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SIGNIFICANCE OF BEDROCK DEPTH IN DYNAMIC SOIL-STRUCTURE INTERACTION ANALYSIS FOR MOMENT RESISTING FRAMES

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ABSTRACT

In this study, a fifteen storey moment resisting building frame, resting on a shallow foundation, is selected in conjunction with two clayey soils with the shear wave velocities less than 600m/s, representing soil classes D_e and E_e, according to AS 1170.4. Different bedrock depths including 10m, 20m, and 30 m are employed in the numerical modelling using finite difference software FLAC 2D. Fully nonlinear dynamic analysis under the influence of different earthquake records is conducted, and the results of the three different cases are compared and discussed. The results indicate that the dynamic properties of the subsoil such as shear wave velocity as well as bedrock depth play significant roles in seismic response of the building frames under the influence of soil-structure interaction. As the bedrock depth increases, lateral deflections and inter-storey drifts of the structures increase. These effects can change the performance level of structures from life safe to near collapse or total collapse. Therefore, the conventional design procedure excluding SSI is not adequate enough to guarantee the structural safety for the building frames resting on soft soil deposits.

Keywords: Soil-Structure Interaction, bedrock depth, FLAC 2D, nonlinear dynamic analysis, soft soil, earthquake

INTRODUCTION

Soil-structure interaction aims at assessing the response of structures resting on the ground and subjected to any stimulation, whilst taking into account coupling with the support medium and the soil, which has its own deformability and even resistance characteristics. This interaction is expressed through modifications of the motion of the ground near the structure as compared with the open field without any structure configuration. This interaction is of variable importance, depending on the nature of the soil, the characteristics of the structure and type of foundations. For light structures with superficial foundations, it can be almost negligible. However, whenever it is necessary to study the seismic response of a structure and to consider it as an integral part of a whole system consisting of the ground, foundations and structure, soil-structure interaction analysis is of significant importance.

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Performance-based seismic engineering design is the modern approach to earthquake resistance design. Seismic performance (performance level) is described by designating the maximum allowable damage state (damage parameter) for an identified seismic hazard (hazard 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). 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.

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.

The importance of SSI both for static and dynamic loads has been well established and the related literature spans at least 30 years of computational and analytical approaches to solve soil–structure interaction problems. Since 1990s, great effort has been made for substituting the classical methods of design by the new approaches based on the concept of performance-based seismic design. Several researchers (e.g. Veletsos and Meek, 1974; Kobayashi et al., 1986; Gazetas and Mylonakis, 1998; Wolf and Deeks, 2004; 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, the necessity of a better insight into the physical phenomena involved in SSI problems has been recognised. In this study, after a brief review of methods to simulate soil-structure interaction, a fifteen storey moment resisting building frame resting on clayey soils is numerically simulated while considering different thicknesses for the sub-soil.

DYNAMIC ANALYSIS OF SOIL-STRUCTURE SYSTEM

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. The standard practice for dynamic analysis of soil-structure systems is traditionally based on equivalent-linear method. However, practical applications of fully nonlinear analyses have increased in the last decade, as more emphasis is placed on reliable predictions in dynamic analysis of complex soil-structure systems (Byrne et al., 2006).

The equivalent linear method has been in use for many years to calculate the wave propagation (and response spectra) in soil and rock at sites subjected to seismic excitation. In equivalent-linear method, a linear analysis is carried out with some assumed initial values for damping ratio and shear modulus in the various regions of the model. Then, the maximum cyclic shear strain is recorded for each element and used to determine the new values for damping and modulus, referring to the backbone curves relating damping ratio and secant modulus to the amplitude of the cyclic shear strain. Some empirical scaling factors are usually utilised when relating these strains to the model strains. The new values of damping ratio and shear modulus are then used in the next stage of the numerical analysis. The whole process is repeated several times, until there is no further change in the properties and the structural response. At this stage, “strain-compatible” values of damping and modulus are found, and the simulation results using these values is the best possible predicted response of the real site. Rayleigh damping may be used in this method to simulate energy losses in the soil-structure system when subjected to a dynamic loading. The method employs linear properties for each element remaining constant throughout the history of shaking which as explained are estimated from the mean level of dynamic motion (Seed and Idriss, 1969).

