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Influence of Soil Structure Interaction in the Seismic Behavior of Residential Steel Building

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Abstract
The present practice neglects the soil structure interaction (SSI) effect and design the base of structure as fixed one. A designer assumes the fixed base case as safe, however, time period and damping characteristics are significantly affected when considering SSI. Different researches regarding SSI is introduced but the finite element (FE) validation of the relations is rarely reported. This research focuses to understand the effect of SSI on the response of typical residential steel structure with the validated FE model. Four different residential steel buildings are used for the case study. The bare frame is modelled and analyzed, using FE method under two different boundary conditions i.e., fixed base and SSI. From the results obtained, it shows that the SSI has significant effect in base shear and time period of the building.

Keywords
SSI, Kinematic interaction, Inertial interaction

1. Introduction

Fixed footing is the combination of rigid base and rigid foundation where rigid base implies to soil support infinite stiffness and rigid foundation possess infinite stiffness while flexible footing considers the deformation of both soil and foundation. SSI actually amplifies the seismic demand on the structure by amplifying the peak acceleration during the ground motion. SSI generally deals with two components. Soil gives motion to the structure is the kinematic interaction and the soil receives from the super structure is the inertial interaction. Kinematic interaction is the inability of the foundation to corporate with the free field motion of the soil while inertial interaction is due to the mass of the superstructure which transmits the inertial force back to the soil causing the further deformations [1]. To account the SSI for surface, partially, fully embedded and along with significant modes of vibration gazetas(1991) [2] gave a complete sets of simple formulas and the graphs which was used by many researchers. xiong et al.(2016) [3] performed experimental observation and analytical verification in the influence of SSI on the fundamental period of buildings. A total of 34 scenarios were modelled with varied overall stiffness and mass of the structure and examined with experimental and analytical simulation. First fundamental time periods were obtained by experiment and then by using SAP2000 to avoid errors in SSI analysis. They concluded that SSI increases the fundamental time period of the building. NIST(2012) [4] gave the different techniques of the evaluation of the SSI modelling parameters with experimental results for different cases and describes both direct method and substructure method in the evaluation of SSI. Pradhan(2002) [5] performed SSI for 2,4,6,8 story with fixed spring base and FEM model of soil structure and concluded that design was greatly affected by the method of analysis chosen, fixed base is more conservative. Chhetri and Thapa(2015) [6] investigated about soil structure interaction and performed seismic design according to the codal provisions and concluded that it was necessary to consider the effect of SSI for seismic design of building founded on soil with shear wave velocity less than or equal to 300 m/sec.Thapa(2017) [7] investigated about the soil structure interaction for Balaju and Sankhu site and found that structure located at stronger soil has higher capacity compared to the corresponding structure located at weaker soil observed that top story displacement was more in case of SSI than in fixed base condition.Poudel and

Shretha(2020) [8]) performed the direct analysis method of SSI of soft story building in the Kathmandu valley and found that the present analysis approach considering buildings fixed at their base are being overestimated for resisting shear.

2. Theoretical Background and methodology

2.1 Soil structure interaction

The flexible footing simply uses the dynamic stiffness and the damping which could be evaluated by the formula and sets of graphs demonstrated by [2].

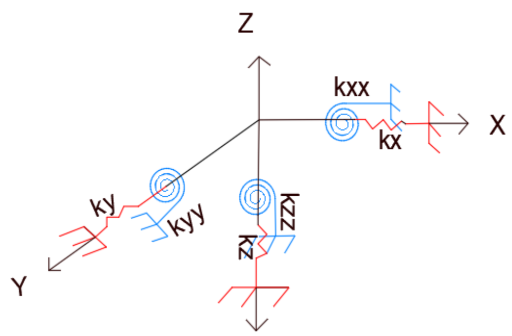

Figure 1: Equivalent spring model along 6 DOF

Dynamic stiffness:

$$\widetilde{K(w)} = K.k(w) \tag{1}$$

Total damping:

$$totalC = radiationC + \frac{2\widetilde{K}}{\omega}\beta \tag{2}$$

where,($\widetilde{K(w)}$)dynamic stiffness,(k)static stiffness,(C) radiation damping,($\frac{2\widetilde{K}}{\omega}\beta$)Material damping

[2] relations regarding the stiffness and damping is used for the soil using the parameters of the soil. The soil properties density (ρ), poision ratio(ϑ) the shear wave velocity(V_s),circular frequency (in radians/sec) of the applied force (ω) and the footing dimensions are used for the determination of stiffness and the damping of the soil.

