Seismic Response of Reinforced Concrete Buildings Considering Soil Structure Interaction

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Abstract. The response of any structure under the action of seismic activity is dependent on three aspects: the structure, the foundation, and the underlying soil. The Soil-Structure-Interaction ascertains that the soil is flexible. The SSI is a function of the stiffness of structure relative to stiffness of the soil. The compliance nature of soil permits various degrees of freedom, which not only increases the damping properties but also decreases the predicted damage of structure, thus opening up the possibilities of a more economical structure. Although Indian codes do account for Soil-Structure Interaction, it does not encompass every bullet detail regarding SSI. The purpose of this study is to analyze the seismic response of low-rise and mid-rise RC buildings, with and without Soil-Structure Interaction using Response Spectrum Method. Isolated foundation is considered, and stiff, medium and soft clay is considered for comparison. The soil property variables such as shear modulus and Poisson's ratio were considered for calculating spring stiffness. For stiff structures resting on soft soil, SSI can be very beneficial as it increases the natural time period of the building. The damping property of the structure is also enhanced. On the other hand, for stiff structure on stiff soil, SSI has very little impact.

Keywords: Soil structure interaction · Isolated footing · Response spectrum method · Seismic analysis

1 Introduction

The traditional design of seismic- resistant structures involves the assumption of considering the base of the structure to be rigid, thereby omitting the possibility of movement of the underlying soil. Although the assumption of fixed base holds true for some cases, it is not universal. In reality, due to seismic waves, there are additional movements created within the soil, which if accounted can lead to a safer and an economical design. Under the occurrence of seismic activities, the displacement of the structure and the ground are dependent on each other. The footing can slide on the ground, so there exists translational motions. Additionally, the footing will have rocking motions into ground. Such degrees of freedom act as the mode of transfer of amongst the soil and the structure. On accounting this potential behavior on the base of our system would be more realistic.

The superstructure, substructure and the underlying soil gives an interlinked response to earthquake (FEMA 2009). The consideration of flexible behavior of soil enables

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the incorporation of degrees of freedom, which permits the translational and rotational response of the footing relative to soil, thereby decreasing the stiffness of the structures. This also enhances the natural time period, and so there is variation in the overall response of the structure (Dutta et al. 2004).The consideration of deformable nature of soil leads to the acceptance that the foundation acts jointly with the underlying soil and the superstructure. Such tendency of soil will influence the bending moments and shear forces in the building frame. Hence, disturbance in the underlying soil will influence the shear forces and bending moments of the superstructure and vice versa. Such interdependent relationship represents the significance of soil structure interaction (Priyanka et al. 2012).

Although there have been active researches carried out about SSI and its complexity, however limited information is available on behavior of types of soil when SSI is incorporated. This study has been carried out to understand the behavior of types of clayey soil (soft, medium and stiff clay) and comparison is done with respect to fixed base condition.

1.1 Idealization of the System

1.1.1 Structure Idealization

To model the superstructure, two-node beam element and two-node column element of suitable dimensions were taken. For modelling of roof and floor slabs, four-nodded plate elements of apt size were used. To recognize the influence of SSI on structures, 2 RC OMRF G+3 storey and G+5 storey buildings are analyzed using Response spectrum method in ETABS 18 software.

The height of each storey is 3 m. The length of each bay is considered to be 4 m. For evaluation of dead loads and imposed loads, IS 875 (Part 1 and Part 2):1987 were used. The peripheral brick walls were considered as 200 mm thick, while the thickness of interior bricks walls was taken as 150 mm. The seismic parameters were taken as per the guidelines of IS 1893 (Part 1): 2016. In this study, the seismic zone is taken to be zone IV. Importance factor is kept to be 1.0. The grade of concrete is taken as M30 and grade of steel as Fe500. The thickness of shell elements is kept as 0.125 m. The plan area of both the buildings is 16 m × 16 m. The percentage rebar is less than 2% for beams, and less than 4% for columns. Stiffness modifier is taken as 0.35 for beams, and 0.7 for columns.

