Importance of Inclusion of Soil–Structure Interaction Studies in Design Codes

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Abstract The Indian seismic design code IS:1893 (Part 1) (BIS, 2002) suggests ignoring soil–structure interaction (SSI) studies for seismic design of structures located on rock or rock-like material. However, for a structure resting on soil, it is imperative that the interaction effects be considered during its analysis. The current study is aimed to assess the differences in the design response and analysis outputs arising due to inconsideration of SSI in the analysis for building frames. Reinforced Concrete (RC) building frames supported on pile foundation and embedded in loose sand are considered and finite element analysis is performed using the OpenSees program. Five types of analysis have been carried out to estimate the different design response and analysis output parameters. The study highlights that it may not always be feasible to ignore time history analysis in cases where site response influences the overall response of the building–foundation–soil system. Thus, detailed investigation is required on possible incorporation of dynamic analysis in code-prescribed seismic design procedure.

Keywords Time history analysis · Soil–structure interaction · Equivalent static method of design

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1   Introduction

The Indian seismic design code IS:1893 (Part 1) [1] suggests ignoring soil–structure interaction (SSI) studies for seismic analysis and design of structures located on rock or rock-like material. Moreover, the equivalent static method of design is suggested for the estimation of design base shear for the structure. The code is silent on whether to consider or ignore SSI for soft/medium hard soil, and the general practice is to design the structure by ignoring SSI. Evidently, the code provides the design spectrum for these classes of soils, the sole use of which is supposed to cater for the prevalent site conditions. However, for a flexible foundation–soil system it is imperative that the interaction mechanism would play a role in the behaviour of the structure in the event of an earthquake. Therefore, to properly account for SSI effects in the design, it becomes necessary to model the soil domain along with the structure and conduct a dynamic time history analysis using spectrum compatible ground motion data, which would yield realistic estimate of the design forces.

The use of appropriate ground motions, suggested by the code, creates the need to consider the effect of the presence of soil on the modification of the seismic motion as it reaches the ground surface. Time history analysis of a structure with bottom restrained against all possible translations and rotations, under site-specific ground motions, would indirectly consider the effect of the presence of the soil at the site. Thus, there could be various methods for estimation of design forces in the structure. Unfortunately, there exists a lack of clarity on which method would be suitable for cases, wherein there is a large possibility of development of SSI effects. Hence, the objective of the current study is to assess the differences in the design response and analysis outputs arising due to the inconsideration of SSI in the analysis of RC building frames.

2   Modelling and Input

The present study involves two-dimensional modelling of the structure, soil, and foundation system using a finite element-based software framework, OpenSees [2]. The following sections explain in detail the modelling and inputs considered for the study.

2.1   Structural System

The structural system, considered in the present study, is a four-storeyed RC frame with a uniform bay length and storey height. The structure is assumed to be located on a soft soil site in Seismic Zone V of the seismic map of India [1]. For the purpose of design and analysis of the structure, relevant Indian standards have been

Fig. 1 Structural system with loading details
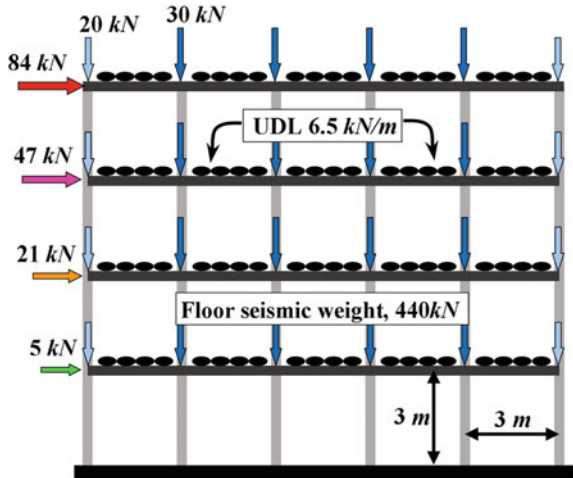
referred. The details of the gravity and lateral loading are shown in Fig. 1. The estimation of the seismic design forces (lateral load) on the structure has been carried out using the equivalent static method (ESM) of analysis as outlined in Ref. [1]. Using the appropriate load combinations, the sizes of the beam and columns have been arrived at Table 1. The modelling of the structural components has been done using two noded frame elements with three translational and three rotational degrees of freedom (DoFs) at each node. M25 grade of concrete and Fe415 grade of rebar are used for design of the frame members, and the material property for the structural element is kept elastic for the present study, as the objective of the current study is not to carry out a performance-based design but to ascertain the differences that arise while adopting different methods to estimate the design forces for the structure.