Dimensionless frequency factor

$$a_0 = \frac{\omega B}{v_s} \tag{3}$$

Lysmer analog wave velocity

$$V_{la} = \frac{3.4}{\Pi(1-\vartheta)} Vs \tag{4}$$

Stiffness in horizontal X direction

$$K_z = \left[\frac{2GL}{(1-\vartheta)}\right] 0.73 + 1.54\chi^{0.75} with \chi = \frac{A_b}{4l} \tag{5}$$

Dynamic stiffness

$$k_z = K_z\left(\frac{L}{B}, \upsilon, a_0\right) \tag{6}$$

Damping

$$c_z = (\rho v_{la}) A_b \hat{c_z} \tag{7}$$

where

$$\hat{c_z} = \hat{C_z}\left(\frac{L}{B}; a_0\right) \tag{8}$$

is plotted based on [2]

Similarly, for X and Y directions similar relations are derived from [2].

Where,G is shear modulus,L is Half length of the footing,$B$is Half breadth of the footing,A_b is area of the contact surface,V_s= shear wave velocity

2.2 Validation

Experimentation done by [3] was used to validate the spring stiffness and damping. Four different models with and without SSI experimental setup ware modelled in SAP2000V22. Variation in story height with and without loading were modelled.

Cases

1. without load and floor height 1 m
2. with load and floor height 1 m
3. without load and floor height 1.5 m
4. with load and floor height 1.5 m

Structural idealization: Building frames of 6 story and 4 story with 1 and 1.5m story height respectively were modelled with bay length of 1m. The thickness of slab plate was taken 10mm, the dimension of beam as H100x50x5x7, the dimension of column was H 125x125x6.9x9. C20 grade of concrete was used with Q235 grade of steel sections from [3].

