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Investigation on Influence of Pile Foundation on Seismic Response of Irregular Building Considering Soil-Structure Interaction

Vaibhav Mittal[1] [0000-0002-5094-2333], Manojit Samanta[2#] [0000-0002-6017-725X], D.P. Kanungo[3]

[1] Research Scholar, Geotechnical Engineering Group, CSIR-Central Building Research Institute (CSIR – CBRI), Roorkee, Academy of Scientific and Innovative Research (AcSIR), Ghaziabad, 201002, India. Email: vaibhav.cbri19a@acsir.res.in
[2]Principal Scientist, Geotechnical Engineering Group, CSIR – Central Building Research Institute (CSIR – CBRI), Roorkee, Academy of Scientific and Innovative Research (AcSIR), Ghaziabad, 201002, India. [#]Corresponding Author, Email: manojit@cbri.res.in
[3]Chief Scientist, Geo-Hazard Risk Reduction Group, CSIR - Central Building Research Institute (CSIR – CBRI), Roorkee, 247667, India; Professor, Academy of Scientific and Innovative Research (AcSIR), Ghaziabad, 201002, India. Email: dpkanungo@cbri.res.in

Abstract. Seismic Soil-Structure Interaction (SSSI) is an important aspect in the satisfactory long-term performance of buildings. Assessments of seismic demand of the buildings supported over rigid/fixed base are more well established. Due to the reduction in flexural and torsional stiffness, irregular structures are more vulnerable to damage during seismic disturbance. The present paper investigates the effects of SSSI for irregular building supported on pile foundation. This study utilizes three-dimensional numerical approach to investigate the seismic response of a mid-rise building. Two different configurations of plan irregularities and two recorded ground motions are being considered in the present study. Different parameters such as lateral displacement, interstorey drift, base shear of irregular building considering the effects of SSSI are systematically investigated and reported here. The comparative study among different lengths of pile foundation supporting the regular and irregular buildings brings out the importance of SSSI on their performance. Results indicated that considering the effects of SSSI amplifies the lateral displacement, interstorey drift and base shear to a larger extent for irregular building in comparison to regular building supported on pile foundations.

Keywords: Plan Irregularity, Soil-Structure Interaction, Chi Chi Earthquake, Northridge Earthquake, Pile Foundation.

1 Introduction

Interaction between super-structure and sub-structure plays an important role in the seismic design of the buildings. Generally, structures are assumed to be supported on a fixed base, nullifying the effect of soil/foundation to generally allow the free field ground motion (Kramer 1996). However, the process in which the influence of soil and structure are estimated relative to each other, is known as seismic soil-structure interaction (SSSI) (Kramer 1996). Seismic soil-structure interaction constitutes two mechanisms i.e., kinematic and inertial interaction. When the stiffness of the foundation system disrupts the free-field motion, kinematic interaction takes place. This interaction results in foundation to rock as well as translate. However, an additional deformation caused due to the transfer of inertial force by superstructure to the soil, leads to inertial interaction. This interaction results in torsional excitation and moment, which causes additional displacement in the soil-structure system (Kramer and Stewart, 2004).

Irregular/Asymmetric building are almost unavoidable in modern civil engineering construction due to various types of functional and architectural requirements. Generally, in these buildings the center of mass (COM) does not coincides with the centre of resistance (COR), leading to a torsional effect. Larger is the eccentricity between the COR and COM, the larger will be the torsional effects. Additional displacements are obtained due to these torsional vibrations. Hence, irregular buildings are more susceptible to seismic excitations compared to the symmetrical buildings. Olariu and Movilla (2014) reported analytical approaches like spectral acceleration method to assess the behavior of shallow foundation supporting asymmetric building. Sharma and Ankit (2014) performed a 3D non-linear analysis to assess the behavior of asymmetrical building with shear wall. In this study, the effect of soil-foundation-structure interaction has been modeled by spring and dashpot. The results show that shear wall reduces the torsional vibrations in the building. Badry and Satyam (2016) reported the effects of SSSI for asymmetrical building supported on piled-raft foundation subjected to 2015 Nepal Earthquake. The results obtained show that a C – Shape building is more vulnerable to damage during any seismic excitation.

