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Soil-Structure Interaction Effects on Seismic Response of Multi-storey Buildings

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Abstract

The effect of soil-structure interaction (SSI) on the seismic responses of multi-storey buildings is investigated. The execution of SSI effects is conducted in two ways viz. Winkler approach and soil continuum approach. Time-history analysis methods are used for the seismic evaluation of parameters like time period, modal mass participation, base shear, lateral displacement, storey drift and inter-storey drift ratio. The present study consists of two parts; one is fixed base analysis i.e. without SSI, and the other is flexible base analysis i.e. with SSI. The buildings are modelled using finite element-based software SAP2000, where the equilibrium equations are solved by Hilber-Hughes-Taylor (HHT) method. A parametric study is performed with existing ground motion and varying numbers of stories to inherit the above parameters' responses. The results obtained from flexible base conditions are compared to those corresponding to fixed base conditions. The study shows that the behaviour of the structure changes under the SSI conditions and it may become vital in some cases; however, ambiguity also subsists with SSI.

Keywords: Building, Seismic load, Soil-structure Interaction, Base shear, Stiffness

1. Introduction

Now a day, multi-storey buildings become more advisable with increasing urbanization in urban areas. These multi-storey buildings not only bear the gravity loads but also bear the lateral loads, i.e. earthquake (seismic) load, wind load, water and earth pressure. Out of these, earthquakes are always menacing to the human being and infrastructures. In the seismic analysis of multi-storey building, soil-structure interaction (SSI) is a vital tool to deal with the actual responses of the building as the interaction forces bring an impact on the buildings. When the building is large and located on the weak soil, SSI is notable for seismic analysis compared to a small building located on hard soil.

In recent times, the SSI effects on the seismic performance of frame structure have attracted researchers' special interest. This phenomenon was neglected in the past, considering that the structure is perfectly fixed at its foundation and rarely integrated into the analysis by using empirical approaches. The flexibility of the soil media leads to supplementary deformations under the static or dynamic loadings. In the building's dynamic analysis, the base support condition is a very vital parameter in assessing the structural responses and distribution of inter-storey drift ratios within structural members. This parameter may be different depending upon the nature of the supporting ground. For hard soil, the base foundation could be assumed as fixed, whereas the base foundation could be assumed as flexible for soft soil. A flexible base causes a decrease in the structure's stiffness and increases the period of vibration during the seismic activity. Subsequently, the building structure's response, such as displacement, drift ratio, and P-Δ effects, will be diverse from the fixed base that can be harmful or favourable. That's why; the seismic analysis of structure on soft soil has gained lots of attention in seismic active areas. The SSI has both kinematic and inertia effects on the structure, though, in this study, only the inertia effect is considered. Dynamic structure-soil-structure-interaction (SSSI) may cause insecure element for the seismic design of tall buildings when the clear distance between structures is close [1].

Many structures are in direct contact with the soil relating a transfer of loads to sub-strata at the foundation and soil interface such as footings, piles, raft foundations, retaining walls, etc. Under seismic excitation, this phenomenon is essential because their outcomes significantly affect humanity, the social and eco-system of countries [2].

The stiffness of the structure remains constant for hard soil during earthquakes because forces produced in the form of the overturning moment will not disturb the base, but for soft soil overturning moment will disturb the base, that's why the stiffness of the structures modifies during seismic vibration. This phenomenon is known as soil-structure interaction (SSI) effect [3]. The state-of-the-art for the design/evaluation of buildings includes the consideration of local site effects; the effects of soil-structure interaction (SSI) are also being considered in some design text.

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However, the effects of SSSI are not yet quantified well as the research on the effects of SSSI is practically more challenging than that of SSI [4].

