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Dynamic SSI of Regular and Stiffness Irregular Buildings Supported on Pile in Soft Clay

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Abstract The configuration of the structure plays an important role in its seismic behaviour. Irregularities in either the building's plan or elevation have been identified as significant contributors to failure during seismic events, making irregular structures, particularly those in seismic zones, a major concern. In traditional seismic analysis, structures are usually assessed with fixed base, neglecting the dynamic interaction between soil, foundation, and the structure itself. The objective of the study is to analyse the impact of dynamic SSI on the response of a 10-storey model, designed to represent a prototype with both regular and stiffness irregular configurations and to find relation between the lateral deflection of fixed and flexible base through numerical investigations for regular building frames. To achieve this, laboratory experiments were conducted utilizing a shake table and FE analyses were carried out. The behaviour of the model structures was examined under two scenarios: fixed base condition and flexible base condition, considering pile foundation. The experimental findings revealed that the soil-pile-structure system leads to amplified lateral deflections and storey drifts of the superstructure compared to the fixed base condition. Moreover, the model with stiffness irregularity exhibited higher response levels than the regular model under both base conditions. Furthermore, the irregular structure displayed an increased response amplification in the presence of soil-structure interaction, which has the potential to alter the overall performance of the structure. Numerical analysis was carried out considering varied height of the building frames under fixed and SSI condition and an attempt has also been made to relate the response of SSI condition to fixed base condition, which helps the designer to carry out conventional fixed base analysis and estimate the response under SSI for regular buildings.

Keywords Stiffness Irregularity, Shake Table Studies, Scaled Model Tests, Soil Pile Structure Interaction, Seismic Response

1. Introduction

The behavior of a building is dependent upon the arrangement of its structural components. Key factors influencing the structural configuration include the building's geometry, shape, and size. When a building is applied with dynamic loads, it generates inertia forces that concentrate at its center of mass. The placement and dimensions of structural elements play a crucial role in determining the dynamic response. The Regular structures exhibit minimal discontinuities in both their horizontal and vertical configurations. In contrast, irregular structures exhibit discontinuities in their plan or elevation, impacting their performance under lateral loads. Vertical irregularities encompass variations in mass, stiffness, and geometry along the building's height, while horizontal irregularities stem from plan discontinuities. Each type of structural irregularity uniquely affects how a structure responds to seismic forces [1].

As per the specifications of IS 1893:2016[2], a building is deemed to have stiffness irregularity or a soft storey irregularity when the lateral stiffness of any given storey is lower than that of the storey directly above it. On the other hand, according to FEMA 450[3], a soft storey denotes a storey whose lateral stiffness is either less than 70% when compared to the storey above it or falls below 80% of the average lateral stiffness of the three storey situated above it.

Soil Structure Interaction (SSI) is an important factor in seismic analysis and structural design. Due to the complexity required in analysis, structures supported by piles have traditionally been designed with the assumption of a fixed base, ignoring the interaction between soil, foundation, and superstructure. Past earthquakes have demonstrated the effect of dynamic SSI including 1995 Kobe earthquake[4]. SSI analysis is very crucial for large and heavy structures supported on soft soil [5].

SSI analysis decreases the stiffness at the base of the structure with elongated time period and increased damping. Inertial interaction intensifies the response due to the additional degrees of freedom at the base of the structure (kinematic Interaction). The combined effect of both these interactions become crucial when the external force resonate with systems natural frequency [6]. The design of structures resting on soft soil is crucial, as the soil can magnify ground acceleration, which is detrimental to the structure [7].

In regular buildings, the number of bays does not affect the dynamic properties and response to dynamic excitations, whereas the height of the building significantly affect its dynamic properties and response[8] [9].

To examine these effects, a sequence of laboratory experiments was conducted using shake table facility, involving scaled building models. The responses were investigated for models with and without vertical irregularity considering different boundary conditions. Flexible boundary condition was modeled considering pile groups in soft clay[10]. Numerical analysis was performed and validated with the experimental results. Further numerical analyses were performed by varying the height of the building frames with and without SSI for regular models.

2. Methodology

A 10-storey structure with single bay is considered as prototype structure which was scaled down by a scaling factor of 30 using similitude analysis and shake table experiments were conducted to find the response of the structure to harmonic excitation for both base conditions. Then the experimental results were compared with regular and irregular models.

2.1. Similitude Analysis

The framework that establishes a connection between measurements obtained from a small-scale model and those from a prototype is similitude analysis. The models are classified as true, adequate, or distorted models [9]. A true model fulfils all the similitude relations, ensuring accurate representation. On the other hand, an adequate model only satisfies the first-order parameters, which have a significant impact on the system's behaviour, while allowing deviations in second-order parameters. The selection of these parameters depends on the specific problem under investigation. The model is treated as distorted if the first order parameters deviate.

Table 1. Overview of similitude relationship used for the study [11] [6]

Parameter	Scaling factor
Mass density	1
Length	λ
Force	λ^{3}
Stress	E
Modulus	λ
EI	λ^{5}
Acceleration	1
Time period	$\lambda^{1/2}$
Frequency	$\lambda^{-1/2}$
Strain	1

Several researchers have proposed similitude relations considering the adequate model of similitude analysis. Table 1 represents the similitude relations summarized by Hokmabadi et al. [6] and the same is been used in present study. The similitude parameters are defined in terms of scaling factor λ.

2.2. Preparation of Soil Mix

A synthetic clay mix of kaolinite, bentonite, fly ash, lime, and water with a proportion of 60%, 20%,20% 10% and 100% respectively has been considered for the study. The resulting mix after curing for a period of 48 hours gains a shear wave velocity of 36 m/s and a density of 1500kg/m^3 [6] which represents a prototype soil mix having a shear wave velocity of 200 m/s and a density of 1500kg/m^3 which also offers a required bearing capacity to support the structure[12]. SSI experimental investigations have been carried out, creating a soil bed in a rigid soil container which supports the structure and foundation system.

