Effects of Dynamic Soil-Structure Interaction on Inelastic Behaviour of Mid-Rise Moment Resisting Buildings on Soft Soils

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Abstract

In this study, a ten storey moment resisting building frame, representing the conventional type of regular mid-rise building frames, resting on shallow foundation, is selected in conjunction with a clayey soil, representing subsoil class Ee, as classified in the AS 1170.4. The structural sections are designed after applying dynamic nonlinear time history analysis, based on both elastic method, and inelastic procedure using elastic-perfectly plastic behaviour of structural elements. The frame sections are modelled and analysed, employing Finite Difference Method using FLAC 2D software under two different boundary conditions: (i) fixed-base (no Soil-Structure Interaction), and (ii) considering Soil-Structure Interaction (SSI). Fully nonlinear dynamic analysis under influence of different earthquake records is conducted and the results of the two different cases for elastic and inelastic behaviour of the structural model are extracted and compared respectively. The results indicate that the lateral deflection increments for both cases are substantially dominating and can change the performance level of the structures from life safe to near collapse or total collapse. Therefore, conventional elastic and inelastic structural analysis methods assuming fixed-base structure may no longer be adequate to guarantee the structural safety. Therefore, considering SSI effects in seismic design of concrete moment resisting building frames resting on soft soil deposit is essential.

Keywords: Dynamic Soil-Structure Interaction, Moment Resisting Building Frame, Inelastic Analysis, Finite Difference Method, Soft Soil

1. Introduction

Soil–Structure Interaction is an interdisciplinary field of endeavour which lies at the intersection of soil and structural mechanics, soil and structural dynamics, earthquake engineering, geophysics and geomechanics, material science, computational and numerical methods, and diverse other technical disciplines. Its origins trace back to the late 19th century, evolving and maturing gradually in the ensuing decades and during the first half of the 20th century, and progressed rapidly in the second half stimulated mainly by the needs of the nuclear power and offshore industries, by the debut of powerful computers and simulation tools such as finite elements, and by the desire for improvements in seismic safety.

The effect of soil on the response of structures depends on the properties of soil, structure and the nature of the excitation. The response can be solved directly, using Fourier analysis or other methods. The process, in which the response of the soil influences the motion of the structure and vice versa, is referred to as *Soil-Structure Interaction (SSI).* Implementing Soil-Structure Interaction effects enables the designer to assess the inertial forces and real displacements of the soil-foundation-structure system precisely under the influence of free field motion. For flexible or small structures resting on a stiff soil, the effects of the interactions are usually insignificant, while the interactions of stiff and heavy structures located on soft ground are very critical.

2. Background

According to available literature, generally when the shear wave velocity of the supporting soil is less than 600 m/s, the effects of soil-structure interaction on the seismic response of structural systems, particularly for moment resisting building frames, are significant (e.g. Veletsos and Meek, 1974; Galal and Naimi, 2008) . These effects can be summarised as: (i) increase in the natural period and damping of the system, (ii) increase in the lateral displacements of the structure, and (iii) change in the base shear depending on the frequency content of the input motion and dynamic characteristics of the soil and the structure.

During the recent decades, the importance of the dynamic soil-structure interaction for several structures founded on soft soils has been well recognised. Several researchers such as Veletsos and Meek (1974), Kobayashi et al. (1986), Gazetas and Mylonakis (1998), Wolf and Deeks (2004), and Galal and Naimi (2008) studied structural behaviour of un-braced structures subjected to earthquake under the influence of soil-structure interaction. Examples are given by Gazetas and Mylonakis (1998) including evidence that some structures founded on soft soils are vulnerable to SSI. Thus, for ordinary building structures, a better insight into the physical phenomena involved in SSI problems is necessary.

3. Fully Nonlinear Dynamic Analysis of the Soil-Structure System

A soil-structure system comprising structure, common nodes, soil foundation system and earthquake induced acceleration at the level of the bed rock is shown in Figure1.

