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Soil Structure Interaction and Seismic Design Code Provision

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Abstract

The current seismic design code neglect the SSI effect and consider the base of structure as fixed one. It tacitly assumes that increase in fundamental Time period of building structures due to SSI effect including the increase in damping characteristics of soil would be beneficial always. This consideration is applicable for light structure in stiff soil but may not hold good for certain class of structure with different soil type. Also most of the buildings are designed considering the smooth response spectra curves as per seismic code. Great earthquake as Kobe earthquake 1995, Mexico earthquake 1985 showed some different behavior deviating from the above response spectra. The 1985 Mexico City earthquake mainly affect the mid-rise building in Mexico City. Whereas the Mexico City lies in old lake bed which is the soft clay. Nepal is the country with high risk of earthquake and Kathmandu valley lies above the soft soil deposit is very much liable to resonance of the structure. The Kathmandu valley consists of many strata of sand, silt and clay sediments, which bring forward a possibility that two or more amplified frequencies occur during an earthquake. This research focuses to know the effect of SSI on the response of heavy structure in different soil strata condition subjected to earthquake ground motion acceleration. Three types of mid-rise moment-resisting building frames, including 5-Storey, 10-Storey and 15-Storey buildings are selected. The bare frame model and frame shear wall modelled and analyzed, employing finite element method under two different boundary condition: (a) fixed base (no SSI) and (b) considering SSI. From the results obtained shows that the SSI plays a considerable role in seismic behavior of mid-rise buildings. Thus, considering SSI effects in the seismic design of mid-rise moment resisting building frames, particularly when resting on soft soil deposit, is essential.

Keywords

Soil Structure Interaction – Seismic Code Spectra – Resonance

1. Introduction

The response of the structure to earthquake shaking is affected by interaction between three linked systems; the structure, the foundation and the soil underlying and surrounding the foundation. The process in which the response of the soil influences the motion of the structure and the motion of the structure influences the response of the soil is termed as soil-structure interaction (SSI). The interaction causes energy dissipation and changes the natural modes of vibration of the structure such as natural frequencies and the corresponding mode shapes [1].

The research [2] regarding the role of SSI in the seismic performance of the structure discuss both the beneficial as well as detrimental role of SSI. Adopting the beneficial role of SSI, many seismic design codes suggested to neglect SSI effects assumes the building to be fixed at their bases. Which is a conservative simplification that would supposedly lead to improved safety margins. The IS: 1893-2002 seismic design code also adopt the same beneficial role of SSI in analysis but it further states that, "However there are some exception where Resonance like conditions have been seen to occur between long distance waves and the Tall structures founded on deep Soft Soil". Whereas, in reality supporting soil medium allows movement to some extent due to flexibility nature of the soil, which decrease the overall lateral stiffness of the structural system resulting in the lengthening of lateral natural periods. Such lengthening of lateral natural periods does considerably change the seismic response of building frames. The resonance effect on the structure becomes prominent by soil amplification even though the soil has good engineering characteristics [3]. The report [4] & [5] discusses about the theoretical background of seismic design as per IS & NNBC code respectively. The report further illustrate the resonance vibration of building and variation in nature of design response spectra and response spectra from various long period earthquake. The possible severities of neglecting the effects of the SSI are fore grounded in previous research works [6] & [7]. The result of the research work [8]& [9] provides the necessary amendment to be done in seismic design code of Iran & Australia respectively for seismic analysis of building considering soil structure interaction. The variation in time period and base shear for two adjacent tall building kept at certain distance due to soil structure interaction was done in research [10]. So this work focus on the behavior of the tall building considering the SSI effect. The effect of soil-flexibility is accounted through consideration of springs of specified stiffness as prescribed in well-accepted literature [11] & [12]. The present study has been carried out for buildings with the same geometry found on varying soil types over raft foundations in Zone V. An attempt has been made to find the variation in Time period, Storey displacement & Storey drift under seismic loading in the structure and raft foundation by incorporating the effect of soil-structure interaction which was further compared with those of fixed base condition. Influence of variation of the parameters such as, different soil conditions and number of stories were also considered in the present study for which the buildings were modelled by four alternate approaches, namely, (1) bare frame with fixed supports, (2) bare frame with supports accounting for soil-flexibility, (3) frame-shear wall with fixed supports and (4) frame-shear wall with supports accounting for soil-flexibility.

Consider a single degree-of-freedom structure with stiffness k, and mass m, resting on a fixed base, as depicted in Figure 1(a). T be the natural period of structure for this case. Then consider the same structure with vertical, horizontal, and rotational springs at its base, representing the effects of soil flexibility against a rigid foundation, as depicted in Figure 1(b). The vertical spring stiffness in the z direction is denoted k_z, the horizontal spring stiffness in the x direction is denoted k_x, and the rotational spring is denoted $k_(yy)$, representing rotation in the x-z plane (about the y-y axis). $\tilde{T}$ be the natural period of structure for flexible base.

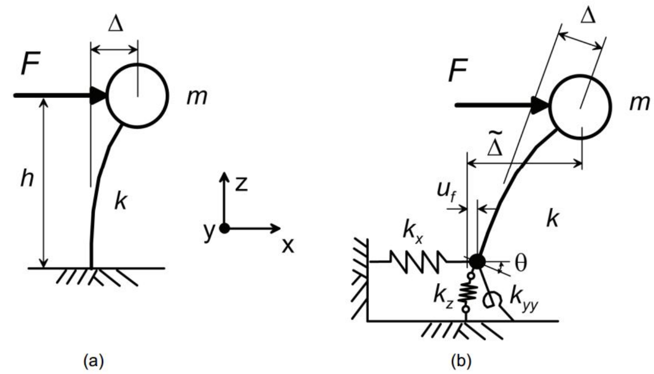

Figure 1: Schematic illustration of deflections caused by force applied to: (a) fixed-base structure; and (b) structure with vertical, horizontal, and rotational flexibility at its base.

After simplification [12], we get classical period lengthening expression as:

$$\frac{\tilde{T}}{T} = \sqrt{1 + \frac{k}{k_x} + \frac{kh^2}{k_{yy}}}$$

The above expression for the period lengthening can be applied to multi degree of freedom structure by taking the height h as the center of mass for the first-mode shape. This height is approximately two-thirds of the overall structure height, and taken as 0.7 times the height in ASCE/SEI 7-10. In such cases, period lengthening applies to only the first-mode only.