Fully nonlinear method, adopted in this study, is capable of precisely modelling nonlinearity in dynamic analysis of soil-structure systems and may follow any prescribed nonlinear constitutive relation. In addition, structural geometric nonlinearity (large displacements) can be accommodated precisely in this method. During the solution process, structural materials could behave as isotropic, linearly elastic materials with no failure limit for elastic analysis, or as elasto-plastic materials with specified limiting plastic moment for inelastic structural analysis to simulate elastic-perfectly plastic behaviour. For the dynamic analysis, the damping of the system in the numerical simulation should reproduce, in magnitude and form, the energy losses in the natural system subjected to the dynamic loading. In soil and rock, natural damping is mainly hysteretic (Gemant and Jackson 1937, and Wegel and Walther 1935). Hysteretic damping algorithm which is incorporated in this solution method enables the strain-dependent modulus and damping functions to be incorporated directly into the numerical simulation.

Byrne et al. (2006) and Beaty and Byrne (2001) summarised the above mentioned methods and discussed the benefits of the fully 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 directly capture any nonlinearity effects due to linear 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. 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. In this method, small strain shear modulus and damping degradation of soil with strain level can be precisely captured in the modelling. Considering the mentioned priorities and capabilities of the fully nonlinear method for the dynamic analysis of soil-structure systems, this method is employed in dynamic analysis of soil-structure systems in this study in order to attain rigorous and more reliable results.

IDEALISATION OF SOIL-STRUCTURE SYSTEM

The governing equations of motion for the structure incorporating foundation interaction and the method of solving these equations are relatively complex. Therefore, direct method, the method in which the entire soil-structure system is modelled in a single step is employed in this study. The use of direct method requires a computer program that can treat the behaviour of both soil and structure with equal rigor simultaneously (Kramer, 1996). Thus, finite difference software, FLAC 2D V6.0, is utilised to model the soil-structure system and to solve the equations for the complex geometries and boundary conditions. FLAC 2D (Fast Lagrangian Analysis of Continua) is a two-dimensional explicit finite difference program for engineering mechanics computations. This program can simulate behaviour of different types of earth and building structures. Materials are represented by elements which can be adjusted to fit the geometry of the model. Each element behaves according to a prescribed constitutive model in response to the applied forces or boundary restraints (Itasca Consulting Group, 2008).

The soil-structure model comprises beam structural elements to model the structural components, two dimensional plane-strain quadrilateral elements to model the soil medium, and interface elements to simulate frictional contact between the soil medium and the structure. Rigid boundary condition is assigned to the bedrock and lateral boundaries of the soil medium are assumed to be quiet (viscous) boundaries to avoid reflection of the outward propagating waves back into the model. Quiet boundaries are coupled to the free-field boundaries at the sides of the model to account for the free-field motion which would exist in the absence of the structure. Different components of soil structure model are illustrated in Figure 1.