Earlier, numerous studies showed that the SSI has together favourable and unfavourable effects on the structure. When considering SSI, the flexibility of the structures increases and due to this base shear decreases. But at the same time, lateral displacement of the structures increases. It is observed that a decrease in base shear is beneficial. Still, other hand increases in lateral displacement prompt the P-Δ effect because of heavy inter-storey drift, which leads to the collision of nearby structures [5]. The phenomenon of reversal of stresses, i.e., tension, may change to compression and vice-versa in the structural component because the earthquake changes its directions abruptly. The high stresses generated in building due to the reversal phenomenon leads to large distortion and yielding in the structures. Due to this huge storey drift in the building occurs which makes the structure insecure for the immigrants to habitat there [6]. In this study, the responses of three different regular reinforced concrete (RC) buildings are investigated under the existing ground motions in terms of the time period, modal mass participation, base shear, lateral displacement, storey drift and inter-storey drift ratio (IDR) considering the fixed base and the flexible (Winkler and Soil Continuum) base conditions [7].

2. Modelling and Validation

2.1 Winkler Model

According to Winkler's model, the foundation's deformations due to applied load are confined to the loaded regions only. Defining elastic springs' stiffness, which is used to replace the soil below the foundation, is a major problem with the Winkler model [8]. Gazetas [9] given the expressions to calculate the soil spring stiffness in the horizontal direction (longitudinal *Kx* and lateral *Ky*) & vertical direction (*Kz*) are as follows

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$$K_x = K_y - \frac{0.2GL}{(0.75-\nu)}\left[1.0-\left(\frac{B}{L}\right)\right] \quad (1)$$

$$K_y = \frac{GL}{(2-\nu)}\left[2.0+2.50\left(\frac{B}{L}\right)^{0.85}\right] \quad (2)$$

$$K_z = \frac{GL}{(1-\nu)}\left[0.73+1.54\left(\frac{B}{L}\right)^{0.75}\right] \quad (3)$$

Where G is the shear modulus of soil, E is the modulus of elasticity of soil, ν is the Poisson's ratio of soil. L and B are the length and width of the foundation, respectively.

2.2 Soil Continuum Model

Many studies show the importance of SSI to evaluate structural members' response due to any seismic activity. To predict the actual structural response, the SSI should be considered in the analysis, especially under dynamic or seismic loading [10]. The SSI analysis can be carried out by applying excitations produced by any seismic activity to the soil. These excitations are firstly taken by the foundation system and then transferred to the structural system. The simple equation of motion for the whole 3D volume under the influence of seismic activity is as follows

$$[M]\left\{\ddot{u}(t)\right\}+[C]\left\{\dot{u}(t)\right\}+[K]\{u(t)\}=-[M]\left\{\ddot{y}_a(t)\right\} \quad (4)$$

Where $[M]$, $[C]$ and $[K]$ are the mass, damping and stiffness matrices for the entire system and $\ddot{u}(t)$, $\dot{u}(t)$ and $u(t)$ are the acceleration, velocity and relative displacement vectors of the system nodes and $\ddot{y}_a$ is the input ground acceleration vector of ground motion [11]. The above governing equation's solution is very complex, which is the combination of different vectors and matrices for the soil-structure system. This combination makes the equations mathematically very abstruse and very tough to be solved by the conventional method. A finite element-based software SAP2000 is used to solve this complex equation in the time domain. The non-linear dynamic can be performed in SAP2000 by direct integration with the help of HHT method. This method is also known as alpha-method, which is broadly used in the dynamics analysis for numerical integration. The HHT method is a one-step implicit method for solving the transient problem [12].

2.3 Validation

A typical 10-storey residential buildings plan of 20.0 m × 12.0 m shown in Fig. 1 is considered for validation problem. A similar model was taken by Farqaleet [13]. The storey height is 3.1 m, and the number of bays in X-direction is four with 5.0 m each and in Y-direction is three with 4.0 m each. The beam sections are 0.23 m × 0.45 m, but the column sizes are different, which is 0.50 m × 0.50 m. The loading conditions, concrete and steel properties are assumed as per Indian standards. After modelling, the nonlinear time history analysis is performed considering El-centro time history with the fixed based condition. The present results are validated with the results reported by Farqaleet [13]. There is a variation of 1.52% in the time period and 4.71% in roof displacement.