3. Experimental and Numerical Analysis

A typical 10-storey building frame with single bay is considered along with stiffness and irregular models of the same configurations. Stiffness irregularity was introduced in the 3rd floor and 7th floor by increasing the storey height to 4.5m, keeping the height of the structure the same as that of regular structure. Physical models were constructed by performing similitude analysis of prototype structure.

The structure was scaled to a 1:30 ratio for conducting dynamic model studies based on the results of modal analysis. To do this, the study adopted the specific similitude parameters mentioned in Table 1. Adjusting the scaled model parameters was necessary to retain the prototype's mass density ratio and comparable stiffness in the fundamental mode direction [6]. Iterative numerical analysis was performed to match the natural frequency. This was achieved by changing the thickness of the slab and the column's cross-section. At each floor level of the model, lumped symmetrical masses were added to preserve consistency in mass density. A graphic illustration of the 10-storey building is shown in Fig. 1.

Figure 1. Three-Dimensional view of prototype structure

3.1. Prototype Regular Building

The symmetric building space frame, shown in Fig. 1, consists of a 10-storey structure with a regular plan. The information of the building frames under investigation is provided in Table 2. For modeling purposes in ETABS, one-dimensional elements were utilized for beams and columns, while the slab was represented using a Two-Dimensional element. To assess its dynamic characteristics, a uniform imposed load of 3KN/m^2 and a floor finish of 1KN/m^2 were applied. Modal analysis was conducted to determine its dynamic properties. The structure was modelled and analyzed as per IS-1893 [2] for earthquake zone-V and soil type III and designed to get the cross section of structural elements.

Table 2. Configuration of the Building Frame

Description	Details
Number of storey	10
Number of bays	1
Bay width	4 m c/c
Typical floor height	3m
Dimensions of beam	0.450m x 0.450m
Dimensions of Column	0.450m x 0.450m
Thickness of slab	0.150 m
Grade of Concrete	M25

To find the mass participation, natural frequency, and stiffness for the purpose of similitude analysis, modal analysis was done and the findings are documented in Table 3.

Table 3. Fundamental Dynamic Property of Prototype

Mode	Time period (sec)	Frequency (Hz)
Mode 1	1.03	0.97
Mode 2	1.03	0.97
Mode 3	0.68	1.47

3.2. Model Constructing

In the context of dynamic model studies, the structure undergoes modal analysis to determine its fundamental frequencies and mode shapes. To facilitate experimental investigations, the structure is scaled down to a 1:30 ratio, and detailed similitude factors listed in Table 1 are employed for the conversion. The scaled model's parameters are adjusted to match the prototype's equivalent stiffness while maintaining the same mass density ratio. To achieve this, a numerical analysis is conducted, involving iterative adjustments of the column cross-sections and slab thicknesses in the scaled model. By introducing lumped symmetrical masses at all floors, the mass density ratio of the scaled model is made equivalent to that of the prototype. The key outcome of this process is tabulated in Table 4, which summarizes the properties of the scaled model. It includes information about the scaled dimensions, material properties, cross-sections, slab thicknesses, mass distributions, and other parameters. The ultimate objective of this scaled model creation is to accurately replicate the prototype's dynamic behavior. Subsequently, the scaled model can be utilized for various dynamic investigations, such as modal analysis, response analysis, and shake table studies, without the need to subject the full-scale prototype to such tests.

Table 4. Configuration of Model and prototype

Parameter	Prototype	Scale Model (1:30)
Super structure material	Concrete	Aluminium
Time period	1.06Sec	0.19 Sec
Frequency	0.97Hz	5.3Hz
Youngs modulus	30GPa	69GPa
Size of column	450mmX450mm	10mmX3mm
Slab thickness	150mm	8mm
Bay Dimension	4m	135mm

The model's fabrication material is aluminum, chosen to fulfill the requirements of matching the mass density and stiffness for the 1:30 scale. To connect the slab and column, 4mm screws are utilized. Additionally, a plate is provided at the base to facilitate mounting the model on a shake table. To simplify fabrication at a larger scale, the beams are omitted by attaining the necessary equivalent stiffness. Fig. 2 and Fig. 3 illustrate the scaled model and prototype respectively.

(a) (b)