2. Idealization of the System

2.1 Structural idealization

To analyze the dynamic behavior while considering the effect of soil-structure interaction, building frames of 5, 10 and 15 story with and without shear wall have been idealized as 3D space frames using two nodded frame elements. Slabs at different story level and shear wall was modelled with four nodded plate elements with consideration of adequate thickness. The storey height as well as length of each bay of all the building frames was chosen as 3 m and 6 m respectively which is reasonable for domestic or small office buildings. The dimensions of reinforced concrete columns and shear wall are as given in Table 1. Similarly, the thickness of the roof slab and floor slabs was taken as 140mm and the dimension of beam as 300x250 mm. Slab thickness of raft was taken as 1 m. M20 grade of concrete for beam , M25 grade of concrete for column with Fe500 grade of rebar material is considered. These dimensions were arrived on the basis of the design following the respective Indian code [13] for design of reinforced concrete structures.

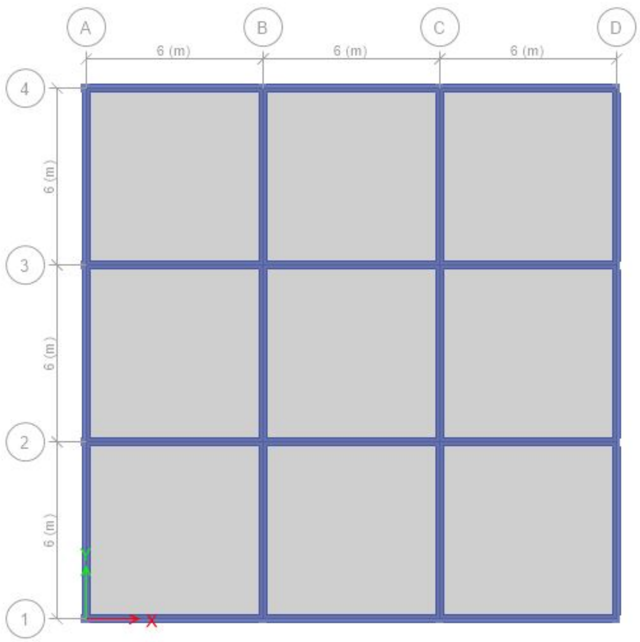

Figure 2: Plan of building

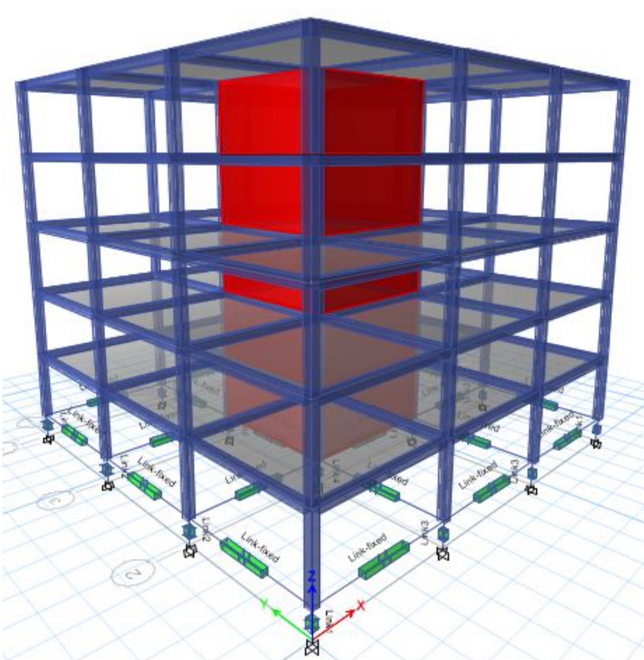

Figure 3: 3D model of 5 storey frame shear-wall building with link support in ETABS

Table 1: Column and Shear wall Dimensions

No. of Stories	Column Size (mm × mm)	Shear-Wall Thickness (mm)
5	300×300	150
10	350×350	200
15	400×400	250

2.2 Soil Idealization

The structure is assumed to support by firm non liquefiable soil produced by the inertia of structure. The modeling of the supporting soil can be done using FEM blocks of soil or by spring and dashpot support. From the analysis output of literature [14] the modeling of soil in this research is done providing spring and dashpot support. To incorporate the effect of soil-structure interaction in the analysis impedance functions associated with rigid massless foundations was utilized. The present study considers translations of foundations in two mutually perpendicular principal horizontal directions and vertical direction as well as rotations of the same about these three directions. For buildings with raft foundation, the link support have been attached below the column to simulate the effect of soil flexibility taking three translation, two along horizontal and one vertical axes together with three rotation about these three mutually perpendicular axes. The stiffness and damping of this centrally placed link for raft type of foundation have been computed on the basis of the guidelines prescribed in a well-accepted literature [12] formed on the basis of an extensive literature survey and study based on boundary element method. The value of stiffness and damping for individual column in all considered degree of freedom is approximated by considering the tributary area of column in raft. The study primarily attempts to see the effect of soil-structure interaction on buildings resting on different types of non-cohesive soil, viz., soft, stiff, dense and rock. To obtain the values of the stiffness of the springs for these varieties of soil, values of shear modulus (G) of soil have been estimated using the shear wave velocity. The other details of different soil parameters are tabulated in Table 2.

2.3 Methodology

Seismic analysis of structure for the effect of soil-structure interaction is carried out based on the design spectrum

Table 2: Detail of soil parameter considered

Description	Shear wave velocity V_s (m/sec)	Poission's ratio	Mass density (ρ) KN/m^3
Rock	1500	0.3	22
Dense Soil	600	0.3	20
Stiff Soil	300	0.35	18
Soft Soil	100	0.4	16

provided in IS: 1893-2002. The seismic analysis of these buildings are obtained due to the design spectrum corresponding to 5% of critical damping [13]. The medium category type of soil is taken in consideration

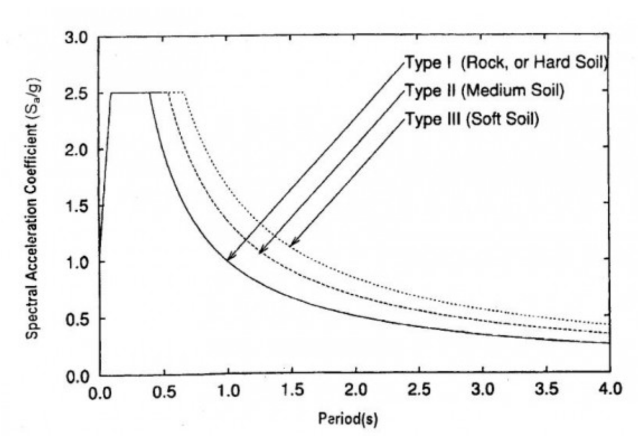

Figure 4: Design Response Spectrum From IS: 1893-2002

Both static method and Response Spectrum method of seismic analysis are performed by applying seismic zone factor value 0.36 for very severe seismic intensity, reduction factor 5 for both special RC moment resisting frame & ductile shear wall with SMRF with importance factor 1.

The linear time history analysis is performed for all the models. The ground motion data of Mexico City earthquake 1985 is used and shown in figure 29.

