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Seismic Soil-Pile-Structure Interaction Studies on High-Rise RC Framed Structure Resting on Pile Groups

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Abstract. Infrastructure will play a vital role in the growth of developing nations like India. Pile foundations in soft soil deposits have increased significantly as a result of the scarcity of land and the need for high-rise structures. Soil-structure interaction is often omitted in conventional design practices considering the base as fixed, which can lead to an underestimation of forces and displacement throughout the system. This study aims to investigate the influence of the Length of the pile to Diameter ratio (L/d) and Embedded length to Length of pile ratio (L_b/L) incorporating soil-structure interaction (SSI) using a numerical tool SAP2000. The seismic analysis of a 25-storey high-rise building has been performed using response spectrum analysis for zone V as per IS 1893: 2016 to assess the seismic response of superstructure consisting of lateral displacement, inter-storey drift, base shear, and column moment. A parametric study has been carried out for different L/d and (L_b/L) ratios such as 30, 24, 20, and 0.042, 0.083, 0.125, and 0.167. The numerical results show that the pile foundation with less L/d and L_b/L ratio offers the least lateral deformation, inter-storey drift, base shear, and column moment.

Keywords: Soil-pile-structure interaction, High-rise building, Pile group, Response spectrum method.

1 Introduction

The foundations of structures such as bridges, transportation infrastructure, earth-retaining structures, and tunnels are all examples of structural elements directly in contact with the ground. Both the structure and foundation must deform and move in a compatible manner when external forces are applied. This is because neither the displacement of structural elements nor the displacement of the ground is independent. Thus, the term Soil-Structure Interaction (SSI) is used to describe this class of problems [1]. Interaction between the three systems influences the deformation of a structure during seismic excitation: the structure, foundation, and soil around and underneath the foundation [2].

The conventional method relies on the idea that the foundation of a building is fixed to the ground, and that the foundation itself is rigid [3]. There are no "SSI effects" if the building is considered as having a rigid base. Most civil engineering constructions lying on hard strata and medium soil will not demonstrate significant SSI effects. The likelihood of SSI effects increases for a given structure and free field seismic stimulation as the soil becomes softer. Generally, the SSI includes two types of interactions, namely, kinematic interaction and inertial interaction. Whenever the stiffness of the substructure system restricts the creation of free-field motion kinematic interaction will take place. Kinematic interaction induces vibration modes such as rocking and torsion [4]. The dynamic behavior of the structure is dictated by the mass of the building. SSI effect induced by the mass of a structure is called inertial interaction. Overturning moment and transverse shear are caused by inertial interaction.

SSI was recognized by several researchers as a factor in the devastation caused by the earthquake. At a certain location, it was observed that the soil is affected by seismic waves, resulting in a higher frequency of ground motion and a longer fundamental time period for a particular structure. This resulted in varying responses to earthquakes, as evidenced by the Hanshin Expressway's collapse in 1997, the tilting buildings at Kandla port and customs tower in 2001, and NHK's building in Niigata during the 1964 earthquake [5]. The described occurrences demonstrate the significance of the soil-structure interaction study.