Figure 2. Flexible base experimental setup (a) Regular model (b) Irregular model

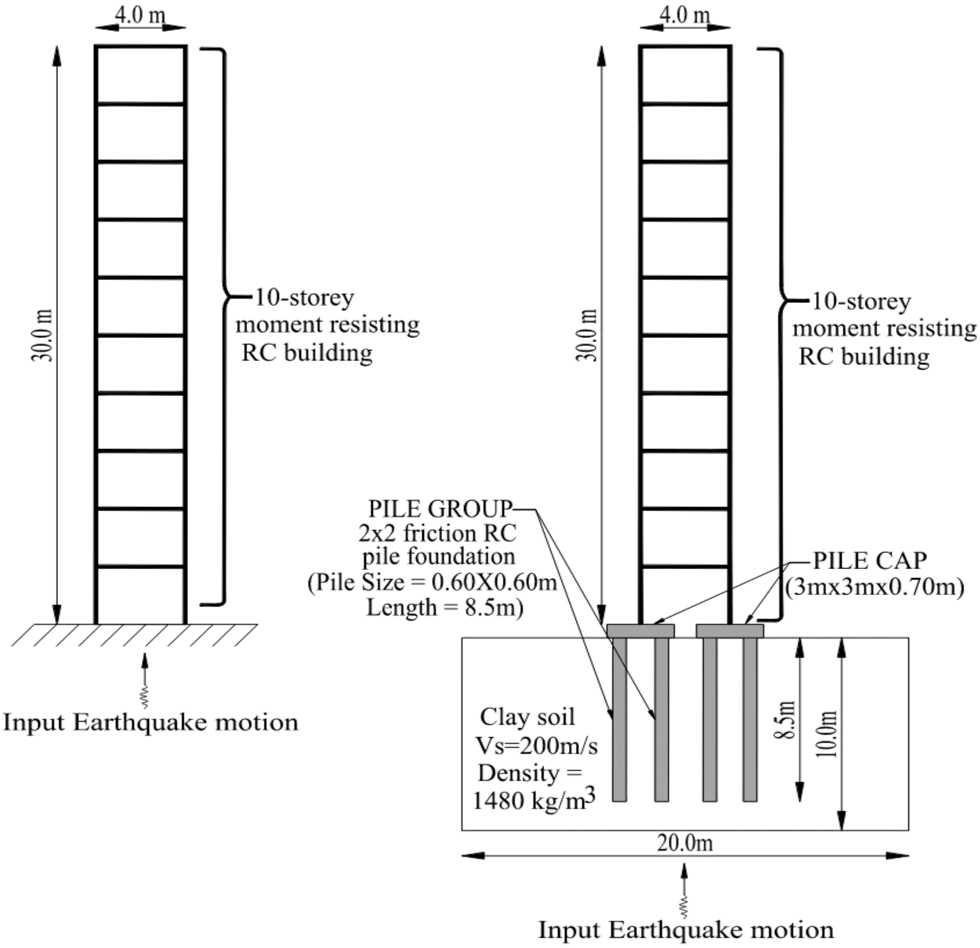
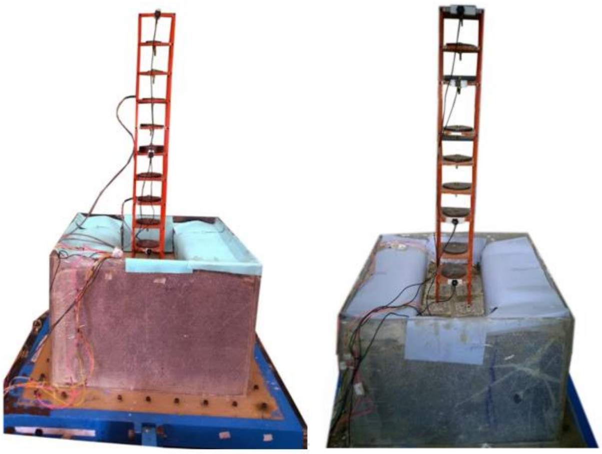


Figure 3. Schematic representation of regular building frame with fixed and flexible base conditions

Just like the primary structure, the model piles have also been scaled as per the scaling relationship considering flexural rigidity. To achieve this, acrylic material was used for square piles with a geometric scaling factor of 1:30.



(a) (b)

Figure 4. Flexible base experimental setup (a) Regular model (b) Irregular model

In this research, acrylic soil container was used to investigate the interaction between soil and pile structures. The container was designed to be rigid, ensuring stable experimentation. The dimensions of the tank were carefully chosen, with the length being five times that of the model's width, to minimalize the effect of artificial boundary in the experiments. In order to achieve the same goal, a flexible boundary was also introduced. This was achieved by attaching a very low-density sponge material along the end walls of the container [13]. The purpose of this flexible boundary was likely to reduce reflection of waves caused by rigid boundaries during the interaction studies between the soil and pile structures. Fig.4 displays the experimental setup, showing both regular and mass irregular models with flexible base conditions, illustrating how the research was conducted.

3.3. Numerical Analysis

Experimental results are very crucial in understanding the actual behaviour and in the design of structures. It is not always possible to do experimental investigations. On the other hand, these experimental investigations play a vital role in FE analysis. It is always essential to verify and validate the numerical model with experimental study. To perform FE analysis, one dimensional element was used to model the super structure and 8 noded solid elements were used to represent substructure and soil [13] [14]. Similar shaking events were simulated numerically to compare and validate FE analysis. After the validation, further the numerical study was extended to buildings with varied heights to find the response of building frames subjected to dynamic loads as the response of the model is dependent on the height of the building rather than the number of bays in a symmetrical regular building[8]. Seven building frames with 3, 5, 7, 9, 11,13 and 15 storeys were considered for the analysis. These building frames were analyzed under fixed and flexible base conditions considering pile foundation in soft clay. Initially, modal analysis was carried out to find the fundamental period of building frames in both base conditions. The building frames were excited with harmonic loading at resonance condition to capture the maximum response of the building frames under both fixed and flexible base conditions. The response of the building frames was captured and compared.

4. Results & Discussion

Overall, the dynamic analysis of the structure in both fixed and flexible base conditions are crucial for understanding how the building will respond to dynamic forces like earthquakes, wind loads, or other excitations[15]. This information is vital for ensuring the safety and integrity of the building's design, ensuring it can withstand anticipated loads without experiencing excessive deformation or damage. In the first stage of dynamic analysis of the prototype and models were carried out for fixed base condition to find the dynamic response. Flexible base condition was considered in the second stage of analysis with buildings resting on pile foundation in soft clay. Later, a series of numerical studies were conducted for regular models varying the height of the structure under both base conditions.

4.1. Fixed Base Analysis

For the fixed base structure, free vibration analysis was carried out and the dynamic properties were found. 6.1 Hz was identified as the fundamental frequency of the regular model which is in close agreement with the required frequency of similitude analysis. Subsequently, an experiment involving forced vibrations was conducted on the same model. A sine sweep was employed, ranging in frequency from 2 Hz to 10 Hz, increasing in 0.5 Hz intervals. The outcome of the model was captured using a Data Acquisition System (DAQ). Notably, it was observed during the experiment that the model's response reached its peak at the resonant frequency. The graphical representation in Fig.5 illustrates how the displacement of the top storey varied across different frequencies during harmonic base excitation.