3. Results and Discussion

In the study, three multi-storey RC buildings of six (G+6), eight (G+8) and ten (G+10) storey are considered for dynamic analysis with (flexible base) and without (fixed) considering the SSI effects. The plan of an RC building, similar to a building situated in MNNIT Allahabad campus, is 45.5 m × 10.8 m, as shown in Fig. 2. For simplicity, dimensions of beam and column are assumed as 400 mm × 400 mm and 500 mm × 500 mm, respectively. The height of each story is 3.0 m. The percentage of the dead and live loads is considered as per IS code [14]. The material

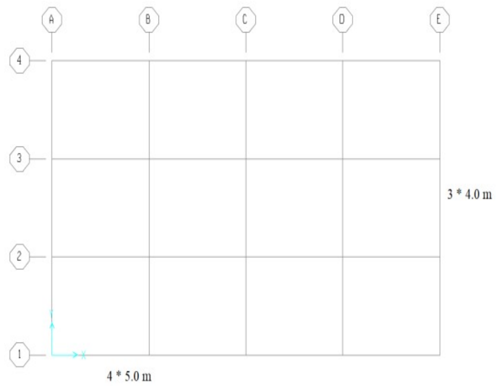

Fig. 1. Plan of the building [13] for validation

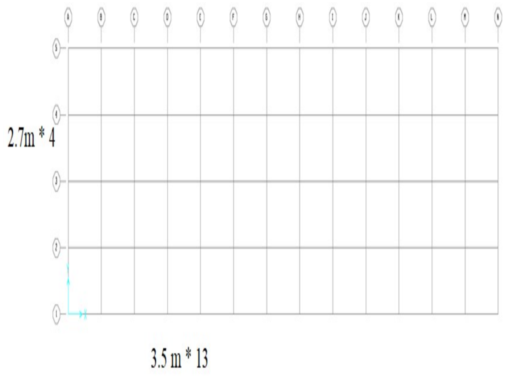

Fig. 2. Plan of the building for present study

properties of concrete (M20) and steel bar (Fe415) are used as per IS code [15, 16]. In the flexible base condition, the soil is modelled in two ways viz. Winkler and soil continuum. In the Winkler approach, the soil is modelled as spring and in the soil continuum approach, the soil is modelled as 3D continuous elastic solid using the finite element meshing. The depth of soil is taken as more than 2B, and the plan is taken as a distance from the structure to boundary not more than 3B, where B is the width of the model of building in a shorter direction. The solid element is used for the meshing of soil, which is eight-noded iso-parametric element. The shell element is used for meshing the structural members, which is homogenous throughout [17].

3.1 Convergence Study

A convergence study is performed on G+6 building with the fixed base condition. It provides the size of the elements required to achieve the minimum error in the evaluated results. In Fig. 3, results converge at the mesh size of 200 mm and after that, the percentage change in roof displacement value is about 0.1%. Hence, the mesh size of 200 mm is adopted for discretizing the models of RC buildings considered for investigation.

3.2 Dynamic Analysis

An existing ground motion of 1979 Imperial (El-Centro) [18] is considered for the dynamic analysis and to design the response spectrum for soft soil conditions conforming to IS code [14]. Figure 4 shows the ground motion data of the Imperial earthquake for 28 seconds. Using this data, time history analysis is performed for both fixed and flexible base conditions.

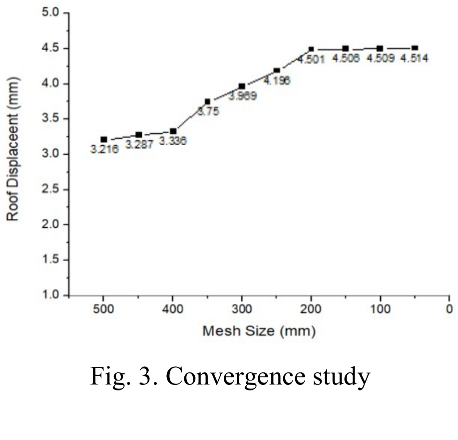

Fig. 3. Convergence study

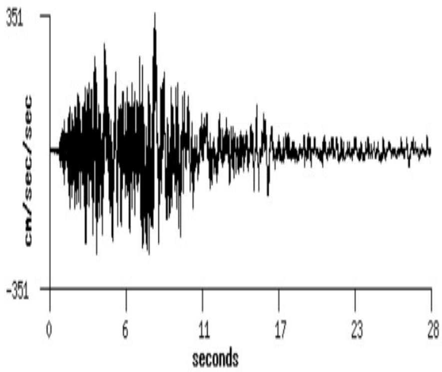

Fig. 4. Ground motion of 1979 Imperial [16]