For several decades, there have been many kinds of research carried out on SSI numerically and experimentally. Tanumoy Bhattacharjee et al., (2021) [6] investigated the seismic response of single and multi-storey asymmetric structures in a plan supported by a symmetric pile-raft foundation deposited in soft clay. The authors concluded that the structure exhibits a substantial increase in the natural period due to the impact of SSI. Mohsen Bagheri et al., (2018) [7] carried out a numerical analysis on mid-rise and high-rise steel structures to investigate the interaction effects on the dynamic behavior of a structure. The study reveals that the shear force can be modified by altering the diameter of the pile, length of the pile, and configuration to obtain optimal distribution. Lei Zhang and Huabei Liu (2017) [8] carried out a 3D finite element analysis to evaluate the dynamic response of pile-raft-structure constructed over soft clay. The authors mainly focused to evaluate the foundation responses such as the pile bending moment. Hamid Reza Bolouri Bazaz et al., (2021) [9] studied the performance of 20 storey structure resting on a pile group foundation embedded in soft clayey soil using FLAC. The authors investigated the structure with and without pile-raft foundation inside an excavation and on the surface. Rajib Saha et al., (2020) [10] presented the study of elastic and inelastic dynamic characteristics of building constructed on pile-raft foundations considering a different period of the structure. The substructure method is used by the authors to evaluate the impact of soil-pile-structure interaction. HuiLong et al., (2021) [11] carried out a 2D finite element analysis on a high-rise structure constructed over a pile-raft foundation. Identical structures with different spacings are considered and static-dynamic coupled numerical simulations are adopted in the study. Amer Hassan and Shilpa Pal (2018) [12] carried out a seismic analysis on base-isolated buildings considering the impact of soil flexibility such as hard, medium, and soft soil according to IS: 1893-2002. The findings of this study revealed that the seismic response of the superstructure increases with an increase in soil flexibility. Han Yingcai (2002) [13] conducted a numerical investigation on a 20-storey structure considering rigid base, linear, and non-linear soil-pile systems. The impact of pile foundations on the performance of the tall structure and shallow foundation are investigated and compared. Sassan Mohasseb (2019) [14] investigated the repercussions of soil-pile-structure interaction as regards the performance of high-rise structures numerically. The present study aims to perform a parametric study on high-rise RC framed structure resting on pile groups considering different ratios of the Length of the pile (L) to the depth of the pile (d) and embedded length (L_b) to the length of the pile (L).

2 Structural Modelling

The seismic behavior of high-rise structures sustained by pile groups is derived by analyzing a G+25-storey structure. The superstructure is modeled as a three-dimensional frame in which the structure includes a slab depth of 0.2m. The slabs are considered rigid diaphragms in the present model. The structural model has a 25m x 30m plan. The structure has five horizontal spans and the distance between center to center of the column is 5m. The total length along the horizontal direction is 25m. The structure consists of six vertical spans and the distance between the center to center of the column is 5m. The total length along the vertical direction is 30m. The standard floor height is 3m and the total height of the structure is 78m. The building consists of reinforced concrete (RC) structural systems with brick walls. The structural plan is shown in Fig. 1. The structural frame column section and beam sections are tabulated in Table 1 and are designed as per IS:456-2000 [15].

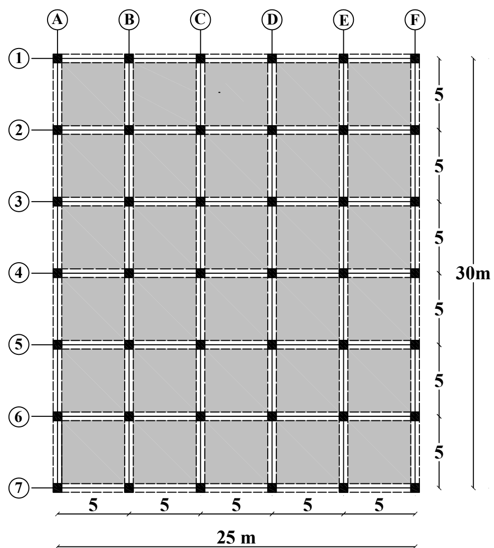

Fig. 1. Typical plan view

Table 1. Typical cross-section of structural elements

Levels	Number of Storey	Beam Section (m)	Column Section (m)	Slab Thickness (m)
1-10	10	0.5 x 0.5	0.7 x 0.7	0.2
11-20	10	0.5 x 0.5	0.6 x 0.6	0.2
20-25	05	0.5 x 0.5	0.5 x 0.5	0.2

3 Soil Properties

The interaction between the soil and the structure greatly depends on the dimension of a building, its dynamic properties, and the soil strata as well as the characteristics of seismic waves. Particularly for the structures erected on soft soil, the underlying soil medium beneath has a significant impact on their seismic behavior. Thus, the dynamic interaction of the structure resting on softer soils must be considered to study the impacts of SSI to obtain accurate and reliable results. To examine the dynamic behavior of high-rise buildings considering the effect of SSI, properties of the soil stratum such as unit weight of soil, cohesion, angle of internal friction, poisons ratio, and shear modulus is defined and tabulated in Table 2. 3-D model is carried out using SAP2000 [16]. Discretization has been carried out with a 1m element size.

