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Study of Soil-Structure Interaction Effects on Seismic Analysis

Sabin Maharjan [a], Kamal Bahadur Thapa [b]

[a, b] *Department of Civil Engineering, Pulchowk Campus, IOE, TU, Nepal*
Corresponding Email: [a] 074msste017.sabin@pcampus.edu.np, [b] kamal.thapa@ioe.edu.np

Abstract
In the past for the design of building, the structure and soil were analyzed in full isolation. But in a dynamic loading scenario, the interaction between structure and soil becomes of great importance. In general design practice, buildings are modeled as fixed at their base. This assumption is only valid when structure is founded on solid rock or stiff soil. But in general the soil is flexible and the soil supporting the structure gets displaced and offers some resistance to motion of structure and vice versa. So it becomes important to understand the SSI effect and its proper modeling. In the present work, G+3, G+5 and G+7 storied traditional RCC buildings regular in plan and elevation are considered. The study is done for different soil condition with different shear wave velocities. This research focuses on the effect of Soil structure interaction under earthquake loads. Direct method is applied to model soil and structure for analysis. The seismic analysis was performed by using Equivalent Static Method from NBC 105:2020. The results in form of lateral displacement, inter story drift, base shear, and time period are compared for models with and without soil interaction. The results obtained from the study shows increase in time period of the system, and also increase in lateral displacement and storey drift of the buildings, while magnitude of shear force decreases, which is due to introduction of soil flexibility in analysis. The analysis for the study is performed using SAP2000.

Keywords
Soil Structure Interaction(SSI), Direct Method, NBC 105:2020

1. Introduction

Soil-Structure Interaction refers to the response of a structure due to influence of soil and the response of soil due to the influence of motion of existing structure. SSI evaluates the collective response of the structure, the foundation and the soil underlying and surrounding the foundation to a specified ground motion. When a structure is built anywhere on the surface, the free field ground motion is obstructed resulting different types of interaction between soil and structure. The energy transfer mechanism from soils to buildings is critical for earthquake resistance design of structures [1]. Although soil structure interaction has its origins trace back to the late 19 century, and gradually progressed and developed in the subsequent decades, only due to recent development of dominant computers and simulation tools such as finite elements, this field has seen more developments as reviewed by [2, 3]

In perivious reseacrh work author [4] presented that the soil structure interaction can have a benificial effect on structure although the research [5] presented both benificial and detrimental aspect of SSI. Since the presence of soil increases the flexibility of strutural system, time period and damping of structure also increases which results in decrease of base shear but at the same time increases the displacement of the structural system. The consequences of this can be instability of the whole structure. The lack of inclusion of SSI in deisgn codes is presented in previous work by [6, 7] and the paper provides a simplified procedure by which SSI effects can be included during analysis of structure. The result from [8] concluded that soil structure interaction played a significant role to increase the seismic base shear of low-rise building frames, and the effect was strongly influenced by the frequency content of the earthquake ground motion. The research paper [9] studied the SSI on multi story RC frame building founded in soft soil (flexible base) and compared it with fixed base by using dynamic seismic analysis. Author in research paper [10] critically reviewed the available and well known modeling techniques for dynamic SSI analysis and discussed the challenges and issues with SSI modelling techniques.

In this current work, the study for SSI effects has been conducted on buildings with regular base dimension but with varying height. Different soil type from various location of Kathmandu valley has been incorporated in this study. Direct method [7, 9, 11, 12] has been applied to model soil and structure for analysis. Separate SSI systems has been modeled for varying soil parameter and varying building height. The seismic analysis has been performed by using Equivalent Static Method from codal provision as suggested by NBC 105:2020. The consequence of soil structure interaction under lateral loads has been studied. The study has been carried out to identify the changes in lateral displacement, inter storey drift, fundamental time period and base shear by incorporating the effects of SSI. The results from SSI models and fixed base model were compared to draw a logical conclusion.

2. Idealization of the System

2.1 Structural Idealization

For the study, two-dimensional regular 4, 6 and 8 storey RC frame building with 3 bays has been modeled. The frames have been modeled using two nodded frame elements. 3m storey height and 4m length of each bay has been selected for modeling. The dimensioning of members of buildings has been done according to preliminary analysis. The dimension of beam was taken as 230 x 350 mm. The detail dimensions for column used for modeling is presented in Table 1. M20 grade concrete for beam and column with Fe500 grade of rebar has been considered. Live and dead loads were considered as per IS 875: Part II.