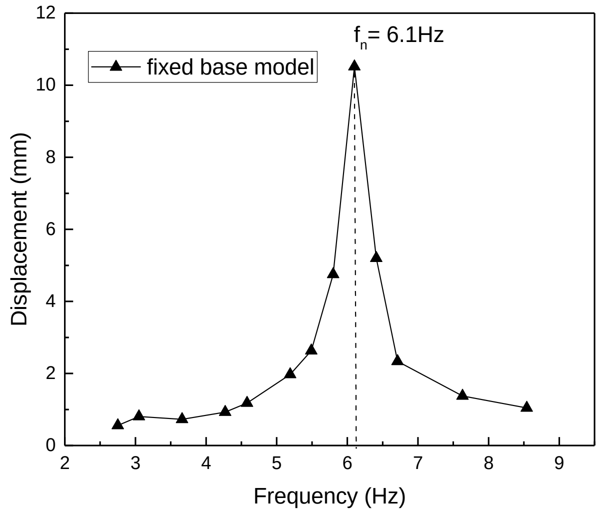


Figure 5. Frequency verses top storey displacement (regular model)

The model's damping value is computed using half power bandwidth method [16] as depicted in Fig.6. The damping ratio is calculated as in Eqn (1).

$$\zeta = \frac{f_B - f_A}{2 f_r} \tag{1}$$

Where f_A *and* f_B are corresponds to frequency at point A and B. and frequency ratio at resonance is denoted as f_r . As depicted in Fig.6, the damping Ratio was calculated and for the fixed base model, it was calculated to be 2.75%.

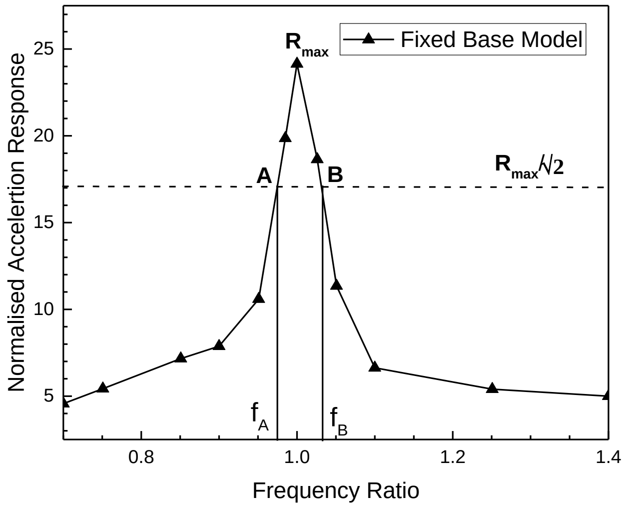
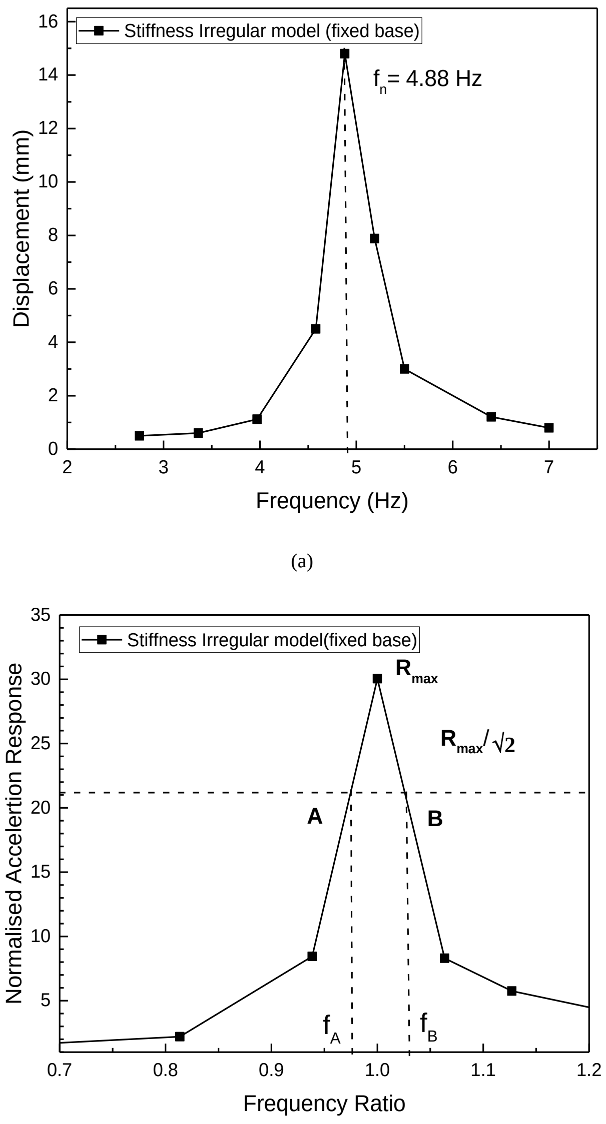


Figure 6. Frequency ratio verses normalised acceleration (Regular model)

The experimental investigations on stiffness irregular model with fixed base condition is also carried out like that of regular model and the frequency of the model was found to be 4.88Hz and the damping was found to be 3.0% as depicted in Fig.7.

