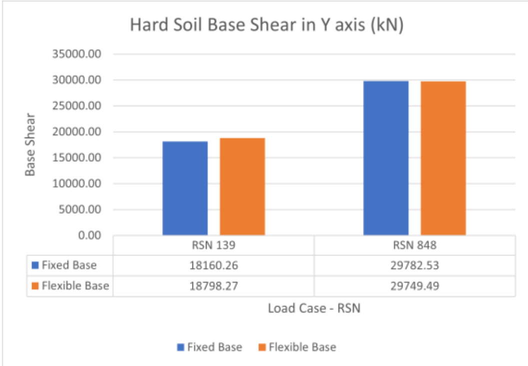

Fig. 4 (b)

Fig. 4: Hard Soil Base Shear - (a) in X axis (b) in Y axis of RSN 139 and RSN 848

5.1.2 Overturning Moment

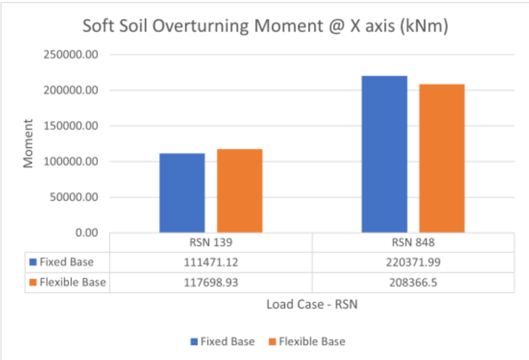

Fig. 5 (a)

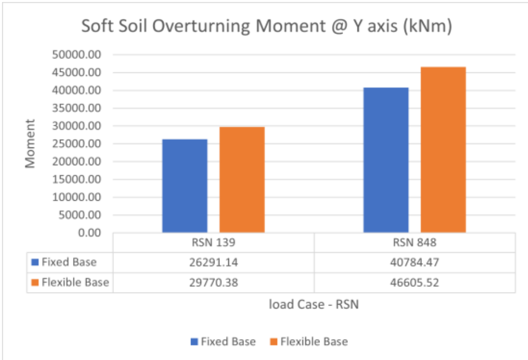

Fig. 5 (b)

Fig. 5: Soft Soil Overturning Moment - (a) in X axis (b) in Y axis of RSN 139 and RSN 848

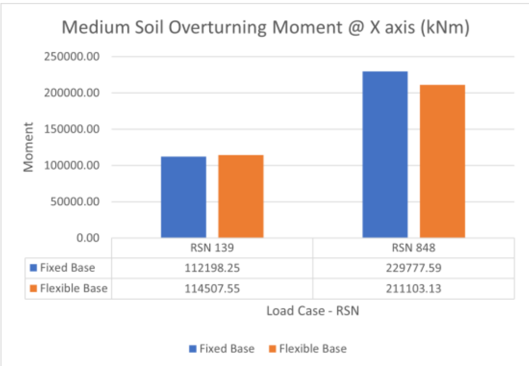

Fig. 6 (a)

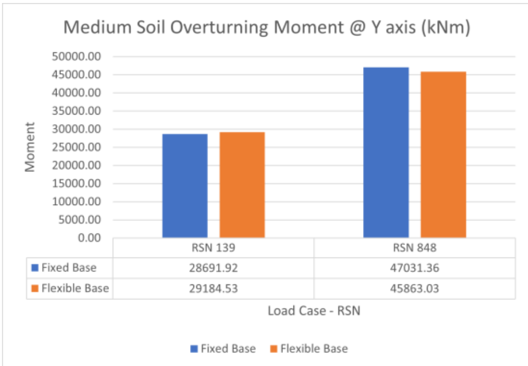

Fig. 6(b)

Fig. 6: Medium Soil Overturning Moment - (a) in X axis (b) in Y axis of RSN 139 and RSN 848

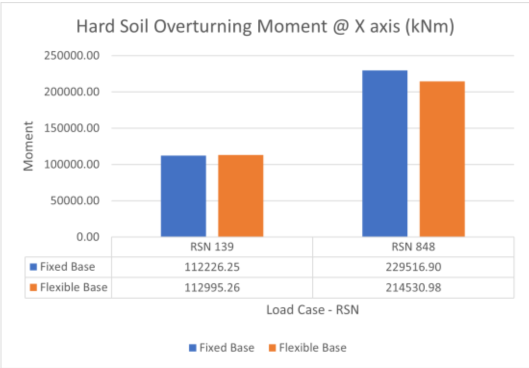

Fig. 7 (a)