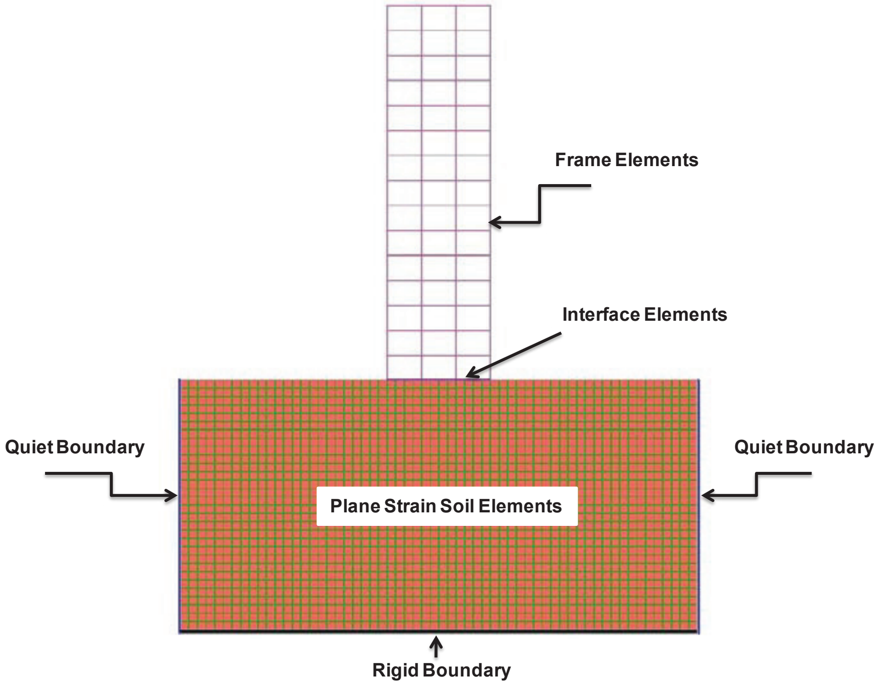


Figure 1. Components of the Soil-Structure model

CHARASTRISTICS OF THE EMPLOYED MODELS

In this study, a fifteen storey concrete moment resisting building frame resting on a shallow foundation (4 meters in width and 12 meters in length) is selected in conjunction with two soil types with the shear wave velocity less that 600m/s representing classes D_e and E_e, according to classification criteria listed in Section 4 of AS 1170.4 (Earthquake action in Australia). As it is a plane strain problem, shallow foundation width has been taken into account to calculate moment of inertia of the footing.

The structural type of the building frame is intermediate moment-resisting frame (moderately ductile) with the following factors for elastic analysis according to Table 6.5(A) of AS 1170.4 (Earthquake action in Australia):

Structural Ductility Factor (μ) = 3.0

Performance Factor (S_p) = 0.67

The specified compressive strength of concrete, the specified yield strength of steel rebar, and the concrete density are assumed to be, 32MPa, 400MPa, and 23.5kN/m3, respectively.

Structural sections are designed according to AS3600-2009 (Australian Standard for Concrete Structures) after undertaking dynamic analysis under influence of four different earthquake ground motions, as a fixed base model. The characteristics of the earthquake ground motions are summarised in Table 1. Performance level of the structural model is considered as life safe level in this design indicating the maximum inter-storey drifts of the model being less than 1.5%.

Table 1. 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

Characteristics of the utilised soils are shown in Table 2. The subsoil properties have been extracted from actual in-situ and laboratory tests (Rahvar, 2006a & 2006b). Therefore, these parameters have merit over the assumed parameters which may not be completely conforming to reality.

It is assumed that watertable is well below the ground surface. The shear wave velocity, shown in Table 2, has been obtained from down-hole test, which is a low strain in-situ test. This test generates a cyclic shear strain of about 10^{-4} present 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 and damping ratio which both vary with the cyclic shear strain amplitude, change relatively. Represented ready to use charts for clayey soils indicating the variations of the shear modulus ratio with the shear strain in nonlinear dynamic analysis as well as material damping ratio versus cyclic shear strain recommended by Sun et al. (1998), have been adopted in this study.

Table 2. Geotechnical characteristics of the utilised soils in this study

Soil Type (AS1170)	Shear wave velocity Vs (m/s)	Unified classification	Shear Modulus *Gmax* (kPa)	Poisson Ratio	SPT	Plasticity Index (PI)	Reference
D_e	320	CL	177304	0.39	30	20	Rahvar (2006a)
E_e	150	CL	33100	0.40	6	15	Rahvar (2006b)

NUMERICAL ANALYSIS

In this study, fully nonlinear time history dynamic analysis method is adopted to simulate dynamic soil-structure interaction using FLAC 2D (Version 6.0) to determine effects of bedrock variation on seismic response of concrete moment resisting building frames subjected to earthquake loading. Dynamic analysis is carried out for 15 storey model in conjunction with two soil types representing soil classes D_e and E_e with geotechnical characteristics presented in Table 2 for two different systems: (i) fixed-base structure on the rigid ground (Figure 2), and (ii) structure considering subsoil using direct method of SSI analysis as the flexible base model using (Figure 3).