3. Results and Discussions

After the modeling of the structure for the various boundary condition, the analysis of the model are done and the results are represent as the function of number of stories and types of soil.

3.1 Lateral natural period

Idealization of building as a bare frame is unrealistic, but such idealization is used many time in the design offices. So, study has been made for such frames and frame shear wall building. The variation in fundamental time period for structure resting different type of soil profile of varying storey height as shown in figure 5, 6, 7, 8, 9 and 10.

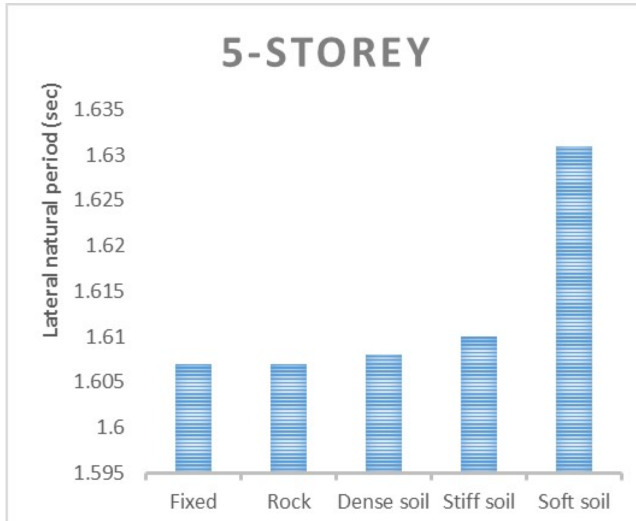

Figure 5: Variation in lateral time period for bare frame building

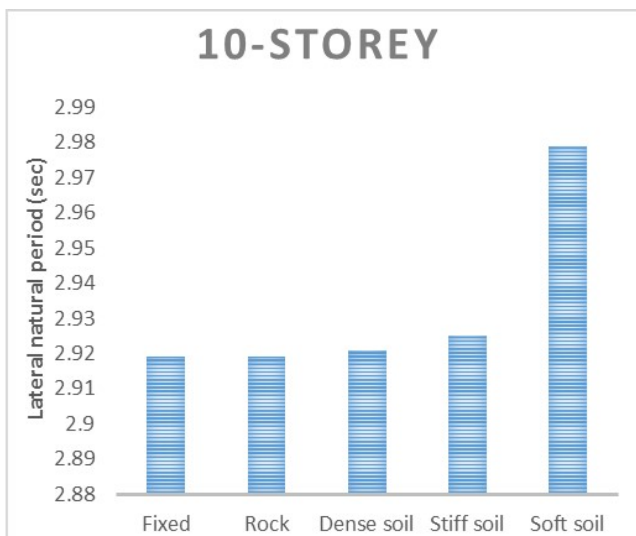

Figure 6: Variation in lateral time period for bare frame building

The lateral time period of the building increase as the flexibility of the supporting soil increases. The lateral time period for structure on soft soil is greater than that of at fixed support. The variation is found to be maximum in case of frame shear wall building rather than bare frame building. Mostly time period of stiff structure are influenced largly by increase in the soil flexibility and also by increase in building height.