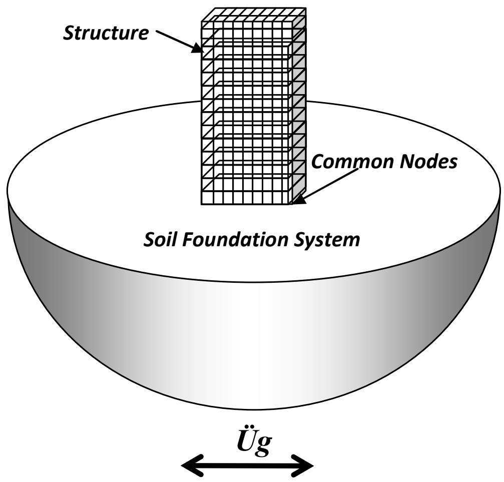


Figure1. Soil-Structure System

The dynamic equation of motion of the soil and structure system can be written as:

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=[M]\{m\}\ddot{u}_g+\{F_v\} \tag{1}$$

where, $\{u\}$, $\{\dot{u}\}$ and $\{\ddot{u}\}$ are the nodal displacements, velocities and accelerations with respect to the underlying soil foundation, respectively. $[M]$, $[C]$ and $[K]$ are the mass matrix, damping matrix and stiffness matrix of the structure, respectively. It is more appropriate to use the incremental form of Eq. (1) when plasticity is included, and then the matrix $[K]$ should be the tangential matrix and $\ddot{U}_g$ is the earthquake induced acceleration at the level of the bed rock. If only the horizontal acceleration is considered, for instance, then $\{m\}=[1,0,1,0,....,1,0]^T$. $\{F_v\}$ is the force vector corresponding to the viscous boundaries. The above mentioned method, where the entire soil-structure system is modelled in a single step, is called *Direct Method*. The use of direct method requires a computer program that can treat the behaviour of both soil and structure with equal rigor (Kramer 1996).

The governing equations of motion for the structure incorporating foundation interaction and the method of solving these equations are relatively complex. Therefore, Direct Method is employed in this study and Finite Difference software, FLAC2D, is utilised to model the soil-structure system and to solve the equations for the complex geometries.

FLAC (Fast Lagrangian Analysis of Continua) is a two-dimensional explicit finite difference program for engineering mechanics computations. This program simulates the behaviour of different kinds of structures. Materials are represented by elements which can be adjusted to fit the geometry of the model. Each element behaves according to a prescribed linear or nonlinear stress/strain law in response to the applied forces or boundary restraints. The program offers a wide range of capabilities to solve complex problems in mechanics such as inelastic analysis including Plastic moment and simulation of hinges for structural systems.

Several efforts have been made in recent years in the development of analytical methods for assessing the response of structures and supporting soil media under seismic loading conditions. There are two main analytical procedures for dynamic analysis of soil-structure systems under seismic loads, *equivalent-linear* and *fully* *nonlinear methods*. Byrne et al. (2006) and Beaty and Byrne (2001) provided some overviews of the above mentioned methods and discussed the benefits of the nonlinear numerical method over the equivalent-linear method for different practical applications. The equivalent-linear method is not appropriate to be used in dynamic soil-structure interaction analysis as it does not capture directly any nonlinear effects because it assumes linearity during the solution process. In addition, strain-dependent modulus and damping functions are only taken into account in an average sense, in order to approximate some effects of nonlinearity (e.g. damping and material softening).

Byrne et al. (2006) concluded that the most appropriate method for dynamic analysis of soil-structure system is *fully nonlinear method.* The method correctly represents the physics associated with the problem and follows any stress-strain relation in a realistic way. Considering the mentioned priorities and capabilities of the fully nonlinear method for dynamic analysis of soil-structure systems, this method is used in this study in order to attain rigorous and more reliable results.