3.2.1 Time period

The time period plays a crucial role in assessing the lateral loads. It depends on mass and stiffness. Based on the time period, the behaviour of buildings under lateral loads can be evaluated. However, it is difficult to determine the exact time period. Figures 5, 6 & 7 show the time period's variation with all the mode numbers for the buildings considered in the study. It is observed that the time period gradually decreases for the first three modes and after that, an abrupt change in the value of time period because the first three modes of the vibration are most significant as they are the main cause for the damage of any structure. The time period is more in G+10 because when the number of storeys increases for the same plan, its mass increases, but the building's overall stiffness decreases. That's why the time period of the building increases with the increase in height. The time period's value is more in SSI condition because the flexibility of the base decreases the structural stiffness and increases the period of vibration during an earthquake.

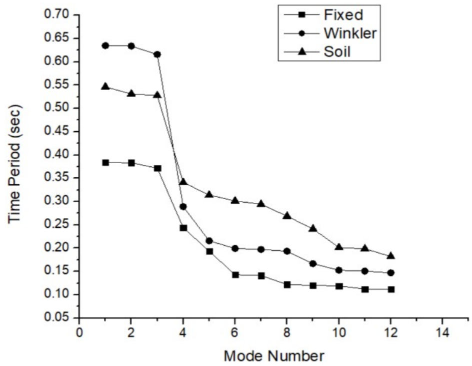

Fig. 5. Time period vs. mode number for G+6

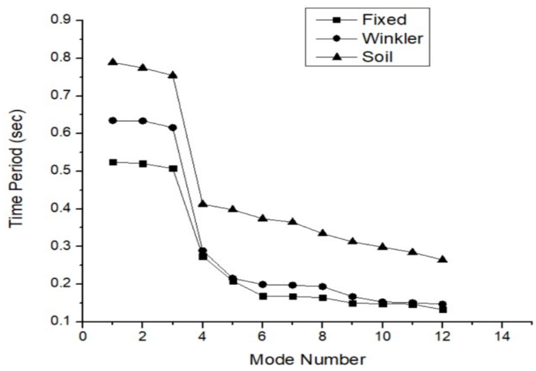

Fig. 6. Time period vs. mode number for G+8

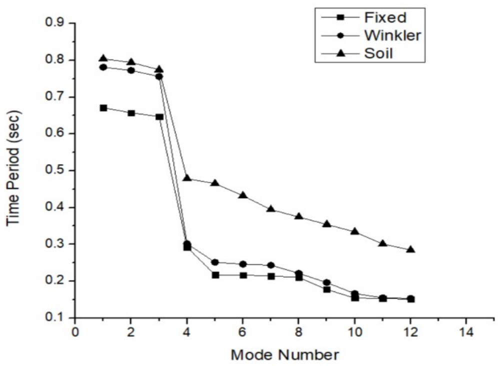

Fig. 7. Time period vs. mode number for G+10

3.2.2 Modal Mass Participation

It gives the information about a particular mode that how much amount of system mass participates in that mode. Here, the Eigen values are calculated by using the time period. A mode with a large effective mass is usually an important contributor to the systems' response. According to IS code [12], the number of modes to be considered in such a way that the minimum participation of the modal mass of all modes is at least 90%. Tables 1, 2 & 3 present the no. of modes required for 90% mass participation and the corresponding percentage of mass participation. The results show that no. of modes required for 90% mass participation is almost the same in fixed and Winkler conditions, whereas in soil condition it is more other than two conditions because the higher modal effect is more important in soil continuum approach to assess the actual response of the structure. Mass participation is maximum in G+10 because, in high storey building, seismic weight contributes more than low storey building with the same building plan.