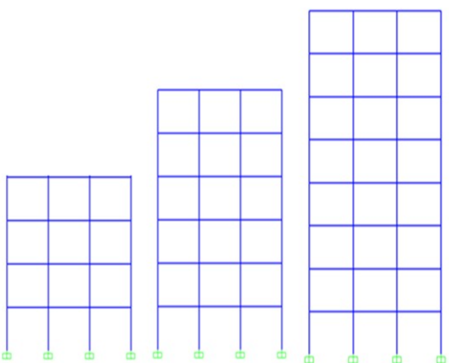

Figure 1: 2D SAP2000 model for fixed supported 4, 6, and 8 storied buildings

Table 1: Description of Buildings

Number of Storey	Total Height (m)	Column Dimension (mm x mm)
4	12	300 x 300
6	18	350 x 350
8	24	400 x 400

2.2 Soil Properties

Soil properties for five different locations around Kathmandu valley has been adopted from paper [13]. The required values of shear wave velocity (Vs), compressional wave velocity (Vp), poissons ratio, unit weight modulus of elasticity (E) and shear modulus (G) were adpoted from paper [13]. These parameters were for shallow depth of 10m. Since shear wave velocity averaged over top 30m (Vs30) of soil is used for seismic analysis so it has been modified for 30m. The modified values are presented in Table 2

Table 2: Soil Properties

SN	Site	Vs30	Poissons Ratio	Unit wt (kN/ m3)
1	Koteswor	65.44	0.442	12.28
2	Horizon, Dhapasi	117.89	0.235	14.22
3	Balaju	126.03	0.202	14.46
4	Balkhu	160.63	0.129	15.37
5	Sankhu	182.9	0.22	15.87

2.3 Soil Structue Modelling

In this study, direct approach has been used for modeling. The direct analysis evaluates SSI by modeling a limited soil domain along with the foundation system, superstructure, transmitting boundaries along the perimeter of the soil domain, and interface elements between the foundation system and soil. Therefore, the direct solution considers the complete soil-structure system and solves this problem in one step. This method has been adopted from papers [7, 9, 11, 12]

Plane Strain elements has been used to model soil half space. Plane strain elements are quadrilateral elements with two degrees of freedom at each node. For modelling of infinite soil surrounding structure, the soil depth D has been considered as 3B, where B is the width of building in short direction and distance