Pile foundations transmit the load through soil strata of low bearing capacity to deeper soil or rock strata having higher bearing capacity. Determination of seismic response of pile foundation is a complex process which involves interaction between the structure and foundation, piles and soil, and non-linear response of soils to different seismic excitations. However, several researchers (e.g., Popov 1957, Baker 1957, Brown et al. 1977 and Bowles 1996) uses simple methods such as Winkler’s model to model the soil-pile-interaction. However, the results obtained by these constitutive models are less accurate due to the simplified assumptions used. Han and Cathro (1997) compare the response of a tall structure supported on pile and shallow foundation, and found that the behavior of building varies with the change in foundation system. Chu and Truman (2004) estimate the effects of configurations of pile groups on buildings. They do not find any significant differences in seismic response obtained between largely and closely spaced piles. Hokmabadi et al. (2014a) studies the effects of floating pile foundation on seismic response of mid-rise buildings. The results show that the floating pile foundation reduces the lateral displacement of the building in comparison to shallow foundation, due to reduced shaking components. Bagheri et al. (2018) studies the influence of group of pile foundations on seismic response of mid- and high-rise steel buildings. The results show that spacing of piles and its geometric characteristics influence the performance level of the structure on the softened ground. Although a large number of studies dealing with the SSSI effects are available in literature, further investigations are required to estimate the influence of piles on seismic response of irregular structures. Literatures related to response of irregular structures supported on pile foundation are rare. The present study aims to study influence of end-bearing pile foundation on the seismic response of irregular structures employing the fully nonlinear time history analysis. For this purpose, a set of numerical investigation involving regular and irregular building configuration (L and T-shape), and foundation type (fixed base and end bearing pile foundation) have been conducted to determine the influence of different lengths of the pile on the seismic response of irregular building in comparison to regular and fixed-base buildings.

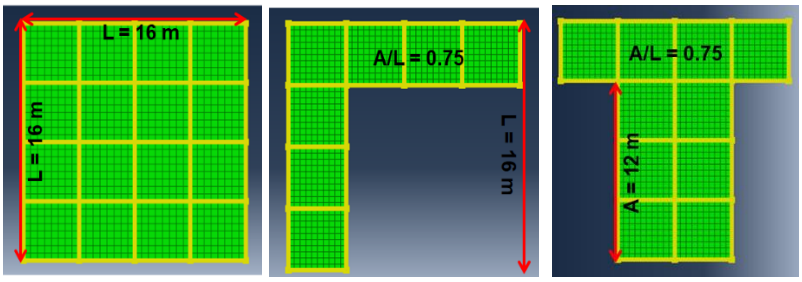
2 Numerical Model

An extensive 3D finite element analysis using ABAQUS has been carried to investigate the responses of regular and irregular structures supported over end-bearing pile-foundations. A fifteen-storey regular building, 45 m high and 16 m wide with four spans in each direction is selected, as shown in Fig. 1 (a). The geometric and material characteristics of the different components of the superstructure are presented in Table 1. These sections are found to be safe against different load combination, as per IS 1893 (Part 1): 2016. The different components of the superstructure are considered to be linear elastic and isotropic. In order to evaluate the influence of irregularity, two different plan configurations (T and L shape) consisting of 75 % irregularity are selected as per IS 1893 (Part 1): 2016, as shown in Fig. 1 (b-c). The 3D, 3-noded beam element (B31) and 4-noded shell elements (S4R) are used to model the superstructural components, as shown in Fig. 2.

Table 1. Characteristics of Superstructure and Foundation

Type	Section/ Thickness (m)	Grade of Concrete	μ
Beam	0.30 x 0.30	M 25	0.15
Column	0.45 x 0.45	M 25	0.15
Pile	Diameter: 0.47 m, Length: 15 m, 20 m, 25 m	M 25	0.15
Slab	0.125	M 25	0.15