Table-1. Modes and mass participation for G+6

Fixed		Winkler		Soil	
No. of Mode	Mass Participa -tion (%)	No. of Mode	Mass Participa -tion (%)	No. of Mode	Mass Participa -tion (%)
06	91.29	06	94.40	08	94.89

Table-2. Modes and mass participation for G+8

Fixed		Winkler		Soil	
No. of Mode	Mass Participa -tion (%)	No. of Mode	Mass Participa -tion (%)	No. of Mode	Mass Participa -tion (%)
07	91.95	08	94.73	10	95.01

Table-3. Modes and mass participation for G+10

Fixed		Winkler		Soil	
No. of Mode	Mass Participa -tion (%)	No. of Mode	Mass Participa -tion (%)	No. of Mode	Mass Participa -tion (%)
10	92.14	10	94.76	12	95.62

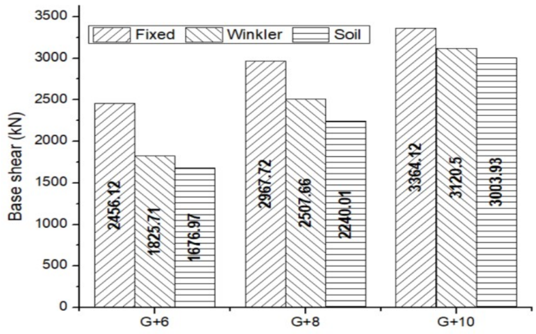

Fig. 8. Base shear of buildings

3.2.3 Base Shear

Base shear is the extreme presumed lateral force at the base of a multi-storey building due to any seismic activity. Figure 8 shows the maximum base shear of buildings with different base conditions. The results show that the base shear value is high for G+10 because of more seismic weight contribution, and the base shear value is low in SSI condition because a flexible base building is tough to excite and generally practices lower accelerations.

3.2.4 Lateral Displacement

Lateral displacement is an absolute value of displacement of a storey under lateral forces like earthquake load, wind load, etc. It is crucial for seismic pounding effect in any seismic activity for making adequate parting between nearby structures. Larger the displacement, the less stiff is structure.

Figures 9, 10 & 11 show the lateral displacement of buildings for different base conditions. The results show that the lateral displacement value is more in SSI condition because, in SSI condition, a large time period value increases the flexibility of the building. The flexible building undergoes large lateral displacement, which is not beneficial for the structure. According to IS code [12], the maximum permissible top storey displacement is H/500, where H is the total height of building in meter. The maximum top storey displacement for G+6, G+8 and G+10 buildings are observed to be 36.0 mm, 48.0 mm and 60.0 mm, respectively. One may see that the present results are within the permissible limit.