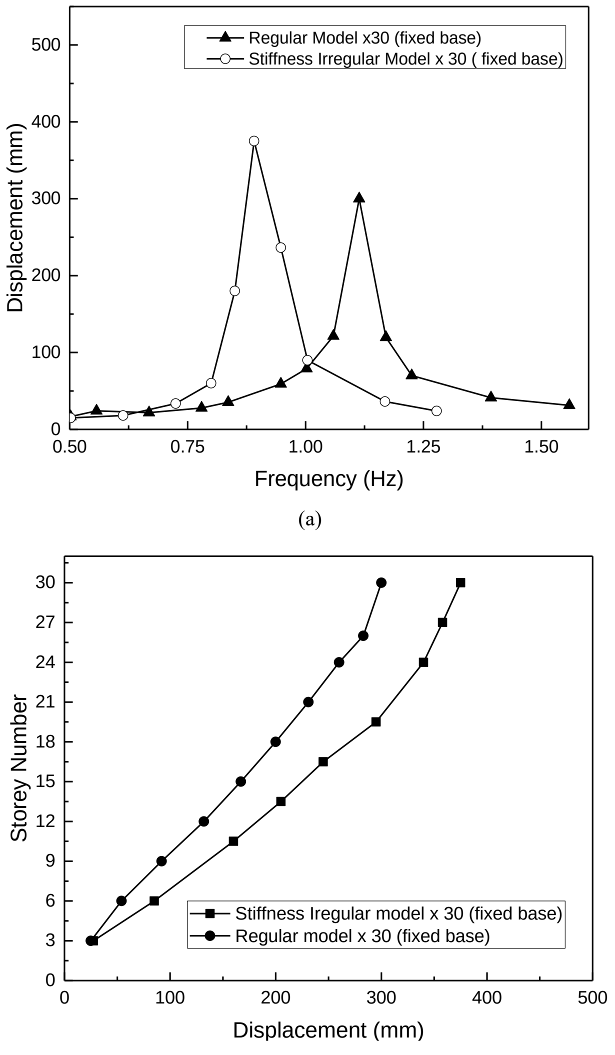


(a)

(b)

Figure 7. (a) Frequency verses top storey displacement (b) Frequency ratio verses normalised acceleration of stiffness irregular model

Fig.8(a) shows the top storey in response to the regular and irregular model for different excitation frequencies with fixed base condition. The increase in response to the structure for stiffness of irregular model was observed compared to the regular model. The frequency of the irregular model has been reduced due to the decrease in the overall stiffness of the structure. Fig.8(b) shows the displacement of the structure along its height under resonant condition. The storey displacement clearly indicated the increase of storey drift for irregular condition compared to regular model as depicted in Fig.9. The increase in storey drift was observed to be at mid height and irregular storey for regular and irregular model respectively.



(a)

(b)

Figure 8. (a) Roof displacement verses frequency (b) Storey displacement v/s height, of structure

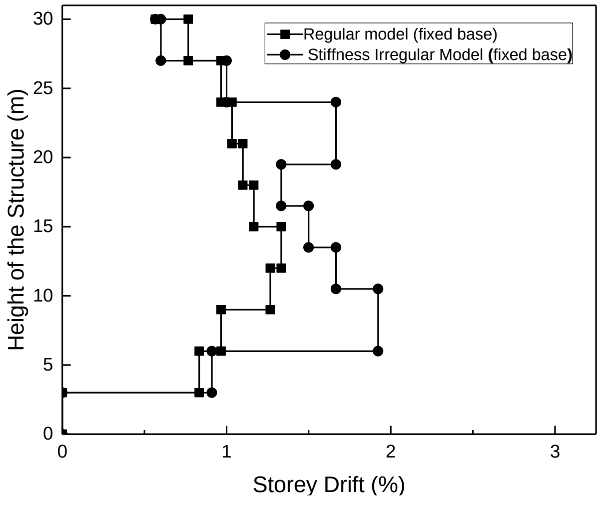
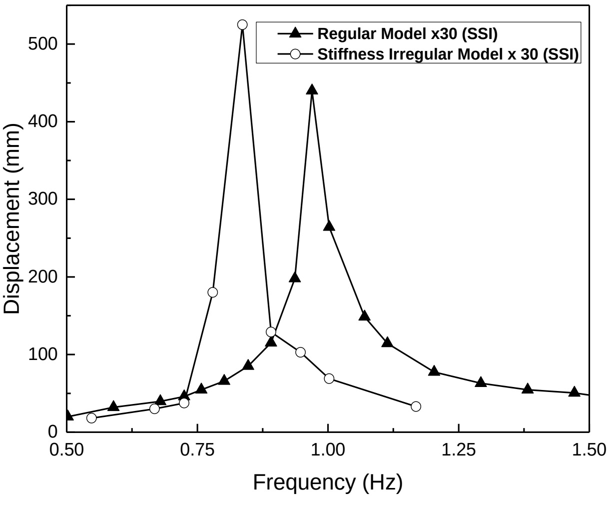


Figure 9. Iner-storey drift v/s height of the structure

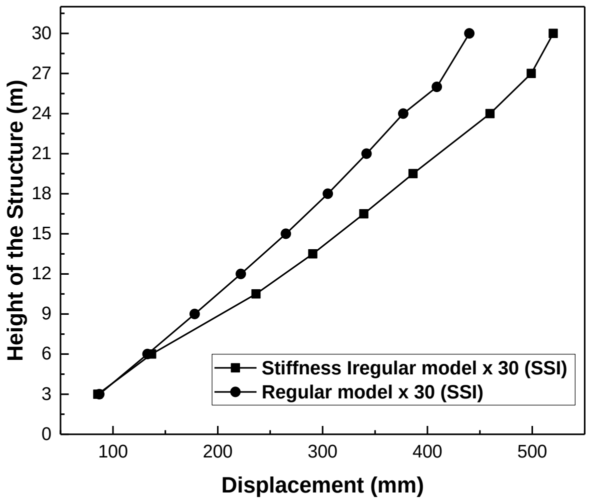
4.2. Flexible Base Condition

The second phase of the experimental investigation aimed to analyze the impact of SSI (Soil-Structure Interaction) on the dynamic behavior of the structural system. To achieve this, all parts of the system were interconnected, and sensors were strategically placed at various floor levels of the model structures, as well as at the pile cap. The objective was to understand the behaviour of both regular and irregular flexible base models under dynamic excitation. To conduct the experiments, the models were applied harmonic load with frequencies ranging from 2 Hz to 10 Hz, incremented by 0.25 Hz. The response of each model was recorded using Data Acquisition (DAQ) techniques. Bending strains were also captured in pile using strain gauges. Results indicated that the models exhibited peak responses at resonant frequencies of 5.3 Hz and 4.58 Hz for the regular and irregular flexible base models, respectively. This observation implies that the soil-pile-structure system alters the fundamental dynamic characteristics of the structure, thereby affecting the response of the superstructure to dynamic loads. Additionally, the study revealed an increase in damping for the SSI condition. Specifically, the damping of the regular model with a flexible base was measured at 3%, while the irregular model exhibited a damping of 3.25%.