4. Inelastic Seismic Analysis of the Structural System

Practising engineers use inelastic analysis methods for the seismic evaluation and design of existing and new buildings. The main objective of inelastic seismic analysis is to predict the expected behaviour of the structure against future probable earthquakes precisely. This has become increasingly important with the emergence of performance-based engineering (PBE) as a technique for seismic evaluation and design using performance level prediction for safety and risk assessment (ATC-40, 1996).

Since structural damage implies inelastic behaviour, traditional design and analysis procedures based on linear elastic techniques can only predict the performance level implicitly. By contrast, the objective of inelastic seismic analysis method is to directly estimate the magnitude of inelastic deformations and distortions (performance level). Performance levels describe the state of structures after being subjected to a certain hazard level and are classified as: fully operational, operational, life safe, near collapse, or collapse (FEMA, 1997). Overall lateral deflection, ductility demand, and inter-storey drifts are the most commonly used damage parameters. The above mentioned five qualitative performance levels are related to the corresponding quantitative maximum inter-storey drifts (as a damage parameter) of: <0·2%, <0·5%, <1·5%, <2·5%, and >2·5%, respectively.

The generic process of inelastic analysis is similar to conventional linear procedures in which engineers develop a model of the building or structure, which is then subjected to a representative, anticipated seismic ground motion. The primary difference is that the properties of some or all of the components of the model include plastic moment in addition to the initial elastic properties. These are normally based on approximations derived from test results on individual components or theoretical analyses. In many instances, it is important to include the structural and geotechnical components of the foundation in the simulation.

Inelastic bending is simulated in structural elements by specifying a limiting plastic moment. If a plastic moment is specified, the value may be calculated by considering a flexural structural member of width b and height h with yield stress σ_y. If the member is composed of a material that behaves in an elastic-perfectly plastic manner (Figure 2), the plastic resisting moments M^p for rectangular sections can be computed as follows:

$$M^p = \sigma_y (\frac{bh^2}{4}) \tag{2}$$

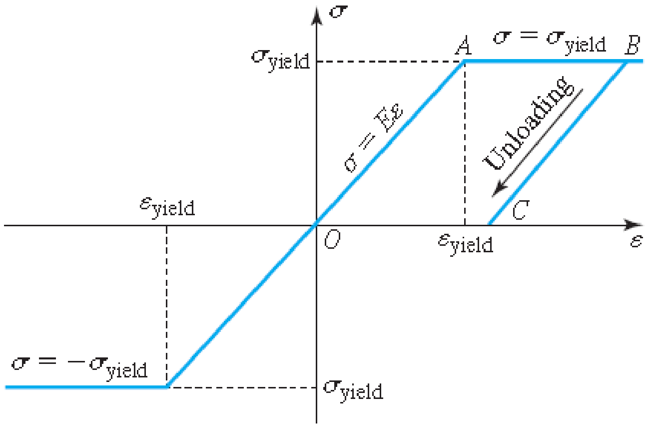


Figure2. Elastic-perfectly plastic behaviour of structural elements (ATC-40, 1996)

It should be noted that the present formulation assumes that structural elements behave elastically until reaching the defined plastic moment. The section at which the plastic moment occurs can continue to deform, without inducing additional resistance, when M^p is reached.