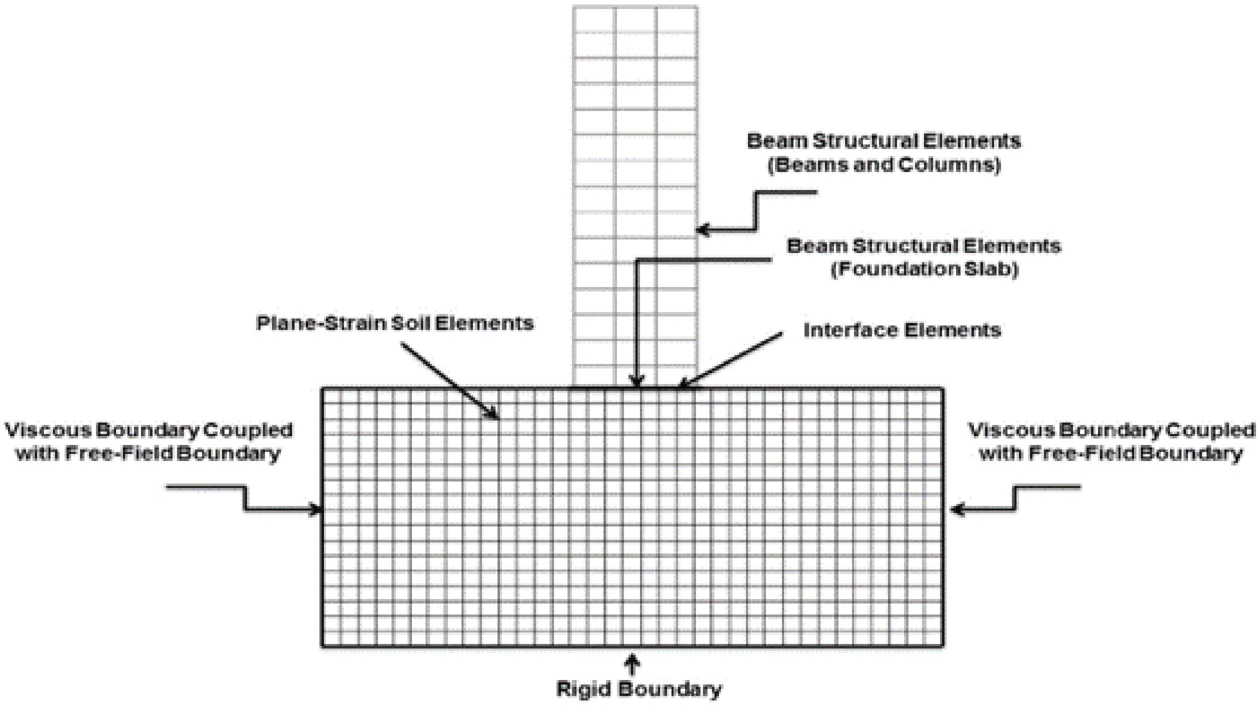

Figure 2: Finite element modeling of soil structure system [12]

from structure to boundary has been considered as 4B as suggested by [9]. The total width of half space has been considered as 10B for this study. The meshing of soil half space has been carried out as suggested by [14]. The boundary conditions of half space soil for the analytical model is fixed boundary at the base of the soil model. Transmitting boundaries has been applied on the vertical boundaries of soil half space as suggested by [14]. The infinite soil media has been replaced by viscous dampers at the vertical boundaries. Link properties with damper type support were used in SAP2000 to imitate the viscous dampers as suugested by [14]. The damping coefficients for horizontal and vertical boundaries are given by

$$Ch = -\rho * Vp * A$$

$$Cv = -\rho * Vs * A$$

Here, Ch and Cv are the horizontal and vertical damping coefficients at the model boundaries, ρ is the material density, Vp and Vs are the P-wave and S-wave velocities and A is the Effective nodal area for the node connected to the damper which is calculated as the total area of all elements around the node at boundary.

The interface between the foundation and soil has been represented by normal (kn) and shear (ks) springs between two planes contacting each other and has been modeled using a linear spring system as suggested by [12]. The relative interface movement is controlled by interface stiffness values in the normal and tangential directions. Normal and shear spring stiffness values for interface elements of the soil-structure model is given by

$$kn = ks = 10 * \frac{K + 4G/3}{\Delta zmin}$$

Here K and G are the bulk and shear modulus of the neighbouring zone and Δzmin is the smallest width of an adjoining zone in the normal direction.

2D SAP model for direct method is shown in Figure 3.

2.4 Methodology

Seismic analysis of the soil structure system has been carried out by equivalent static method as instructed by NBC 105:2020. Static analysis has been performed by considering the building structure as stationary and the loads acting on the structure as constant and not time dependent. For performing static analysis spectral shape factor is selected as 2.25, seismic zone factor is selected as 0.35, Ductility factor of 4, over strength factor of 1.5 and importance factor of 1 is selected. Soil type D is considered for analyisis. SAP2000 has been used for analysis of system.

