FINITE DIFFERENCE MODELLING OF SOIL-STRUCTURE INTERACTION FOR SEISMIC DESIGN OF MOMENT RESISTING BUILDING FRAMES[1]

S. Hamid Reza Tabatabaiefar[1], Behzad Fatahi[2] and Bijan Samali[3]
[1]PhD Candidate, [2]Senior Lecturer, [3]Professor, School of Civil and Environmental Engineering, University of Technology Sydney (UTS), NSW, Australia

ABSTRACT

The importance of Soil-Structure Interaction (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 for solving soil–structure interaction problems. Since the 1990s, great effort has been made to substitute the classical methods of design by new ones based on the concept of performance-based seismic design. Also, the necessity of estimating the vulnerability of existing structures and assessing reliable methods for their retrofit have greatly attracted the attention of engineering communities in most seismic zones throughout the world. In the present study, in order to draw a clear picture of soil characteristics effects on seismic response of moment resisting building frames, a ten storey moment resisting building frame, resting on shallow foundation, is selected in conjunction with three soil types with shear wave velocities less than 600m/s, representing soil classes C_e, D_e and E_e, according to Australian Standard AS 1170.4. The structure is modelled considering the three mentioned types of the soil deposits employing Finite Difference approach using FLAC 2D software. Fully nonlinear dynamic analyses under influence of different earthquake records are conducted, and the results of the different cases are compared and discussed. The results indicate that as shear wave velocity and shear modulus of the subsoil decrease, inter-storey drifts and subsequently the necessity of considering SSI effects in seismic design of moment resisting building frames increase. In general, by decreasing the subsoil stiffness, the effects of soil-structure interaction become more dominant and detrimental to the seismic behaviour of moment resisting building frames. These effects substantially alter performance level of the building model resting on soil classes D_e and E_e from life safe to near collapse. Consequently, structural safety for the mentioned building frames could not be ensured by employing the conventional design procedure excluding SSI.

1 INTRODUCTION

The problem of Soil–Structure Interaction in the seismic analysis and design of structures has become increasingly important, as it may be inevitable to build structures at locations with less favourable geotechnical conditions in seismically active regions. For instance, the 28 December 1989 Newcastle earthquake (Australia) killed and injured over 150 people and many mid-rise buildings (approximately 6-15 stories) constructed on weak soil were severely damaged. The 1985 Mexico City and many other recent earthquakes such as Christchurch 2011 (New Zealand) and Japan 2011 (Fukushima) earthquakes clearly illustrate the importance of local soil properties on the seismic response of structures. These earthquakes demonstrated that the rock motions could be amplified at the base of the structure. The determination of a realistic site-dependent free-field surface motion at the base of the structure can be the most important step in the earthquake resistant design of structures. For determining the seismic response of building structures, it is a common practice to assume the structure is fixed at the base. However, this is a gross assumption since flexibility of the foundation could be overlooked and underestimated in this case. This assumption is realistic only when the structure is founded on solid rock. The main concept of site response analysis is that the free field motion is dependent on the properties of the soil profile including stiffness of soil layers. The stiffness of the soil deposit can change the frequency content and amplitude of the ground motion. Likewise, on the path to the structure, wave properties might be changed due to the stiffness of the foundation. When an earthquake ground motion in a free-field intercepts with a rigid foundation, it can be constrained and modified by the rigid foundation. This deviation from free field motion is called kinematic interaction between the soil and foundation. In fact, kinematic interaction is due to the inability of the foundation to conform to the deformations of the free field motion. Moreover, stiffness of the foundation can cause variation of ground motion with depth and scattering of waves at the corners of the foundation. If the foundation dimensions are small compared to the wavelength of the frequency range, kinematic interaction has negligible effects on the response, while when the foundation dimensions are in the same order of the wave length, a base slab averaging effect takes place. In this case, motion amplitude decreases by increasing the depth of the foundation (Figure 1). In addition to kinematic interaction, there is another effect considering the existence of soft soil

[1] This paper was presented at the Sydney Chapter YGP night 2011

under the foundation of the structure which is called inertial interaction. Inertial forces induced by foundation motion during the earthquake can cause the compliant soil to deform which in turn affects the structure inertial forces. The whole process including kinematic interaction and inertial interaction is commonly referred to as *Soil-Structure Interaction (SSI)*.