5. Geotechnical and Structural Characteristics of the Models

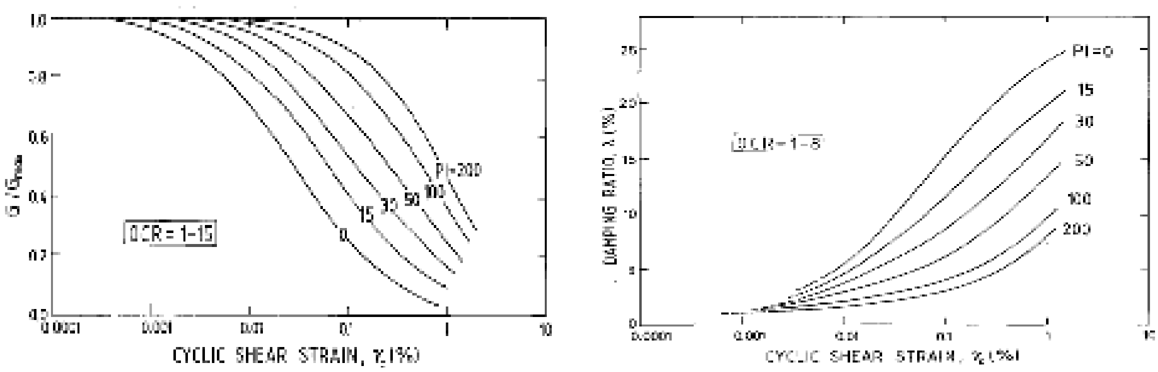
5.1. Geotechnical Characteristics of the Subsoil

Low plasticity clayey soil (CL) representing subsoil class Ee according to the classification of AS1170.4:2007 (Earthquake actions in Australia) is selected in this study. Since Galal and Naimi (2008) concluded that for moment resisting building frames up to 20 storeys, considering the effect of SSI on seismic behaviour is only necessary for soil deposits with shear wave velocity less than 180 m/sec, only subsoil class Ee falling into this category is considered in this study. Geotechnical characteristics of the soil are tabulated in Table 1, and have been extracted from the actual geotechnical report. Therefore, these parameters have merit over the assumed parameters which may not be completely conforming to reality.

Table 1. Geotechnical characteristics of the utilised soil

Soil Type (AS1170)	Shear wave velocity *Vs* (m/s)	Unified classification (USCS)	Shear Modulus *Gmax* (kPa)	ρ (kg/m^3)	Poisson Ratio (ν)	SPT (N)	Plastic Index (*PI*)	C (kPa)	Φ (degree)
Ee	150	CL	33,100	1,471	0.40	6	15	20	12

The shear wave velocity shown in Table 1 is obtained from down-hole test, which is a low strain in-situ test. This test generates a cyclic shear strain of about 10^{-4} percent where the resulting shear modulus is called G_{max}. In the event of an earthquake, the cyclic shear strain amplitude increases and the shear strain modulus (G_{sec}) and damping ratio (ξ) which both vary with the cyclic shear strain amplitude change relatively. These nonlinearities in soil stiffness and damping ratio for cohesive soils were elucidated by Vucetic and Dobry (1991) as two ready to use curves. They represented relations between G/G_{max} and damping ratio versus cyclic shear strain γ_c and soil plasticity *PI* for normally and over consolidated cohesive soils as illustrated in Figure 3.



(a) Relations between G/G_{max} versus cyclic shear strain and soil plasticity

(b) Relations between material damping ratio versus cyclic shear strain and soil plasticity

Figure3. Ready to use curves presented by Vucetic and Dobry (1991)

Applying the fully nonlinear method for dynamic analysis, will enable us to apply these charts directly to the model and take soil nonlinearity into account in an accurate and realistic way.

5.2. Structural Characteristics of the Models

In this study, a concrete moment resisting building frame resting on a shallow foundation (4 meters in width and 12 meters in length), representing conventional types of buildings in a relatively high risk earthquake prone zone has been chosen. In the selection of the frames' span width, attempt was made to make this width to be conforming to architectural norms and constructional practices of the conventional buildings in mega cities. Dimensional characteristics of the structural model are summarised in Table 2.

Table 2. Dimensional characteristics of the studied frames

Reference Name (Code)	Number of Stories	Number of Bays	Story Height (m)	Bay Width (m)	Total Height (m)	Total Width (m)
S10	10	3	3	4	30	12

5.3. Structural Analysis and Design

For the above mentioned frame, as fixed-base model (Figure 4), dynamic nonlinear time history analysis has been carried out using Finite Difference software, FLAC 2D, once based on elastic behaviour of the structural system, and the next time considering inelastic behaviour. This behaviour is specified by limiting the plastic moment as described in Section 4, using elastic-perfectly plastic behaviour of the structural elements under the influence of four different earthquake records tabulated in Table 3. The acceleration records of Northridge (1994), Kobe (1995), El-Centro (1940), and Hachinohe (1968) earthquakes are illustrated in Figures 5, 6, 7, and 8, respectively. The concrete sections of the structural model have been designed afterward according to AS3600: 2001 for elastic and inelastic models assuming un-cracked sections.