It can be inferred form Fig.10 that the flexible base models exhibited higher responses to base excitation compared to the fixed base model. The presence of a pile group supporting the structure led to increased displacements due to the higher flexibility and soil amplification effects. Specifically, the stiffness irregular model displayed approximately 20% higher response compared to the regular model. Fig.11 illustrates the increase in storey drift in the flexible base of irregular model when compared to the regular model. Notably, both flexible models displayed higher drift values at the 2nd floor level, whereas the fixed base model exhibited more significant drift values at the 3rd and 7th floors where the storey stiffness was relatively lower. It indicates the effect of flexibility of soil on the relative displacement of floors.



(a)



(b)

Figure 10. (a) Roof displacement v/s frequency (SSI) (b) Storey displacement v/s height of the structure (SSI)

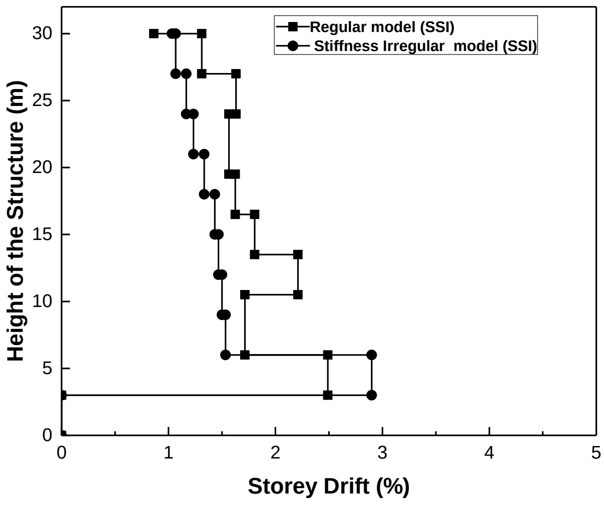


Figure 11. Inter-storey drift v/s height of the structure

The comparison of frequency response and displacement for regular and irregular models with fixed and flexible base conditions is presented in Fig.12 and Fig.13. The plots show the dominant role of soil foundation interaction on the fundamental dynamic property and on the response of the superstructure. It also highlights the shift in the fundamental frequency under flexible base condition for both regular and irregular building frames. There is increase in damping value from fixed base to flexible base condition.

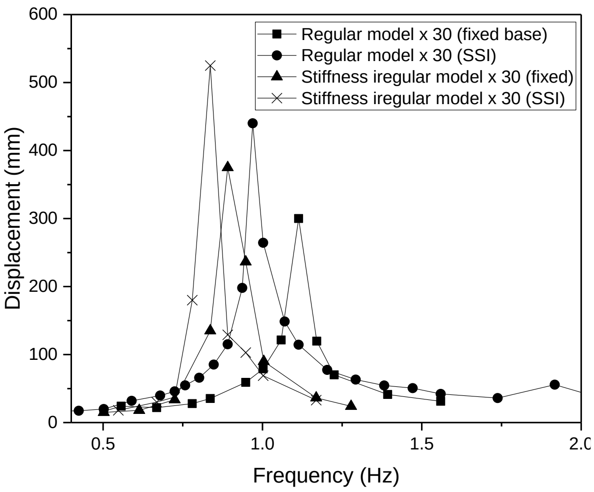


Figure 12. Roof displacement v/s frequency of regular & irregular models

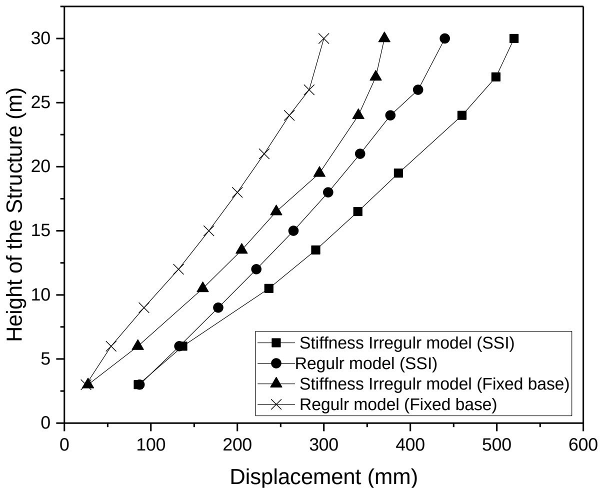


Figure 13. Storey displacement v/s height of the structure

4.3. Numerical Analysis of Regular Buildings

The numerical analysis of the prototype was carried out using FE approach adopting the experimentally computed damping ratio. The magnitude of the base accelerations was maintained and excited at resonance to compare the response of experimental and numerical studies. Fig.14 shows the SSI model of 10-stoery regular model. The width of the soil is considered to be 5 times that of the building frame to minimize the artificial boundary effect[17]. The base of the soil mass is considered to be fixed and hinged support was provided at the periphery[18]. The variation of lateral displacements along the height of the structure for both model and prototype regular building are presented in Fig.15.