A group of end-bearing pile foundations has been selected to support the building in order to transfer the load of the superstructure to the soil strata. In order to obtain the dimensions and properties of pile foundation, the unfactored load from the superstructure has been superimposed and are checked against different load combination as per IS: 6403 – 1986 (R2005). In order to investigate the influence of lengths of pile foundation on seismic response of irregular building, three different lengths, including 15 m, 20 m and 25 m are selected. The diameter of the pile foundation considered is 0.47 m. Each column is supported by 4 piles with a spacing of 2.5D. The factor of safety has been estimated for all these foundation systems, and satisfies the strength and serviceability criterion. The grade of concrete used for concrete piles is M 25. The pile elements are modeled with solid elements considering the linear elastic behavior. These piles are discretized using C3D8R elements.



a) b) c)

Fig. 1. Configurations of Superstructure

The superstructure rests on soft soil having unit density of 14.21 kN/m^3, shear wave velocity of 150 m/s, plasticity index of 15% and an un-drained shear strength of 49 kPa. The nonlinearity of soil plays an important role in the seismic response of the building resting over a soft stratum. In this study, the fully non-linear time history analysis has been used. Shear modulus and damping ratio are represented as a function of maximum shear strain to obtain the non-linear behavior of soil. Vucetic and Dobry (1991) performed a number of cyclic tests to evaluate the influence of plasticity index for a wide range of cohesive soils. In this study, the modulus degradation and damping ratio of the soil as shown in Fig. 3 are used. The mechanical properties of the soil used in this study are provided in Table 2. In this study, it has been assumed that the water table is below the bedrock level. The soil continuum is discretized using 8-noded linear brick, reduced integration with hourglass control element (C3D8R).

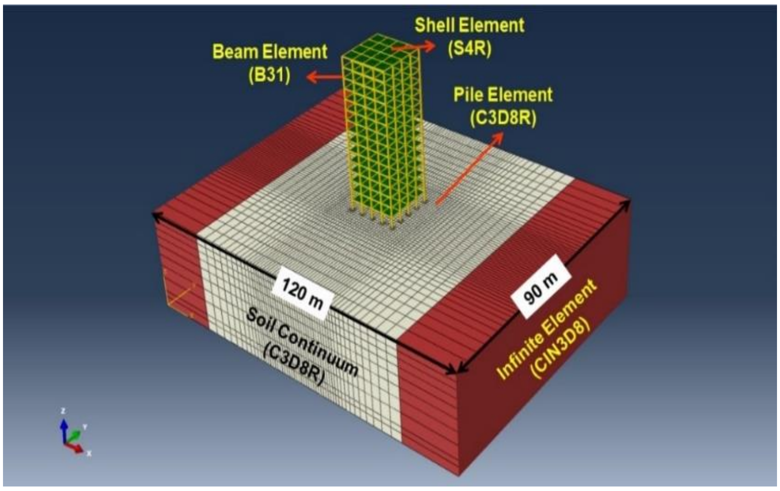


Fig. 2. Three – dimensional (3D) Numerical Model

In order to accurately the seismic response of mid-rise structures, it is important to model the contact/interfacial properties properly. Normal and tangential properties represent the contact surfaces amongst the soil and pile foundation. Since the clearance between the two surfaces is nearly zero, normal contact properties are assigned between the two surfaces of pile foundation and soil. In order to transmit the frictional behavior between the pile and soil, tangential interaction properties are provided. In the numerical model, a friction coefficient = 0.67 has been assigned to simulate the frictional behavior. In order to simulate the soil-structure interaction behavior, a surface – based tie constraint has been provided at the bottom of columns and top of the pile cap.

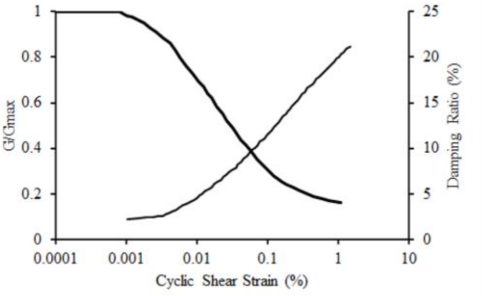
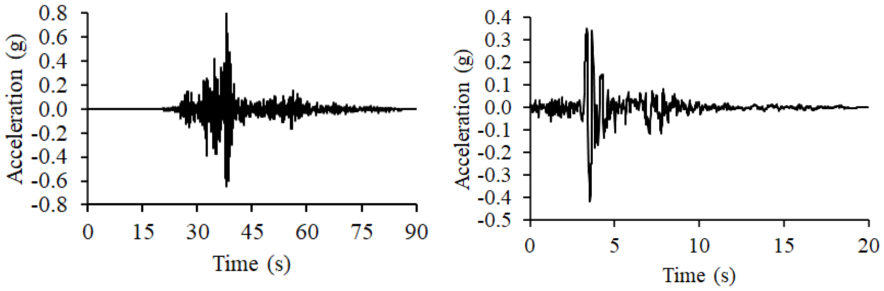