Table 3. Earthquake ground motions used in this study

Earthquake	Country	Year	PGA (g)	Mw (R)
Northridge	USA	1994	0.843	6.7
Kobe	Japan	1995	0.833	6.8
El Centro	USA	1940	0.349	6.9
Hachinohe	Japan	1968	0.229	7.5

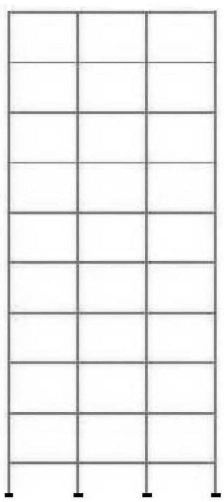


Figure4. Fixed base model for elastic and inelastic analysis in FLAC 2D

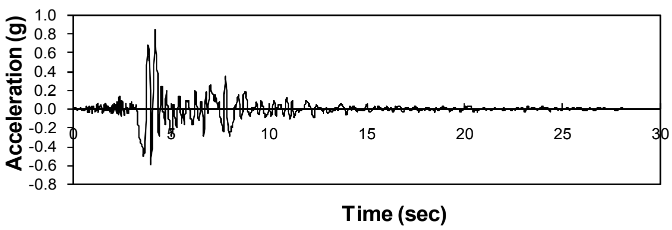


Figure 5. Acceleration record of Northridge earthquake (1994)

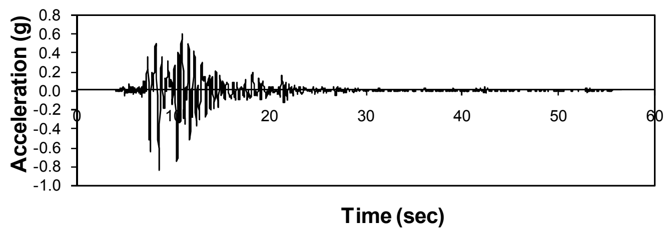


Figure 6. Acceleration record of Kobe earthquake (1995)

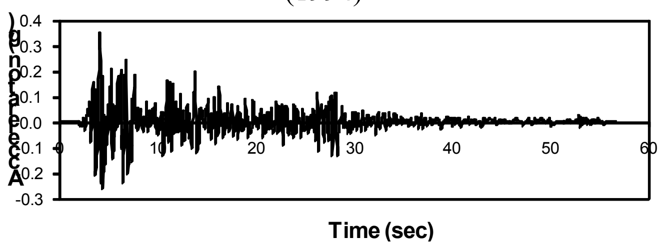


Figure 7. Acceleration record of El-Centro earthquake (1940)

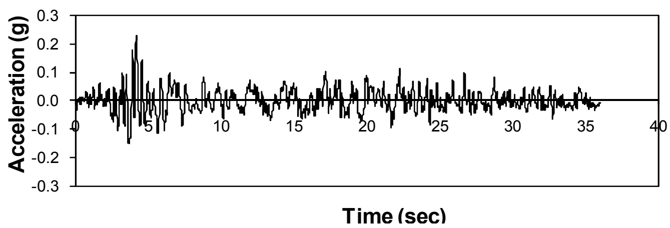


Figure 8. Acceleration record of Hachinohe earthquake (1968)

6. Numerical Simulation and Dynamic Analysis of the Soil-Structure System

In this study, fully nonlinear time history dynamic analysis has been employed using FLAC 2D to define elastic and inelastic seismic response of the concrete moment resisting frame under the influence of SSI. Dynamic analyses are carried out for two different systems: (i) fixed-base structure on the rigid ground (Figure 4), and (ii) frames considering subsoil (Figure 9) using direct method of soil-structure interaction analysis as the flexible base model. The analyses are undertaken for two different cases by including elastic and inelastic behaviour of the structural system.