The four tabulated earthquake ground motions in Table 1 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 model.

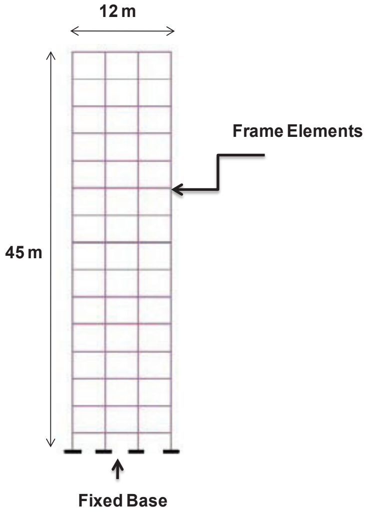


Figure 2. Fixed-base model

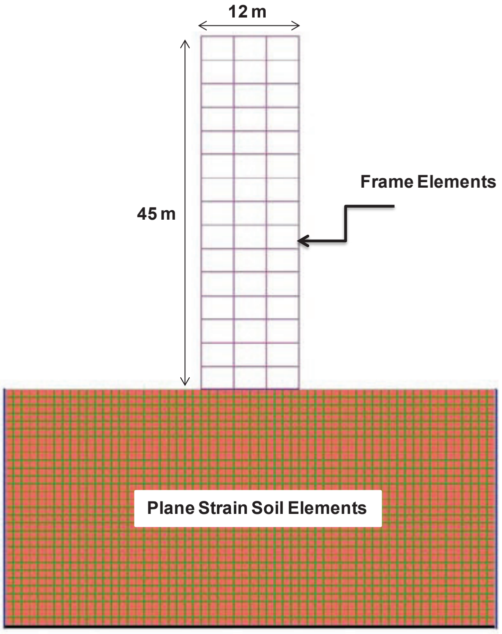
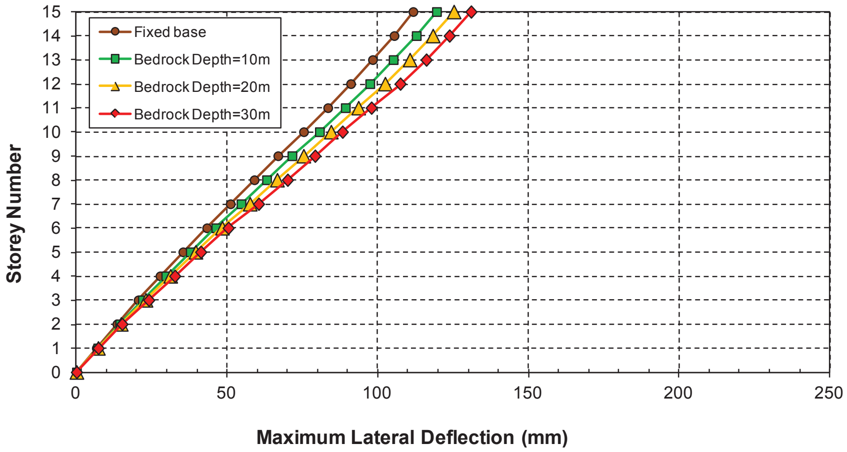