Loadings: Area load of 1.51 kN/m^2 on each floor

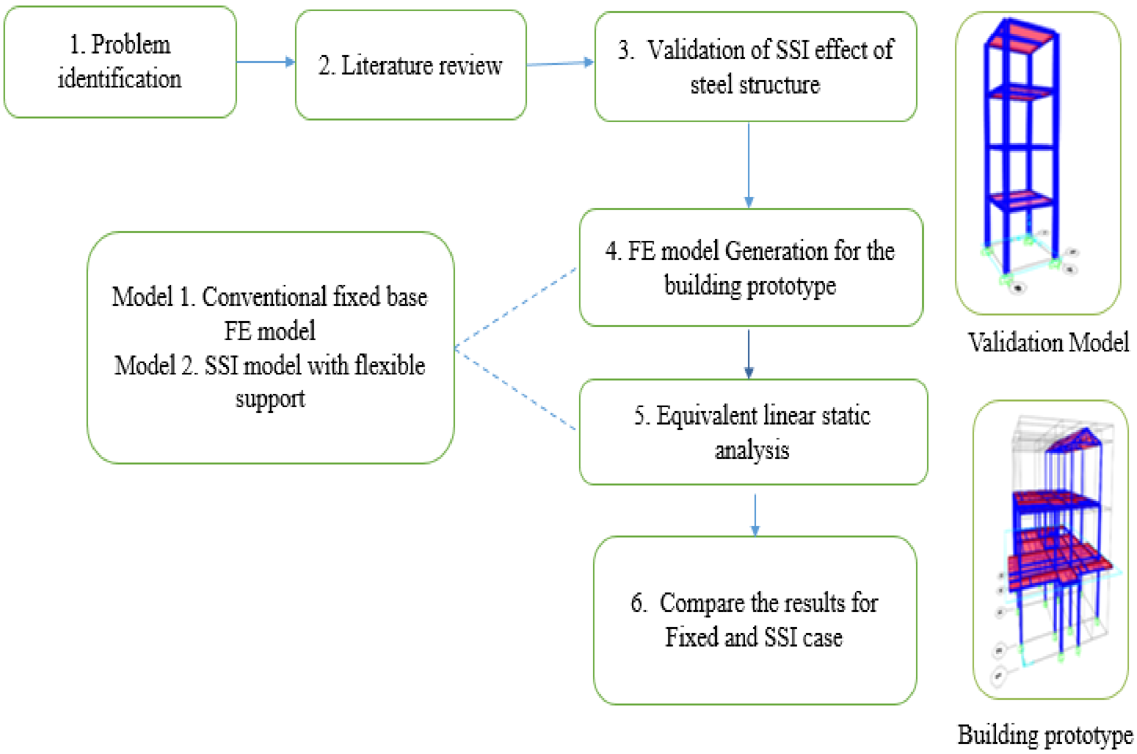

Figure 2: Flow chart showing methodology

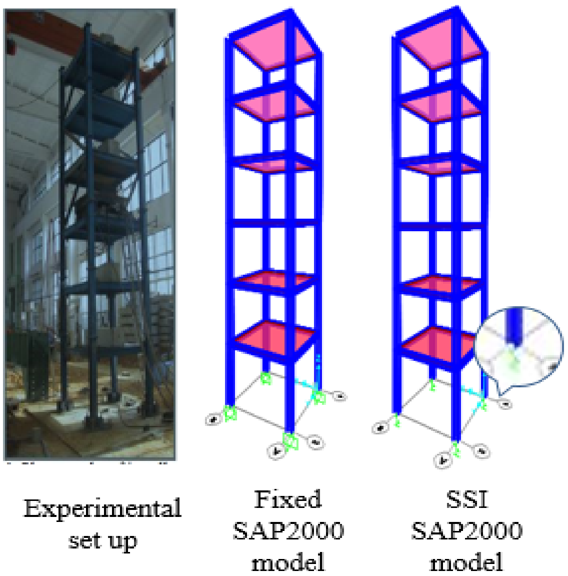

Figure 3: FEM modelling of experimental setup

Soil idealization: To obtain the values of the stiffness of the springs for the soil, density of the soil (ρ)1.64gm/cm^3 , poison's ratio(μ) 0.3 and shear wave velocity (V_s) 211 m/s were used from [3].

Spring: The relations to obtained springs constant used in this thesis is based on the [2].The foundation of the soil is being replaced by the link with stiffness and damping value as shown in Fig.3

Table 1: Comparison of time period for fixed case

		SAP 2000	Test	Difference (%)
Case	Direction	Fixed (sec)	Fixed (sec)	
1	x	0.204	0.21	2.92
	y	0.3	0.31	3.51
2	x	0.26	0.288	9.93
	y	0.423	0.426	0.84
3	x	0.226	0.213	6
	y	0.423	0.377	12.11
4	x	0.276	0.297	6.88
	y	0.518	0.515	0.45

The results of the time period obtained from SAP2000 were comparable with the experimental results for fixed case as shown in Table1 and for SSI in table2.Average(%)difference in the values of time period for fixed base case is 5.3(%) and for SSI base shear is 9.3(%).The same procedure for defining the base spring elements was employed for the case study residential building in the next section.