2.2 Soil–Foundation System

For modelling SSI in the present study, a rectangular soil domain is considered and four noded quadrilateral elements with bilinear isoparametric formulation are used to represent the soil. The design forces on the pile foundation have been obtained by determining the design forces at the base of the ground storey columns. For estimation of the flexural and lateral design forces on the piles, Broms' method is used [1, 3, 4]. The grade of concrete used for piles is M30. Equivalent monopiles have been provided to resist the estimated forces as it is not possible to model pile group in 2D. The sectional details of the pile foundations are shown in Table 1.

The structure and foundation considered are supported on a sandy soil layer of depth 30 m from the base of the superstructure. The sandy layer is assumed to be located above bedrock. The width of the soil domain considered is 20 times the

Table 1 Frame and pile member details

Beam section (mm × mm)	Column section (mm × mm)	Column r/f, main	Pile diameter (mm)	Pile length (m)
250 × 350	400 × 400	12 # 12 mm Ø	1000	15

width of the structure [5]. Driven concrete pile foundations support the framed structure and are also modelled using two noded frame elements. The pile nodes are connected to the soil system using a zero-length rigid link member. Interface nonlinearity has not been considered in the study. The structure–foundation system is placed at the central region of the soil domain. Modelling of the pile cap has not been considered, and the material properties of the pile have been kept linear in the study.

2.3 Nonlinear Properties of Soil

For simulating the nonlinear behaviour of the soil, pressure-dependent multi-yield material model, available in OpenSees, is used. The plastic behaviour in this material model is accounted by using Drucker–Prager yield surface (nested yield surface) criteria. Moreover, a non-associative flow rule exists to capture the effect of dilatancy [6]. Table 2 shows the basic parameters considered for the soil used in the present study. Twenty numbers of nested yield surfaces are used for the simulation of the constitutive behaviour of the material.

2.4 Modelling of Absorbent Boundaries

For SSI studies, radiation damping is incorporated by proper modelling of vertical and horizontal boundaries of the soil domain. It also allows truncation of the soil domain to a finite extent. In the present study, the vertical and horizontal boundaries have been modelled using Lysmer–Kuhlemeyer viscous dashpots (using appropriate coefficients) [7] to arrest the waves at the boundary along the transverse and longitudinal directions, and preventing the same from reflecting back into the soil

Table 2 Basic properties of soil

Density of soil (kg/m^3)	Friction angle of sand (φ)	Poisson's ratio (v)	Shear wave velocity (m/s)
1700	29	0.34	180

medium after being incident at the far-off boundaries. The ground motion input, for SSI cases, has been applied in the form of equivalent nodal forces using the procedure outlined in [8].

2.5 Gravity Analysis and Validation

To carry out dynamic analysis of the structure–soil system, it is a prerequisite to carry out static gravity analysis in a staged manner. This staged analysis procedure has been presented in [9]. Moreover, before conducting a full-fledged analysis of the soil–structure system, it is necessary to accurately incorporate the boundary conditions. For this, a linear elastic soil model (without structure) with sine wavelet as input has been analysed and the model validated for the response in the centre of the soil domain as shown in Fig. 2.

2.6 Rayleigh Damping

The presence of nonlinearity in soil produces high-frequency spurious oscillations in the numerical solution of the SSI system. It is possibly due to the excitation of high-frequency modes which are undamped. To overcome this issue, the HHT-α method for time step integration may be used [10]. For cases wherein the HHT-α method is ineffective for removal of the spurious oscillations, incorporation of a small amount of Rayleigh damping is useful. Moreover, for the fixed base analysis it is important to incorporate some amount of damping to obtain a realistic response of the structure. Therefore, in the present study, Rayleigh damping has been considered. All contributing modes are assumed to have near about the dame damping ratio of 5%. For the fixed base analysis, the frequencies of the various modes of the structure are estimated using the conventional eigenanalysis. However, for the
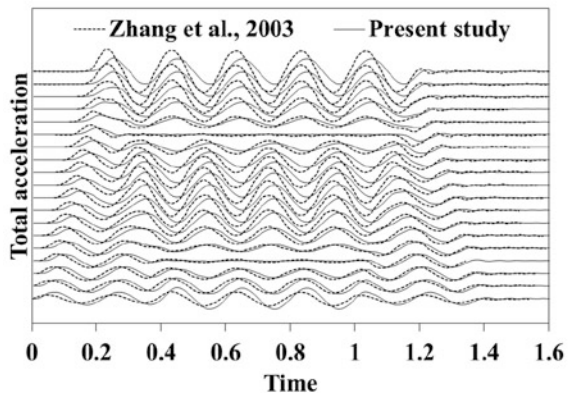