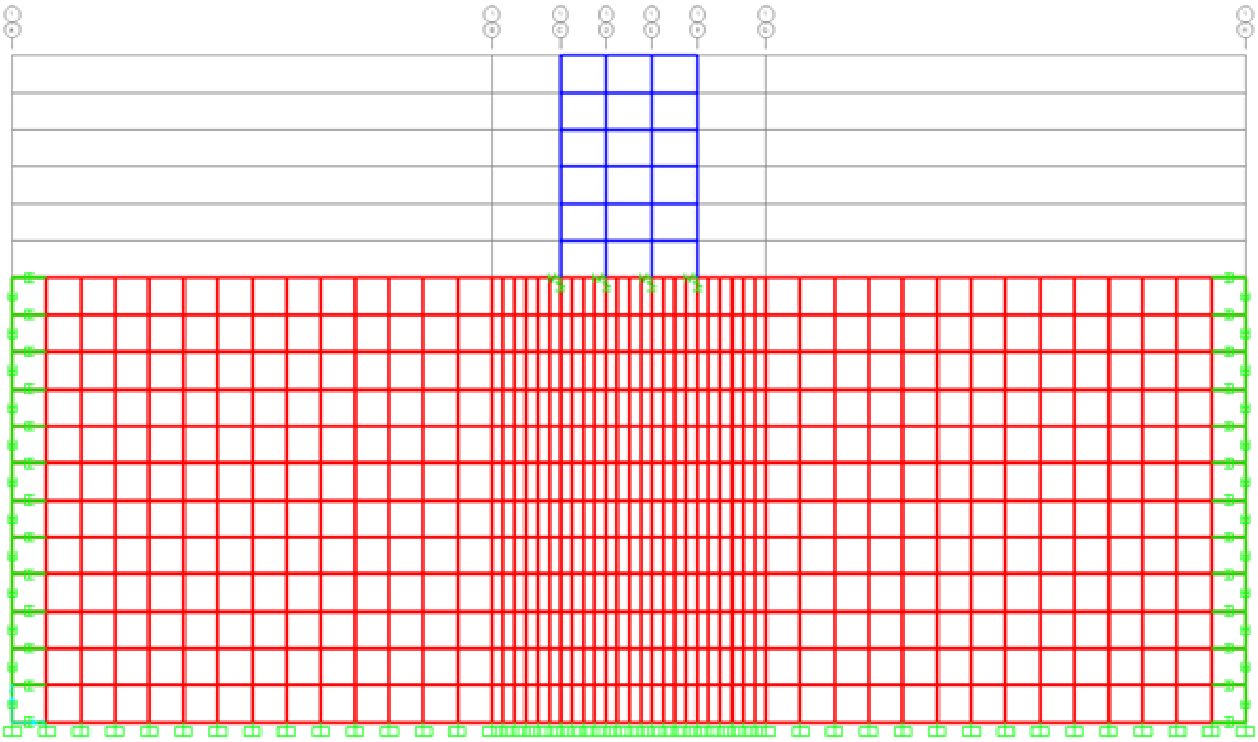

Figure 3: 2D SAP2000 model for direct method of analysis

3. Results and Discussion

For different soil condition static analysis of buildings with and without SSI effects of G+3, G+5, G+7 storied buildings is performed in SAP2000. Bare frame models are used for analysis of structure. The results are presented below .

3.1 Results on Storey Dispalement

Storey displacement is the total displacement of any storey with respect to base or ground. Soil-structure interaction mostly for MRF buildings constructed on comparatively soft soils could considerably intensify the lateral displacements. The lateral displacement profile are presented in Figure 4, 5 and 6. As observed from the results, it is seen that the displacement increases with introduction of SSI effects on model. The relative displacement on foundations located on soft soil is more and the value of lateral displacement decreases with increasing soil rigidity.

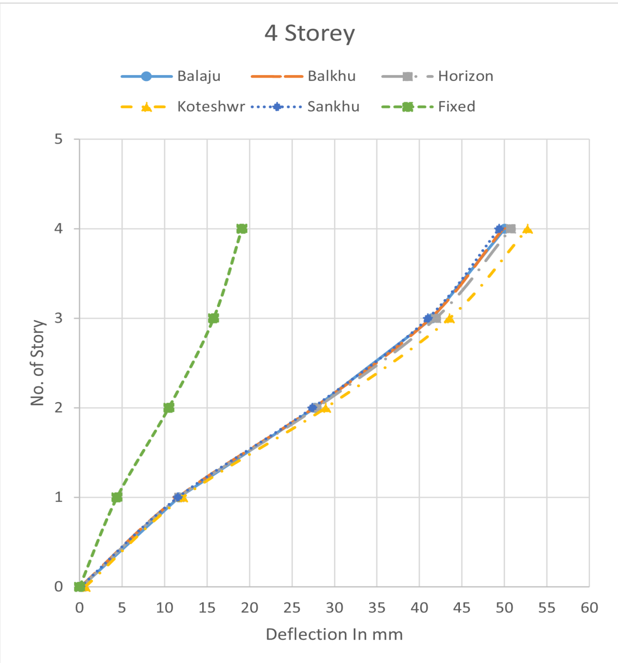

Figure 4: Displacement comparison of G+3 Buildings for different sites and fixed support