Table 2: Comparison of time period for SSI case

		SAP 2000	Test	Difference (%)
S.N.	Direction	SSI(sec)	SSI(sec)	
1	x	0.217	0.221	1.66
	y	0.305	0.342	10.75
2	x	0.275	0.304	9.62
	y	0.432	0.47	8.13
3	x	0.235	0.26	9.47
	y	0.428	0.393	8.89
4	x	0.287	0.352	18.47
	y	0.524	0.568	7.85

Table 3: Description of two and half story steel building

Comp.	Description	Data(m)
Frame	Number of story	2 and half
	Number of bays in X direction	4
	Number of bays in Y direction	4
	Story height(m)	3.048
	Size of beam	IMB 200
	Size of column	2ISMC 250
	Thickness of slab(m)	0.0762
Foundation	Length of footing(m)	13.1064
	Breadth of footing(m)	10.9728
	Thickness of footing(m)	0.5

3. Case Study

The case study prototype includes four typical residential steel buildings of two, three, four and five stories. Table3 shows the details for the case study two-storied building. The building has 4 bays in both x and y direction with storey height of 3.048 m. The building uses ISMB200 beam and 2ISMC250 for column. The slab with thickness of 76.2 mm is adopted. The footing has dimensions of 12.2 m x 9.12 m with depth of footing 0.5m. The other building models of three, four and five-storied have similar bays and structural components. Same structural element sizes are chosen for all chosen building types.The building cases are adopted from the real building constructed in the Kathmandu valley.

3.1 Material Properties

Fe250 grade steel is used for all the beams and columns in this study. The weight per unit volume is assumed to be 76.97 kN/m^3 with the Modulus of elasticity to be 210 GPa and Poisson ratio as 0.3. The minimum yield stress is taken as 250 MPa and minimum tensile stress is taken as 410 MPa.

Table 4: Soil properties used for the case study

Description	Shear wave velocity (V_s)(m/s)	Poisson's ratio (μ)	Unit weight (ρ)(kN/m^3)
Soil	100	0.3	16

Table 5: Dynamic stiffness(kN/m) for one representative A5 column

k_z	k_y	k_x	k_{xx}	k_{yy}	k_{zz}
17869	14542	14327	434516	564676	876401

3.2 Soil idealization

Table 4 lists soil properties adopted for the case study based on work of [8] based on SPT tests done in Kathamndu. Based on the values from Table4 and the foundation details, spring stiffness and damping characteristics for soil below each column were derived using formulations proposed by [2]. A total of six spring stiffness and six damping values are computed for each column base. Table5 shows dynamic stiffness and Table6 shows damping constant lists derived values for one such representative column A5 of two-storied building.

where k_x, k_y and k_z is dynamic stiffness along horizontal X , Y direction andZ direction respectively k_{xx},k_{yy},k_{zz} is rocking about X axis, Y axis,and torsion about Z axis respectively c_x ,c_y ,c_z is damping constant along horizontal X ,Y and Z direction respectively c_{xx} ,c_{yy} and c_{zz} is rocking about X axis, Y axis and torsion about Z axis respectively

Figure 4shows the 3D FE model of the two and half storied prototype building. The beams and columns were modeled as regular frame elements and floor slab was modeled using thin shell elements. The floor finish load of 1.25kN/m^2 and live load of 2.5kN/m^2 was applied over the floor area elements. A prefab wall load of 1 kN/m was applied on the frame elements.

Table 6: Damping constant (kNs/m) for one representative A5 column

c_z	c_y	c_x	c_{xx}	c_{yy}	c_{zz}
1053	612	680	1056	1809	1658

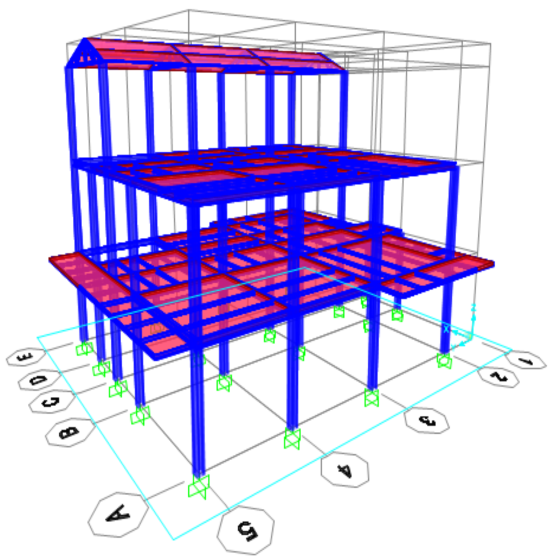

Figure 4: 3D FE model of the two and half storied prototype building

4. Results and Discussion

For two and half storied building model natural time period was 0.375 sec and 0.501sec from modal analysis for fixed and SSI case respectively. Maximum roof displacement was 14.842mm and 16.375mm for fixed and SSI respectively. Likewise maximum base shear was found to be 96.97 kN and 82.98 kN for fixed and SSI respectively.