(a) (b)

Figure 1: (a) Averaging effect ; (b) Decreasing motion amplitude with depth

During the past two decades, various analytical formulations have been developed to solve complex practical problems assuming linear SSI. Several researchers such as Veletsos and Meek (1974), Kobayashi *et al*. (1986), Gazetas and Mylonakis (1998), Wolf and Deeks (2004), Galal and Naimi (2008), and Tabatabaiefar and Massumi (2010) 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. However, the effects of non-linear behaviour of the supporting soil on the seismic response of structures have not been fully addressed in literature.

2 ANALYTICAL PROCEDURE FOR DYNAMIC ANALYSIS

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. Successful application of these methods for determining ground seismic response is vitally dependent on the incorporation of the soil properties in the analyses. As a result, substantial effort has also been made toward the determination of soil attributes for using in these analytical procedures. There are two main analytical procedures for dynamic analysis of soil-structure systems under seismic loads, equivalent-linear and fully nonlinear method. Byrne *et al.* (2006) and Beaty and Byrne (2001) provided overviews of the above mentioned methods and discussed the benefits of the nonlinear numerical method over the equivalent-linear method for different practical applications. According to their research, the equivalent-linear method is not appropriate for use in dynamic soil-structure interaction analysis as it does not capture directly any nonlinearity effects because it assumes linear behaviour 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. They concluded that the most appropriate method for a dynamic analysis of soil-structure system is a fully nonlinear method. This method correctly represents the physics and follows any stress-strain relations in a realistic way. Considering the above 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 reach rigorous and reliable results.

3 CHARACTERISTICS OF STRUCTURAL MODEL

A ten storey concrete moment resisting building frame with 12 m width is chosen, representing the conventional type of building in a relatively high risk earthquake prone zone. Structural sections were designed according to AS3600:2001 (Australian Standard for Concrete Structures) after undertaking dynamic time history analysis under the influence of four different earthquake ground motions, as a fixed base model. The specified compressive strength of concrete, the specified yield strength of steel rebar, and the concrete density were assumed to be 32 MPa, 400 MPa, and 25 kN/m^3, respectively. Performance level of the structural model is considered as life safe level indicating the maximum inter-storey drifts of the model are less than 1.5%. 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 273/274). 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 characteristics of the earthquake ground motions used in this study are tabulated in Table 1. It is assumed that the earthquake ground motions are bedrock records.

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

4 SUBSOIL PROPERTIES

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). Therefore, in order to study the effects of subsoil properties on seismic response in this range, three soil types with the shear wave velocity less that 600 m/s, comprising one granular and two cohesive samples, representing classes C_e, D_e and E_e, according to AS 1170.4 have been utilised in this study. Characteristics of the utilised soils are shown in Table 2. The subsoil properties have been extracted from actual *in situ* and laboratory tests (Rahvar 2005, 2006a, 2006b).

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

Soil Type (AS1170)	Shear Wave Velocity V_s (m/s)	Unified Classification	Shear Modulus G_{max} (kPa)	Poisson's Ratio	SPT	Plasticity Index (PI)	Reference
C_e	600	GM	623409	0.28	N>50	-	Rahvar (2005)
D_e	320	CL	177304	0.39	30	20	Rahvar (2006a)
E_e	150	CL	33100	0.40	6	15	Rahvar (2006b)