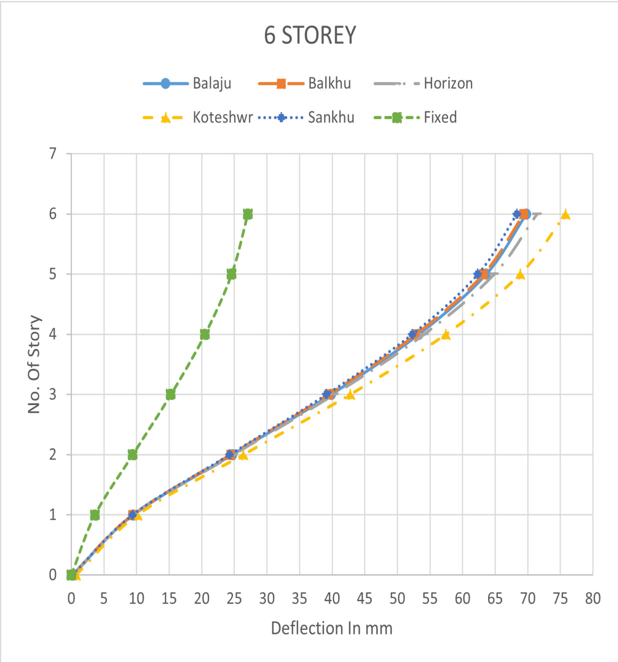

Figure 5: Displacement comparison of G+5 Buildings for different sites and fixed support

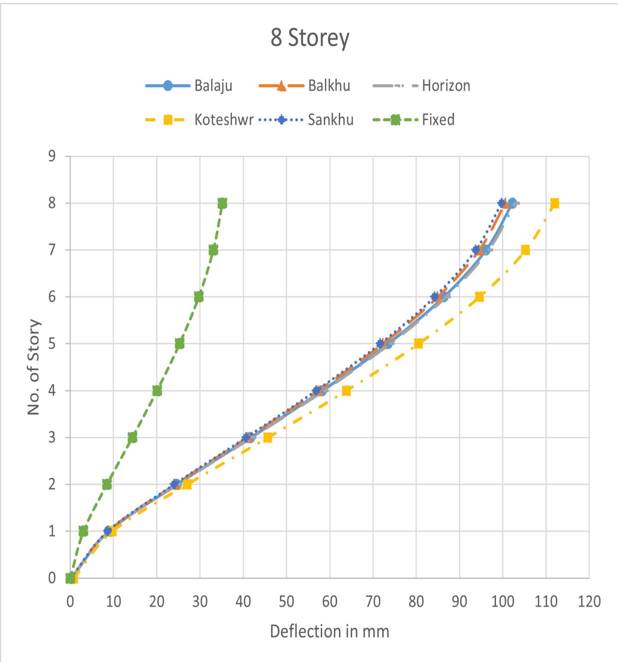

Figure 6: Displacement comparison of G+7 Buildings for different sites and fixed support

3.2 Results on Storey Drift

The story drift is examined for RCC building of 4, 6 and 8 storey buildings. The story drift ratio over the building's height for different location and soil conditions are presented in the graphical form. Figures 7,8 and 9 show the story drift distribution over building height compared to that response value of fixed based model for 4, 6 and 8 story model. As seen from the results, the story drift ratio increases over the building height as the supporting soil changes. This increase trend is more significant in the lower stories. The inter-storey drift in bottom stories for soft soil are large compared to fixed base model. This is due to the fact that the base shear at bottom decreases significantly which leads to larger drift.

