SSI Effects on Behavior of a Low-Rise Load-Bearing Structural Walled Building Including Foundation

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Abstract The process of soil response influencing the motion of the structure and vice-versa is termed as soil-structure interaction. Conventionally, SSI has been considered to pose beneficial effects on the seismic response of a structure because of causing the structure more flexible resulting in the increased natural period and enhanced effective damping ratio. These modifications suggest a reduction in base shear demand for a structure as compared to its fixed-base counterpart. This study presents analyses of a four-storeyed load-bearing structural walled building. It has been analyzed with the base of the walls as fixed and supported on stiff, medium and soft soil springs. The structure has also been analyzed considering stepped brick masonry strip footing fixed at base and supported on same springs as used in the structure. The results are somewhat different than the assumption of fixed-base analyses being always conservative. The study also suggests appropriate modeling to capture maximum response in structural members.

Keywords Soil-structure interaction · SSI · Dynamic · Earthquake · Seismic · Shear wall · Concrete · Foundation

1 Introduction

The process of soil response influencing the motion of the structure and vice-versa is termed as soil-structure interaction (SSI). It is a phenomenon that comprises various mechanisms leading to the interdependence of soil and structural displacements. These mechanisms broadly fall under either the kinematic or inertial component of SSI. Roesset [1] and Kausel [2] presented reviews of the early-stage developments

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in the field of soil-structure interaction. In addition to the two components of SSI—kinematic and inertial, Roesset also discussed direct and substructure approaches to perform SSI analyses. Kausel presented chronological development in SSI, starting from fundamental solutions (commonly termed as Green's functions) devised by mathematicians and scientists way back in the early nineteenth century. Kausel initiated the development of a substructure approach to solve SSI problems.

Conventionally, SSI has been considered to pose beneficial effects on the seismic response of a structure. The usual reasoning provided in this regard is that considering SSI makes a structure more flexible, increases its natural period and enhances its effective damping ratio. These modifications suggest a reduction in base shear demand for a structure as compared to its fixed-base counterpart. With such assumptions, SSI has usually been disregarded by designers to reduce the complications involved in analyses. However, observations from many earthquake-damaged sites tell a different story. Noticeable instances include damage in a number of pile-supported bridge structures in the 1989 Loma Prieta earthquake as cited by Yashinsky [3] and the collapse of Hanshin Expressway Route 3 (Fukae section) in the 1995 Kobe Earthquake as investigated by Mylonakis and Gazetas [4]. Further Badry and Satyam [5] obtained SSI analysis for asymmetrical buildings supported on the piled raft which got damaged during the 2015 Nepal Earthquake. They observed that detrimental effects of SSI can be greatly intensified by the asymmetry in the geometry of the superstructure. These observations suggest that the traditional belief of SSI being ever-beneficial does not stand good for all structures on all soil conditions [6].

Ciampoli and Pinto [7] identified structure-to-soil stiffness ratio and aspect ratio of structure to be regulating the phenomenon. Nguyen et al. [8, 9] established the significance of foundation characteristics, viz. footing size in shallow foundations and pile size and load-bearing mechanism in pile foundations on seismic response of structure-soil systems. The possibility of differential settlement arising out of soil flexibility has been remarked by Raychowdhury [10] for low-rise steel moment-resisting framed buildings. She also concluded that SSI needs to be tackled more critically for heavily loaded footings owing to high inertial effects. This suggests a need to develop a rational basis for seismic design incorporating SSI.

Further, Jarernprasert et al. [11] studied the effects of SSI on the response of yielding single-storey structures embedded in an elastic half-space to a set of accelerograms representative of diverse geology. Unlike elastic structures, SSI may lead to an increase in ductility demands and total displacements in the case of inelastic structures. Aydemir [12] studied soil-structure interaction effects on structural parameters for stiffness degrading systems built on soft soil sites and found smaller strength reduction factors for interacting systems than those for corresponding fixed-base systems. This implies that neglecting SSI may result in an unconservative design.

Dutta and Roy [13] presented a critical review of idealization and modeling for interaction among various components of the soil-foundation structure system. These modeling strategies are broadly classified as discrete and continuum depending on elements used at the structure-soil interface. In discrete modeling, springs and dashpots are usually used as interface elements. On the other hand, continuum modeling is achieved using either finite element or boundary element methods.