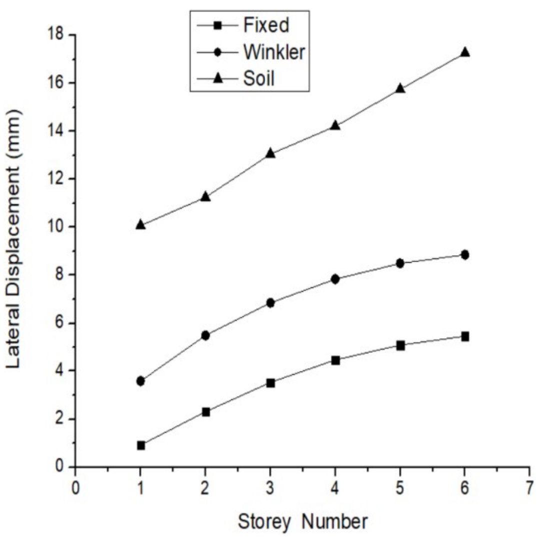

Fig. 9. Lateral displacement of G+6

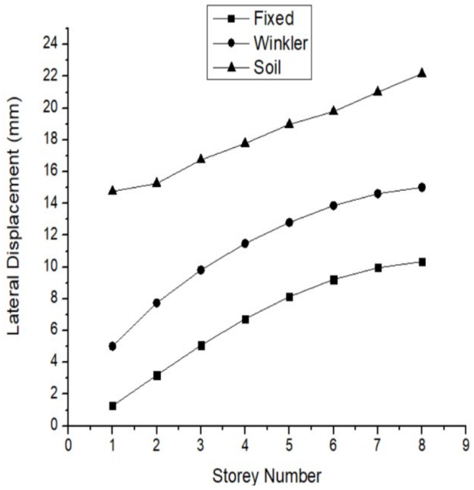

Fig. 10. Lateral displacement of G+8

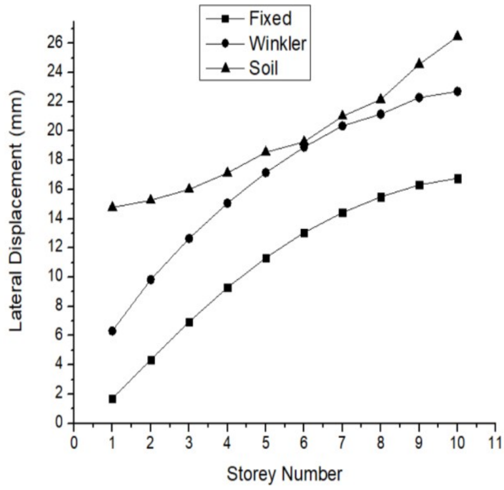

Fig. 11. Lateral displacement of G+10

3.2.5 Storey Drift

It is the inter-storey lateral displacement of one storey to the other storey below. As per IS, due to the design lateral force, the storey drift in any story shall not exceed 0.004 times the storey height. Tables 4, 5 & 6 present the buildings' storey drift for different base conditions found under the permissible limit. The Winkler model gives the larger storey drift as compared to the soil model because this may be the higher modal effect for the 90% mass participation in the soil model. The maximal allowable storey drift is 12.0 mm for all buildings. The storey drift must be within the permissible limit because the non-structural element such as partition wall, pipe work etc. must be able to acknowledge the deflection enacted on them during the seismic activity.

Table-4.Storey Drift in G+6

Storey	Storey Drift (mm)		
	Fixed	Winkler	Soil
1st - 2nd	1.385	1.901	1.180
2nd - 3rd	1.228	1.194	1.800
3rd - 4th	0.937	0.989	1.160
4th - 5th	0.621	0.652	1.540
5th - 6th	0.369	0.367	1.511

Table-5. Storey Drift in G+8

Storey	Storey Drift (mm)		
	Fixed	Winkler	Soil
1st - 2nd	1.936	2.723	0.498
2nd - 3rd	1.874	2.239	1.482
3rd - 4th	1.669	1.675	1.077
4th - 5th	1.393	1.327	1.189
5th - 6th	1.083	1.055	0.818
6th – 7th	0.739	0.756	1.233
7th – 8th	0.387	0.402	1.150

Table-6. Storey Drift in G+10

Storey	Storey Drift (mm)		
	Fixed	Winkler	Soil
1st - 2nd	2.646	3.513	0.496
2nd - 3rd	2.598	2.810	0.744
3rd - 4th	2.340	2.424	1.118
4th - 5th	2.036	2.083	1.418
5th - 6th	1.731	1.749	0.724
6th – 7th	1.359	1.448	0.889
7th – 8th	1.081	0.801	2.007
8th – 9th	0.820	1.139	2.401
9th – 10th	0.453	0.419	1.953

3.2.6 Inter-storey Drift Ratio

Inter-story drift ratio (IDR) is an essential parameter of structural behaviour in the performance-based seismic analysis, especially for high-rise buildings. IDR is defined as the relative lateral displacement between two continuous floors divided by the same floor height.