The soil-structure model (Figure 9) comprises beam elements to model structural elements, two dimensional plane strain grid elements to model soil medium, fixed boundaries to model the bed rock, quiet boundaries (viscous boundaries) to avoid reflective waves produced by soil lateral boundaries, and interface elements to simulate frictional contact and probable slip due to seismic excitation. According to Rayhani and Naggar (2008), horizontal distance between soil boundaries is assumed to be five times the structure width, and the bedrock depth is assumed to be 30 m.

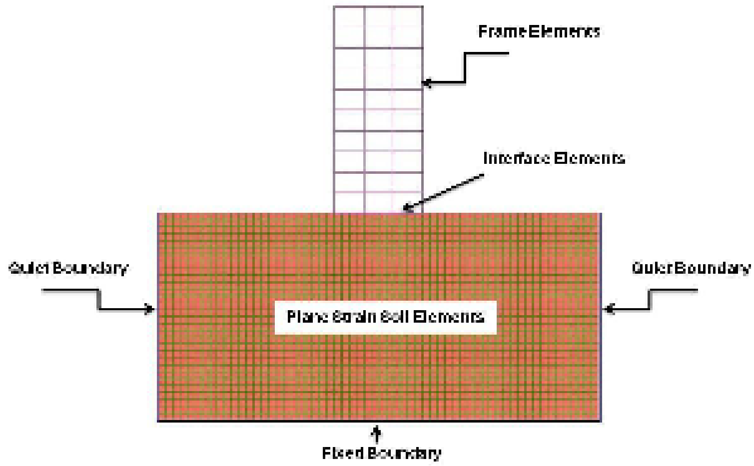


Figure 9. Components of the soil-structure model in FLAC 2D

Earthquake ground motions (Table 3) are applied to both systems in two different ways. In the case of modelling soil and structure simultaneously using direct method (flexible base), the earthquake records are applied to the combination of soil and structure directly at the bed rock level, while for modelling the structure as the fixed base (without soil), the earthquake records are applied to the base of the structural models (Foundation model).

7. Results and Discussion

The results of the elastic and inelastic analyses for both fixed and flexible models including the base shear and the maximum lateral deflections are determined and compared. According to the results summarised in Table 4, it is observed that the ratio of the base shear of the flexible-base models ($\widetilde{V}$) to those of fixed-base *(V)* in all models are less than one.

Table4. Base shear ratio of flexible-base to fixed-base models

Method of Analysis	Earthquake	V (kN)	$\widetilde{V}$ (kN)	$\widetilde{V} / V$
Elastic	Northridge	102	58	0.568
	Kobe	196	95	0.484
	El Centro	80	38	0.475
	Hachinohe	66	30	0.454
Inelastic	Northridge	40	30	0.750
	Kobe	50	36	0.720
	El Centro	36	25	0.694
	Hachinohe	25	18	0.720

The range of base shear ratio is between 45% to 57% for the elastic analysis while for inelastic analysis is between 69% to 75% indicating the base shear reduction in the case of elastic analysis is more than the one for inelastic case.

Generally, the base shear of structures modelled with soil as flexible-base are always less than the base shear of structures modelled as fixed base for both elastic and inelastic cases. These results have good conformity to the NEHRP-2003 regulations.

In addition, it is observed that in the elastic analysis, the maximum lateral deflections of the flexible base model substantially increase when subjected to the four mentioned earthquake records in comparison with the fixed base model (Figures 10-13). For the inelastic analysis, the lateral deflection increments are also substantial, but the ratio of the increments is smaller (Figures 14-17).

