

SSI Effects on the Behavior of a Low-Rise Load Bearing Masonry 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 to be 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 the analyses of a four-storeyed load-bearing brick masonry 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 the base and supported on the 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 · Masonry · 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 which 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

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developments 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 a 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 superstructures. 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 structures to be regulating the phenomenon. Nguyen et al. [8, 9] established the significance of foundation characteristics, viz., footing size in shallow foundations, 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, Jarenpasert 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 a 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 the analyses of a four-storeyed load-bearing brick masonry structure 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 the 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 brick masonry building has been considered for the study. The details of the building are as follows:

- Grade of concrete used is M20 and 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.
- Masonry wall thickness is 230 mm.
- Live load on floor is 3 kN/m^2 and Live load on roof is 1.5 kN/m^2 .
- Floor finish 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 to be 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.

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/m³, 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 4 noded shell elements. The material properties of the brick masonry have been taken from the literature [16]. For each soil type, 4 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 the base and A4 has foundation below the walls supported on the 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–B4 and C1–C4 look alike in appearance. The foundation has been added as a shell element with its width 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 is fixed. In reality, all the structures have a foundation which is supported on 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.

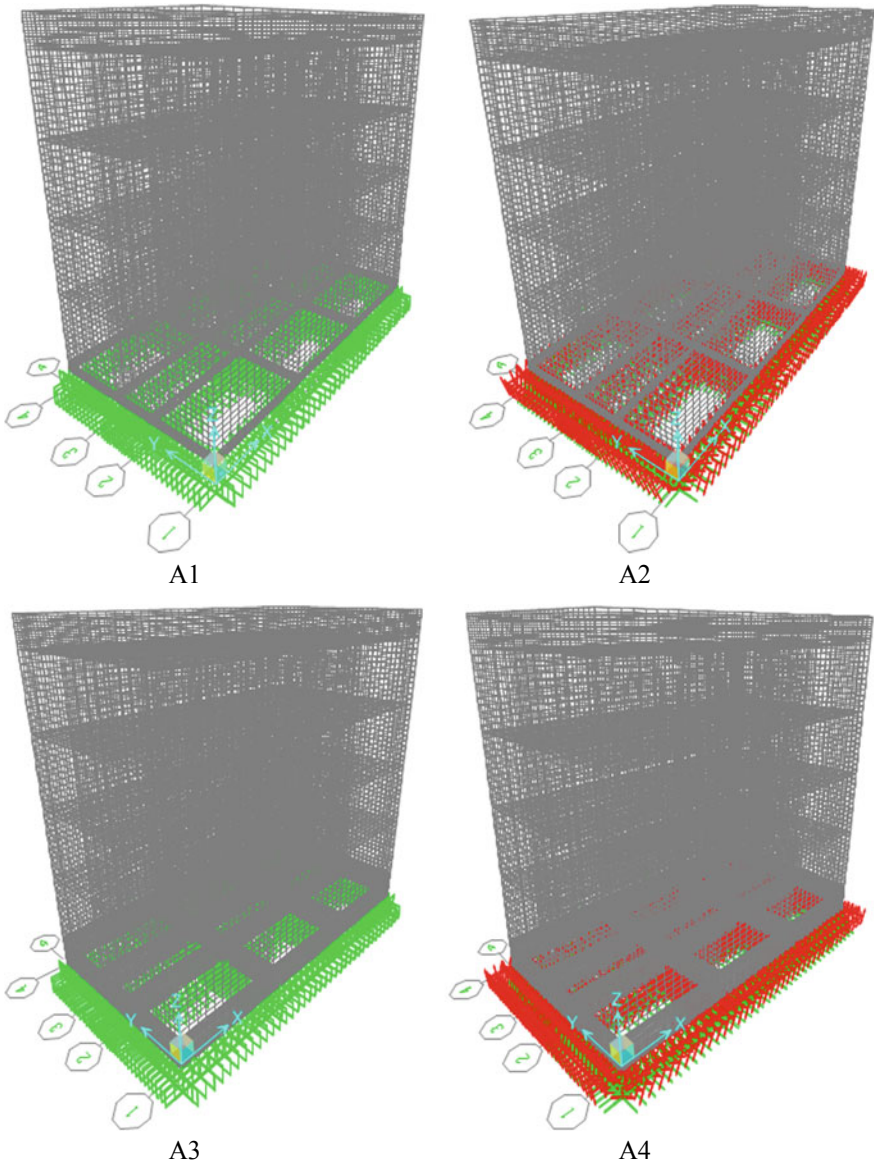


Fig. 1 Three-dimensional models of the masonry building: A1—Walls fixed at the base, A2—Walls restrained by springs, A3—Foundation fixed at the base, and A4—Foundation restrained by springs