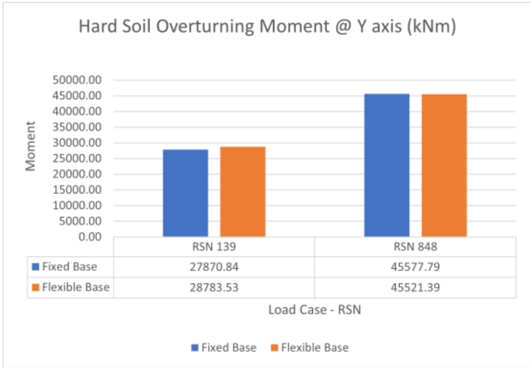

Fig. 7 (b)

Fig. 7: Hard Soil Overturning Moment - (a) in X axis (b) in Y axis of RSN 139 and RSN 848

5.1.3 Displacement

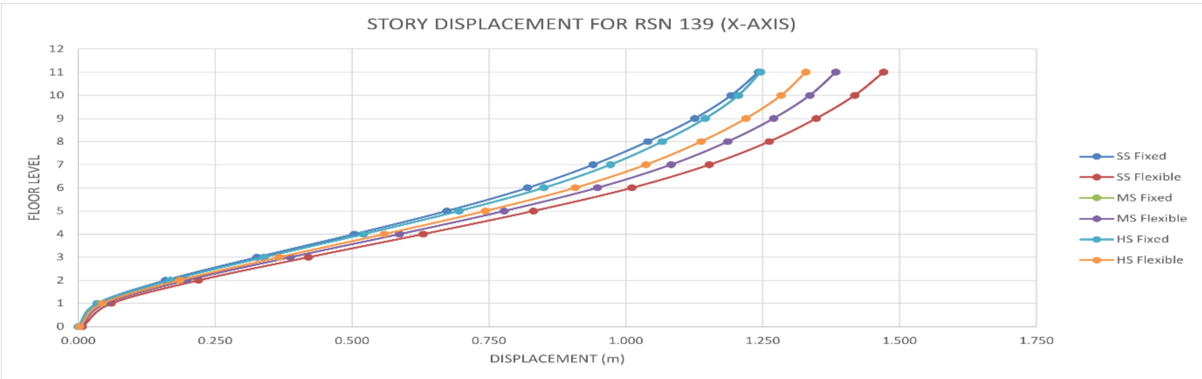

Fig. 8 (a)

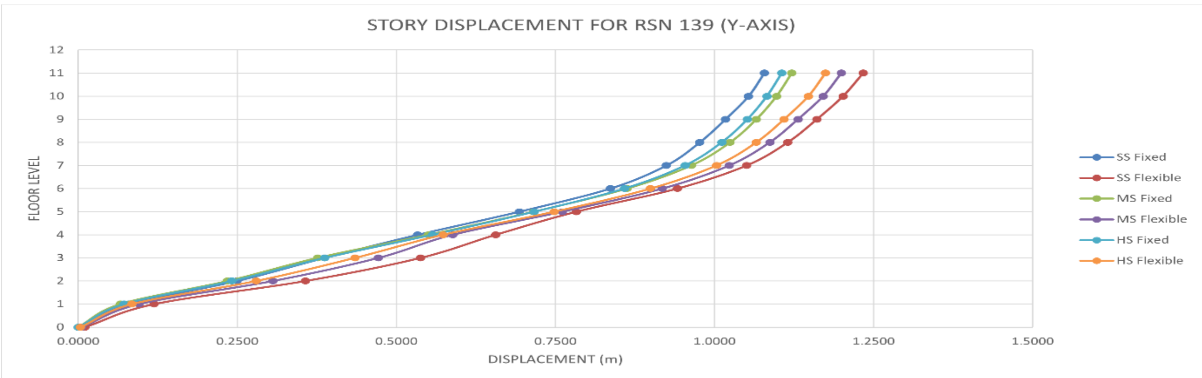

Fig. 8 (b)