5 NUMERICAL MODELLING OF SOIL-STRUCTURE SYSTEM

The governing equations of the motion for a structure including foundation interaction and the method of solving these equations are relatively complex. Therefore, Direct Method using Finite Difference software, FLAC2D, is used to model the soil-structure system and solve these equations for complex geometries. Fully nonlinear time history dynamic analysis has been employed using FLAC 2D to define 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 2), and (ii) frames considering subsoil (Figure 3) using direct method of soil-structure interaction analysis as the flexible base model. The soil-structure model (Figure 2) comprises beam elements to model beams, columns, and strip foundation, two dimensional plane-strain grid elements to model soil medium, fixed boundaries to model the bed rock, absorbent boundaries (viscous boundaries) to avoid reflective waves produced by soil boundaries, and interface elements to simulate frictional contact and probable slip due to seismic excitation. The strip reinforced concrete foundation is 4 metres in width and 12 metres in length with 1 metre depth. Rayhani and Naggar (2008), after undertaking comprehensive numerical modelling and centrifuge model tests, concluded that the horizontal distance of the soil lateral boundaries should be at least five times the width of the structure. They also recommended 30 metres as the maximum bedrock depth in the numerical analysis as the most amplification occurs within the first 30 metres of the soil profile, which is in agreement with most modern seismic codes (e.g. ATC-40, 1996; NEHRP, 2003). Thus, in this study, the horizontal distance of the soil lateral boundaries is assumed to be 60 metres (five times the width of the structure which is 12 metres) and the maximum bedrock depth is 30 metres. As it is a plane strain problem, strip foundation width has been taken into account to calculate the moment of inertia of the concrete element only. It is assumed that the water table is well below the ground surface.

The foundation facing zone is separated from the adjacent soil zone by interface elements in numerical simulations. The interfaces between the foundation and soil are represented by normal and shear springs between two planes contacting each other and are modelled as linear spring–slider systems, with interface shear strength defined by the Mohr–Coulomb failure criterion. The relative interface movement is controlled by interface stiffness values in the normal and tangential directions. Based on recommended formula for the maximum interface stiffness values given by Itasca Consulting Group (2008), normal and tangential spring stiffness values are set to ten times the equivalent stiffness of the neighbouring zone.