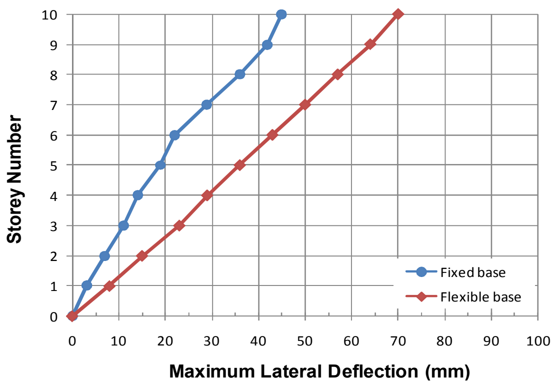


Figure 10. Maximum elastic lateral deflection for the fixed base and flexible base models (Northridge earthquake, 1994)

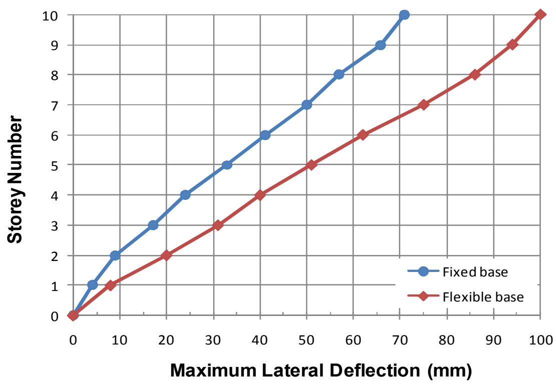


Figure 11. Maximum elastic lateral deflection for the fixed base and flexible base models (Kobe earthquake, 1995)

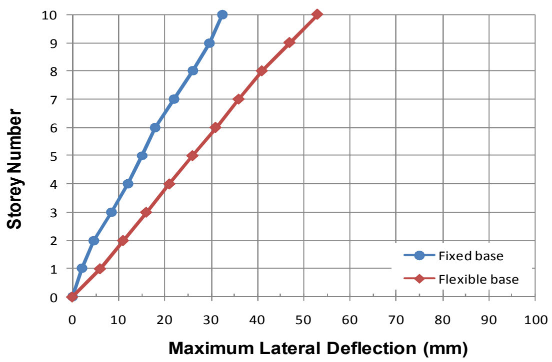


Figure 12. Maximum elastic lateral deflection for the fixed base and flexible base models (El Centro earthquake, 1940)

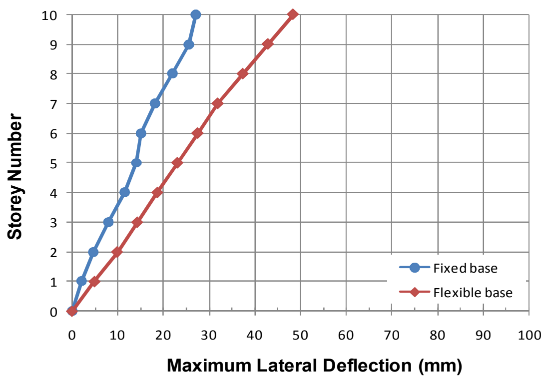


Figure 13. Maximum elastic lateral deflection for the fixed base and flexible base models (Hachinohe earthquake, 1968)

In this study, the spectral displacement may change considerably with changes in natural period due to SSI effects for both elastic and inelastic cases. Therefore, such increases in the natural period may considerably alter the response of the building frames under seismic excitation. This is due to the fact that the natural period lies in the long period region of the response spectrum curve because of the natural period lengthening for such systems. Hence, the displacement response tends to increase. Therefore, performance level of the structure, especially for the structures analysed and designed based on the elastic method, may be changed from life safe to near collapse or total collapse. The risk for the structures analysed and designed based on the inelastic analysis is a bit smaller but the structures are still vulnerable to the change of the performance level.