Fig. 8: All Soil Types Displacements (a) in X axis (b) in Y axis of RSN 139

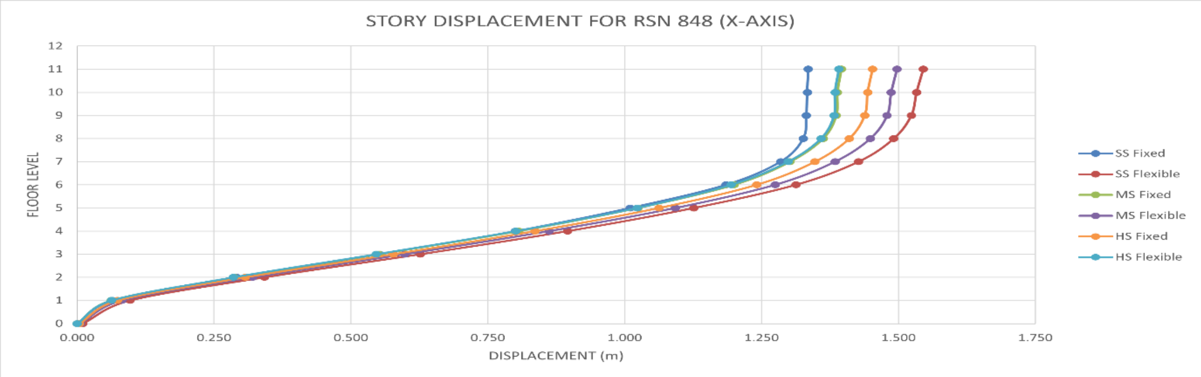

Fig. 9 (a)

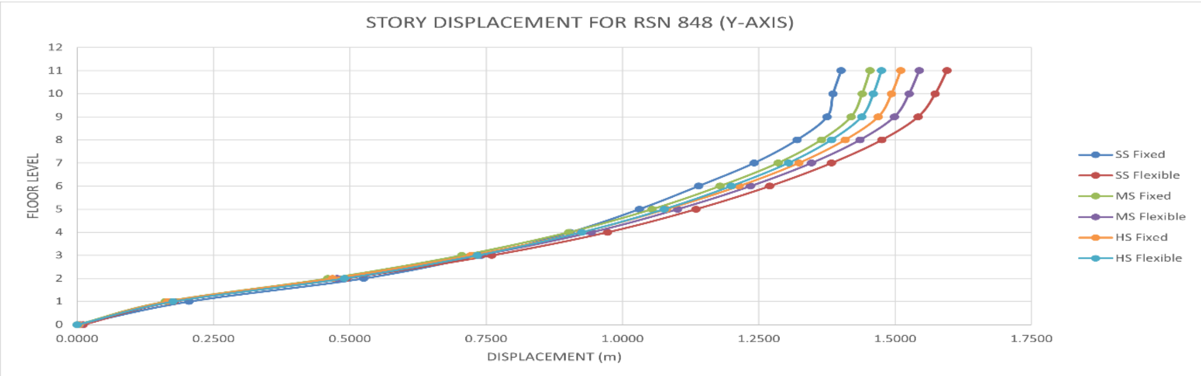

Fig. 9 (b)

Fig. 9: All Soil Types Displacements (a) in X axis (b) in Y axis of RSN 848

5.1.4 Drift

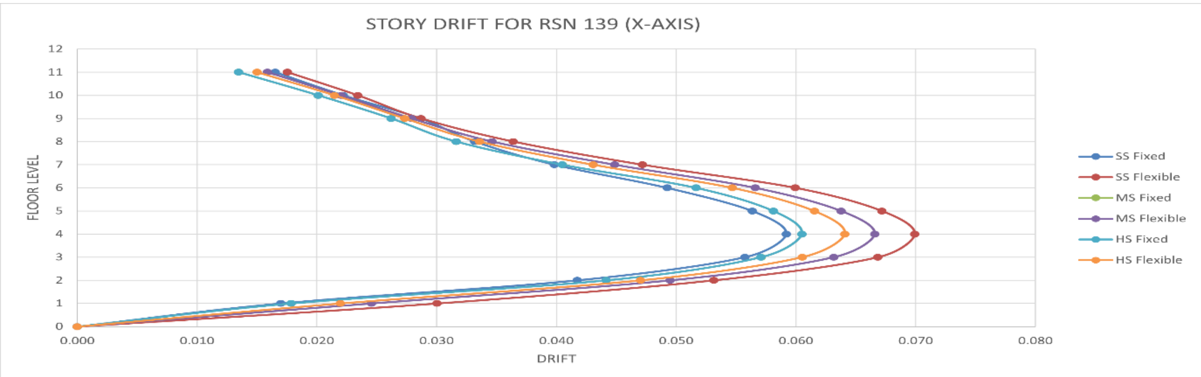

Fig. 10 (a)