Vaseghiamiri et al. [14] proposed a novel probabilistic approach to account for SSI in the seismic design of building structures. In this approach, an SSI response modification factor is introduced to capture SSI effects on the seismic performance of structures. The proposed procedure quantifies factors such that the probability distribution of the collapse capacity of the structure designed to account for SSI concurs with that of the structure designed using the default fixed-base provisions. It is employed for special steel moment frame buildings (3–15 storey) with surface foundation. To model the superstructure, a surrogate SDOF system with a multilinear backbone curve is used that represents the nonlinear response of the actual structure oscillating according to its fundamental mode of vibration. A lumped-parameter mass-spring-dashpot model representing a rigid disk foundation on a uniform half-space is used to represent the soil-foundation system. The results indicate that no reduction in the design base shear is advisable for structures located on moderately soft to firm soils with shear wave velocities above 150 m/s. This conclusion is at odds with the current prescription of SSI provisions of seismic design code, which allow some reduction in the design base shear for such buildings.

This study presents analyses of a four-storeyed load-bearing structural walled building assuming the base of the walls as fixed as well as supported on stiff, medium and soft soil springs. The study also includes strip-stepped brick masonry footing with its width as 1.38 m at a depth of 1.0 m below the walls fixed at the base as well as supported on the same springs as used in the structure alone. The results are somewhat different than the assumption of fixed-base analyses being always conservative. The study also suggests appropriate modeling to capture maximum response in structural members.

2 Modeling and Analyses

A typical four-storeyed load-bearing structural walled building has been considered for the study. The details of the building are as below:

- Grade of concrete used is M20 and the grade of steel used is Fe415.
- Floor to floor height is 3.1 m.
- Plinth height above GL is 0.30 m.
- Depth of foundation is 1.15 m below GL.
- Parapet height is 1.2 m.
- Slab thickness is 150 mm.
- Structural wall thickness is 150 mm of concrete grade M20.
- Live load on the floor is 3 kN/m^2 and Live load on the roof is 1.5 kN/m^2.
- The load for floor finishes is 1 kN/m^2 and roof treatment is 1.5 kN/m^2
- The building is located in Seismic Zone IV.
- Importance Factor is taken as 1.0.
- Damping for concrete and masonry is considered as 5%.

Table 1 Model parameters

Description	Modulus of elasticity (MPa)	Weight density (kN/m^3)	Poisson's ratio
Concrete	22,360	25.0	0.15
Masonry	4200	20.0	0.30

The behavior of the materials has been assumed to be elastic. The foundation below the walls is considered made of brick masonry with its width gradually increasing to 1.38 m at a depth of 1.15 m below the GL. The structure has been modeled in SAP2000.