Fig. 2 Validation of the numerical model

Table 3 Rayleigh coefficients

Soil		Structure	
$\omega_1 = 9.42$	$a_0 = 0.85$	$\omega_1 = 13.08$	$a_0 = 1.16$
$\omega_4 = 9.42$	$a_1 = 0.0088$	$\omega_4 = 104.7$	$a_1 = 0.0085$

soil–structure system, the conventional eigenanalysis cannot be applied. Hence, a theoretical relationship mentioned in Ref. [11] is used. The frequencies corresponding to the first and the fourth mode are chosen for estimation of Rayleigh coefficients using the relationships mentioned in Ref. [12]. Based on the damping ratios and the frequency of the modes, the coefficients are estimated, and these are used to form the damping matrix (Table 3).

2.7 Ground Motion Input and Scaling

The ground motion input selected for the time history analysis is the same as one of the recorded motions during the 1995 Kobe earthquake. The PGA level of the motion considered is that corresponding to the design basis earthquake (DBE) on a soft soil site located in the Seismic Zone V of India and the corresponding response spectrum (Fig. 3). To make the original motion relevant for the chosen site, the original time history is made compatible with the design spectrum using wavelet-based scaling [13] (Fig. 3).

3 Analysis Cases

In the present study, the design forces on the structure are estimated using five different methods each representing an analysis case. The description of the five cases is as follows:

Fig. 3 **a** Response spectrum and **b** corresponding spectrum compatible ground motion used
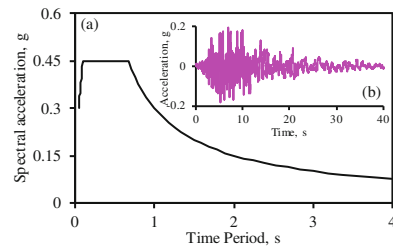
1. Equivalent Static Method (ESM): In this method, the design forces are estimated using the procedure outlined in Ref. [1]. The base of the structure is kept fixed (restrained in all DoF) for this method.
2. Fixed Base Analysis (FBA): In this method, the design forces are estimated using the spectrum compatible motion keeping the structure fixed at the base.
3. Linear Soil–Structure Interaction (LSSI): In this method, the pile foundation and the supporting soil medium are modelled along with the superstructure. The spectrum compatible motion with half the PGA value is used to provide the input motion at the base of the structure–soil system [11].
4. Nonlinear Soil–Structure Interaction (NLSSI): This method is similar to the LSSI case, with the only difference being in the use of nonlinear properties of soil for the analysis.
5. Fixed Base with Free Field Motion (FBFFM): In this method, the effect of soil is considered by using the modified motion, recorded at the surface of the soil domain which is obtained by conducting a free field analysis of the soil domain while keeping the structure fixed at the base.

4 Results and Discussion

The present section discusses the prime results of the various analysis cases. Base shear is a design parameter that could provide appropriate estimate of the amount of lateral force being induced into the system resulting from the various analysis cases. In the present study, storey-wise absolute maximum shear force, encountered over the entire time history duration, is obtained by summing the shear forces at the base of the column corresponding to each storey level (Fig. 4). From the figure, it is observed that FBA and ESM produce the largest and the smallest shear forces in the lower storey columns. Moreover, LSSI produces values greater than that produced by ESM but less than that produced by NLSSI. For the lower stories, the difference