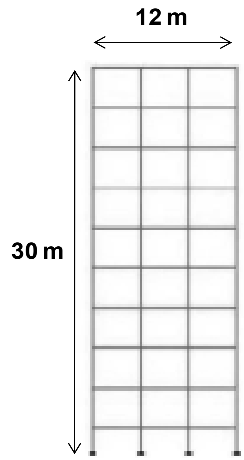


Figure 2: Fixed-base model

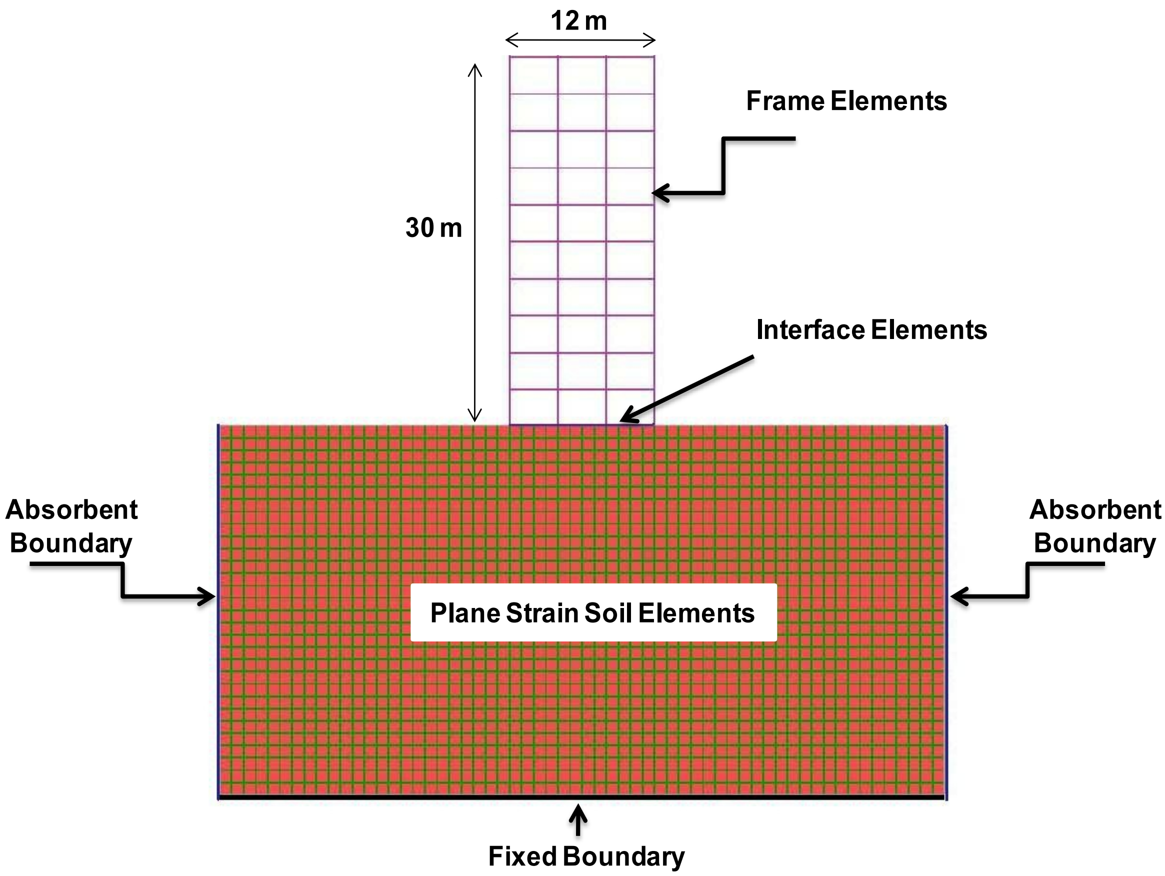
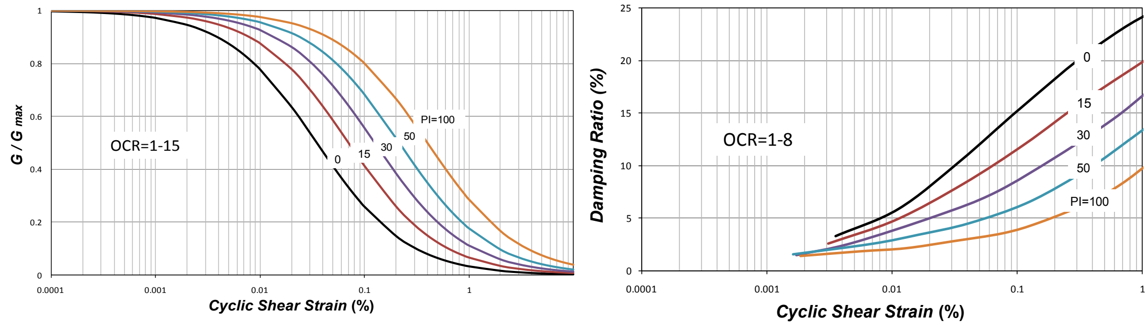


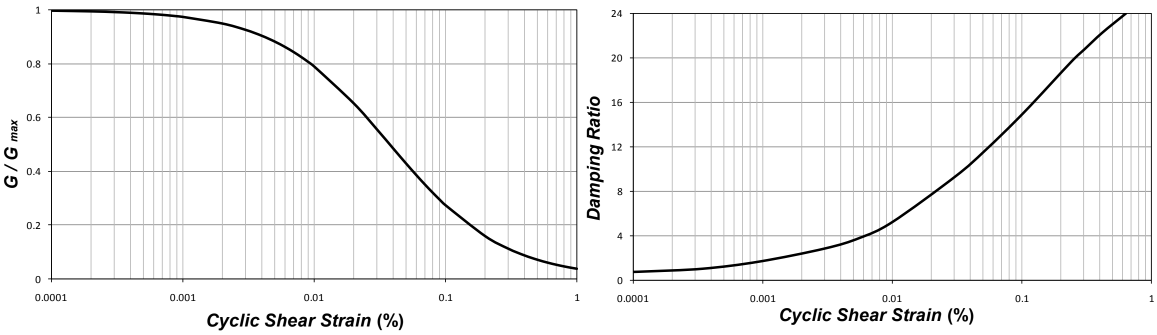
Figure 3: Components of the Soil-Structure model in FLAC