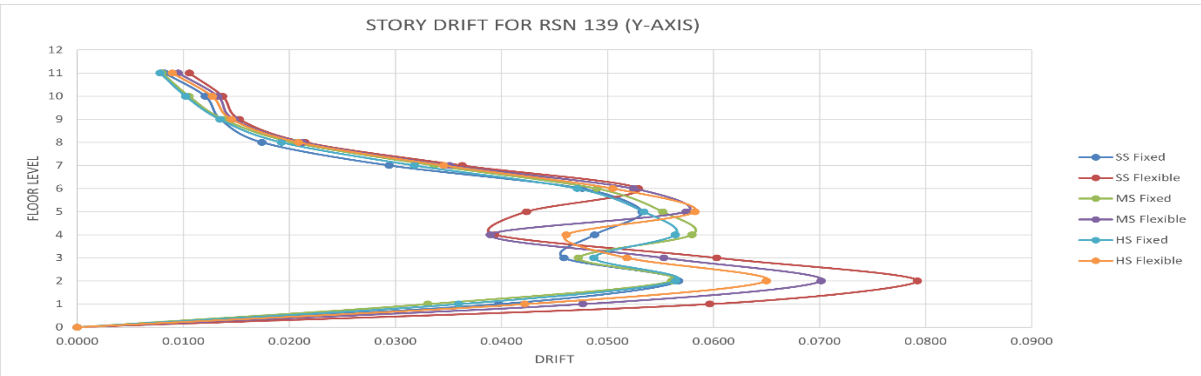

Fig. 10 (b)

Fig. 10: All Soil Types Drifts (a) in X axis (b) in Y axis of RSN 139

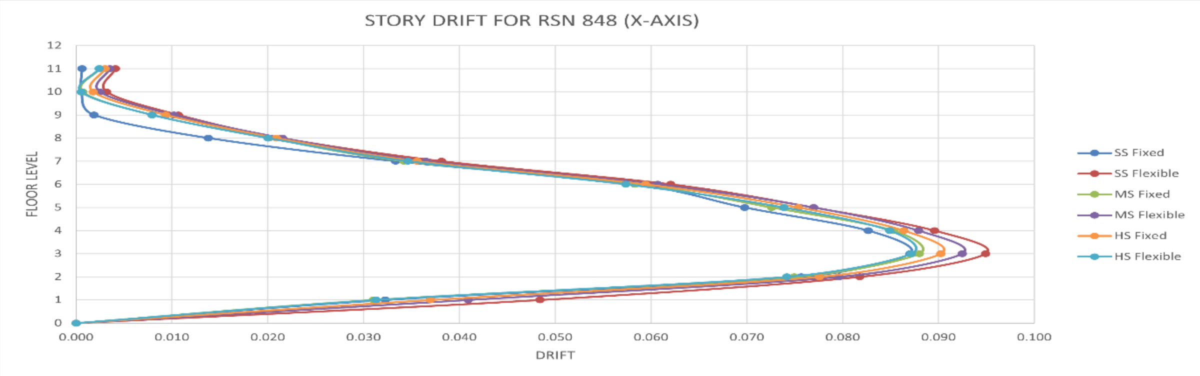

Fig. 11 (a)

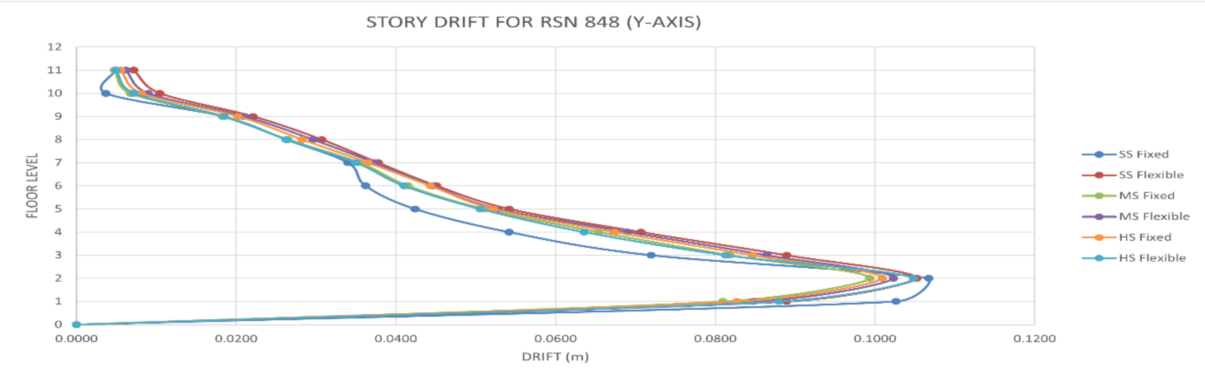

Fig. 11 (b)