Table 2 Load combinations considered in analyses

1. 1.5DL
2. 1.5(DL + LL)
3. 1.2(DL + LL + EQ _x)
4. 1.2(DL + LL + EQ _y)
5. 1.2(DL + LL-EQ _x)
6. 1.2(DL + LL-EQ _y)
7. 1.5(DL + EQ _x)
8. 1.5(DL-EQ _x)
9. 1.5(DL + EQ _y)
10. 1.5(DL-EQ _y)
11. 0.9DL + 1.5(EQ _x)
12. 0.9DL-1.5(EQ _x)
13. 0.9DL + 1.5(EQ _y)
14. 0.9DL-1.5(EQ _y)
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 0.165 s. The maximum percent (%) increase compared to fixed-base models are 12.8(A4), 28.7(B4) and 47.7(C4), respectively. The increases in peak values with soils Type-II and Type-III compared to Type-I are 14.1 and 31.0%, respectively.

The base shear of fixed-base models in the X-direction is 1660.4 kN which is the same in the Y-direction also. The maximum value is 1999.0 kN in both X- and Y-directions of models A3, A4, B3, B4, C3 and C4. It is found to be equal in A2, B2 and C2 models compared to fixed-base models. There is no change with soils Type-II and Type-III compared to Type-I in this problem.

It is found that in general there is an increase in the fundamental time period in all SSI systems. Models having foundation fixed at the base (A3, B3 & C3) and foundation restrained by soil springs (A4, B4 & C4) have maximum base shear in both the directions of same magnitude.

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	0.165	0.111	0.100	1660.4	1660.4
A2	0.181	0.121	0.104	1660.4	1660.4
A3	0.170	0.115	0.102	1999.0	1999.0
A4	0.186	0.125	0.106	1999.0	1999.0
B1	0.165	0.111	0.100	1660.4	1660.4
B2	0.207	0.137	0.107	1660.4	1660.4
B3	0.170	0.115	0.102	1999.0	1999.0
B4	0.213	0.142	0.109	1999.0	1999.0
C1	0.165	0.111	0.100	1660.4	1660.4
C2	0.240	0.158	0.110	1660.4	1660.4
C3	0.170	0.115	0.102	1999.0	1999.0
C4	0.244	0.164	0.112	1999.0	1999.0

3.2 Peak Joint Displacements of the Models

The peak joint displacements in X-, Y- and Z-directions of the fixed-base model A1 are -2.2 , -4.9 and -1.9 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 34.2, 39.8 and 34.9 compared to A1, those for B4 are 64.8, 76.0 and 78.2 compared to B1 and those for C4 are 106.1, 123.7 and 138.4 compared to C1. The percentage increases in peak values with soils Type-II and Type-III compared to Type-I are 22.8 and 53.6 in X, 25.9 and 59.9 in Y and 32.1 and 76.7 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 the Z-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 the fixed-base model A1 is 1.43 MPa which is the same in B1 and C1. The maximum peak values out of all models are 1.43(A1), 1.43(B4) and 1.80(C4) MPa which are 0, 0 and 25.8% higher compared to A1, B1 and C1, respectively. It is found to be lesser with A2, A3, A4, B2, B3, B4 and C3 compared to fixed-base models. The increases in peak values with soils Type-II and Type-III compared to Type-I are 0.0 and 25.8%, respectively. The tensile strength of the masonry can be considered as 0.07 and 0.14 MPa for induced tensile stresses normal and parallel to bed joint, respectively, as mentioned in NBC Clause 5.4.2, Part 6, Sect. 4 [15]. The results

Table 4 Joint displacements of the models

Models	X (mm)	Y (mm)	Z (mm)
A1	-2.2	-4.9	-1.9
A2	-2.5	-5.7	-2.3
A3	-2.7	-6.0	-2.2
A4	-3.0	-6.9	-2.6
B1	-2.2	-4.9	-1.9
B2	-3.0	-7.2	-3.0
B3	-2.7	-6.0	-2.2
B4	-3.7	-8.7	-3.4
C1	-2.2	-4.9	-1.9
C2	-3.8	-9.3	-4.0
C3	-2.7	-6.0	-2.2
C4	-4.6	-11.0	-4.6

Table 5 Peak response of walls of the models

Models	Tensile stress (MPa)	Compressive stress (MPa)	Shear stress (MPa)
A1	1.43	-2.67	0.54
A2	1.25	-2.68	0.67
A3	1.39	-2.92	0.65
A4	1.37	-2.99	0.67
B1	1.43	-2.67	0.54
B2	1.27	-2.83	1.02
B3	1.39	-2.92	0.65
B4	1.43	-3.09	0.94
C1	1.43	-2.67	0.54
C2	1.52	-3.13	1.41
C3	1.39	-2.92	0.65
C4	1.80	-3.30	1.28

indicate that the induced peak tensile stresses in the masonry are much higher than the tensile strength.