Table 2. Input parameters for foundation soil

Soil type	**Unit weight (kN/m^3)** [19]	**Cohesion, C (kN/m^2)** [19]	**Angle of internal friction, φ (degrees)** [19]	**Poisson's ratio** [20]
Clay	13.92	50	19	0.4
Hard rock	27	0	40	0.3

4 Pile Characteristics

A Pile foundation is adopted in the present numerical study to mitigate the uplift and rocking effects of structures caused during seismic excitations. Earthquakes may put enormous strain on piles, especially near the corners of structures, which can result in significant tensile and compression stresses being applied to them. Following the appropriate design standards IS: 2911 [17], pile foundations are designed. Twelve different configurations were adopted, where the pile length is kept fixed. The length of the pile is 12m, whereas their diameter (d) and embedded length (L_b) vary proportionally and are tabulated in Table 3.

Table 3. Pile foundation details

Configuration	**Diameter of pile (d) in 'm'**	**Embedded length (L_b) in 'm'**	**Number of piles**	**Length of pile**	**L/d ratio**	**L_b/L ratio**
1	0.4	0.5	3x3	12	30	0.042
2		1.0				0.083
3		1.5				0.125
4		2.0				0.167
5	0.5	0.5			24	0.042
6		1.0				0.083
7		1.5				0.125
8		2.0				0.167
9	0.6	0.5			20	0.042
10		1.0				0.083
11		1.5				0.125
12		2.0				0.167

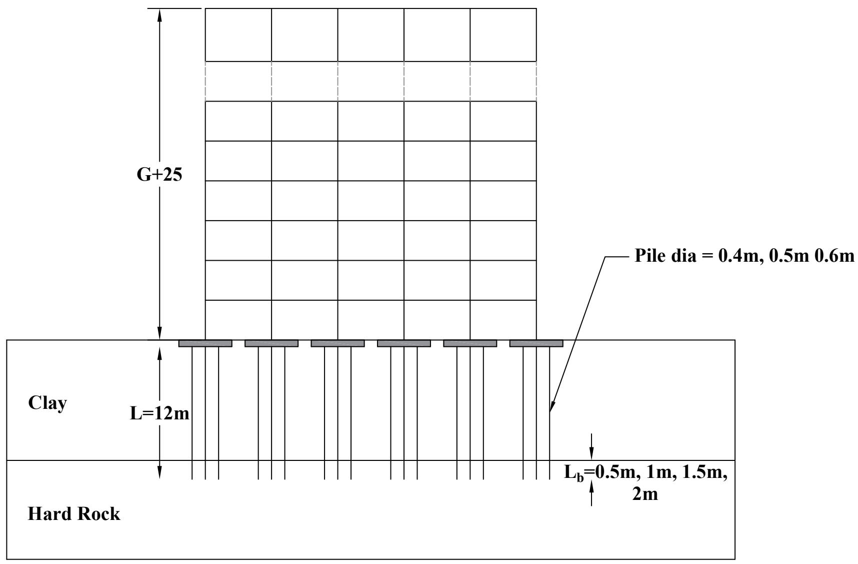

Fig. 2. Elevation of the Soil-Pile-Structure system adopted in the study

5 Response Spectrum Analysis

5.1 General

The response spectrum method can be performed on any structure irrespective of the construction material used, corresponding to 5% damping using the designed acceleration coefficient for soft, medium, and hard soil [18]. Fig. 3 shows the design response spectrum curve for the hard soil, medium soil, and soft soil respectively. For the present numerical study, the zone factor, the importance factor, and the response reduction factor of 0.36, 1.5, and 3 are considered as per the IS code [18].