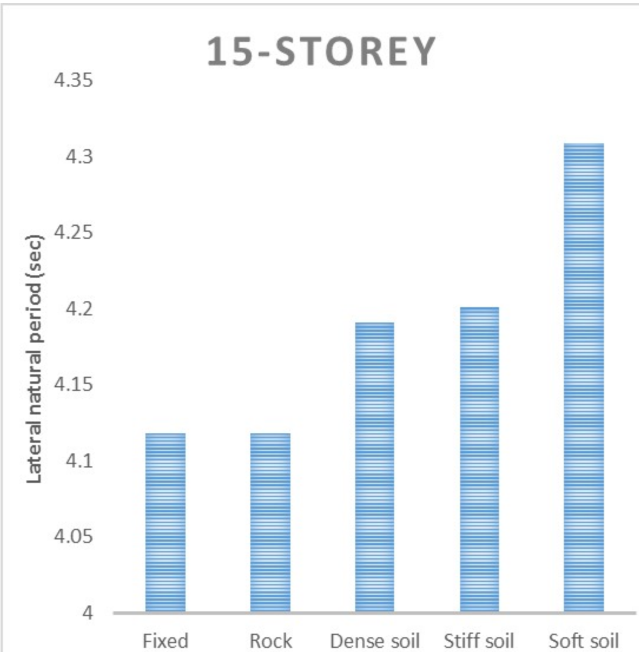

Figure 7: Variation in lateral time period for bare frame building

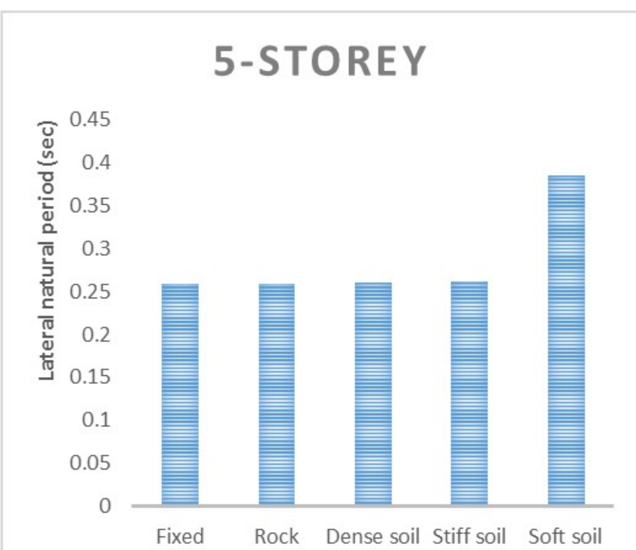

Figure 8: Variation in lateral time period for frame shear wall building

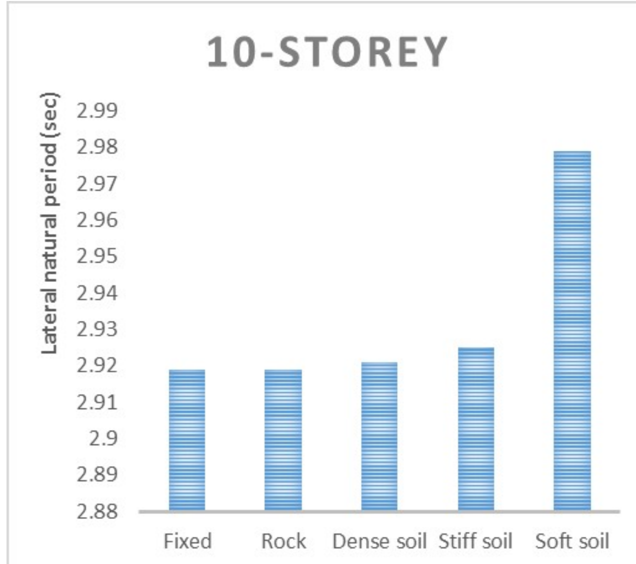

Figure 9: Variation in lateral time period for frame shear wall building

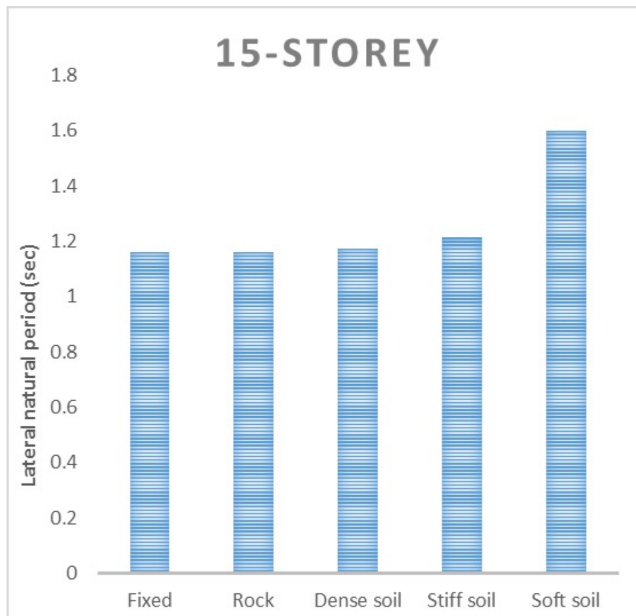

Figure 10: Variation in lateral time period for frame shear wall building

3.2 Seismic Base Shear

Seismic base shear reflects the seismic lateral vulnerability and is considered as one of the primary input for seismic design. The variation in Base shear for structure resting different type of soil profile of varying storey height as shown in figure 11, 12, 13, 14, 15 and 16.

Figure 11: Variation in seismic base shear for bare frame building

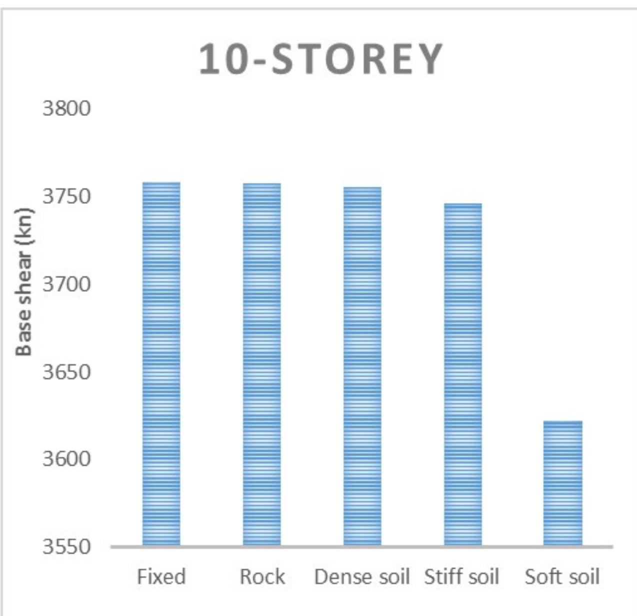

Figure 12: Variation in seismic base shear for bare frame wall building

The decrease in base shear is due to displacement of foundation on flexible soil. The study shows that decrease in base shear for same building is more in case of frame shear wall building than bare frame mode having same type of foundation support. There is significant decrease in the value of base shear due to increase in flexibility of soil(rock, dense and stiff soil) for the frame shear wall building but lesser decrease in the value for bare frame building.