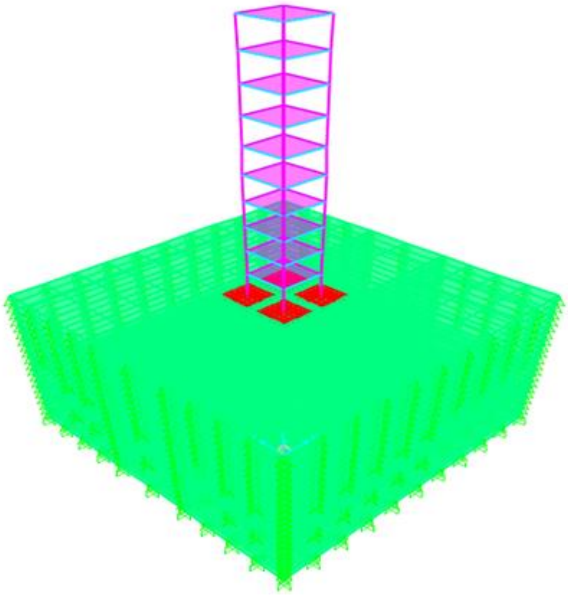


Figure 14. FE Model of 10-Storey Regular structure with SSI

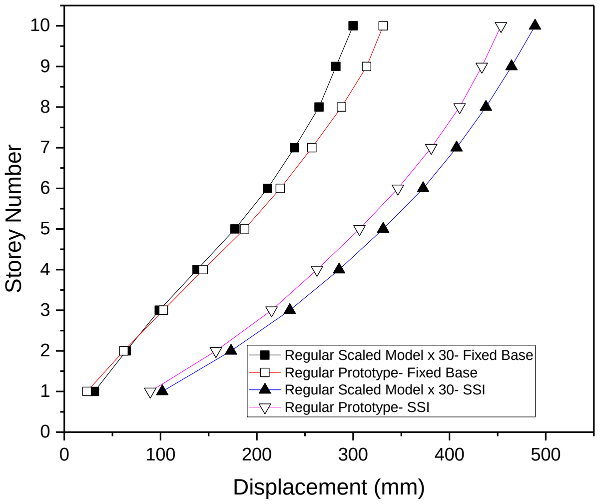


Figure 15. Storey v/s Displacement of Model and Prototype

From Fig.15, it can be observed that the response of the numerical model is in close agreement with the experimental model both under fixed and flexible base conditions, indicating the adequacy of the FE model. Further the calculation of displacement for the design of building frames under SSI condition involves complex FE model and increased computing time. An attempt has been done to find the relation between the displacement of regular building under fixed and flexible base conditions.

Further, the numerical study was extended to buildings with varied heights. Seven building frames with 3, 5, 7, 9, 11, 13 and 15 storeys were considered for the analysis. These building frames were analyzed under fixed and flexible base conditions considering pile foundation in soft clay. Initially, modal analysis was carried out to find the fundamental period of building frames in both base conditions. The building frames were excited with harmonic loading at resonance condition to capture the maximum response of the building frames under both fixed and flexible base conditions.

A ratio of maximum lateral deflection of building frames with flexible base to lateral deflection of building frames with fixed base was calculated. The ratio is termed as lateral deflection increment factor (β)[19]. Table 5 shows the ratio of maximum elastic structural deflection with flexible-base to fixed-base. The maximum lateral deflection increment factor is a ratio that is expressed in Eqn (2).

$$\beta = \frac{U_{SSI}}{U_{FB}} \qquad (2)$$

Where,

U_{SSI} is the maximum later displacement under SSI condition

U_{FB} is the maximum lateral of building frame deflection under fixed base condition

Table 5. Ratio of Maximum Lateral Deflection with Flexible-Base to Fixed-Base for Soft Clay

No. of Stories	***β***
3	1.45
5	1.52
7	1.58
9	1.65
11	1.73
13	1.83
15	2.02

Using curve fitting technique (Fig.16), an empirical equation was derived to relate the number of stories and the lateral deflection increment factor was as given in Eqn (3).

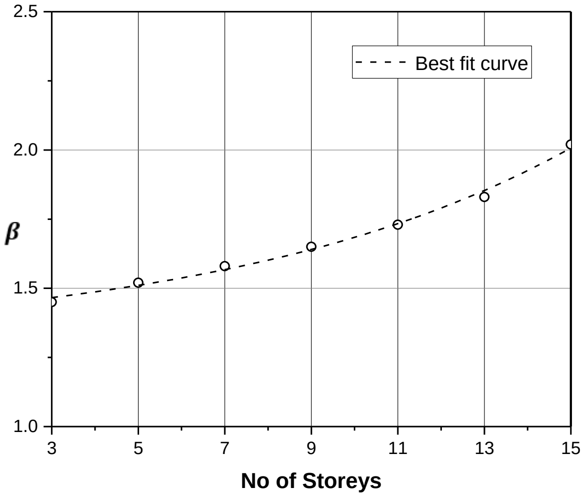


Figure 16. Maximum Deflection Increment Factor (β) vs. No of Stories

$$\beta = 1.31 + 0.1e^{0.12S} \qquad (3)$$

Where S= No of Stories

Finally, to find the maximum deflection for the range of structures resting on pile in soft clay, where soil–structure interaction is required, it is sufficient to find the maximum deflection of the fixed-base structure using conventional methods and multiply it by Maximum Deflection Increment Factor (β), which could be calculated by Eqn (3).

5. Conclusions

This study aims to investigate how the seismic behavior of building frames is affected by the soil pile structure system, considering regular and stiffness irregular frames. To achieve this, shake table studies were carried out on scaled models with both fixed and flexible base conditions. The tests were conducted on regular and irregular frames supported on a pile group in soft clay. The foundation and the soil conditions have significantly influenced the dynamic properties and response of the superstructure. Buildings with flexible base systems experienced amplified lateral deflection compared to those with fixed bases, highlighting the crucial role of the foundation and subsoil in governing the structure's behavior. Furthermore, the irregularity in the building frames also led to an increased response compared to the regular model, regardless of whether it had a fixed or flexible base condition. The irregular models with flexible bases exhibited higher storey drift due to reduced overall stiffness of the structural system. Additionally, the bending stresses in the piles were higher in the irregular model compared to the regular model, primarily due to inertial interaction. The damping value has increased for model with stiffness irregularity compared to regular building. Considering the observed increased response of the soil pile structure system, it becomes evident that the performance level of the building can be affected. To achieve more realistic and accurate predictions of seismic behaviour, it is advised that the soil-foundation-structure system be included in the study and design of structures in soft soil.