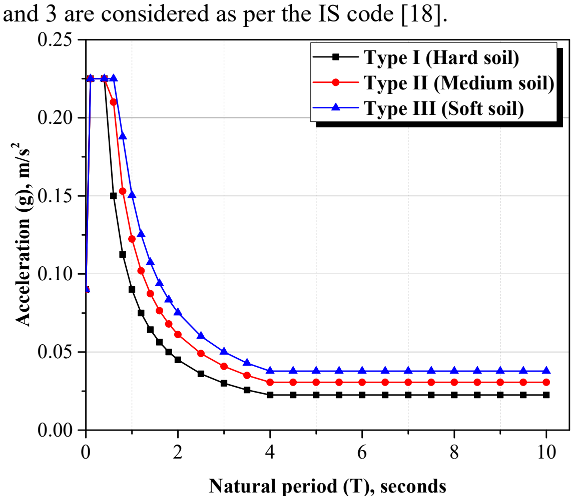

Fig. 3. Design acceleration spectrum for zone V

5.2 Results of Response Spectrum Analysis

5.2.1 Maximum displacement

The effect of pile groups plays a vital role in the behavior of high-rise structures founded on soft soil. Due to the destructive effects of adjacent structures on one other say pounding effect, the result of displacement of the structure due to seismic hazards is essential to study. Lateral displacement in the superstructure consists of structural distortion and rocking effects. SSI amplifies the rocking component in the raft foundation which increases the displacement in the superstructure.

The results of the numerical study for the lateral displacement of 25 storey structure sustained by pile groups for various configurations of the length of the pile (L) to the diameter of the pile (d) and embedded length (L_b) to the length of the pile (L) such as 30,24, 20 and 0.042, 0.083, 0.125, 0.167 are summarized and compared from Fig 4 to Fig 7. According to

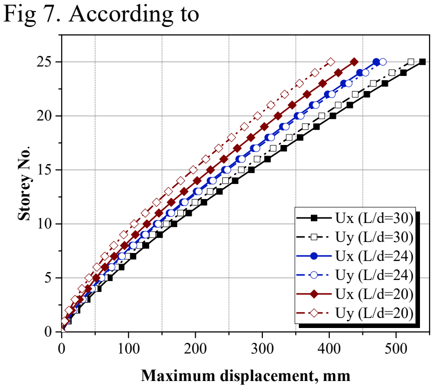

Fig. 4. Maximum displacement (L_b/L= 0.042)

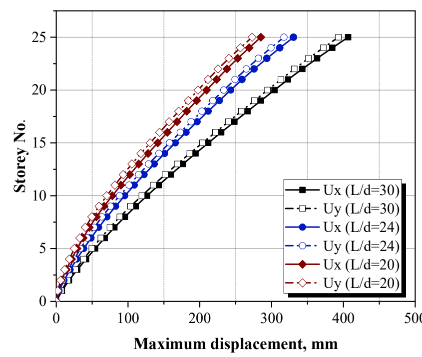

Fig. 5. Maximum displacement (L_b/L= 0.083)

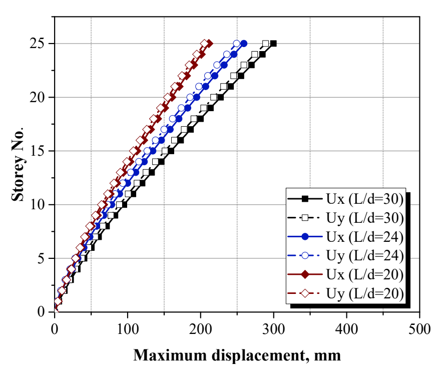

Fig. 6 Maximum displacement (L_b/L= 0.125)

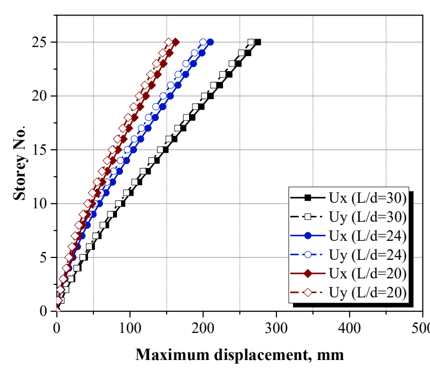

Fig. 7. Maximum displacement (L_b/L= 0.167)

Fig 4 the structure supported by an embedded length of 0.5m i.e., embedded length (L_b) to length of the pile (L) of 0.042 generated maximum displacement in the structure. For example, from Fig. 4, the maximum displacement of the structure resting on L/d ratio of 30 with L_b/L ratio of 0.042 embedded length was 539.5mm, while the corresponding value for the structure resting on L/d ratio of 20 with L_b/L ratio of 0.042 embedded length was 437.3mm (decreased by 23.4%).

