INFLUENCE OF SOIL CHARACTERISTICS ON SEISMIC RESPONSE OF MID-RISE MOMENT RESISTING BUILDINGS CONSIDERING SOIL-STRUCTURE INTERACTION

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ABSTRACT

In this study, a fifteen storey moment resisting building frame, representing the conventional types of regular mid-rise building frames, resting on a shallow foundation, is selected in conjunction with three soil types with the shear wave velocity less that 600m/s, representing classes Ce, De and Ee, according to AS 1170.4. Characteristics of the employed soils have been extracted from the available geotechnical investigation reports of various projects. Furthermore, the structure is modelled considering the three mentioned types of the subsoil medium underneath employing the Finite Difference approach using FLAC 2D software. Three strong ground motion records adopted by the international community as benchmark earthquakes are used. These are the 1968 Hachinohe, the 1995 Kobe and the 1994 Northridge earthquakes. Fully nonlinear dynamic analysis under 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 play a significant role in seismic response of the building frames under the influence of soil-structure interaction. As the shear wave velocity of the subsoil decreases, lateral deflections and inter-storey drifts of the structures increase which can change the performance level of the structures from life safe to near collapse or total collapse.

1 INTRODUCTION

The 28 December 1989 Newcastle earthquake killed and injured over 150 people and damage bill was about $4 billion (Newcastle City Council, 2010). Recently, a similar disaster hit Haiti on 12 January 2010 causing over 200,000 deaths, and leaving over 3 million people homeless. The similarity of these two earthquakes is that both of them are intra-plate earthquakes occurring in the interior of a tectonic plate. In both cases, many mid-rise buildings (approximately 6-15 stories) constructed on weak soil were severely damaged. Therefore, there is a need to design structures safely but not costly against natural disasters such as earthquakes.

The estimation of earthquake motions at the construction sites is the most important phase of design to retrofit the performance of the structures. When the structure resting on hard rock is subjected to seismic loads of an earthquake, the high stiffness of the rock compels the rock motion to be very close to the free-field motion. Structures founded on the rock are assumed to be fixed-base structures for structural analysis purpose. However, the same structure would respond differently if it is supported by the soft soil deposits rather than hard rock. The inability of the foundation to conform to the deformations of the free-field motion would cause the motion of the base of the structure to deviate from the free-field motion. The dynamic response of the structure itself would induce deformation of the supporting soil. This process, in which the response of the soil influences the motion of the structure and response of the structure influences the motion of the soil, is referred to as Soil-Structure Interaction (SSI).

According to available studies in 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. In this paper, background on dynamic soil-structure interaction analysis and the required geotechnical and structural parameters for the analysis are explained. Furthermore, numerical analysis is employed to simulate the effects of soil characteristics on the seismic performance of a fifteen storey concrete moment resisting building frame.

2 BACKGROUND

The presence of a flexible foundation soil influences the nonlinear dynamic behaviour of the structure. Under strong shaking, the soil located in the vicinity of the structure will have a nonlinear behaviour with permanent deformations causing changes in the natural period compared to the fixed-base condition (Dutta *et al.*, 2004).

The soil–structure interaction (SSI) results in kinematic and inertial effects giving changes in the dynamic properties of the structure and the characteristics of the ground motion. If the foundation soil is stiff enough, the dynamic response of the structure is not influenced by the soil characteristics and the structure can be assumed as fixed at its base. If the structure is resting on a flexible medium, the dynamic response of the structure will be different from the case of a fixed base condition due to the interaction between the soil and the structure. Therefore, a complete dynamic analysis to evaluate the performance level of a structure should consider the effect of SSI in the model. When SSI is considered, the ground motion imposed at the foundation of the structure is a function of the soil parameters, the travel path, the local site effects and the geometry of the surrounding soil.

Performance-based seismic engineering design is a 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). 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.

During recent decades, the importance of 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 moment resisting building frames subjected to earthquake under influence of soil-structure interaction. Examples are given by Gazetas and Mylonakis (1998) including evidences that some structures founded on soft soils are vulnerable to SSI. Thus, especially for ordinary building structures, which are the most vulnerable among the built-in environment, the necessity of a better insight in the physical phenomena involved in SSI problems has been precipitated.

3 DYNAMIC ANALYSIS OF SOIL-STRUCTURE 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. 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 some overviews of the above mentioned methods and discussed the benefit 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 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).