The seismic analysis is done by Response Spectrum method. The beams and column size are same for both G+3 and G+ 5 model. The function damping ratio is taken as 0.05. The mass source is defined for 100% dead loads and 25% live loads. Load combinations taken were in accordance with Ultimate and serviceable Limit states as per IS codes. For efficient comparison of results, parameters such as size of beams, columns and slabs are kept same for both G +3 and G +5 storey buildings.

The sizes of structural elements are given as follows:

Figures 1 and 2 represent idealized representation of G+5 storey building with fix base and SSI respectively. Figure 3 represents the plan of building incorporating SSI.

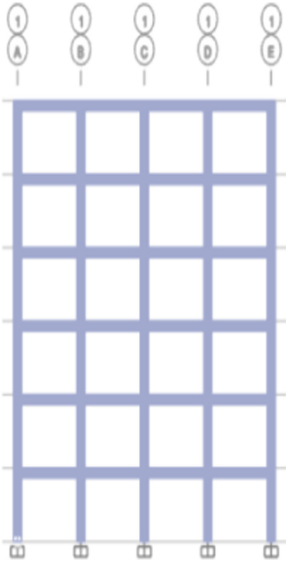

Fig. 1. Elevation, G+5 fix base.

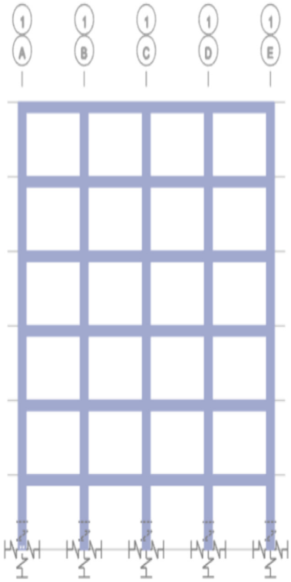

Fig. 2. Elevation, G +5 with SSI.

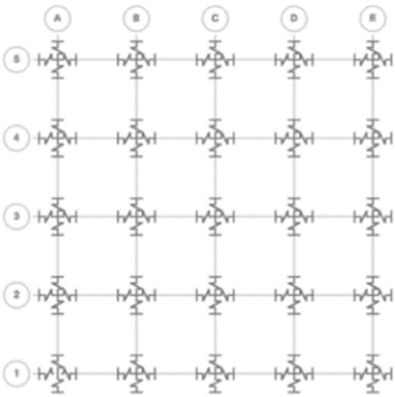

Fig. 3. Plan, G+5 with SSI.

1.1.2 Soil Idealization

In the present study, isolated footing is designed on the basis of load acting on the structure with fixed base. The footings were designed for of allowable bearing capacity of soft clay which is taken as 135 kN/m^2. The soil properties are shown in Table 2.

The results obtained as Fix base in this study are determined by keeping soil conditions as stiff. Table 3 gives the sizes of isolated footing designed (Table 1).

Table 1. Dimensions of structural elements

Model	Beam size (m)	Column size (m)	Slab thickness (m)	No of bays	Grade of concrete	Grade of steel
G +3	230 × 300	400 × 400	125	4 × 4	M30	Fe500
G+5	250 × 400	500 × 500	125	4 × 4	M30	F500

Table 2. Soil properties

Soil type	Poisson's ratio	Shear modulus of soil (kN/m^2)
Soft clay	0.5	30502.6
Medium clay	0.5	53108.1
Stiff clay	0.5	104602

Table 3. Isolated footing dimensions

Model		Footing size (m)	
	Corner footings	Peripheral footings except corners	Interior footings
G+3	2.3 × 2.3	2.8 × 2.8	3.3 × 3.3
G+5	2.3 × 2.3	2.8 × 2.8	3.3 × 3.3

The soil spring stiffness of isolated footings is calculated by the equations given by Gazetas (1991). Kz is the translational spring stiffness in vertical direction, whereas *Kx* and *Ky* are soil spring stiffness in the translational X and Y direction respectively. K_{xx} and K_{yy} are rotational stiffness, and K_{zz} is torsional stiffness. Table 4 represents the spring stiffness values calculated in this present study.