Fig 5 shows that the maximum displacement of the structure supported by L/d ratio of 30 with L_b/L ratio of 0.083 embedded length ratio increased by 42.69% compared to L/d ratio of 24 with L_b/L ratio of 0.083. It is observed that configuration number 12 shows the minimum displacement compared to the all-configuration cases. Lateral displacement decreases with an increase in the diameter of the soil and the embedded length of the pile. The effect of SSI in increasing displacement is more prominent in structures with L/d ratio of 30 and with L_b/L ratio of 0.042.

5.2.2 Inter-storey drift (ISD)

The Inter-storey drift (ISD) is described as the variance between the displacement of two adjacent floors. Fig 8 to Fig 11 represents the inter-storey drift of the structure resting on pile groups of different diameters of the pile and embedded length. SSI tended to amplify the ISD of the structure, although the maximum ISD of the superstructure sustained by L/d ratio of 30 and L_b/L ratio of 0.042 (Fig 8) was more than the corresponding value for the L/d ratio of 20, and the L_b/L ratio of 0.167 (Fig 8).

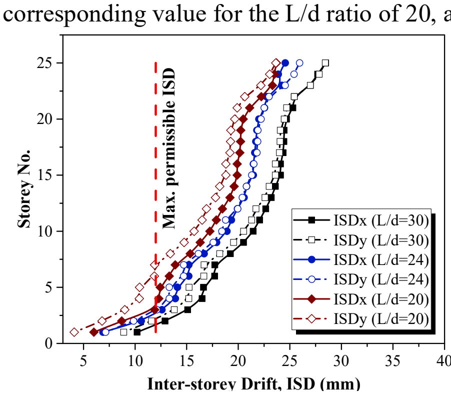

Fig. 8. Inter-storey drift (L_b/L= 0.042)

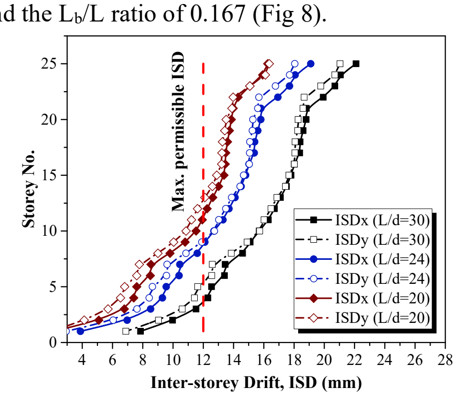

Fig. 9. Inter-storey drift (L_b/L= 0.083)

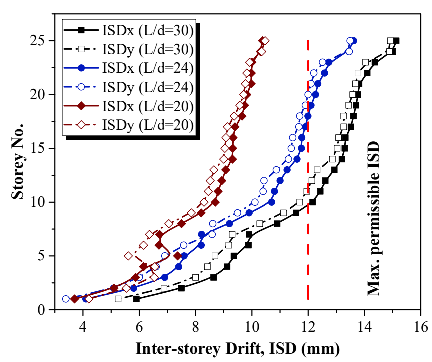

Fig. 10 Inter-storey drift (L_b/L= 0.125)

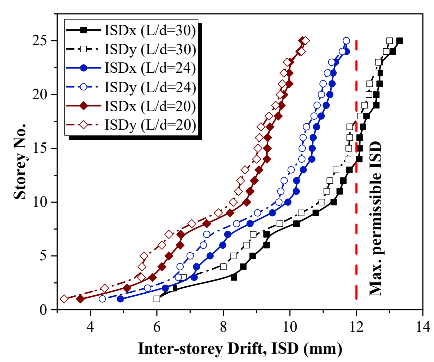

Fig. 11. Inter-storey drift (L_b/L= 0.167)