Nonlinear behaviour of the subsoil is taken into account by using the relationships between soil stiffness and material damping ratio versus cyclic shear strain proposed by Vucetic and Dobry (1991) and Seed and Idriss (1986). These nonlinearities in soil stiffness and damping ratio (Hysteretic damping) for cohesive soils were presented by Vucetic and Dobry (1991) as two ready to use charts showing relationships between (G/G_{max}) and damping ratio versus cyclic shear strain and soil plasticity for normally and over consolidated cohesionless soils (Figure 4). Based on the review of a number of available cyclic loading results, they concluded that the soil plasticity index (PI) is the main factor controlling the modulus reduction (G/G_{max}) and cyclic shear strain relationship as well as material damping ratio (λ) versus cyclic shear strain curve, for a wide variety of cohesive soils. As the soil plasticity index increases, (G/G_{max}) increases and damping ratio decreases. For cohesionless soils, Seed and Idriss (1986) represented the modulus reduction (G/G_{max}) and cyclic shear strain curve as well as material damping ratio versus cyclic shear strain curve, for a wide variety of cohesionless soils (Figure 5). Based on the results, in cohesionless soils, as the cyclic shear strain increases, (G/G_{max}) decreases and damping ratio increases.



(a) (b)

Figure 4: (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 (after Vucetic and Dobry, 1991)



(a) (b)

Figure 5: (a) Relations between G/G_{max} versus shear strain; (b) Relations between material damping ratio versus shear strain (after Seed and Idriss, 1986)

Four different earthquake ground motions (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.

6 RESULTS AND DISCUSSION

The results of fully nonlinear dynamic analyses including maximum inter-storey drifts have been determined and compared for fixed-base model and flexible-based model so as to clarify the effects of subsoil properties on seismic response of moment resisting frames. Inter-storey drifts shown in Figure 6 are determined from corresponding values of the maximum lateral deflections for each two adjacent stories using equation 6.7 (1) of AS 1170.4 (Earthquake action in Australia). Comparing the inter-storey drifts of fixed base and flexible base models resting on soil classes Ce, De, and Ee (Figures 6), it is observed that the inter-storey drifts of the flexible base model resting on soil class Ce do not differ much from that of the fixed-base model.

As a result, the performance level of the model resting on soil class C_e remains in life safe level. However, inter-storey drifts of the flexible base model resting on soil class D_e increases to more than 1.5% by incorporating dynamic SSI. Thus, performance level of the model resting on soil D_e changes from life safe level to near collapse level. The situation is more critical for the model on soil class E_e as the performance level of the model substantially increases from life safe to near collapse. Such a significance change in the inter-storey drifts and subsequently performance level of the model resting on soils D_e and E_e (especially for soil class E_e) is absolutely dangerous and safety threatening. Thus, considering SSI effects in seismic design of concrete moment resisting building frame resting on soil classes D_e and E_e is vital.