Figure 3. Flexible-base model

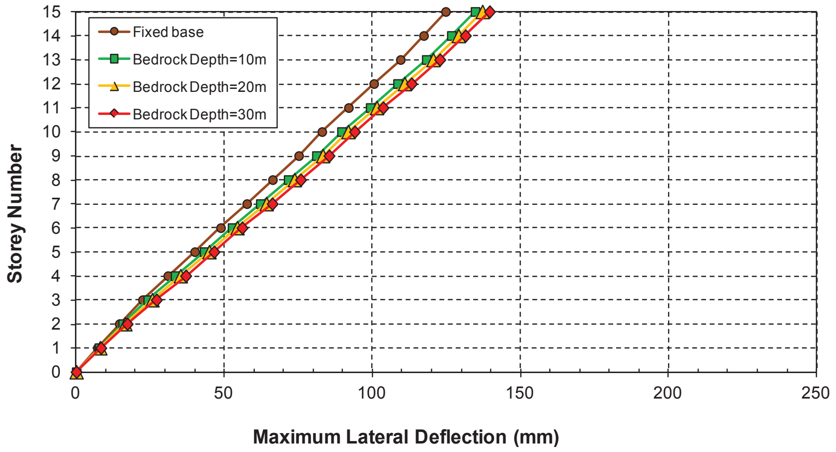
As most of the modern seismic codes (e.g. AS1170.4 and FEMA 273) evaluate local site effects based on the properties of the top 30 meters of the soil profile as most amplification occurs within the first 30 m of the soil profile. Therefore, in this study, the maximum bedrock depth has been assumed to be 30 m. In order to observe the effects of bedrock depth variations on seismic response of the structural model, fully nonlinear dynamic analysis is carried out for structural model resting on soil classes D_e and E_e with bed rock depths of 10, 20, and 30 meters.

RESULTS AND DISCUSSIONS

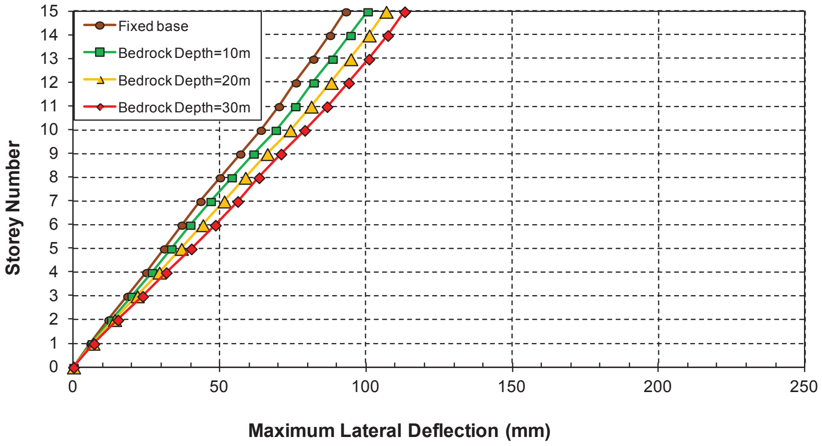
The results of the dynamic analyses in terms of lateral deflections are determined and compared for the fixed-base and flexible-based cases resting on the two different types of soil with bed rock depths of 10, 20, and 30 meters. The results are illustrated in Figures 4a - d and 5a – d, for the model resting on soil class De and E_e, respectively.



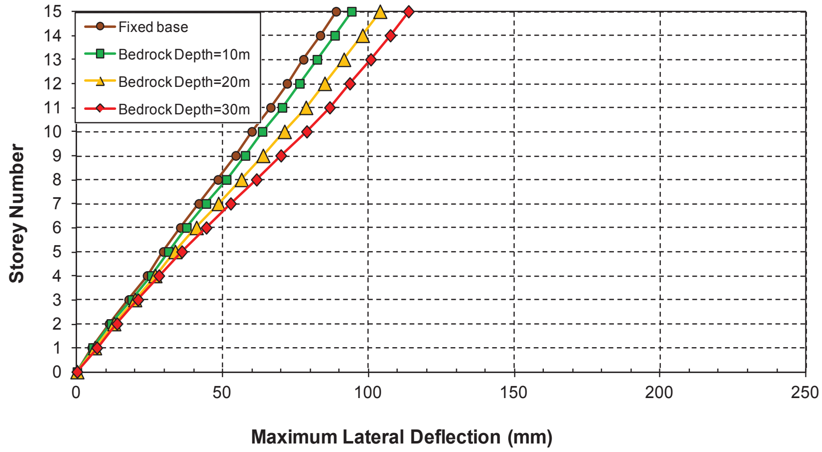
(a)



(b)