Regular building frames with varied heights have been investigated through numerical approach considering fixed and flexible base conditions. Based on the studies conducted, an empirical relation has been proposed to find the ratio of maximum lateral deflection of building frames supported on pile in soft clay to lateral deflection under fixed base. It facilitates the designer to estimate the lateral deflection of the building frame under SSI using the empirical relation just by calculating the deflection considering fixed base condition.

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REFERENCES

[1] S. Varadharajan, V. K. Sehgal, and B. Saini, “Review of different structural irregularities in buildings,” *Journal of structural engineering*, vol. 39, no. 5, pp. 393–418, 2012. https://www.researchgate.net/publication/273447330_Review_of_different_structural_irregularities_in_buildings_Journal_of_Structural_Engineering

[2] IS 1893-2016 (Part 1), “Criteria for Earthquake Resistant Design of Structures.” Bureau of Indian Standards, New Delhi.

[3] I. S. Safety, “Nehrp Recommended Provisions For Seismic Regulations For New Buildings And Other Structures (FEMA 450)”, Washington D C, 2004.

[4] G. Gazetas and G. Mylonakis, “Seismic soil-structure interaction: new evidence and emerging issues,” *Geotechnical special publication*, no. 75 II, pp. 1119–1174, 2000. https://research- information.bris.ac.uk/en/publications/seismic-soil-structure-interaction-new-evidence-and-emerging-issu

[5] B. Gatmiri and S. M. Haeri, “Guidelines of SSI Analysis and its Effects on Dynamic Response of Structures,” *Natural Disaster Defense Research Center*, 1996.

[6] A. S. Hokmabadi, B. Fatahi, and B. Samali, “Physical modeling of seismic soil-pile-structure interaction for buildings on soft soils,” *International Journal of Geomechanics*, vol. 15, no. 2, p. 04014046, 2015. DOI:10.1061/(ASCE)GM.1943-5622.0000396

[7] P. Maymand, M. Reimer, and R. Seed, “Large scale shaking table tests of seismic soil-pile interaction in soft clay,” in *Proc. 12th World Conf. Earthquake Eng. New Zealand*, 2000. https://www.iitk.ac.in/nicee/wcee/article/0915.pdf

[8] K. G. Subramanya, L. Govindaraju, and R. R. Babu, “Shake Table Studies on the Dynamic Response of Pile Supported

Framed Structure in Soft Soil," *Civil Engineering and Architecture*, vol. 8, no. 6, pp. 1313–1324, 2020. DOI: 10.13189/cea.2020.080615

[9] L. Govinda Raju, G. V. Ramana, C. Hanumantha Rao, and T. G. Sitharam, "Site-specific ground response analysis," *Current* Science, pp. 1354–1362, 2004. https://www.jstor.org/stable/24109475

[10] S. Bhattacharya, D. Lombardi, L. Dihoru, M. S. Dietz, A. J. Crewe, and C. A. Taylor, "Model container design for soil-structure interaction studies," in *Role of seismic testing facilities in performance-based earthquake engineering*, Springer, pp. 135–158, 2012. DOI: 10.1007/978-94-007-1977-4_8

[11] H. G. Harris and G. Sabnis, "*Structural modeling and experimental techniques"*. CRC press, 1999.

[12] P. J. Meymand, *Shaking table scale model tests of nonlinear soil-pile-superstructure interaction in soft clay*. University of California, Berkeley, PhD diss., 1998. https://search.proquest.com/openview/2876927c755022eb24eadceea0f6e684/1?pq-origsite=gscholar&cbl=18750&diss=y

[13] D. Lombardi, S. Bhattacharya, F. Scarpa, and M. Bianchi, "Dynamic response of a geotechnical rigid model container with absorbing boundaries," *Soil Dynamics and Earthquake Engineering*, vol. 69, pp. 46–56, 2015. DOI: 10.1016/j.soildyn.2014.09.008

[14] "SAP, Advanced 14.2.4- Manual." Computers and Structures Inc., University Avenue Berkeley, California, United State, 2000.

[15] D. S. Pulikanti and P. K. Ramancharla, "SSI Analysis of Framed Structure Supported on Pile Foundations - With and Without Interface Elements," *Frontiers in Geotechnical Engineering*, vol. 3, no. 1, p. 8, 2014. https://seipub.org/fge/paperInfo.aspx?ID=2973

[16] V. Hirave and M. Kalyanshetti, "Seismic response of steel braced building frame considering soil structure interaction (SSI): an experimental study," *Journal of the Institution of Engineers (India): Series A*, vol. 99, no. 1, pp. 113–122, 2018. DOI: 10.1007/s40030-018-0262-2

[17] Rudu Cruciat and Cristian Ghindea, "Experimental determination of dynamic characteristics of structures," *Mathematical Modelling in Civil Engineering*, vol. 4, pp 1-9, 2012.https://www.researchgate.net/publication/233502209_Experimental_Determination_of_Dynamic_Characteristics_of_Structures

[18] Tabatabaiefar, Sayed Hamid Reza. "Determining seismic response of mid-rise building frames considering dynamic soil-structure interaction." PhD diss., 2012. https://opus.lib.uts.edu.au/handle/10453/21855

[19] H. R. Tabatabaiefar and A. Massumi, "A simplified method to determine seismic responses of reinforced concrete moment resisting building frames under influence of soil–structure interaction," *Soil Dynamics and Earthquake Engineering*, vol. 30, no. 11, pp. 1259–1267, 2010. DOI: 10.1016/j.soildyn.2010.05.008