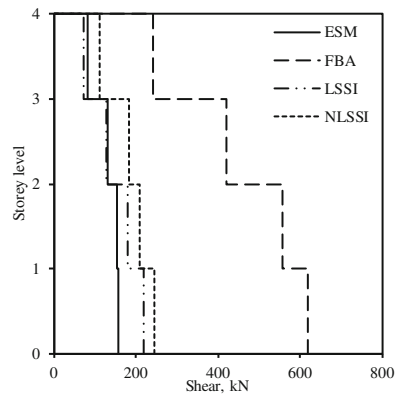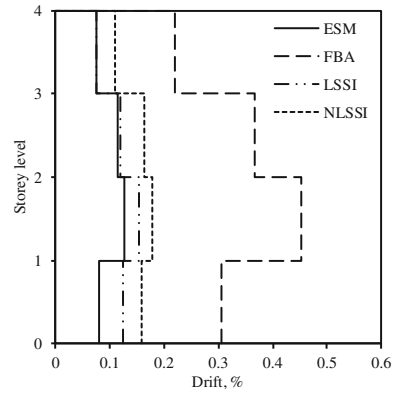**Fig. 4** Storey shear for various analysis cases

Fig. 5 Percentage drift for various analysis cases

between the ESM and LSSI cases is high whereas for the higher stories, the difference diminishes. The difference between LSSI and NLSSI values is lower for lower stories but increases for higher stories.

The inter-storey drift ratios (in %) for all the stories show similar trend as observed for storey shear (Fig. 5); i.e. FBA produces largest and ESM produces smallest drift for each storey level. NLSSI produces drift larger than LSSI. For the ground storey, the drift is smaller with respect to other stories even as the shear is higher due to the fixity of the structure at the base.

The comparison of absolute maximum moment profile, induced over the entire duration of each analysis, at the base of each storey level is shown in Fig. 6a (exterior most column) and Fig. 6b (interior most column). Moreover, the storey-wise moment capacity of the column is also plotted in Fig. 6b. It can be seen that the induced forces corresponding to FBA profusely exceed the design moment capacity in exterior columns for lower stories and in interior columns for all the stories. The moment induced corresponding to LSSI and NLSSI also exceeds the design flexural capacity of the columns but for ground storey only for exterior columns. For interior columns, the induced moment is very close to the column capacity.

The instantaneous moment distribution corresponding to the time instant when the maximum bending moment developed in the ground storey columns is shown in Fig. 7. The observations corresponding to Fig. 6 are very much applicable for Fig. 7 as well. In both the figures, it can be seen that at the ground storey level there is a sharp increase in the moment induced for all the analysis cases. This is possibly due to the fact that in the interior columns there is one additional beam member present. This is not so for the exterior columns, and hence, additional moments are induced onto the exterior columns.

Moreover, for the ground storey column, the difference in the moments shared by the exterior and the interior columns is less and it increased for the upper stories. This may be possibly due to the same boundary condition at the base of ground storey for the exterior and the interior columns being same. However, at the top of

Fig. 6 Absolute maximum moment profile for **a** exterior columns and **b** interior columns
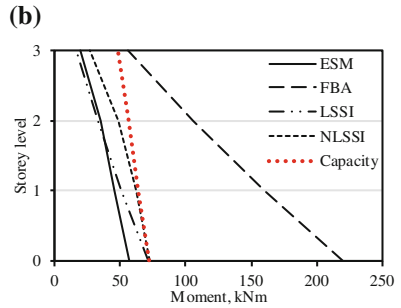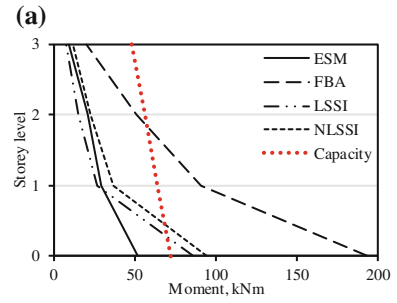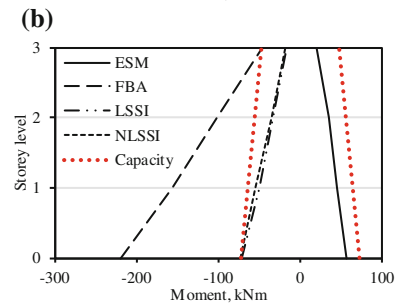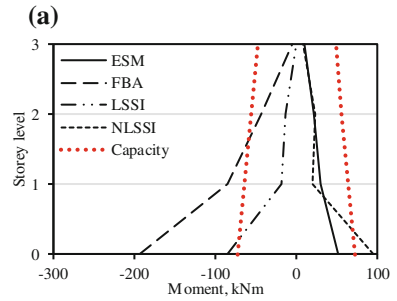

Fig. 7 Instantaneous moment profile for **a** exterior columns and **b** interior columns

the ground storey level, the exterior columns have the boundary condition which is less stiff in comparison with that of internal column due to the absence of one beam member. This leads to the reduction of moments in the exterior columns above ground storey.