Under the impact of the L/d ratio of 30 and L_b/L ratio of 0.042, the maximum inter-storey drift was increased by 20% compared to the L/d ratio of 20 and L_b/L ratio of 0.042 respectively. Fig 11 Shows the inter-storey drift profile over storey height modelled with L/d ratio of 20 and L_b/L ratio of 0.167. The inter-storey drift response demands of these structures modelled with L/d ratio of 24, 20: L_b/L ratio of 0.083 was 19.1mm, 16.26mm respectively; for L_b/L ratio of 0.125 was 13.61mm, 11.58mm respectively; and L_b/L ratio of 0.167 was 10.38mm, 8.47mm respectively. The results showed that the SSI changed the performance level of the structure, moving it from the life-safe zone to the near collapse or collapse zone. With each pile having a variable diameter and length, input parameters attracted various parts of the structure with larger mode responses, resulting in a dispersion of inter-storey drift throughout the superstructure.

5.2.3 Column moment

As a way to examine how soil and structure interacted, 3D numerical estimates of the column moments of structures supported on pile groups are provided and analyzed in this section.

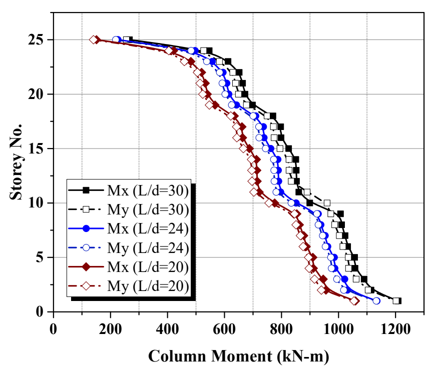

Fig. 12. Column moment (Lb/L= 0.042)

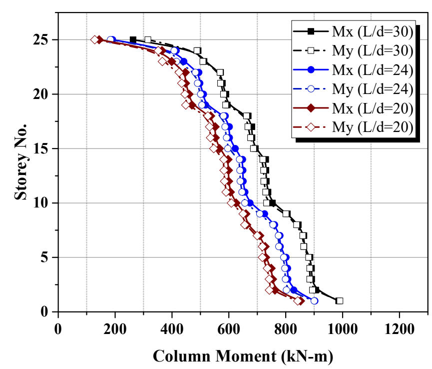

Fig. 13. Column moment (Lb/L= 0.083)

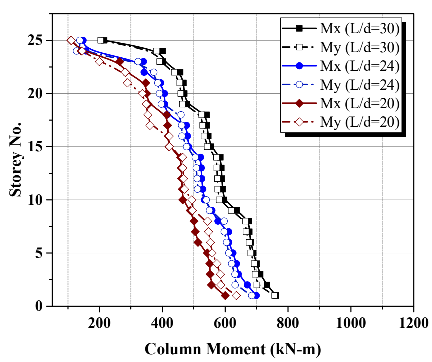

Fig. 14. Column moment (L_b/L= 0.125)

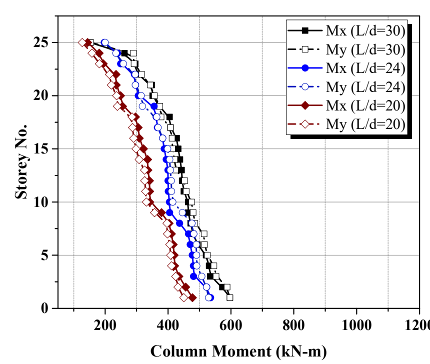

Fig. 15. Column moment for (Lb/L= 0.167)

For instance, column moment at a 1-F column (Fig. 1) for twelve configurations over storey height. According to the results shown in Fig. 12 and 15 the least and the highest values of column bending moment are observed for L/d ratio of 20 with L_b/L ratio of 0.167 and L/d ratio of 30 with L_b/L of 0.042 respectively. From Fig. 12 it is illustrated that column moment observed for the structure simulated in L/d ratio of 30, 24, 20 with L_b/L ratio of 0.042 are 1209.7kN-m, 1134 kN-m and, 1059.5kN-m respectively. Similarly, Fig 13 clearly shows that the profile observed in L/d ratios of 30, 24, and 20 with L_b/L ratio of 0.167 is decreased by 51%, 53%, and 55% respectively.