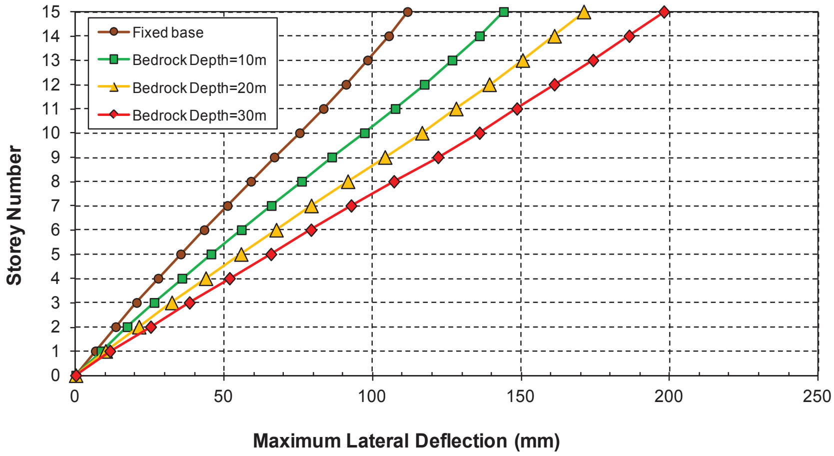


(c)

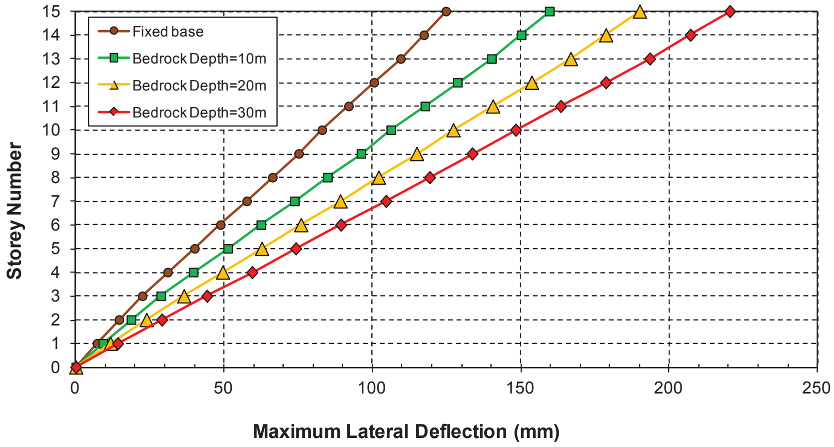


(d)

Figure 4. Maximum lateral deflections on soil type De with variable bedrock depths; (a) Northridge earthquake (1994); (b) Kobe earthquake (1995); (c) El Centro earthquake (1940); (d) Hachinohe earthquake (1968)


Fixed base
Bedrock Depth=10m
Bedrock Depth=20m
Bedrock Depth=30m
Storey Number
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
0
50
100
150
200
250
Maximum Lateral Deflection (mm)

(a)


Fixed base
Bedrock Depth=10m
Bedrock Depth=20m
Bedrock Depth=30m
Storey Number
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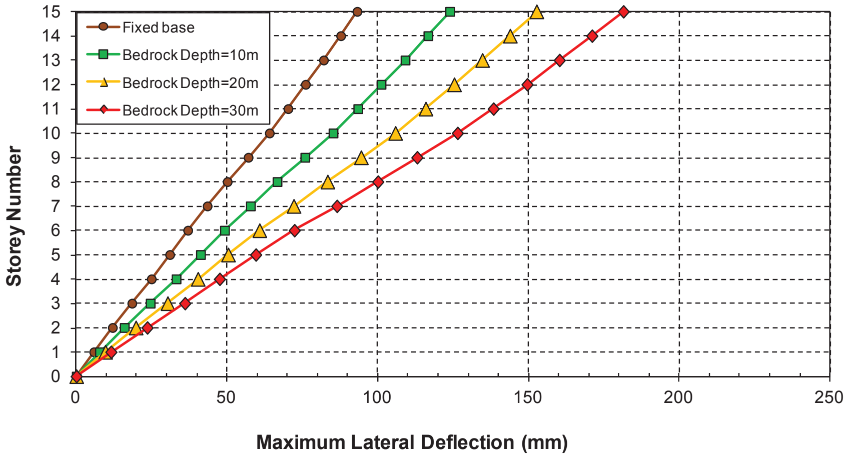
Maximum Lateral Deflection (mm)