Fig. 3. Shear Modulus Reduction and Damping Degradation Curve for Cohesive Soil (Data from Vucetic and Dobry 1991)

Table 2. Characteristics of the Soil Medium

Type	Parameter
Soil Medium (Along the Length of the Pile)	γ = 14.21 kN/m³, S_u = 49 kPa, μ = 0.40, V_s = 150 m/s
Rock Strata (Below the Pile Tip)	γ = 19.61 kN/m³, μ = 0.30

Boundaries in the vertical direction (Y – direction) are fixed in the transverse directions, but allowed to move in-plane. While, the boundaries of the soil at the bottom are fixed in all directions, while the top surface is allowed to move in all the directions. However, the recorded ground motion is applied at the bedrock and propagated through the system. During the dynamic time-history analysis, infinite boundaries are placed along the lateral directions (X – direction) to avoid the reflection of seismic waves, as shown in Fig. 2. The infinite boundaries are modelled using 8-noded linear brick (CIN3D8) elements.



a) b)

Fig. 4. Adopted Earthquake Records a) Chi Chi Earthquake (1999) b) Northridge Earthquake (1994)

The numerical model for the fixed-base condition consists of 33,000 elements for a 15-storey regular building, which increases to 1,12,166 elements on considering the effects of SSSI. In the present study, the number of elements lies in the range of 15,720 – 1,55,130 for different building type considering fixed and flexible bases. A comparatively finer mesh surrounding the footing area, while a broader mesh across the distant boundaries is used in this study. Since the model is quite large, a system having configuration of 2.30 GHz (24 processor) and 128 GB RAM is used to simulate this analysis.

All the models are subjected to two ground motions chosen from Pacific Earthquake Engineering Research (PEER) strong motion database. A variety of intensities, duration, and frequency contents are selected by choosing the recorded ground motion to evaluate the effects of SSSI on the softened ground. Table 3 shows the characteristics of the recorded ground motion used in the present study. Fig. 4 shows the acceleration vs. time characteristics of the recorded ground motions. In the present study, the significant duration/bracketed duration, defined as the interval between the first & last exceedances of the seismic acceleration of 0.05g in the acceleration-time history of ground motion has been selected. These recorded ground motions are applied in the lateral direction (along X – direction) at the base of the system.

Table 3. Characteristics of the Adopted Earthquake Records

Earthquake	M_w (R)	PGA (g)	Hypocentral distance (km)	Type	Duration (s)
Chi Chi (Taiwan) - 1999	7.62	0.809	8.0	Near Field	90
Northridge (United States) - 1994	6.69	0.420	17.5	Far Field	20

Condition, location, and type of load on the foundation depends on the super-structure. The present study involves calculation in four phases. These phases are the determination of initial condition (a geostatic stress condition), application of axial/surface load transferred from the superstructure, determination of the natural frequency of the system, and fully non-linear dynamic analysis to estimate the behavior of the structure for different earthquake records. The results obtained by 3D numerical investigation has been discussed in the following sections.

3 Results and Discussion

The present section provides the results obtained from the numerical investigation in terms of natural frequency of the system, peak lateral displacement at each floor level, maximum interstory drifts, rocking of the foundation, and the maximum base shear experienced by the structures.