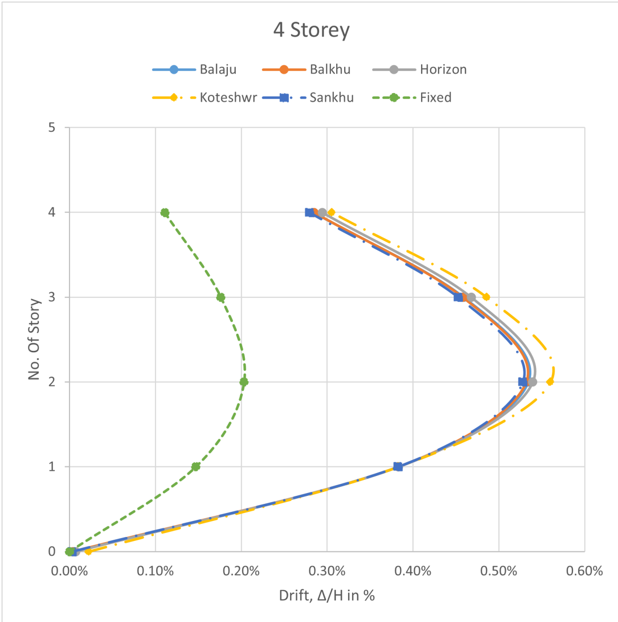

Figure 7: Drift comparison of G+3 Buildings for different sites and fixed support

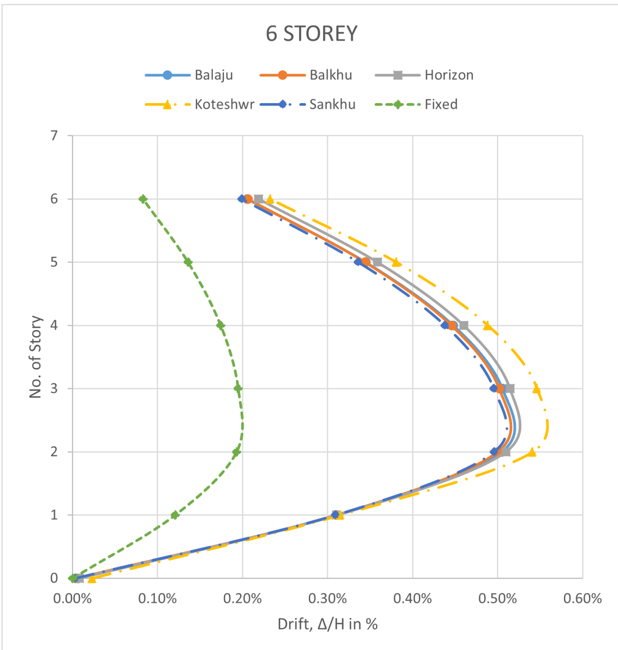

Figure 8: Drift comparison of G+5 Buildings for different sites and fixed support

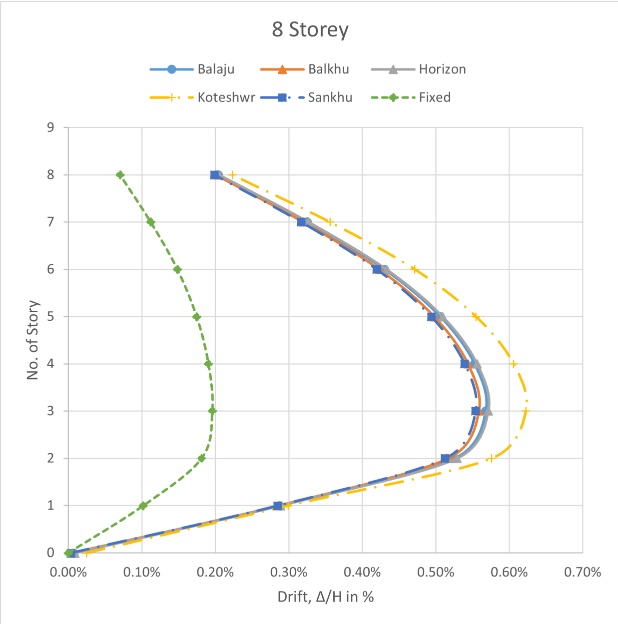

Figure 9: Drift comparison of G+7 Buildings for different sites and fixed support

3.3 Results on Fundamental Time Period

In modelled 4 storey, 6 storey and 12 storey buildings, the computed periods from empirical expressions are significantly shorter than those computed from structural models especially for building structures with soft soil.