5   Importance of Soil–Structure Interaction

Apart from the four types of analysis discussed so far, another fixed base analysis is also carried out using the motion obtained by conducting a free field analysis of the soil domain (FBFFM). Spectrum compatible motion obtained for SSI analysis is applied at the base of the free field soil domain and analysed. The acceleration response obtained at the surface is noted, and that motion is applied at the base of the building frame with fixed base. Time history analysis using this motion was carried out, and various response entities were noted. Figure 8 shows the comparison of the base shear obtained for this analysis case with other cases. It can be seen that the estimation of base shear for FBFFM analysis case is extremely large and is attributed to the motion obtained from the free field analysis.

Figure 9 shows the original motion used for fixed base analysis and the free field motion (FFM) obtained from free field analysis of the soil domain. It can be seen that there is a large amplification of the acceleration and it is due to the presence of the soft soil deposit. Although the amplified motion considers the modification in the acceleration due to the presence of the soil, the interaction mechanism between the soil and the structure is absent while generating the ground motion. Thus,

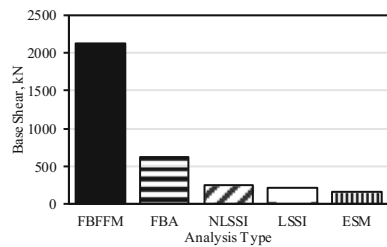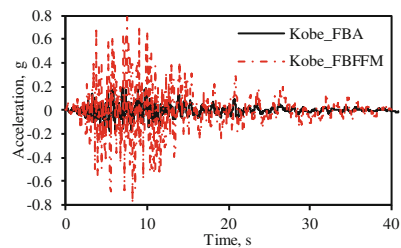**Fig. 8** Base shear comparison for various analysis cases

Fig. 9 Motions used for FBA and FBFFM

overestimated member forces in the structure are observed. Hence, if the modified ground motions due to the presence of soil domain are to be used, then, in such cases, it becomes imperative to consider the interaction mechanism by suitable modelling of the soil–foundation system along with the superstructure to get a realistic estimate.

The present study clearly highlights how ESM would fall short of estimation of the actual design forces that would arise by considering the actual interaction between the soil and the structure. Moreover, FBA, with or without modified ground motions, as per the sites, could produce forces that may be very large compared to the actual scenario. This is because of the absence of huge energy dissipation that exists due to the interaction mechanism and also due to the radiation phenomenon inherent in the soil. It is also to be noted that the forces produced corresponding to LSSI and NLSSI are slightly higher with respect to ESM which may render a structure unsafe in the event of an earthquake. Hence, this advocates the importance of considering soil–structure interaction studies for the design of structure located at soft soil sites.

6   Summary and Conclusions

The present article highlights the importance of inclusion of SSI studies for estimation of design forces on the structure. In the present study, five different types of methods for estimation of design forces on the structure are considered and the differences arising in the design forces using these methods are presented. It has been found that the most widely used method, ESM, produces the lowest estimate of forces and drift values, and FBA, using spectrum compatible ground motion, produces the largest values. The estimates of force obtained using LSSI and NLSSI are significantly lesser than that obtained by FBA but moderately larger than ESM. The margin is sufficient to push the structure into an unsafe zone, especially making the exterior bay columns vulnerable to damage. Although the effect of soil deposit is considered by modifying the ground motion, direct application of motion is not recommended for estimating the design forces. The foundation–soil medium should be modelled to obtain the realistic estimate of design forces. Hence, ESM and FBA may not always provide a realistic estimate and it may sometimes not be possible to ignore dynamic SSI studies for the design of structures located on soft soil. The present study highlights the need of detailed investigation on possible incorporation of dynamic SSI analysis in code-prescribed seismic design procedure. Detailed parametric studies are required to be carried out in this regard.

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