Figure 13: Variation in seismic base shear for bare frame wall building

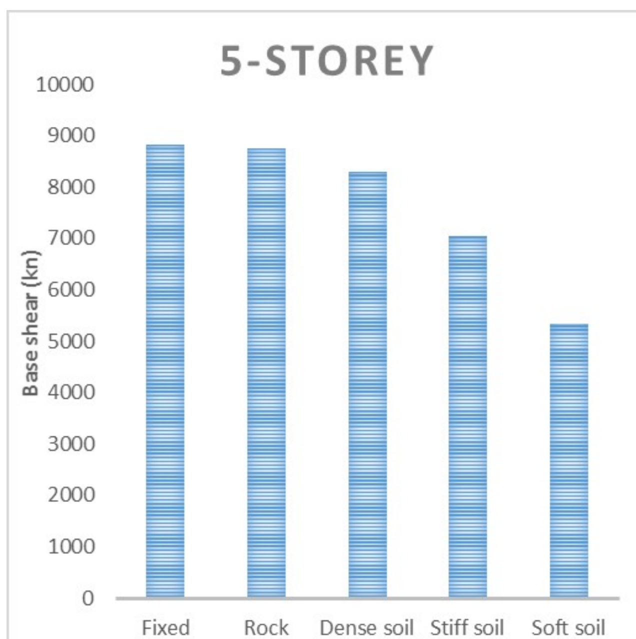

Figure 14: Variation in seismic base shear for frame shear wall building

Figure 15: Variation in seismic base shear for frame shear wall building

Figure 16: Variation in seismic base shear for frame shear wall building

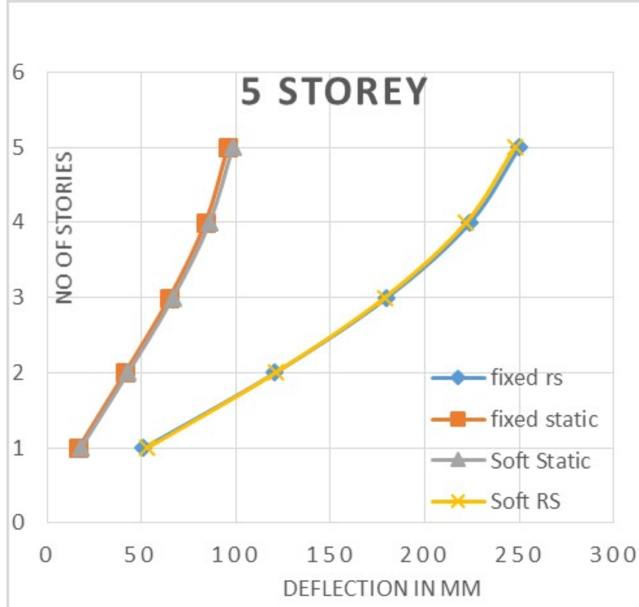

Figure 17: Variation in lateral storey displacement for bare frame building

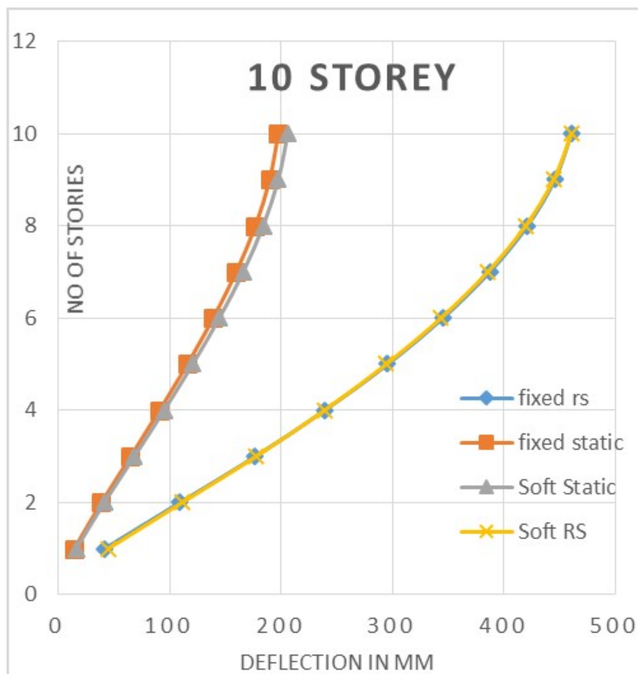

Figure 18: Variation in lateral storey displacement for bare frame building

3.3 Storey displacement

The variation in storey displacement along horizontal x-direction for structure resting in different type of soil profile of varying storey height as shown in figure 17, 18, 19, 20, 21 and 22.

The deformation due to both static method and Response spectrum method are taken in consideration. The graph shows the comparison between structures in soft soil deposit and fixed type support of system. The variation in storey displacement due to soil flexibility is smaller value in case of lower storey level for bare frame model.

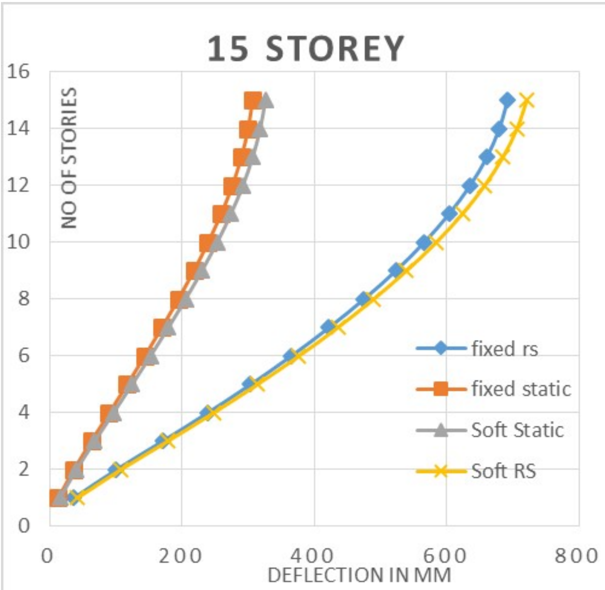

Figure 19: Variation in lateral storey displacement for bare frame building

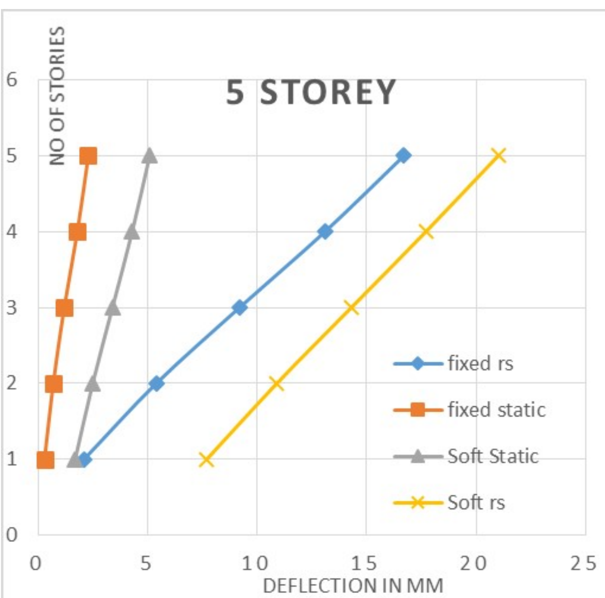

Figure 20: Variation in lateral storey displacement for frame shear wall building

The variation pattern of storey displacement is uniform in case of bare frame building but in frame shear wall building the variation is not uniform. The deflected shape of the bare frame building is different than that of frame shear wall building.

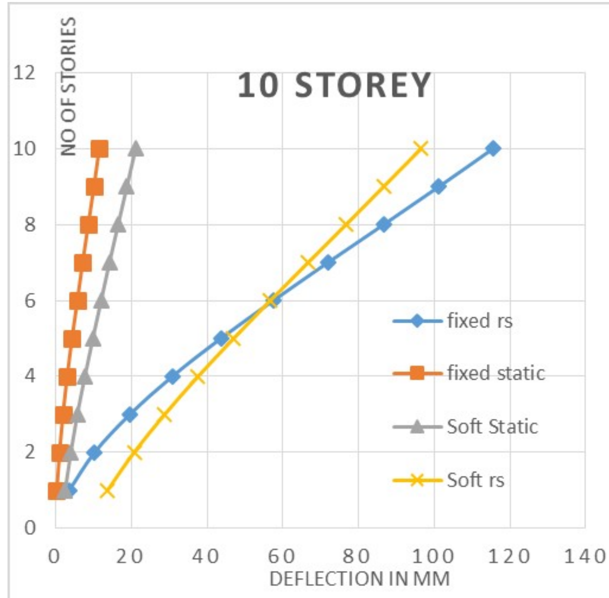

Figure 21: Variation in lateral storey displacement for frame shear wall building

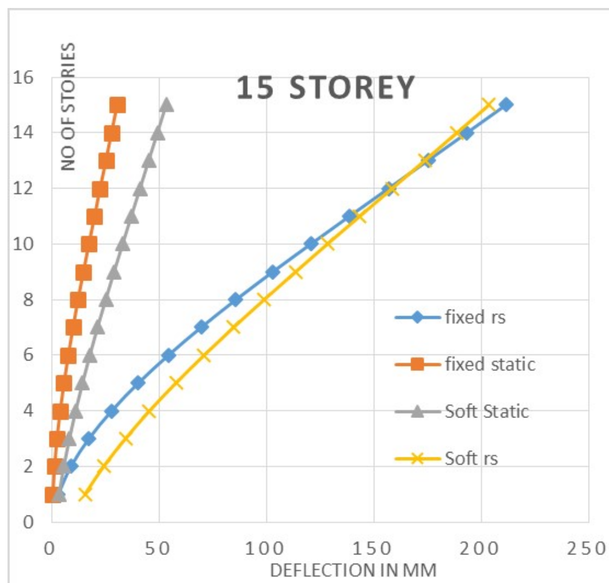

Figure 22: Variation in lateral storey displacement for frame shear wall building

Note: In graph fixed rs refers to fixed base support for response spectrum method, Soft Static refers to Soft base support for static earthquake loading method and respectively for other case.