Fig. 9: All Soil Types Drifts (a) in X axis (b) in Y axis of RSN 848

5.1.5 Failure Pattern

Table 6 (a) Failure Pattern of RSN 139 X axis

Failure Pattern for RSN 139 in X-axis							
Floor	Level	SS Fixed	SS Flexible	MS Fixed	MS Flexible	HS Fixed	HS Flexible
Base	0	IO	IO	IO	IO	IO	IO
Plinth	1	LS	CP	LS	CP	LS	CP
1st	2	Collapse	Collapse	Collapse	Collapse	Collapse	Collapse
2nd	3	Collapse	Collapse	Collapse	Collapse	Collapse	Collapse
3rd	4	Collapse	Collapse	Collapse	Collapse	Collapse	Collapse
4th	5	Collapse	Collapse	Collapse	Collapse	Collapse	Collapse
5th	6	Collapse	Collapse	Collapse	Collapse	Collapse	Collapse
6th	7	CP	Collapse	Collapse	Collapse	Collapse	Collapse
7th	8	CP	CP	CP	CP	CP	CP

8th	9	CP	CP	CP	CP	CP	CP
9th	10	CP	CP	CP	CP	CP	CP
10th	11	LS	LS	LS	LS	LS	LS

Table 6 (b) Failure Pattern of RSN 139 Y axis

Failure Pattern for RSN 139 in Y-axis							
Floor	Level	SS Fixed	SS Flexible	MS Fixed	MS Flexible	HS Fixed	HS Flexible
Base	0	IO	IO	IO	IO	IO	IO
Plinth	1	CP	Collapse	CP	Collapse	CP	Collapse
1st	2	Collapse	Collapse	Collapse	Collapse	Collapse	Collapse
2nd	3	Collapse	Collapse	Collapse	Collapse	Collapse	Collapse
3rd	4	Collapse	CP	Collapse	CP	Collapse	Collapse
4th	5	Collapse	Collapse	Collapse	Collapse	Collapse	Collapse
5th	6	Collapse	Collapse	Collapse	Collapse	Collapse	Collapse
6th	7	CP	CP	CP	CP	CP	CP
7th	8	LS	CP	CP	CP	LS	CP
8th	9	LS	LS	LS	LS	LS	LS
9th	10	LS	LS	LS	LS	LS	LS
10th	11	IO	LS	IO	IO	IO	IO

Table 7 (a) Failure Pattern of RSN 848 X axis

Failure Pattern for RSN 848in X-axis							
Floor	Level	SS Fixed	SS Flexible	MS Fixed	MS Flexible	HS Fixed	HS Flexible
Base	0	IO	IO	IO	IO	IO	IO
Plinth	1	CP	Collapse	CP	Collapse	CP	CP
1st	2	Collapse	Collapse	Collapse	Collapse	Collapse	Collapse
2nd	3	Collapse	Collapse	Collapse	Collapse	Collapse	Collapse
3rd	4	Collapse	Collapse	Collapse	Collapse	Collapse	Collapse
4th	5	Collapse	Collapse	Collapse	Collapse	Collapse	Collapse
5th	6	Collapse	Collapse	Collapse	Collapse	Collapse	Collapse
6th	7	CP	CP	CP	CP	CP	CP
7th	8	LS	CP	CP	CP	CP	CP
8th	9	IO	LS	IO	LS	IO	IO