The 3D numerical investigation provides the several possible motions and vibrations which are accompanied by the natural frequency for each case, as shown in Table 4. The numerical tool utilizes a linear perturbation procedure for extracting the eigen values to provide the frequencies and corresponding mode shapes for the soil-structure system. The natural frequency of the fixed-base regular structure obtained is 0.43 Hz. However, when the regular building is supported over 15 m, and 25 m end pile foundations possess a natural frequency of 0.368 Hz, and 0.374 Hz, respectively. Several factors such as stiffness, mass & height of the building affect the natural period of the system. Numerical results obtained signifies the influence of these factors on the natural period. Table 4 shows the comparison of natural frequency of soil-pile-structural system for different shapes of the building with different lengths of piles. Due to irregularity in the building, the natural frequency tends to decrease significantly, as shown in Table 4. For instance, the first mode natural frequency of a L shape building is 0.416 Hz, which reduces to 0.346 Hz to 0.348 Hz when supported by 15 m and 25 m piles, respectively.

Table 4. Natural Frequency (Hz) of 15-storey Structure supported by Pile Foundation

Type	Regular		T Shape		L Shape	
	First Mode	Second Mode	First Mode	Second Mode	First Mode	Second Mode
Fixed Base	0.43394	0.43680	0.42410	0.42818	0.41685	0.41796
15 m Pile	0.36892	0.36902	0.34711	0.35440	0.32401	0.34693
20 m Pile	0.37221	0.37384	0.34820	0.35544	0.32640	0.34799
25 m Pile	0.37441	0.37458	0.35121	0.35679	0.32722	0.34804

In order to estimate the performance level of the building, lateral displacement and interstorey drift at each floor level is calculated. Fig. 5 shows the typical variation of maximum lateral displacement of different floors of a 15-storey building supported on pile foundation (PF) and fixed base (FB), estimated for Northridge Earthquake 1994. According to Indian Standard (IS 1893 (Part 1): 2016), the maximum lateral displacement of any building shall not exceed H/500, where H is the total height of the building. For instance, the top storey lateral displacement of the building supported on a fixed - base is found to be in the 126.93 mm, which is increased to a range of 212.32 – 243.60 mm on consideration of the soil-pile-structure system. It can be observed that the lateral displacement of the regular building supported on pile foundation has increased by an average of 80 % of the fixed – base building. However, an increase in length of pile from 15 m to 25 m, resulted in a reduction up to 212.32 mm under the Northridge Earthquake, as shown in Table 5. Table 5 provides a comparison between the maximum lateral deflections obtained for regular and irregular structures under the Chi Chi Earthquake and Northridge Earthquake. The results show that the near-field earthquake has generated more lateral displacement in the superstructure compared to the far-field earthquake.

Fig. 6 shows the comparison between the interstorey drift at each floor level for fixed-base structures and structures supported on pile foundations. The interstorey drift is the ratio of relative lateral displacement between two floors to the respective floor height. It generally shows a similar trend as maximum lateral displacement. However, this parameter helps in governing the performance level of the building. According to Indian Standard guidelines, the interstorey drift under any excitation must not exceed 0.4 % of the floor height (IS 1893 (Part 1): 2016). However, different countries follow different guidelines for governing the performance level of the building. For instance, as per FEMA 243/273, the performance level of any building is classified into five groups depending on the percentage of interstorey drift. The five groups of performance are fully operational (< 0.2%), operational (< 0.5%), life safe (< 1.5%), near collapse

(< 2.5%), or collapse (> 2.5%). According to ASCE 7-16, the permissible limit of the interstorey drift varies in the range of 1.5% - 2.5%, which depends on the category of occupancy by the building.

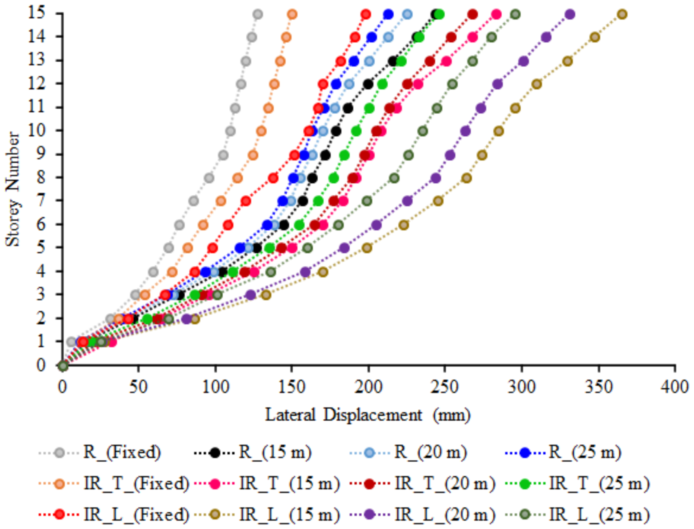


Fig. 5. Variation in Lateral Displacement for Northridge Earthquake (1994)