If the value of IDR is larger than 0.06 then it indicates the severe damage, while the value larger than 0.025 indicates that the destruction could be serious enough for human safety. IDR values exceed 0.10 indicate the possibility of building collapse. Figures 12, 13 and 14 show the variation of IDR with storey. The pattern of the inter-storey drift ratio of the fixed base model and Winkler model is different from the soil model because it undergoes large lateral displacement due to a more flexible base in SSI building. The IDR value for G+10 building exceeds the 0.10 value, so the shear wall needs to be provided to prevent the building collapse.

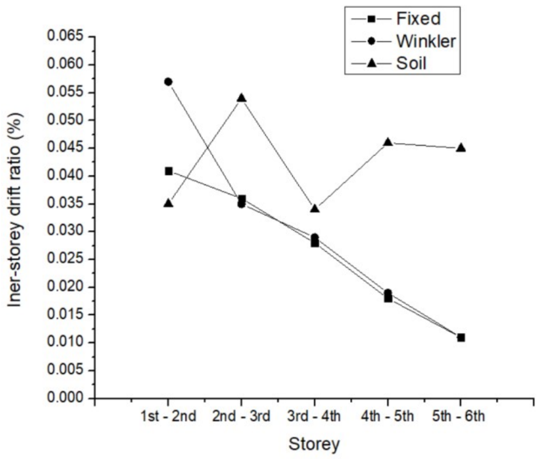

Fig. 12. Inter-storey drift ratio of G+6

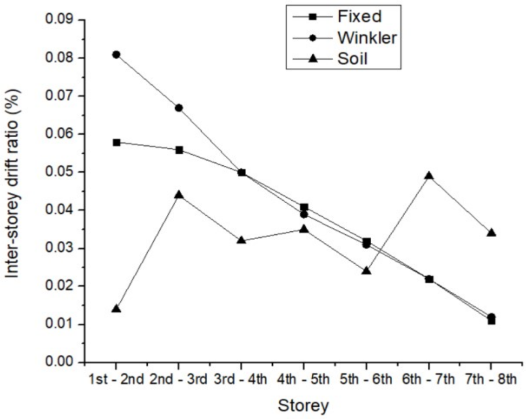

Fig. 13. Inter-storey drift ratio of G+8

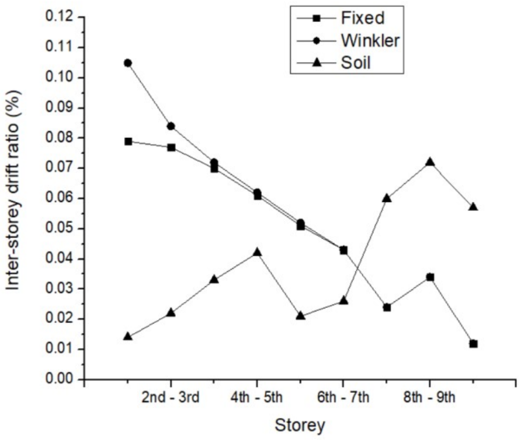

Fig. 14. Inter-storey drift ratio of G+10

4. Conclusions

The SSI models (Winkler and soil) contribute a larger time period of vibration and lateral displacement with reduced base shear than the fixed base model. The pattern of inter-storey drift ratio of the fixed base model is closer to the Winkler model. Based on the present study, the following conclusions are drawn.

- The fundamental time period of the flexible base is greater than the fixed base by 28% (Winkler) and 44% (Soil) in G+6, by 20% (Winkler) and 42% (Soil) in G+8 and 17% (Winkler) and 20% (Soil) in G+10.
- The base shear of the flexible base is lower than the fixed base by 25% (Winkler) and 31% (Soil) in G+6, by 13% (Winkler) and 24% (Soil) in G+8 and 07% (Winkler) and 15% (Soil) in G+10.
- The roof displacement of the flexible base is greater than the fixed base by 62% (Winkler) and 216% (Soil) in G+6, by 42% (Winkler) and 114% (Soil) in G+8 and 35% (Winkler) and 57% (Soil) in G+10.

The present results may be useful to compute the effects of SSI in structural response. This study still needs the analysis for more numbers of ground motions before used for design recommendations.

Disclosures

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