K_x: Horizontal spring stiffness (lateral)

K_y: Horizontal spring stiffness (longitudinal)

K_z: Vertical spring stiffness

K_{xx}: Rotational spring stiffness

K_{yy}: Rotational spring stiffness

K_{zz}: Torsional spring stiffness

Kxi, Kyi, Kzi, Kxxi, Kyyi, Kzzi are the spring stiffness at all the interior joints.

K_{xe}, K_{ye}, K_{ze}, K_{xxe}, K_{yye}, K_{zze} are the spring stiffness at all the exterior joints except corners.

K_{xe}, K_{ye}, K_{ze}, K_{xxe}, K_{yye}, K_{zze} are spring stiffness at the four corner joints.

Table 4. Spring stiffness values for clayey soil

Values of spring stiffness for different types of soil for isolated footing			
Stiffness (kN/m)	Soft Clay	Medium Clay	Stiff Clay
Kz_i	456989.50	795665.10	1567154.05
Kx_i	301975.44	525769.89	1035564.35
Ky_i	301975.44	525769.89	1035564.35
$Kxxi$	986098.52	1716897.61	3381627.58
Kyy_i	1020101.92	1776100.98	3498235.42
Kzz_i	1217661.58	2120072.39	4175726.74
Kz_e	387748.66	675109.78	1329706.47
Kx_e	256221.58	446107.78	878660.66
Ky_e	256221.58	446107.78	878660.66
Kxx_e	602355.09	1048761.34	2065656.24
Kyy_e	623125.95	1084925.53	2136885.77
Kzz_e	743804.63	1295039.35	2550729.14
Kz_c	318507.83	554554.46	1092258.88
Kx_c	210467.73	366445.68	721756.97
Ky_c	210467.73	366445.68	721756.97
Kxx_c	333858.16	581280.94	1144899.76
Kyy_c	345370.51	601325.11	1184379.06
Kzz_c	412257.24	717781.69	1413753.71

2 Results and Discussions

2.1 Variation of Fundamental Time Period Due to SSI

It is observed that SSI is a function of stiffness of the structure relative to stiffness of the soil. The effect of SSI dominates for stiff structure - flexible soil condition. Table 5 gives the time periods for low-rise and mid-rise models with and without SSI.

Table 5. Comparison of time period (s) for various soil densities and number of stories

Storey		Time period (seconds)		
	Fix base	Stiff soil	Medium soil	Soft soil
G+3	0.914	0.92	0.926	0.935
G+5	1.039	1.052	1.065	1.083

Accounting for SSI increases the predicted natural time period of the system. The increase in stiffness of the soil leads to the decrease in the fundamental time period on considering the effect of SSI, fundamental time period of soft clay is more than medium and stiff clay.

2.2 Variation of Base Shear Due to SSI

Base shear is a function of mass, stiffness, height, and the natural period of the building structure. As the storey height increases, the value of base shear increases. Base shear can be quantified as the seismic demand of the structure. On considering the influence of SSI, the seismic demand of the structure may decrease. Due to larger variation in time period, the change is base shear is also significant. Table 6 shows the values of obtained base shear for varying soil types and number of storey. Figures 4 and 5 shows the variation of storey displacements for fixed base condition with SSI condition.

It is observed that for mid-rise structure, due to SSI, the base shear of the structure decreases. Hence SSI tends t o reduce the structural demand of the system. As the structure becomes more flexible, lesser lateral forces are attracted to it. In the low-rise structure, there in slight increase on base shear when SSI is compared to fixed base condition.