For three and half storey building, natural time period of the model was 0.584sec and 0.645sec from modal analysis for fixed and SSI case respectively. Further, maximum roof displacement was 17.795mm and 20.622mm for fixed and SSI respectively. The maximum base shear was 147.83 kN and 131.046 kN for fixed and SSI respectively.

Similarly for four and half storied building model, natural time period of the model was obtained as 0.767sec and 0.84sec from modal analysis for fixed and SSI case respectively. Maximum roof displacement was 24.521mm and 29.028mm for fixed and SSI respectively. Likewise maximum base shear was found to be 155.35 kN and 143.37 kN for fixed and SSI respectively.

For five and half storied building, natural time period of the model was obtained as 1.08sec and 1.286sec from modal analysis for fixed and SSI case respectively. Maximum roof displacement was 30.2mm and 36.647mm for fixed and SSI respectively. Likewise maximum Base shear was found to be 173.52 kN and 160 kN for fixed and SSI respectively.

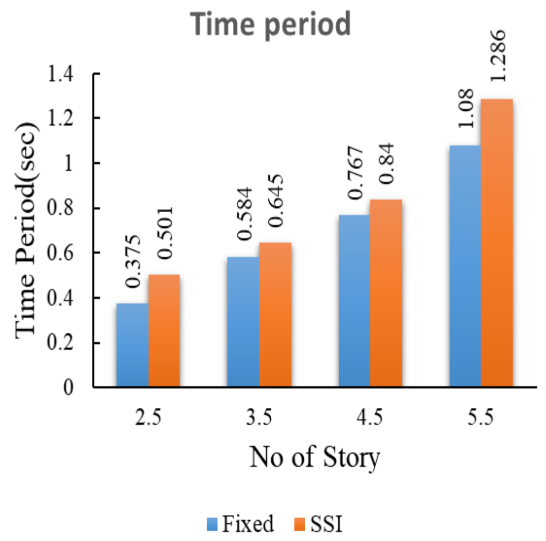

Figure 5: Time period of the different story

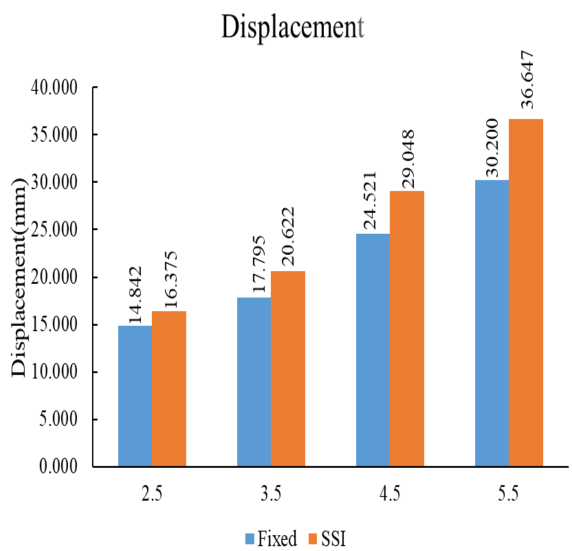

Figure 6: Top story displacement for different story building

Fig.5shows the variation in fundamental time periods for the 4 building models with fixed base and SSI base.It can be seen that time period of the building increases with increase in the story height and also for the same height of the building the fixed case has less time period than the SSI case. Fig.6shows the top story displacements for the 4 building models with fixed base and SSI base. From the graph, it can be seen that top story displacement increases with increase in the height of the building and also for the same height

Table 7: Design horizontal seismic coefficient

no.story	Sa/g		Ah calculation	
	fixed	Ssi	fixed	Ssi
2.5	2.5	2.5	0.090	0.090
3.5	2.17	1.74	0.078	0.063
4.5	1.46	1.32	0.052	0.047
5.5	1.24	1.12	0.045	0.040

of the building the top story displacement of the SSI case is more than the fixed case.