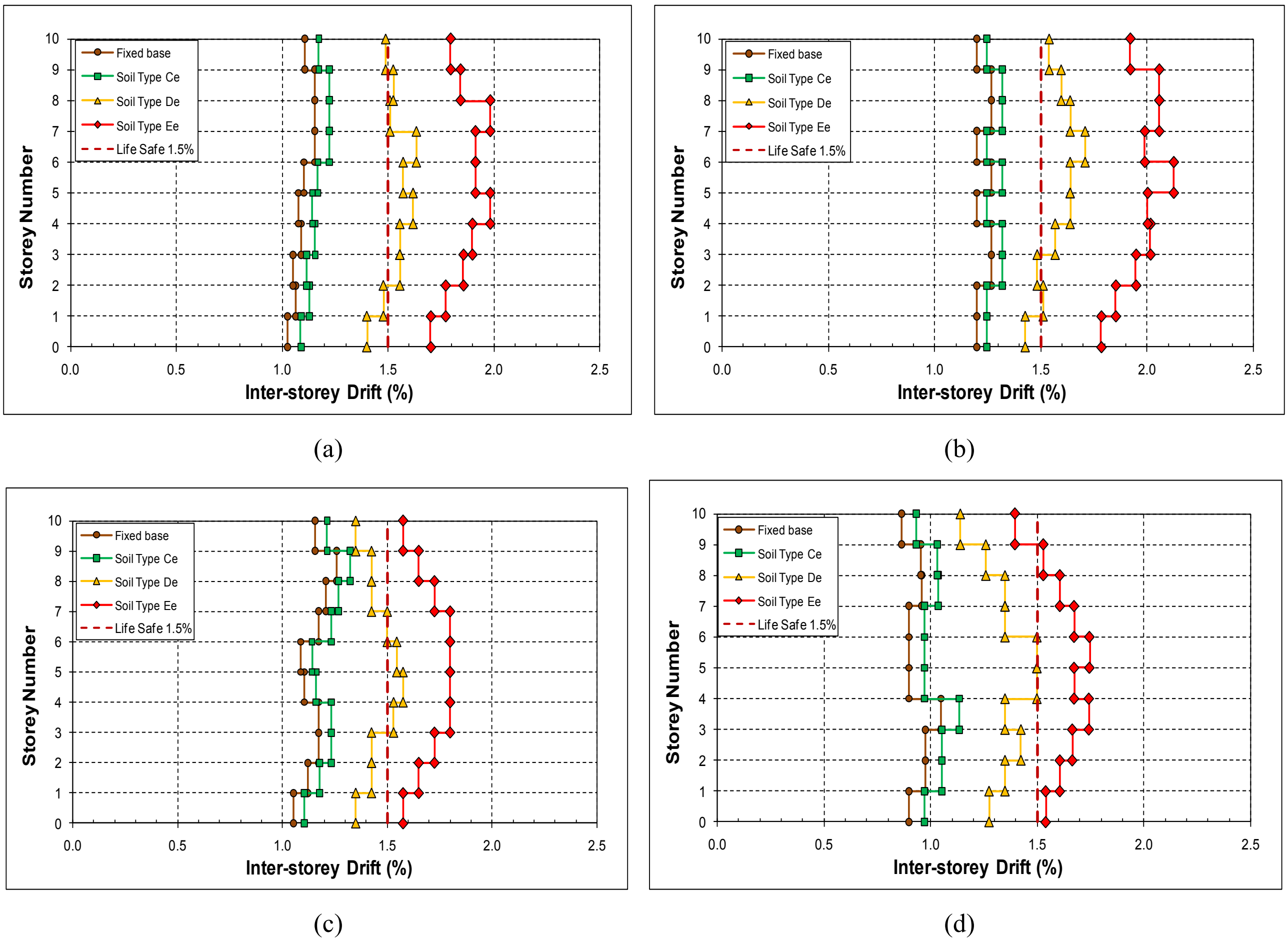


Figure 6: Inter-story drifts for fixed base and flexible base models under influence of (a) Northridge earthquake, 1994; b) Kobe earthquake, 1995; c) El Centro earthquake, 1940; d) Hachinohe earthquake, 1968.

7 CONCLUSIONS

According to the results of the numerical investigation conducted in this study for the ten storey concrete moment resisting building frame resting on soil classes C_e, D_e and Ee, it is observed that performance level of the model resting on soil class C_e does not change substantially and remains in life safe level. Therefore, the effects of soil-structure interaction for seismic design of moment resisting buildings founded on soil type C_e is negligible, while performance level of the model resting on soil classes D_e and E_e substantially changes (especially for soil class E_e) from life safe to near collapse. As a result, considering SSI effects in seismic design of concrete moment resisting building frame resting on soil classes D_e and E_e is vital. As dynamic properties of the subsoil such as shear wave velocity (V_s) and shear modulus (G_{max}) decrease, inter-storey drifts and subsequently necessity of considering SSI effects in seismic design of moment resisting building frames increase. As the stiffness of the subsoil decreases, the effects of soil-structure interaction become more dominant and detrimental to the seismic behaviour of moment resisting building frames.