Table 6. Base shear for G+5 and G+ 3 storey buildings

Base shear (kN)						
Storey	Soft clay	Fix base	Medium clay	Fix base	Stiff clay	Fix base
G +3	1200.63	1180.68	983.45	961.66	725.703	707.08
G+5	2645.67	2865.65	2175.34	2187.09	1609.44	1608.17

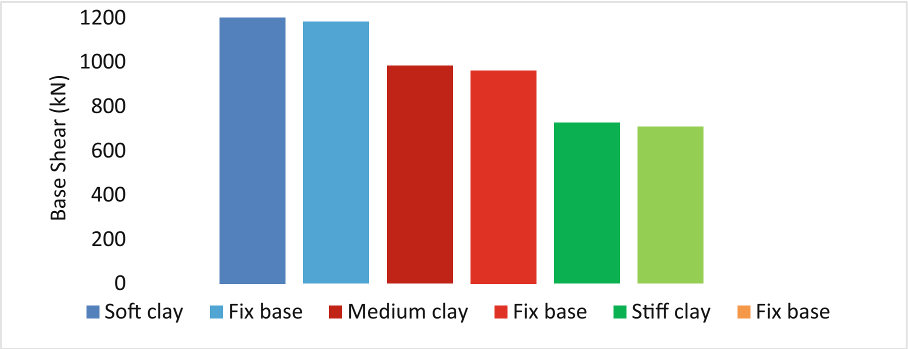

Fig. 4. Variation of base shear for G+3 storey for different types of clayey soil.

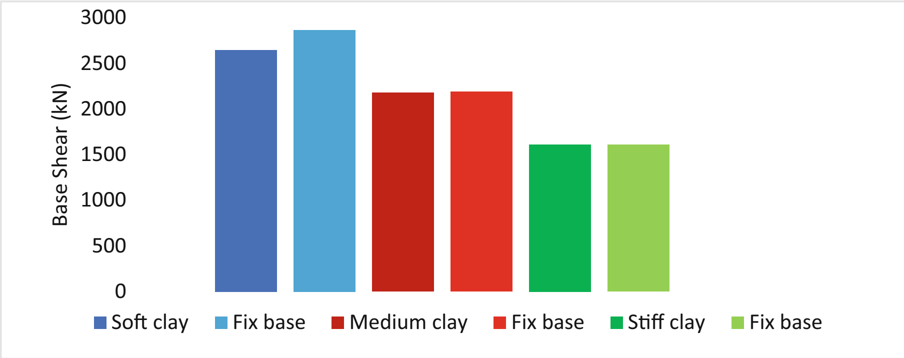

Fig. 5. Variation of base shear for G+5 storey for different types of clayey soil.

2.3 Storey Displacement

The storey displacement is almost converging for fix base considering soil type I and SSI with stiff clay (Soil type I). This proves that SSI has insignificant effect on Stiff structures on Stiff soil. However, for stiff structures on soft soils, SSI plays its role.

Variation of lateral displacements for different soil type are shown in Figs. 6 and 7. It is observed that the displacement values are increasing as the soil type changes from stiff to soft.

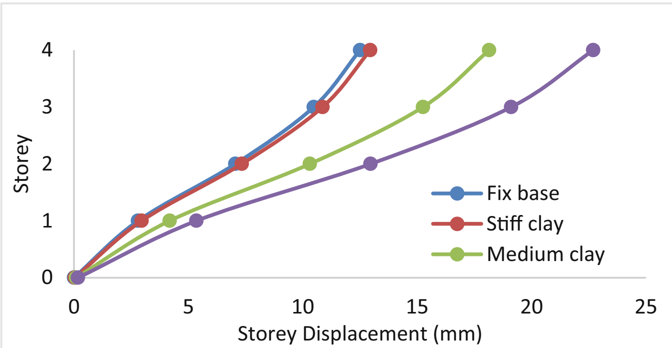

Fig. 6. Variation of storey displacement of G+3 storey building for various soil types.

Storey displacement is increasing from Stiff clay to medium clay to soft clay, and for soft clay it is maximum. Both low-rise and high-rise model abide by the above observations.

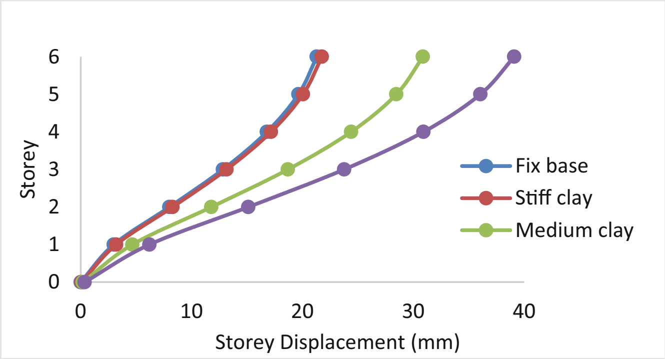

Fig. 7. Variation of storey displacement of G+5 storey building for various soil types.