9th	10	IO	IO	IO	IO	IO	IO
10th	11	IO	IO	IO	IO	IO	IO

Table 7 (b) Failure Pattern of RSN 848 Y axis

Failure Pattern for RSN 848 in Y-axis							
Floor	Level	SS Fixed	SS Flexible	MS Fixed	MS Flexible	HS Fixed	HS Flexible
Base	0	IO	IO	IO	IO	IO	IO
Plinth	1	Collapse	Collapse	Collapse	Collapse	Collapse	Collapse
1st	2	Collapse	Collapse	Collapse	Collapse	Collapse	Collapse
2nd	3	Collapse	Collapse	Collapse	Collapse	Collapse	Collapse
3rd	4	Collapse	Collapse	Collapse	Collapse	Collapse	Collapse
4th	5	Collapse	Collapse	Collapse	Collapse	Collapse	Collapse
5th	6	CP	Collapse	Collapse	Collapse	Collapse	Collapse
6th	7	CP	CP	CP	CP	CP	CP
7th	8	CP	CP	CP	CP	CP	CP
8th	9	LS	CP	LS	CP	LS	CP
9th	10	IO	LS	IO	IO	IO	IO
10th	11	IO	IO	IO	IO	IO	IO

5.2 Discussion

5.2.1 Fundamental Period

As per table 5, Fundamental Period analysis revealed that incorporating SSI led to a noticeable increase in the building's natural period across all soil conditions. The fixed-base model exhibited a uniform Fundamental Period of 2.256 seconds for all soil types. When flexible base conditions were introduced, the Fundamental Period increased to 2.382 seconds in soft soil, 2.336 seconds in medium soil, and 2.307 seconds in hard soil. This trend clearly shows that as soil stiffness decreases, the natural period becomes longer due to greater flexibility at the foundation level. Even in harder soils, the difference is measurable and highlights the sensitivity of dynamic characteristics to soil conditions.

5.2.2 Base Shear

The inclusion of SSI was observed as shown in Fig. 2, Fig.3, and Fig.4 to alter the base shear values significantly. For soft soil, the flexible-base model generated a noticeable increase in base shear, attributed to the amplification of ground motion through the compliant soil layer. In contrast, medium soil presented a moderate increase, while hard soil showed only a slight variation from the fixed-base model. This variation aligns with the stiffness characteristics of each soil type and suggests that softer soils tend to transfer greater inertial forces to the superstructure under dynamic excitation.

5.2.3 Overturning Moment

Overturning moments were found to follow a similar trend as base shear. The highest increase was observed in soft soil under flexible conditions, reflecting enhanced lateral displacement and moment generation. Medium soil showed a moderate increase, while hard soil exhibited minimal change. These results from Fig.5, Fig.6, and Fig.7 emphasize the importance of accounting for

SSI, especially for structures resting on softer strata, where the potential for overturning and rocking is significantly heightened.

5.2.4 Displacement

Storey displacement patterns as shown in Fig.8 and Fig. 9 a consistent increase in lateral movement when flexible base conditions were applied. In soft soil, the displacement values rose sharply, especially toward the upper storeys. Medium soil also experienced increased displacement, albeit to a lesser extent, and even hard soil demonstrated noticeable differences when compared to fixed-base results. This reinforces the importance of considering soil flexibility in estimating lateral displacements accurately during design.

5.2.5 Drift

The inter-storey drift values were observed from Fig. 10 and Fig. 11 to peak at mid-height levels, particularly in soft soil under flexible base conditions. This could potentially lead to critical damage zones and plastic hinge formations. Medium soil showed moderate drift amplification, while hard soil maintained more uniform and lower drift responses. These patterns underscore how soil properties influence not only overall deformation but also the localization of damage within the structural system.

5.2.6 Failure Patterns

As shown in Table 6 and Table 7, the failure tendencies inferred from drift and displacement data indicate that flexible-base buildings on soft soil are more prone to drift-induced damage, especially at intermediate levels. Medium soil presented a balanced response with observable yielding in a few storeys. In hard soil, the failure pattern remained well-distributed with no sharp concentrations, suggesting better resilience. These observations confirm that SSI has a direct impact on how and where failure mechanisms develop within a building during seismic loading.

6. Conclusion

1. Inclusion of SSI results in an increase in the structure's natural Fundamental Period, with soft soils showing the most pronounced effect.

2. Base shear and overturning moments are more severe in soft soil, while medium and hard soils show comparatively stable responses.

3. Storey displacements rise across all soil types with flexible base conditions, requiring appropriate lateral design considerations.

4. Inter-storey drift is highest in mid-storey levels of soft soil, potentially leading to localized failure zones.

5. Fixed-base models tend to underestimate seismic demand, highlighting the necessity of SSI modelling in all soil conditions.

6. Flexible-base modelling provides a more realistic and performance-based design approach, improving safety and reliability across variable soil profiles.

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