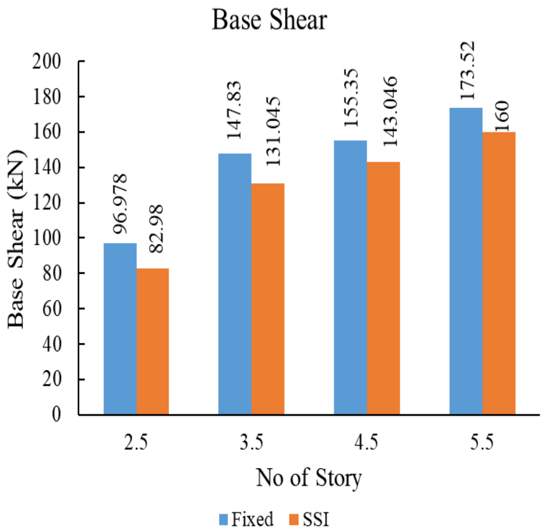

Figure 7: Base shear for different story building

Fig.7 shows the variation in base shear for the four models selected with fixed base and SSI base.It can be seen that the base shear of the building increases with the increase in the height of the building and also for the same height of the building fixed case has higher base shear than the SSI case.However, the increase isnot considerable for four and half and five and half even with increase in the seismic weight. for the higher values of time period for the increased height of the building, the response spectra for the equivalent static method goes beyond the peak response region and the value of sa/g is reduced, thus resulting in the decrease of the horizontal seismic coefficient for calculation of base shear.. Respective horizontal seismic coefficient (Ah)value is given in Table 7.

It can be seen due to decrease in the horizontal seismic coefficient the base shear decrease with the increase in the height of the building.

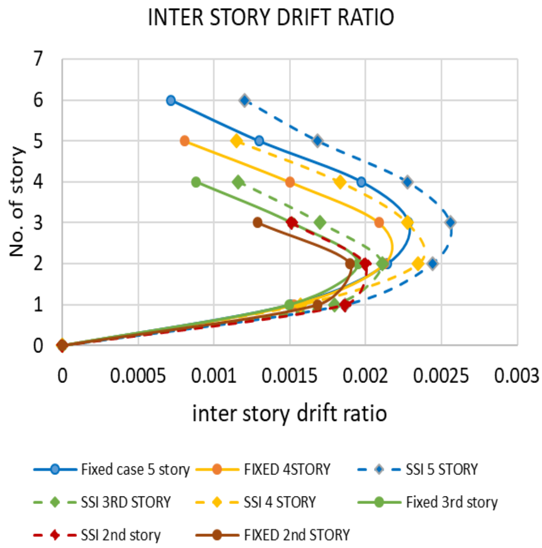

Figure 8: Inter story drift ratio of the different story

Inter story drift ratio Figure8 shows the interstorey drifts for the four building models with fixed base and SSI base. From Fig. 8, it is clear that higher drifts are experienced at the middle height of the building. Further, the interstorey drifts for SSI incorporated building are more than the fixed base case of the same height.

5. Conclusions

A case study with four different types of residential steel buildings were selected to assess their response considering SSI effect. The developed FE model with SSI effect was validated from experimental results. The comparison of results for fixed base and SSI incorporated buildings show that the time period of the steel building with footing considering SSI is more than fixed base case. Further, base shear of the steel building with fixed footing is more than structure considering SSI, hence, the results show that the base shear is more conservative for fixed base than SSI. The base shear of the steel building also are found to increase with increase in the height of the building. The storey drifts on the other hand were higher in case of SSI models. The authors' future works will focus on assessing the performance of the steel building with inclusion of SSI effects through fragility curve generation.

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