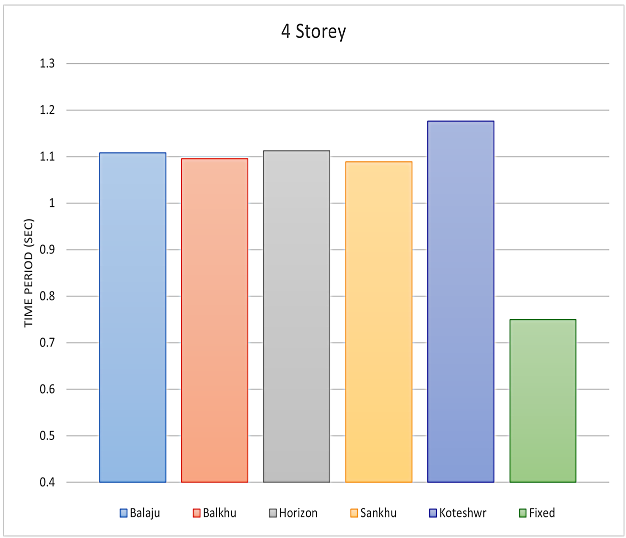

Figure 10: Time Period comparison of G+3 Buildings for different sites and fixed support

It is observed that the time period for soft soil at koteshwor area is highest among the models whereas time period is minimum for fixed base model. Also, the study reveals that time period is increased considering the flexibility of the soil. This means fundamental time period of the building considering fixed base condition is shorter than the flexible base condition. It is because, considering soil-structure interaction makes a structure more flexible compared to the corresponding rigidly supported structure.

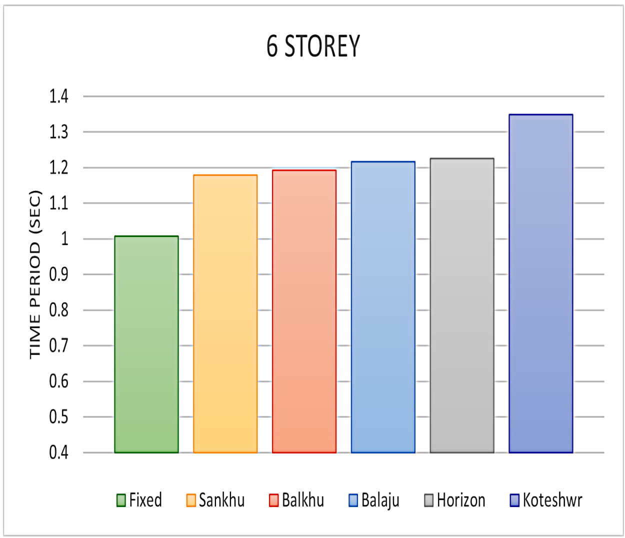

Figure 11: Time Period comparison of G+5 Buildings for different sites and fixed support

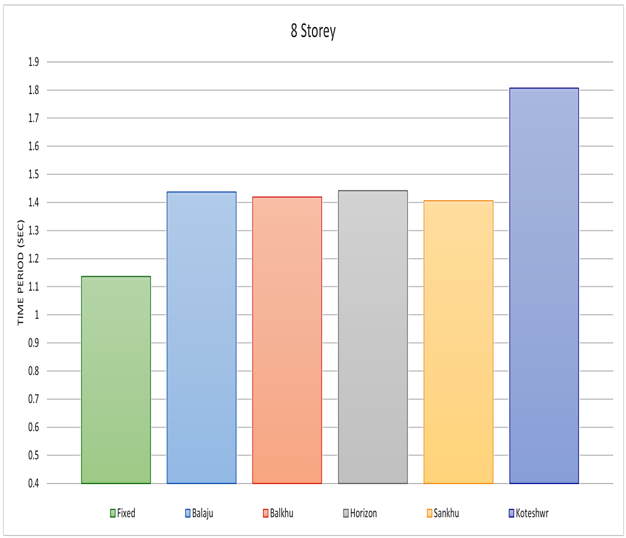

Figure 12: Time Period comparison of G+7 Buildings for different sites and fixed support

3.4 Results on Base Shear

The difference in base shear for fixed base condition and considering SSI for different site and different storey buildings is shown as graphical representation in Figure 13,14 and 15. It is observed that base shear decreases considering the flexibility of soil. It is due to the increase in effective damping ratio and natural time period of the structure. Base shear is maximum for fixed base condition, minimum for Koteshwor site. Minimum base shear in Koteshwor area considering SSI is about 64% of base shear in fixed base condition for 4 storey building and the minimum base shear in Koteshwor area considering SSI is about 59% of base shear in fixed base condition for 6 and 8 storey building.