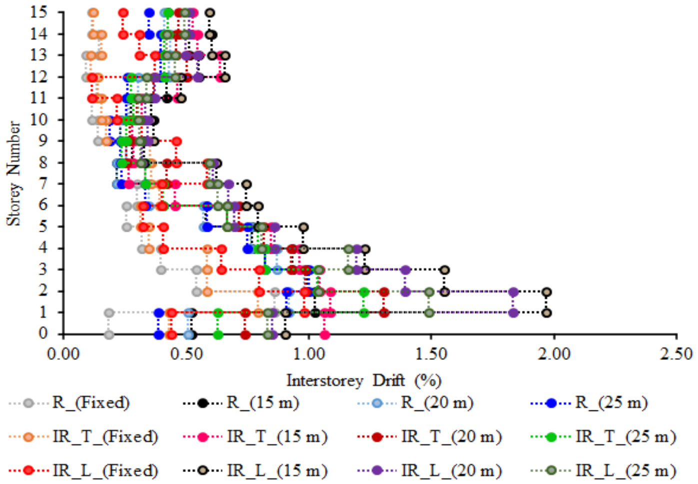


Fig. 6. Variation in Interstorey Drift for Northridge Earthquake (1994)

The results show that on increasing the length of pile, the performance level of the regular building has substantially increased. For instance, the maximum interstorey drift for a 15-storey regular structure is 0.86 %, while the same structure experiences an interstorey drift of 1.09%, when it is supported by an end-bearing pile foundation of 15 m length. However, on increasing the length of the pile, the interstorey drift has been reduced substantially below 1.0 %. However, building with an irregular distribution of stiffness and strength in plan undergoes coupled lateral and torsional movements during the seismic excitation. Generally, in irregular buildings, COR does not match with the COM of the building, resulting in development of torsional movements, leading to increase in lateral displacement and drift of the building. For instance, the maximum lateral displacement of a 15-storey T-shape and L-shape building supported on 25 m pile under the Northridge Earthquake is 245.65 mm (15% more) and 295.02 (39% more), respectively, as shown in Fig. 5 and Table 5. In case of L-building, the peak storey displacement is found to be 20 – 30% more than T-shape building, under the Northridge Earthquake. A similar kind of observation is made for Chi Chi Earthquake also, as shown in Table 5. This observation signifies that complexity in the configuration of the building, affects the performance level during the seismic excitation. Thus, larger the complexity in the building, the chances of failure under earthquake are substantially more.

Table 5. Peak Lateral Displacement (mm) of 15-storey Structure supported by Pile Foundation

Type	Chi Chi Earthquake (1999)			Northridge Earthquake (1994)		
	Regular	T Shape	L Shape	Regular	T Shape	L Shape
Fixed Base	365.94	451.63	671.63	126.93	149.71	197.86
15 m Pile	490.85	576.46	940.71	243.60	282.86	364.98
20 m Pile	453.55	544.89	848.61	225.09	267.37	330.80
25 m Pile	416.25	513.32	756.82	212.32	245.65	295.02

Table 6 shows the variation of rocking for the different lengths of pile foundations supporting a regular fifteen storey structure. Rocking generally occurs due to the inertial forces generated due to the movement of superstructure, which causes compression on one side and tension on the other. This leads to occurrence of settlement and uplift on the two opposite ends. Table 6 show that longer piles experience less rocking in comparison to shorter piles. For instance, in the 1994 Northridge Earthquake, when the length of piles increased from 15 m to 25 m, the maximum rocking has gradually decreased from 0.031° to 0.022°. However, due to development of torsional movements in the irregular structures, the rocking in foundation has increased when compared to regular shaped structures. The results show that L-shape building experiences more rocking in comparison to T-shape building, due to more complexity in the shape of the building.