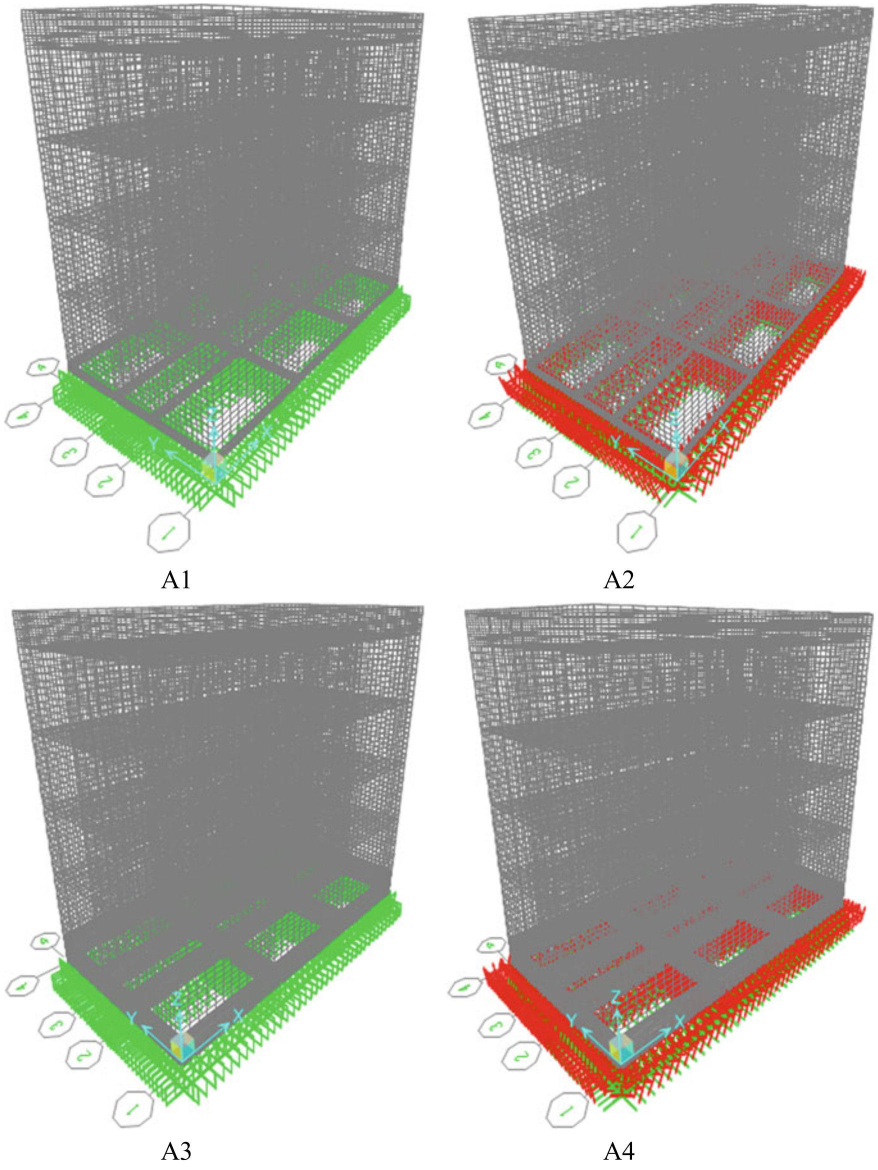
There are three classifications of soils namely Type-I (Rock or hard soils), Type-II (Medium of stiff soils) and Type-III (soft soils) for determining the response spectrum to be used to estimate design earthquake forces. In terms of penetration number (N), the soil Type-I, Type-II and Type-III have been categorized having $N > 30$, $10 < N > 30$ and $N < 10$, respectively [17]. The models have incorporated linear soil springs representing Type-I, Type-II and Type-III soils with their modulus of subgrade reaction as 90,000, 30,000 and 15,000 kN/m^3, respectively, as mentioned in NBC Clause 7.4.1.11 of Part 6, Sect. 2 [15]. The walls, slabs and foundation have been modeled as four noded shell elements. The material properties of the brick masonry have been taken from literature [16]. For each soil type, four models were developed where for soil Type-I, A1 represents structure fixed at the base of the walls, A2 has soil springs below the walls, A3 has foundation below the walls fixed at base and A4 has foundation below the walls supported on same soil springs. Similarly, B1, B2, B3 and B4 models consider soil Type-II and C1, C2, C3 and C4 models consider soil Type-III. The other model parameters considered are shown in Table 1.

The three-dimensional models of A1, A2, A3 and A4 are shown in Fig. 1. The Models B1 to B4 and C1 to C4 look alike in appearance. The foundation has been added as a shell element with its width as 0.46 m just below the walls and 1.38 m at a depth of 1.15 m below the GL.

The response spectrum analyses have been carried out on these models with the load combinations as per IS1893 [17] shown in Table 2. The last mode considered for the response belongs to have 34 Hzs frequency. The results have been obtained for the envelop case of these combinations.

3 Results and Discussion

The structures are generally designed assuming their base as fixed. In reality, all structures have a foundation that is supported on the soil. So, in this discussion, the emphasis has been given to know the models capturing the maximum response along with a comparison with the response obtained from fixed-base analyses.


A1 A2

A3 A4

Fig. 1 Three-dimensional models of the structural walled building: A1—Walls fixed at the base, A2—Walls restrained by springs, A3—Foundation fixed at the base, A4—Foundation restrained by springs

Table 2 Load combinations considered in analyses

1. 1.5DL
2. 1.5(DL + LL)
3. 1.2(DL + LL + EQx)
4. 1.2(DL + LL + EQy)
5. 1.2(DL + LL-EQx)
6. 1.2(DL + LL-EQy)
7. 1.5(DL + EQx)
8. 1.5(DL-EQx)
9. 1.5(DL + EQy)
10. 1.5(DL-EQy)
11. 0.9DL + 1.5(EQx)
12. 0.9DL-1.5(EQx)
13. 0.9DL + 1.5(EQy)
14. 0.9DL-1.5(EQy)
15. 1.2(DL + LL + response spectrum-XY)
16. 1.5(DL + response spectrum-XY)
17. 0.9DL + 1.5response spectrum-XY
18. Envelope load case

3.1 Dynamic Characteristics and Base Shear of the Models

The dynamic characteristics and base shear induced in all models are shown in Table 3. The fundamental time period of fixed-base models is 0.084 s. The maximum percent (%) increase compared to fixed-base models is 37.6(A4), 78.6(B4) and 121.4(C4), respectively. The increases in peak values with soil Type-II and Type-III compared to Type-I are 29.8 and 61.0%, respectively.