In conclusion, the conventional design procedure excluding SSI is not adequate to guarantee the structural safety for the moment resisting building frames resting on soil classes D_e and E_e. It is highly recommended to practicing engineers and engineering companies working in high earthquake risk zones, to consider SSI influences in dynamic analysis and design of moment resisting building frames on soft soils to ensure designs are reliable and the structures perform safely.

8 REFERENCES

AS1170.4 .2007. Earthquake action in Australia. Standards Australia, NSW, Australia.

AS3600. 2001. Concrete Structures. *Standards Australia,* NSW, Australia.

Beaty, M.H., & Byrne, P.M. (2001). Observations on the San Fernando Dams. In Proc., 4*th International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, San Diego, California, March 26-31, 2001. University of Missouri-Rolla.

Byrne, P. M., Naesgaard, E. and Seid-Karbasi, M. (2006). Analysis and Design of Earth Structures to Resist Seismic Soil Liquefaction, in Sea to Sky Geotechnique (*59th Canadian Geotechnical Conference & 7th Joint CGS/IAH-CNC Groundwater Specialty Conference, Vancouver, Canada, October 2006*), pp. 1-24. R. M. Hardy Address.

Itasca Consulting Group, Inc. Itasca. 2008. FLAC2D: Fast Lagrangian Analysis of Continua, version 6.0. User's manual, Minneapolis.

Kobayashi, H., Seo, K., and Midorikawa, S. (1986). Estimated Strong Ground Motions in the Mexico City Earthquake: The Mexico Earthquakes 1985, Factors Involved and Lessons Learned, American Society of Civil Engineers: New York.

FEMA 273/274. 1997. NEHRP Guidelines for the Seismic Rehabilitation for Buildings. *Emergency Management Agency*, Washington, D.C.

Galal, K. and Naimi, M. 2008.Effect of conditions on the Response of Reinforced Concrete Tall Structures to Near Fault Earthquakes, *Struct.Design tall Spec.build,* 17(3), 541-562.

Gazetas, G. and Mylonakis, G. 1998. Seismic soil-structure interaction: new evidence and emerging issues, *Geotechnical Earthquake Engineering and Soil Dynamics,* 10(2), 1119-1174.

Rahvar. (2005). "Geotechnical and Geophysical Investigations and Foundation Design Report of Musalla Construction Site in Tehran", P. O. Rahvar Pty Ltd., Vol. 1, Tehran, 1-64.

Rahvar. (2006a). "Geotechnical Investigations and Foundation Design Report of Kooh-e-Noor Commercial Building", P. O. Rahvar Pty Ltd., Final Report, Tehran, Iran, 1-69.

Rahvar. (2006b). "Geotechnical Investigations and Foundation Design Report of Mahshahr Train Station", P. O. Rahvar Pty Ltd., Iran Railways Authority, Mahshahr, Iran, 1-42.

Rayhani, M.H. and El Naggar, M.H. 2008. Numerical Modelling of Seismic Response of Rigid Foundation on Soft Soil, *International Journal of Geomechanics* 8(6), 336-346.

Seed, H. B., and Idriss, I.M., 1969. Influence of Soil Conditions on Ground Motion During Earthquakes, *J. Soil Mech. Found. Div. ASCE*, 95(2), 99-137.

Tabatabaiefar, H.R., Massumi, A. 2010. A simplified Method to Determine Seismic Responses of Reinforced Concrete Moment Resisting Building Frames under Influence of Soil–Structure Interaction, *Soil Dynamics and Earthquake Engineering,* 30(11), 1259-1267, Elsevier Ltd., (ISI).

Veletsos, A.S. and Meek, J. W. 1974. Dynamic Behaviour of Building-Foundation system, *Journal of Earthquake Engineering and Structural Dynamics*, 3(2), 121-38.

Vucetic, M. and Dobry, R. 1991. Effects of Soil Plasticity on Cyclic Response, *Journal of Geotechnical Engineering*, 117(1), 89-10.

Wolf, J.P. and Deeks, AJ. (2004). Foundation Vibration Analysis: A Strength-of-Materials Approach, Elsevier, Oxford, UK.