Table 6. Maximum Rocking (degree) of 15-storey Structure supported by Pile Foundation

Type	Chi Chi Earthquake (1999)			Northridge Earthquake (1994)		
	Regular	T Shape	L Shape	Regular	T Shape	L Shape
Fixed Base	0.000	0.000	0.000	0.000	0.000	0.000
15 m Pile	0.105	0.118	0.151	0.031	0.033	0.035
20 m Pile	0.100	0.114	0.144	0.028	0.027	0.033
25 m Pile	0.099	0.107	0.137	0.022	0.025	0.028

In order to estimate the influence of irregularities and length of pile foundation on the energy absorbed by the superstructure during the seismic excitation, maximum shear force at each floor level has been calculated. To determine the base shear, the shear forces generated in each column at the particular floor level has been summed up at every time increment, and the absolute value has been reported, as shown in Table 7. In general, it has been observed that base shear for longer piles is larger in comparison to shorter piles, as longer piles absorb extra energy due to more contact area with the surrounding soil. It is found that when the length of piles increased from 15 m to 25 m, the maximum base shear has gradually increased from 73.93 MN to 443.95 MN, for the Northridge Earthquake. However, longer piles do not necessarily lead to a safer design on considering the influence of seismic-soil-pile-structure interaction (SSPSI). Asymmetric buildings experiences substantial reduction in base shear, for similar length of pile supporting a regular structure. Due to the eccentricity between the centre of mass and centre of rigidity of an asymmetric building, the lateral torsional coupling generates torsional vibrations, which then reduces the base shear of the structure, as shown in Table 7. For instance, a L-shape building supported over 25 m long end-bearing piles experiences a base shear of 231.64 MN (about 47.82% less), while a T-shape building experiences a base shear of 307.78 MN (about 30.67% less) under similar conditions. This reduction in base shear corresponds to decrease in performance level of the building, which may exceed the safe limit of performance-based design during any seismic excitation.

Table 7. Maximum Base Shear (MN) of 15-storey Structure supported by Pile Foundation

Type	Chi Chi Earthquake (1999)			Northridge Earthquake (1994)		
	Regular	T Shape	L Shape	Regular	T Shape	L Shape
Fixed Base	719.21	465.26	369.55	500.77	347.17	260.57
15 m Pile	106.18	84.98	63.19	73.93	61.88	47.46
20 m Pile	336.54	220.04	165.34	226.67	163.14	118.34
25 m Pile	631.61	418.68	321.41	443.95	307.78	231.64

4 Conclusion

The present study aims at evaluating the performance level of irregular building during seismic excitation, considering the effects of seismic soil-structure interaction. In the present study, the response of a fifteen-storey building, supported on the end-bearing foundation of different lengths, resting over soft soil conditions has been inferred. The numerical modelling technique used for estimating the influence of SSSI in ABAQUS has been described. By adopting a method of direct-calculation, a fully nonlinear time history analysis has been conducted to simulate the coupled behavior under seismic excitations. The numerical investigation leads to the following broad conclusions:

- The results show that the maximum lateral displacement of the building increases with decrease in the length of end-bearing pile foundation. This can push the interstorey drift that may develop the superstructure to exceed the life-safe limit for performance-based design.

- The lateral displacement of the structure consists of two components: structural distortion, and foundation rocking. The study shows that the length of the pile foundation influences the total shear forces absorbed by the superstructure during the seismic excitation. It is found that the base shear for longer piles is larger in comparison to shorter piles, as longer piles absorb extra energy due to more contact area with the surrounding soil, and hence experiences less rocking than shorter piles.
- The complexity in the configuration of the building also influences the response during the seismic excitation. Generally, in a L-shape building, the eccentricity between the centre of resistance and centre of the mass is more, resulting in excess torsional movements, than a T-shape building. This leads to increase in lateral displacement and drift of the building. The results show that on increasing the complexity in the configuration, more lateral displacement occurs, which in turn increases the drift at each floor level. This study shows that the L-shape building is more vulnerable to damage in comparison to a T-shape building under similar conditions.

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