The peak compressive stress of the fixed-base model A1 is 2.67 MPa which is the same in B1 and C1. The maximum peak values out of all models are 2.99(A4), 3.09(B4) and 3.30(C4) Mpa, which are 11.9, 15.8 and 23.7% higher compared to A1, B1 and C1, respectively. The increases in peak values with soils Type-II and Type-III compared to Type-I are 3.5 and 10.5%, respectively. The compressive strength of the masonry would be 7.6 Mpa corresponding to the modulus of elasticity as 4200 Mpa [16]. It can be seen that the induced peak compressive stresses are significantly less than the compressive strength of the masonry.

The peak shear stress of the fixed-base model A1 is 0.54 MPa which is the same in B1 and C1. The maximum peak values out of all models are 0.67(A4), 1.02(B2) and 1.41(C2) MPa, which are 23.7, 88.8 and 160.1% higher compared to A1, B1 and C1, respectively. The increases in peak values with soils Type-II and Type-III compared to Type-I are 52.6 and 110.2%, respectively.

It is found that models with foundations restrained by soil springs have maximum tensile and compressive stresses. The shear stresses are maximum with walls restrained by soil springs in all soil types.

3.4 Peak Responses in Slabs of the Models

The peak responses in slabs are shown in Table 6. The peak tensile stress of the fixed-base model A1 is 2.15 MPa which is the same in B1 and C1. The maximum peak values out of all models are 2.16(A4), 2.16(B4) and 2.17(C4)MPa, which is close to the response of fixed-base models. The slabs are assumed to be made of concrete having characteristic compressive strength 20 MPa. The permissible direct tensile strength can be considered as 2.8 MPa as per NBC Clause B-2.1, Part 6, Sect. 5 [15]. The results indicate that the peak tensile stresses are less than the permissible strengths.

The peak compressive stress of the fixed-base model A1 is 2.03 MPa, which is the same in B1 and C1. The maximum peak values are close to the response of fixed-base models. The permissible direct compressive strength can be considered as 5.0 MPa as per NBC Clause B-2.1, Part 6, Sect. 5 [15]. The results indicate that the peak compressive stresses are significantly less than the permissible strengths.

Table 6 Peak responses of slab of the models

Models	Tensile stress (MPa)	Compressive stress (MPa)	Shear stress (MPa)
A1	2.15	-2.03	0.77
A2	2.16	-2.03	0.78
A3	2.15	-2.03	0.81
A4	2.16	-2.03	0.81
B1	2.15	-2.03	0.77
B2	2.16	-2.03	0.78
B3	2.15	-2.03	0.81
B4	2.16	-2.03	0.81
C1	2.15	-2.03	0.77
C2	2.17	-2.03	0.78
C3	2.15	-2.03	0.81
C4	2.17	-2.03	0.80

The peak shear stress of the fixed-base model A1 is 0.77 MPa, which is the same in B1 and C1. The maximum peak values out of all models is 0.81 MPa in A3, B3 and C3 models, which is 5.3% higher compared to respective fixed-base models. The increase in peak values of both soils Type-II and Type-III compared to Type-I is 0.4%.

Comparing the peak responses, it is found that SSI does not significantly affect the tensile and compressive responses. The shear stress is found to be maximum in models with foundation fixed at the base.

4 Conclusions

The study has been carried out on a four-storeyed load-bearing brick masonry 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 the base and supported on the 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. The 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 soils Type-II and Type-III compared to Type-I have been computed to be 14.1 and 31.0%, respectively.
- The SSI models have a higher base shear in both the directions. There is no increase in peak values with soils Type-II and Type-III compared to Type-I.
- In general, the displacements have increased in SSI systems. The percent (%) increases in peak values with soils Type-II and Type-III compared to Type-I are 22.8 and 53.6 in X, 25.9 and 59.9 in Y and 32.1 and 76.7 in Z directions, respectively. Thus, the increase is more pronounced in the Z (vertical) direction.
- Comparing the peak responses in walls, it is found that maximum tensile and compressive stresses are found in the models with foundation restrained by soil springs except in the case of wall fixed at the base (soil Type-I). The increases in peak values of tensile stresses with soils Type-II and Type-III compared to Type-I are 0.0 and 25.8%, respectively. The increases in peak values of compressive stresses with soils Type-II and Type-III compared to Type-I are 3.5 and 10.5%, respectively. The shear stresses are maximum with walls restrained by soil springs in soils Types II and III. In the case of soil Type-I, it is maximum with foundation restrained by soil springs. The increases in peak values with soils Type-II and Type-III compared to Type-I are 52.6 and 110.2%, respectively.

- Comparing the peak responses in slabs, it is found that SSI does not significantly affect the tensile and compressive stress responses. However, the shear stress is found maximum in models with foundation fixed at the base.

Thus, the study infers that SSI models having foundations restrained by soil springs respond to maximum tensile and compressive stresses in walls except in the case of wall fixed at the base (soil Type-I). The maximum shear stress in walls is found in SSI models with walls restrained by soil springs. The maximum shear stress in slabs is found in the models with the foundation fixed at the base.

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