3.4 Storey drift

The variation in storey drift along the horizontal x-direction for structure resting in different type of soil profile of varying storey height as shown in figure 23, 24, 25, 26, 27 and 28.

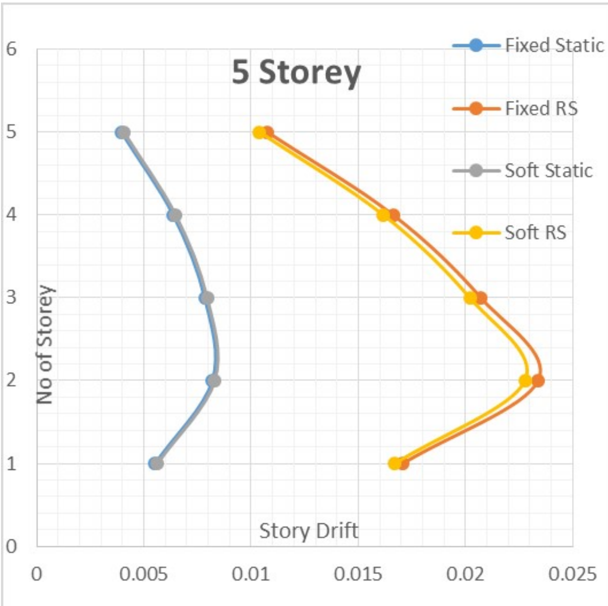

Figure 23: Variation in lateral storey drift for bare frame building

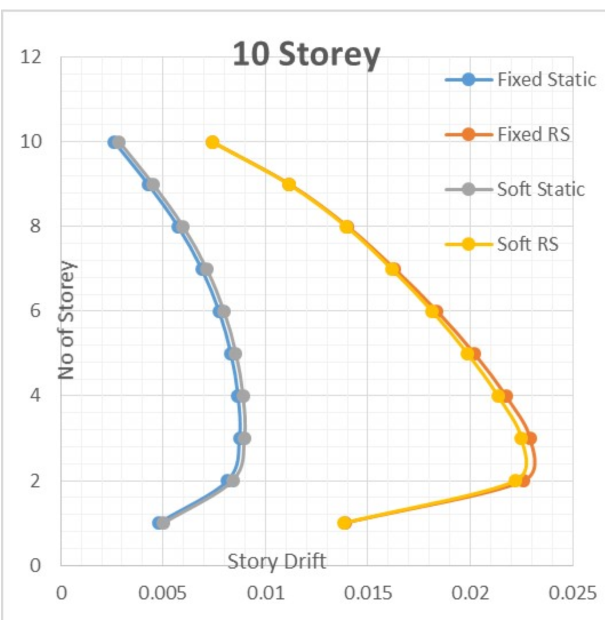

Figure 24: Variation in lateral storey drift for bare frame building

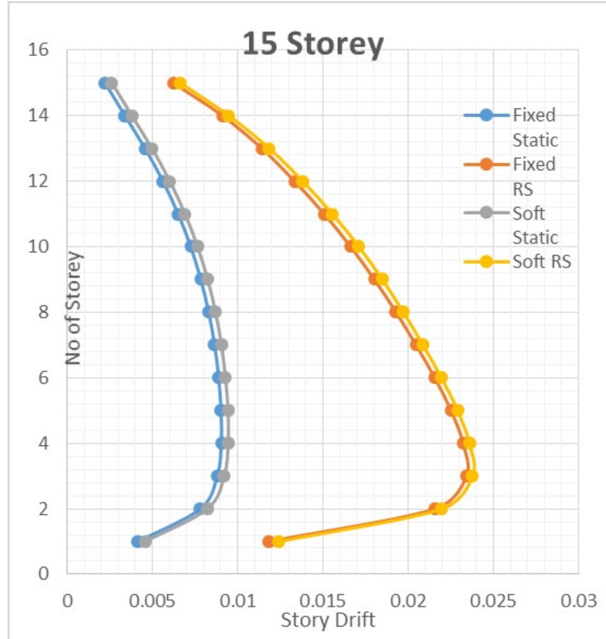

Figure 25: Variation in lateral storey drift for bare frame building

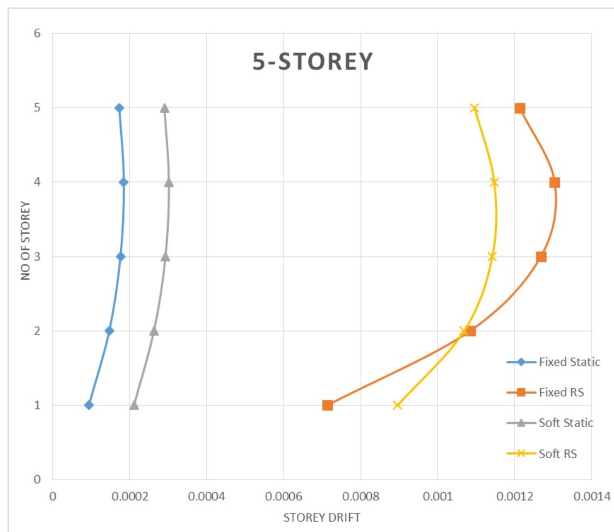

Figure 26: Variation in lateral storey drift for frame shear wall building

The drift due to both static method and Response spectrum method are taken in consideration. The graph shows the comparison between structure in soft soil deposit and fixed type support of system. The variation pattern of storey displacement is uniform in case of bare frame building but in frame shear wall building the variation is not uniform. For the bare frame building, the maximum storey drift lies in the lower storey level i.e., between 2nd and 4th storey level.