The base shear of fixed-base models in X-direction is 1067.0 kN for all models. The maximum values out of all models are 1536.6 (A4), 1787.9(B4) and 1788.6(C4) kN. The increase in peak values with soil Type-II and Type-III compared to Type-I is the same as a value of 16.4%. The base shear of fixed-base models in Y-direction is 1308.6 kN for all models. The maximum value is 1788.6 kN which is the same for A4, B4 and C4. There is no increase in peak values with soil Type-II and Type-III compared to Type-I.

It is found that in general there is an increase in the fundamental time period in all SSI systems. The maximum base shear is found in the models with foundation restrained by soil springs.

Table 3 Dynamic characteristics and base shear of the models

Models	First mode (s)	Second mode (s)	Third mode (s)	Base shear—X (kN)	Base shear—Y (kN)
A1	0.084	0.056	0.051	1067.0	1308.6
A2	0.108	0.071	0.056	1196.3	1450.1
A3	0.091	0.061	0.054	1370.2	1692.3
A4	0.115	0.077	0.059	1536.6	1788.6
B1	0.084	0.056	0.051	1067.0	1308.6
B2	0.142	0.093	0.060	1388.3	1450.1
B3	0.091	0.061	0.054	1370.2	1692.3
B4	0.150	0.100	0.064	1787.9	1788.6
C1	0.084	0.056	0.051	1067.0	1308.6
C2	0.181	0.118	0.063	1450.0	1450.0
C3	0.091	0.061	0.054	1370.2	1692.3
C4	0.185	0.127	0.067	1788.6	1788.6

3.2 Peak Joint Displacements of the Models

The peak joint displacements in X, Y and Z-directions of fixed-base model A1 are −0.5, −1.4 and −0.7 mm, respectively. The corresponding displacements of B1 and C1 are the same as that of A1. The percent (%) increase in peak joint displacements of A4 are 98.1, 102.8 and 61.7 compared to A1, B4 are 236.9, 211.8 and 147.8 compared to B1 and C4 are 392.3, 353.6 and 278.7 compared to C1. The percentage increases in peak values with soil Type-II and Type-III compared to Type-I are 70.1 and 148.5 in X, 53.7 and 123.7 in Y and 53.2 and 134.2 in Z-directions, respectively (Table 4).

It is found that in general, the displacements have increased in SSI systems but the increase is more pronounced in X-direction.

3.3 Peak Responses in Walls of the Models

The peak responses in walls are shown in Table 5. The peak tensile stress of fixed-base model A1 is 1.66 MPa, which is the same in B1 and C1. The maximum peak values out of all models are 2.02(A4), 2.92(B4) and 4.10(C4) MPa, which are 22.0, 75.9 and 147.3% higher compared to A1, B1 and C1, respectively. It is found lesser with A3, B3 and C3 compared to fixed-base models. The increases in peak values with soil Type-II and Type-III compared to Type-I are 44.1 and 102.6%, respectively.

The peak compressive stress of fixed-base model A1 is 3.25 MPa, which is the same in B1 and C1. The maximum peak values out of all models are 4.20(A4), 5.19(B4) and 6.42(C4) MPa, which are 29.2, 59.6 and 97.3% higher compared to

Table 4 Joint displacements of the models

Models	X (mm)	Y (mm)	Z (mm)
A1	−0.5	−1.4	−0.7
A2	−0.8	−2.2	−1.0
A3	−0.7	−1.9	−0.8
A4	−1.0	−2.8	−1.2
B1	−0.5	−1.4	−0.7
B2	−1.3	−3.4	−1.5
B3	−0.7	−1.9	−0.8
B4	−1.8	−4.3	−1.8
C1	−0.5	−1.4	−0.7
C2	−2.0	−5.2	−2.3
C3	−0.7	−1.9	−0.8
C4	−2.6	−6.3	−2.7

Table 5 Peak response of walls of the models

Models	Tensile stress (MPa)	Compressive stress (MPa)	Shear stress (MPa)
A1	1.66	−3.25	0.71
A2	1.92	−3.62	1.53
A3	1.54	−3.49	0.93
A4	2.02	−4.20	1.63
B1	1.66	−3.25	0.71
B2	2.55	−4.60	2.69
B3	1.54	−3.49	0.93
B4	2.92	−5.19	2.90
C1	1.66	−3.25	0.71
C2	3.95	−6.01	4.20
C3	1.54	−3.49	0.93
C4	4.10	−6.42	4.49

A1, B1 and C1, respectively. The increases in peak values with soil Type-II and Type-III compared to Type-I are 23.5 and 52.7%, respectively.