(b)


Fixed base
Bedrock Depth=10m
Bedrock Depth=20m
Bedrock Depth=30m
Storey Number
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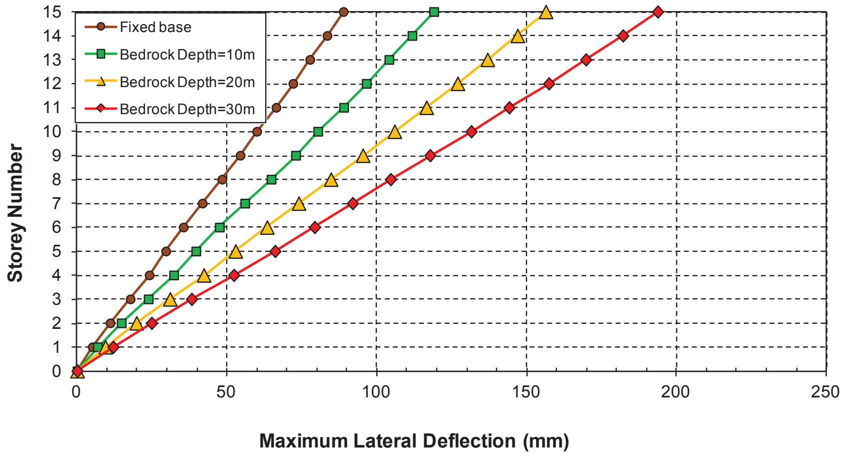
Maximum Lateral Deflection (mm)

(c)



(d)

Figure 5. Maximum lateral deflections on soil type Ee with variable bedrock depths; (a) Northridge earthquake (1994); (b) Kobe earthquake (1995); (c) El Centro earthquake (1940); (d) Hachinohe earthquake (1968)

Comparing the lateral deflections for the model resting on soil class D_e (Figures 4), it is observed that lateral deflections for the flexible base model on soil depths of 10 m do not differ much from that of the fixed-base model which is negligible, while the maximum lateral deflections of the model on soil depths of 20 m and 30m substantially increase in comparison with the fixed-base model. It is also noted that the maximum lateral deflections of the flexible base model resting on soil class E_e (Figures 5) with 30, 20, and 10 m bedrock depths substantially increase in comparison with fixed-base model. Thus, effects of soil structure interaction for the structural model resting on soil class D_e with bedrock depth of more than 10 m is considerable while for the model on soil class Ee, it is considerable for all the bedrock depths. Obviously, performance level of the mentioned building frames may change from life safe to near collapse when SSI is considered in the analysis, which is dangerous and safety threatening.

In addition, it can be noted that by increasing the bedrock depth, the natural period of the subsoil increases and consequently the difference between period of vibration in two cases (structures modelled on flexible soils and structures modelled as fixed base) increase. Thus, the effects of soil-structure interaction for deeper bedrock depths are more considerable. In the case of deeper bedrock depth, natural period lies in the long period region of the response spectrum curve due to the natural period lengthening for such systems. *Hence, the displacement response tends to increase,* and eventually performance level of the structures can be changed from life safe to near collapse.

CONCLUSIONS

From the numerical investigation conducted in this study regarding the mid-rise concrete moment resisting building frame resting on soil classes D_e and E_e, according to AS 1170.4, it is observed that by decreasing the bedrock depth, lateral deflections of the moment resisting building frames decrease. It is essential to consider effects of SSI for seismic design of moment resisting building frames resting on soil class D_e with bedrock depth of more than 10 m while considering SSI for seismic design of moment resisting buildings on soil class E_e is essential for al bedrock depths as performance level of the structures similar to the model used in this study change from life safe to near collapse or total collapse if seismic SSI is considered. Therefore, the conventional design procedure excluding SSI is no longer adequate to guarantee the structural safety for the mentioned building frames. It is highly recommended to practicing engineers working in high earthquake risk zones, to consider SSI influences in dynamic analysis and design of the moment resisting frames to ensure structures perform safely.

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