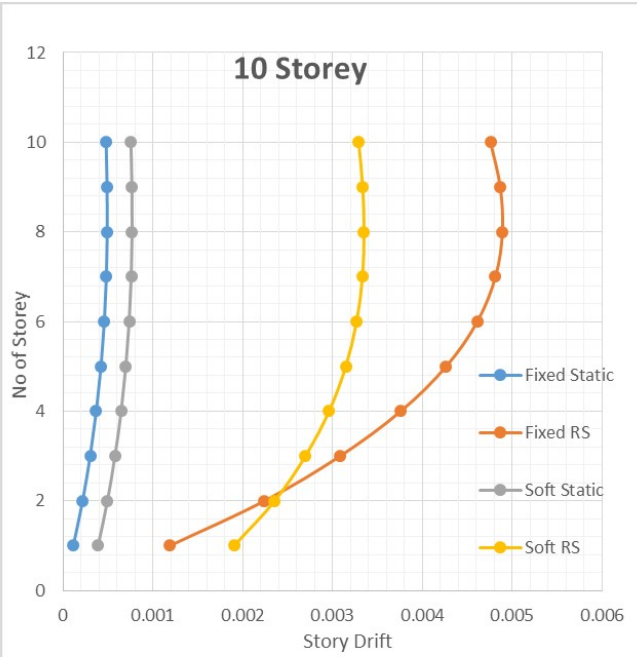

Figure 27: Variation in lateral storey drift for frame shear wall building

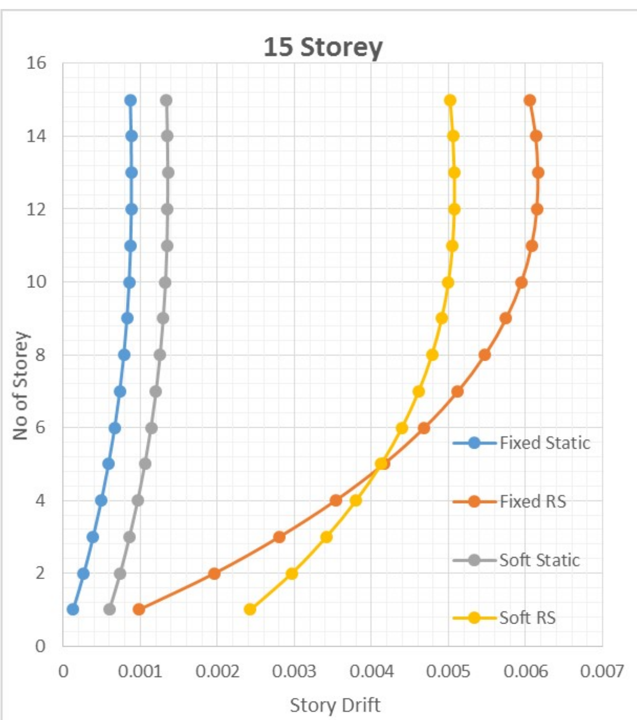

Figure 28: Variation in lateral storey drift for frame shear wall building

3.5 Time history analysis

The linear time history analysis is performed by linear direct method of integration using Hilber Hughes Taylor method along x-direction for all the models. The ground motion data of Mexico City earthquake 1985 is used and shown in figure 29.

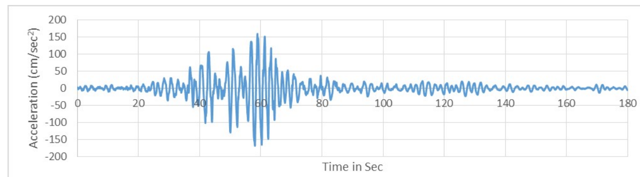

Figure 29: Ground acceleration time history for Mexico City earthquake 1985

Response spectrum

The spectral acceleration of the top floor of the building due to input ground motion for different soil support condition is as shown in figure 33, 34, 30, 31 and 32.The response of the top floor of the building shows some different nature than that of design spectrum from code. The seismic design spectra which attain constant acceleration up to a certain period and thereafter decrease monotonically with period but the predominant period of the structure is more than that value from the code. The maximum ordinate of the actual spectra is more than the value given by the code. And from the graph, the maximum ordinate of response spectra curve tends to decrease as the flexibility of soil increases for bare frame building. The study of response spectrum curve for 5 storey and 10 storey bare frame building shows maximum ordinate than the design response spectrum. The response spectra curve of 10 storey and 15 storey frame shear wall shows double point peak curve. These shows that the stiff structure in soft soil deposit are liable to resonance twice. These multiple amplified frequencies in a particular area can create a resonance effect both for low rise as well as tall building. The soft soil modified the incoming seismic waves such that resulting motion of the structure become detrimental. The local site amplification must be taken in consideration for seismic design of the structure.

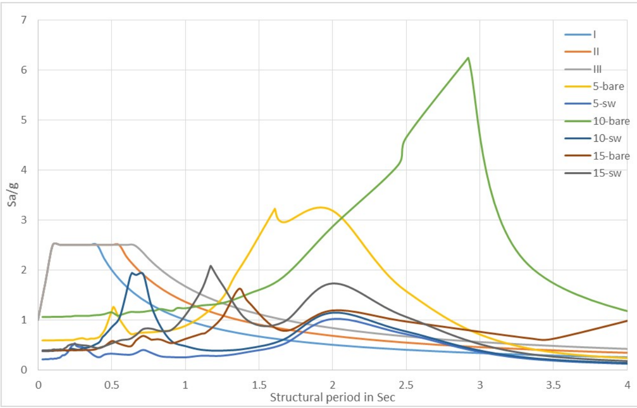

Figure 30: Comparison of a seismic code design spectrum to actual spectra for Dense soil support, damping 5 %

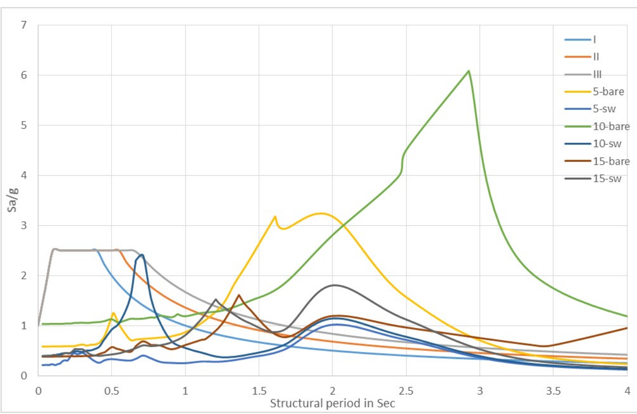

Figure 31: Comparison of a seismic code design spectrum to actual spectra for Stiff soil support, damping 5 %

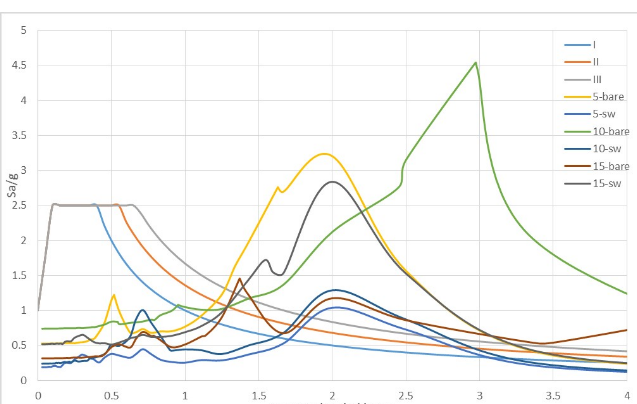

Figure 32: Comparison of a seismic code design spectrum to actual spectra for Soft soil support, damping 5 %