The peak shear stress of fixed-base model A1 is 0.71 MPa, which is the same in B1 and C1. The maximum peak values out of all models are 1.63(A4), 2.90(B4) and 4.49(C4) MPa, which are 129.9, 310.4 and 533.9% higher compared to A1, B1 and C1, respectively. The increases in peak values with soil Type-II and Type-III compared to Type-I are 78.5 and 175.7%, respectively.

It is found that models with foundations restrained by soil springs have maximum tensile, compressive stresses and shear stresses.

Table 6 Peak responses of slab of the models

Models	Tensile stress (MPa)	Compressive stress (MPa)	Shear stress (MPa)
A1	2.14	−2.09	0.51
A2	2.15	−2.09	0.52
A3	2.14	−2.09	0.51
A4	2.15	−2.09	0.52
B1	2.14	−2.09	0.51
B2	2.15	−2.09	0.52
B3	2.14	−2.09	0.51
B4	2.15	−2.09	0.52
C1	2.14	−2.09	0.51
C2	2.15	−2.09	0.52
C3	2.14	−2.09	0.51
C4	2.15	−2.09	0.52

3.4 Peak Responses in Slabs of the Models

The peak responses in slabs are shown in Table 6. The peak tensile stress of fixed-base model A1 is 2.14 MPa, which is the same in B1 and C1. The maximum peak value out of all models is 2.15 MPa in A2, B2 and C2, which is close to the response of fixed-base models.

The peak compressive stress of fixed-base model A1 is 2.09 MPa, which is the same in all models.

The peak shear stress of fixed-base model A1 is 0.51 MPa, which is the same in B1 and C1. The maximum of peak values out of all models is 0.52 MPa in A2, B2 and C2 models, which is 1.7% higher compared to respective fixed-base models. The increase in peak values of both soil Type-II and Type-III compared to Type-I is 0.6%.

Comparing the peak responses, the maximum tensile, compressive and shear stresses are found in models with walls restrained by soil springs. However, the increase is not significant compared to fixed-base models.

4 Conclusions

The study has been carried out on a four-storeyed load-bearing structural walled building. It has been analyzed with the base of the walls as fixed and supported on stiff, medium and soft soil springs. The structure has also been analyzed considering stepped brick masonry strip footing fixed at base and supported on same springs as used in the structure. Considering the structure to be in seismic zone IV, response spectrum analyses were carried out considering the last mode with 34 Hzs frequency.

The peak values of modal time periods, base shear, joint displacements, normal tensile stresses, normal compressive stresses and shear stresses in walls and slabs have been presented. Following conclusions have been drawn about SSI effects compared to fixed-base analyses:

- There is an increase in the fundamental time period in all SSI systems. The increase in peak values with soil Type-II and Type-III compared to Type-I has computed to 29.8 and 61.0%, respectively. This increase is due to SSI systems getting flexible from soil Type-I to Type-III.
- The maximum base shear is found in the models with foundation restrained by soil springs. The increase in peak values with soil Type-II and Type-III compared to Type-I is the same as a value of 16.4% in X-direction due to higher spectral acceleration in the models. In Y-direction, there is no increase in peak values with soil Type-II and Type-III compared to Type-I due to unchanged spectral acceleration.
- In general, the displacements have increased in SSI systems. The percentage increases in peak values with soil Type-II and Type-III compared to Type-I are 70.1 and 148.5 in X, 53.7 and 123.7 in Y and 53.2 and 134.2 in Z-directions, respectively. The increase is more pronounced in X-direction. This increase is due to SSI systems getting flexible from soil Type-I to Type-III.
- It is found that models with foundations restrained by soil springs have maximum tensile, compressive stresses and shear stresses in walls. The increases in peak values of tensile stresses with soil Type-II and Type-III compared to Type-I are 44.1 and 102.6%, respectively. The increases in peak values of compressive stresses with soil Type-II and Type-III compared to Type-I are 23.5 and 52.7%, respectively. The increases in peak values of shear stresses with soil Type-II and Type-III compared to Type-I are 78.5 and 175.7%, respectively. This increase is due to higher base shear in the models.
- Comparing the peak responses in slabs, the maximum tensile, compressive and shear stresses are found in models with walls restrained by soil springs. However, the increase is not significant compared to fixed-base models.

Thus, the study infers that SSI models having foundation restrained by soil springs respond to maximum tensile, compressive and shear stresses in walls which is significant. In the case of slabs, the maximum tensile, compressive and shear stresses are found in SSI models with walls restrained by soil springs but it is not significant.

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