5.2.4 Base shear

Base shear is the sum of designed lateral forces at the base considering all the storey above. The base shear of a building depends on both spectral acceleration (S_a/g) and mass. The base shear depicts the shear force generated in a superstructure along seismic excitation. When SSI is taken into account, a decrease in base shear is often seen in medium to stiff subsoils. In contrast, base shear usually increases in soft soil. Fig. 16 to Fig. 19 shows the structural response with regard to the base shear for response spectrum analysis.

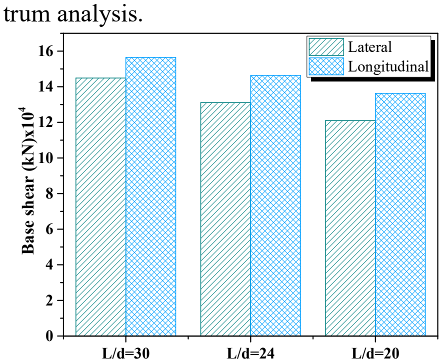

Fig. 16. Base shear (Lb/L= 0.042)

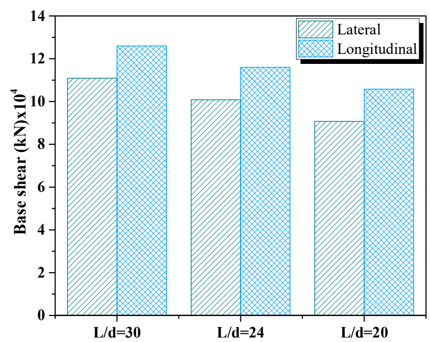

Fig. 17. Base shear (Lb/L= 0.083)

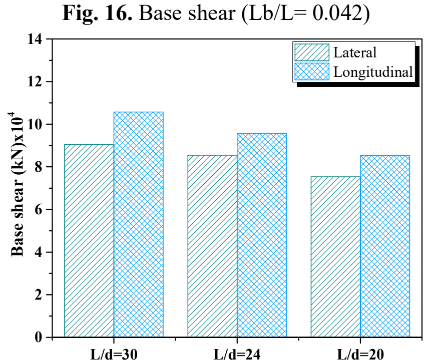

Fig. 18. Base shear (Lb/L= 0.167)

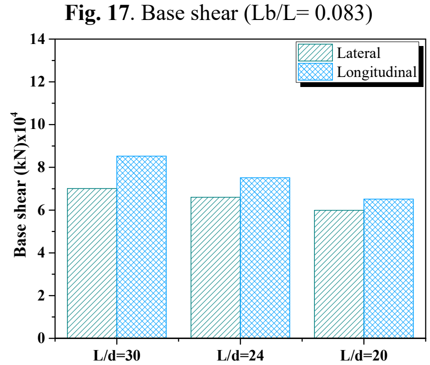

Fig. 19. Base shear (Lb/L= 0.125)

Under the impact of the L/d ratio of 30 and L_b/L ratio of 0.042, the base shear was increased by 14.8% compared to the L/d ratio of 20 and L_b/L ratio of 0.042 respectively. The inter-storey drift response demands of these structures modeled with L/d ratio of

24, 20: L_b/L ratio of 0.083 decreased by 8%, and 16% respectively compared to L/d ratio of 30; for L_b/L ratio of 0.125 decreased by 9.6%, 19.2% respectively compared to L/d ratio of 30, and L_b/L ratio of 0.167 decreased by 8%, 16% respectively compared to L/d ratio of 30.

Conclusions

From the parametric study, it is concluded that the structure supported by a pile diameter of 0.6m and embedded length of 2.0m has better performance under seismic excitations. When soil-pile-structure interaction is taken into account, the super-structure reactions in terms of displacement and inter-storey drift values are enhanced in all types of structures. In addition, the reduction in pile diameter and embedded length of the pile increased the displacement, inter-storey drift, column moment, and base shear. The Inter-storey drift values exceeded the maximum permissible value of 0.4% considering soil-pile-structure interaction. It is concluded that configuration number 12 shows the minimum displacement compared to the all-configuration cases. Lateral displacement decreases with an increase in the diameter of the soil and the embedded length of the pile. The effect of SSI in increasing displacement is more prominent in structures with L/d ratio of 30 and with L_b/L ratio of 0.042.

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