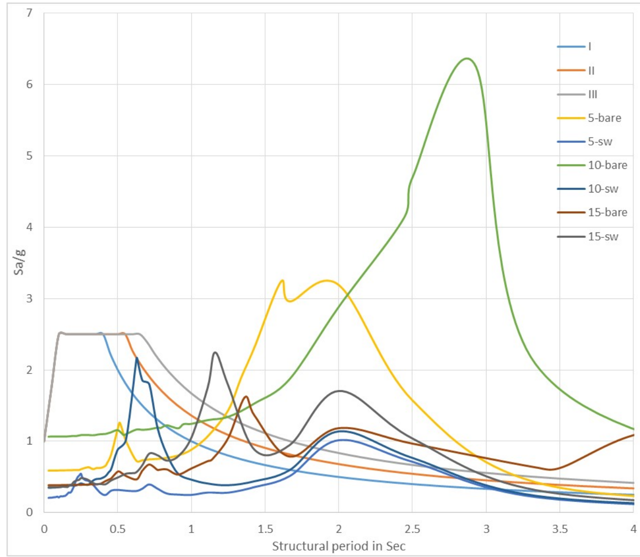

Figure 33: Comparison of a seismic code design spectrum to actual spectra for fixed soil support, damping 5 %

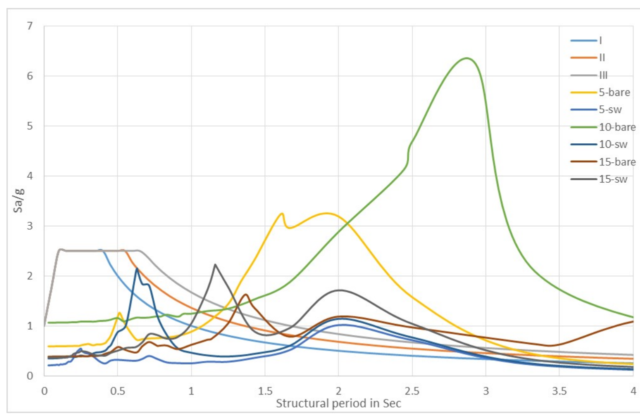

Figure 34: Comparison of a seismic code design spectrum to actual spectra for Rock soil support, damping 5 %

Note: In graph I, II & III refers to soil type in design response spectrum of IS1893:2002, 5-bare refers to 5 storey building with bare frame model, 5-sw refers to 5 storey building with frame shear model and respectively.

3.6 Soil Structure System Behavior

Considering h be the structure height, B & L refers to the half-width and half-length of the foundation. T be the first mode period of the structure and V_s be the shear wave velocity of soil below the foundation. The term h/T quantifies the stiffness of the superstructure and has the unit of velocity, the term h/(V_sT) represents the structure to soil stiffness ratio. The term h/B represent the structure height to foundation width ratio. Using different models for square footing (L=B) the period lengthening ratios can be calculated considering dimensionless parameter h/(V_sT) and h/B and plotted in the figure 35 and 36.

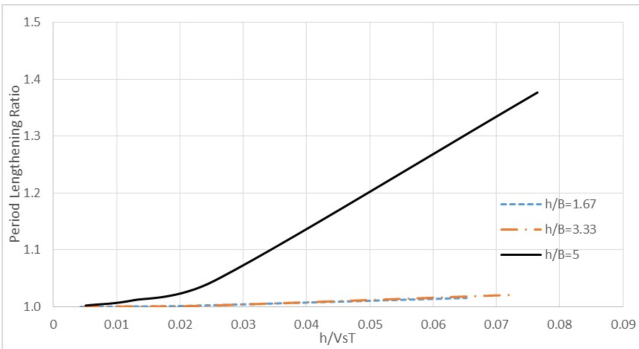

Figure 35: Plot of period lengthening ratio versus structure-to-soil stiffness ratio for square footing and varying ratio of h/B (for Bare frame model)

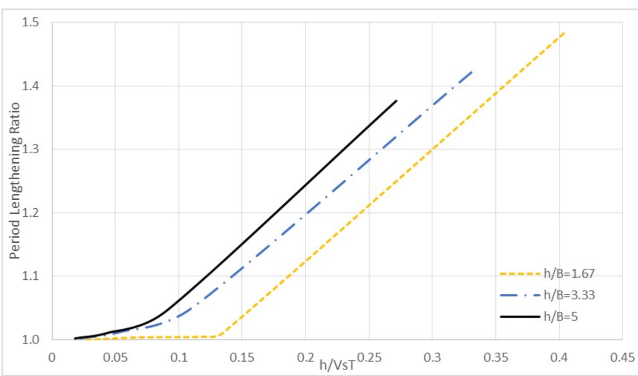

Figure 36: Plot of period lengthening ratio versus structure-to-soil stiffness ratio for square footing and varying ratio of h/B (for frame shear wall model)

From the graph stiff structure on the soft soil deposit are more affected by period lengthening than the structure on the rigid support. Whereas flexible structure are less affected as compared to stiff structure. As the value of h/B increase that means more slender the structure become greater the value of period lengthening. Tall and high rise structure are more influenced than the short and low rise building due to soil flexibility.

The natural period of ground varies from about 0.4 seconds up to 2 seconds, depending on the nature of the ground. Hard ground or rock will experience short period vibration. Very soft ground may have a period of up to 2 seconds but, unlike a structure, it cannot sustain longer period motions except under certain unusual conditions. Since this range is well within the range of common building periods, it is quite possible that the pushes that earthquake ground motion imparts to the building will be at the natural period of the building. The period lengthening of the building due to soil structure interaction cause the increase in natural period of building. This may create resonance of the building with the ground motion, causing the structure to encounter accelerations of perhaps 1g when the ground is only vibrating with accelerations of 0.2g. Because of this, buildings suffer the greatest damage from ground motion at a frequency close or equal to their own natural frequency. Thus the predominant frequency of ground motion acceleration leading to the enhanced vibration of the structure and higher possibilities of collapse.

4. Conclusion

The present study makes an effort to evaluate the effect of soil structure interaction on the seismic behavior of bare frame buildings and building with frame-shear wall of varying height over varying soil property on raft foundation. The scope of the work is to highlight rather than fully resolve the role of SSI. After the observation of the change in lateral natural period, seismic base shear, storey displacement and storey drift the following conclusion were drawn.

- The variation in fundamental period, seismic base shear & storey displacement of the building increases with the reduction in stiffness of soil.
- The variation of storey drift is more in case of shear frame building on fixed soil support than the soft soil support corresponding to same type of frame building on same type of soil profile.
- The stiff structure are more affected by the soil structure interaction.
- These increase in fundamental period of structure in soft soil deposit leads to resonance of the building for long period ground motion.
- The stiff structure on hard rock support is more affected by short period wave and the flexible struc-

ture on soft soil deposit are affected by long period wave.

- It is essential to consider the effect of soil-structure interactions for seismic design of the building when the following criterion exists: $\frac{h}{V_s T} > 0.1$.

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