2.4 Interstorey Drift Ratio

The interstorey drift ratio shows a decreasing trend with increasing stiffness of soil. It is dependent on Storey displacement. As per IS 1893 (Part 1): 2002, clause 7.11.1. the storey drift should be less than 0.004 times the height of the storey. The Maximum Drift Ratio (MDR) is less than 0.004 in all cases of the present study.

Figures 8 and 9 shows the variations of interstorey drift ratio for various types of clayey soil and fixed base.

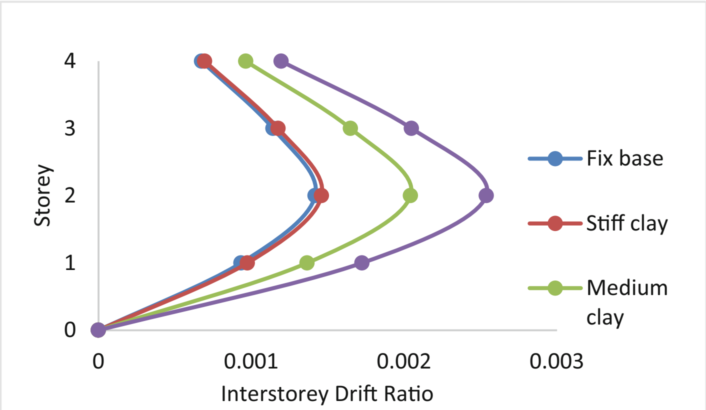

Fig. 8. Variation of Interstorey drift ratio of G+3 storey building for various soil types.

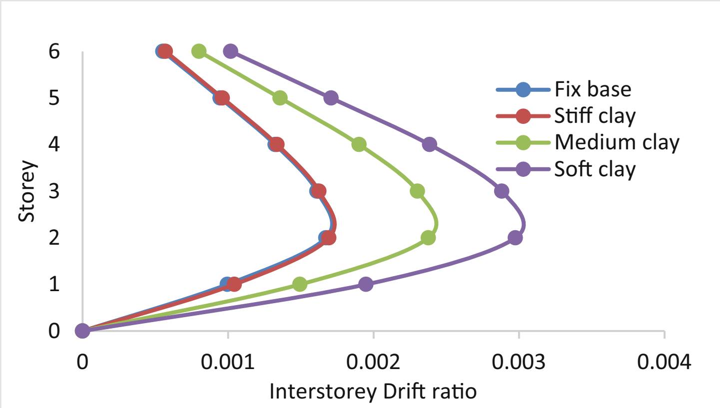

Fig. 9. Variation of Interstorey drift ratio of G+5 storey building for various soil types.

3 Conclusions

The aim of this study was to estimate the influence of SSI on the response of low-rise and mid-rise structures with isolated footing for various site conditions.

- It is observed for both low-rise and mid-rise buildings, SSI contributes predominantly for the soft clay site condition, the natural frequency of the structure for soft clay is minimum.
- The time period for both low-rise and mid-rise buildings is maximum for the structure in soft clay when SSI is considered.
- Base shear gets reduced for mid-rise structures for isolated footing, hence type of foundation plays crucial role in governing the influence on SSI.
- The storey displacements, and interstorey drift ratios are maximum for structure resting on soft clay, and are minimum for stiff clay.
- The maximum interstorey drift ratio is obtained at the second floor for both mid-rise and low-rise building.
- The storey displacement curves for G+5 model for stiff clay, with and without SSI are almost coinciding. This proves, SSI plays a negligible role when stiff structures rest on stiff clay.
- For low-rise structures resting on medium and soft soil, there is a significant increase in the seismic response parameters of the structure, thereby making the role of SSI crucial.

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