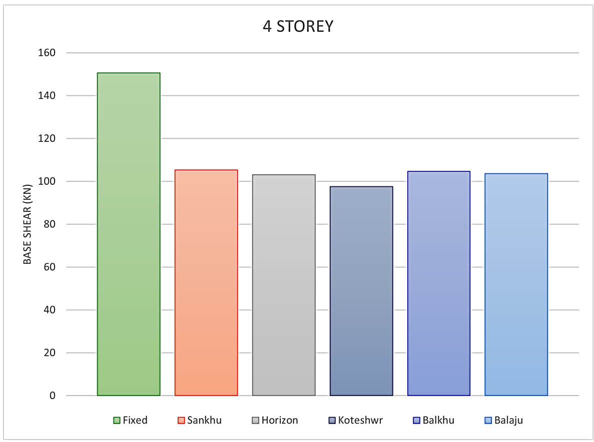

Figure 13: Base Shear comparison of G+3 Buildings for different sites and fixed support

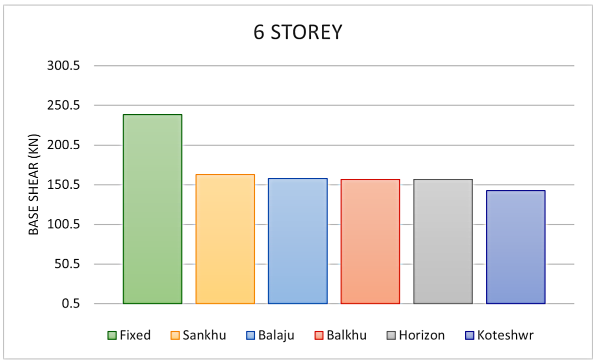

Figure 14: Base Shear comparison of G+5 Buildings for different sites and fixed support

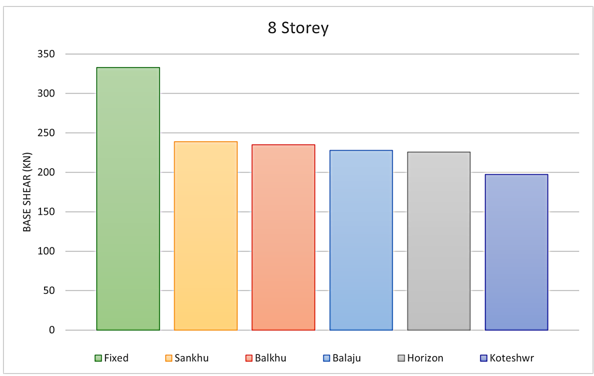

Figure 15: BaseShear comparison of G+7 Buildings for different sites and fixed support

4. Conclusion

The present study is an attempt on understanding the seismic response and behavior of structure when soil flexibility is introduced in the structural system. With the use of varying soil and structural parameters an effort has been made to shed light on the effect of soil structure interaction on seismic performance of buildings. The study reveals that time period is increased considering the flexibility of the soil. This means fundamental time period of the building considering fixed base condition is shorter than the flexible base condition. It is because, considering soil-structure interaction makes a structure more flexible compared to the corresponding rigidly supported structure. This could lead to resonance of structure. As observed from the results, it is seen that the displacement increases with introduction of SSI effects on model. The displacement on foundations located on soft soil is more and the value of lateral displacement decreases with increasing soil rigidity. As seen from the results, the story drift ratio increases over the building height as the supporting soil changes. This increase trend is more significant in the lower stories. The inter- storey drift in first, second storey for soft soil are large compared to fixed base model. This could be very serious concern when soft storey structure are constructed over soft soil. It is observed that base shear decreases considering the flexibility of soil. It is due to the increase in effective damping ratio and natural time period of the structure.

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