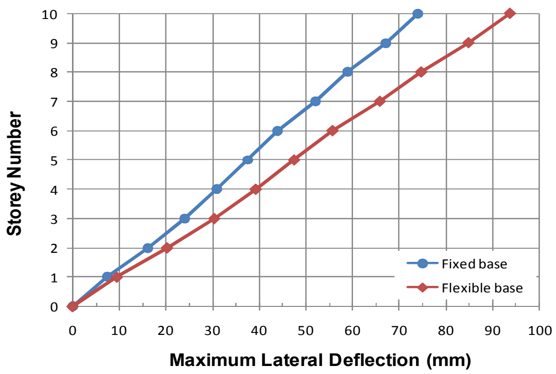


Figure 14. Maximum inelastic lateral deflection for the fixed base and flexible base models (Northridge earthquake, 1994)

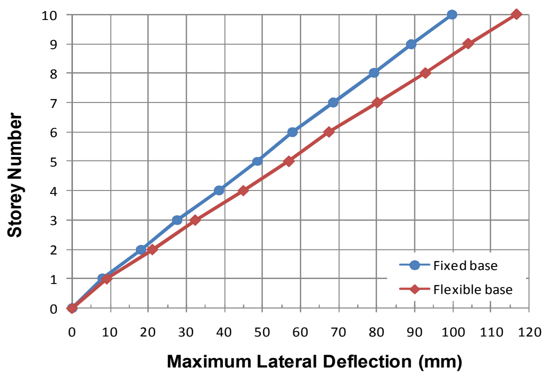


Figure 15. Maximum inelastic lateral deflection for the fixed base and flexible base models (Kobe earthquake, 1995)

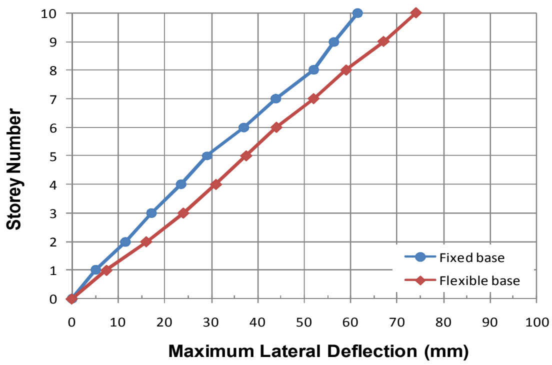


Figure 16. Maximum Inelastic lateral deflection for the fixed base and flexible base models (El Centro earthquake, 1979)

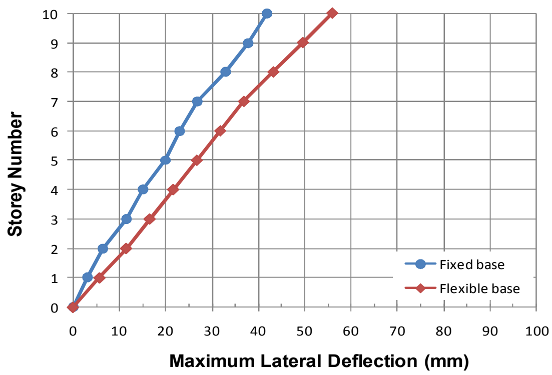


Figure 17. Maximum Inelastic lateral deflection for the fixed base and flexible base models (Hachinohe earthquake, 1968)

8. Conclusions

According to the results of the numerical investigation conducted in this study, the base shear of the structures modelled with soil are always less than the base shear of the structures modelled as fixed-base as expected. However, the maximum lateral storey drifts of the structures resting on soft soil deposit substantially increase when the Soil-Structure Interaction is considered. The base shear reductions and lateral deflection increments are smaller for the case of inelastic analysis in comparison with the elastic analysis, although they are still substantial and considerable. Considering the results of this study, performance level of structures similar to the model used in this study can be changed from life safe to near collapse or total collapse. It can be concluded that the conventional structural analysis methods assuming fixed-base structures is no longer adequate to guarantee the structural safety. Therefore, considering SSI effects in seismic design of concrete moment resisting building frames resting on soft soil deposit is essential.

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