They concluded that the most appropriate method for a dynamic analysis of soil-structure system is a *fully nonlinear method.* The method correctly represents the physics and follows any stress-strain relations in a realistic way. In addition, the following characteristics for a fully nonlinear method are desirable:

- The method follows any prescribed nonlinear constitutive relation;
- Using a nonlinear material law, interference and mixing of different frequency components occur naturally;
- Irreversible displacements and other permanent changes are modelled automatically;
- A proper plasticity formulation is used in all of the built-in models whereby plastic strain increments are related to stresses;
- Both shear and compression waves are propagated together in a single simulation, and the material responds to the combined effect of both components.

The governing equations of the motion for a structure including foundation interaction and the method of solving these equations are relatively complex. Therefore, in this study, a Finite Difference approach is used to solve these equations for complex geometries. Regarding to the above mentioned priorities and capabilities of the fully nonlinear method for dynamic analysis of soil-structure systems, this method is used in this research in order to reach rigorous and reliable results.

4 GEOTECHNICAL AND STRUCTURAL CHARACTERISTICS OF THE MODELS

In this research, a fifteen 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. The selection of the span width of the frames has tried to conform to architectural norms and constructional practices of conventional buildings in mega cities.

This frame is modelled as a fixed-base structure, loaded vertically (dead and live loads) and laterally (seismic loads) according to Australian Standard AS1170. Dynamic analyses of the structure for design have been conducted using the dynamic spectral (modal) analysis method according to normalised response spectra of AS1170.4:2007 (Figure 1), implementing structural ductility factor $\mu = 4$ and performance factor S_p=0.67 for fully ductile concrete moment-resisting frames and hazard factor Z=0.22 for a relatively high risk zone. Eventually, after seismic analyses, structural sections were designed according to AS3600:2001 (Concrete structures).

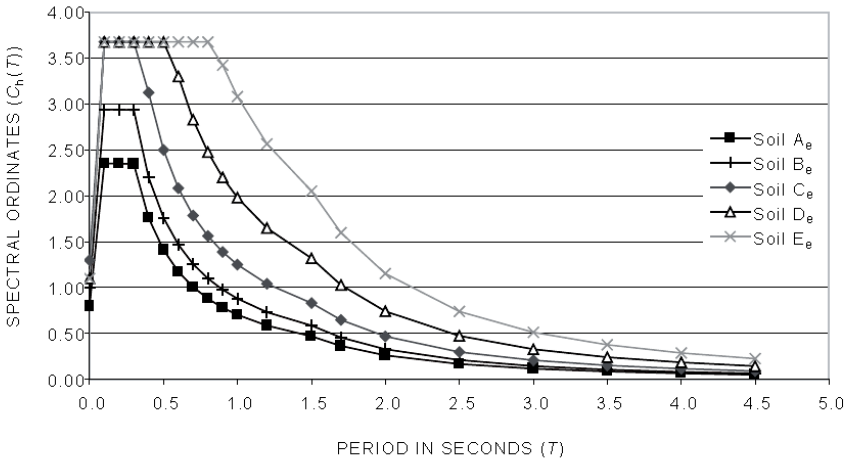


Figure 1: Normalised response spectra for different subsoil classes (AS1170.4:2007)

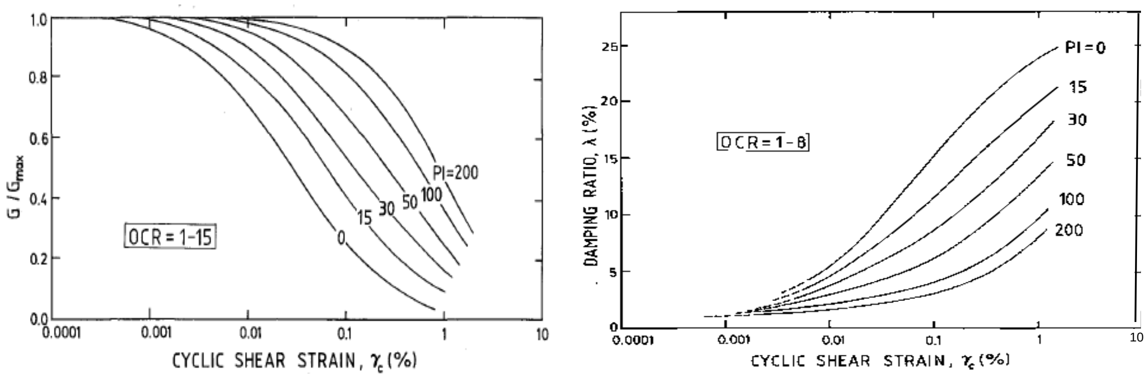
Three soil types with a shear wave velocity less than 600 m/s comprising one cohesionless and two cohesive samples, representing classes Ce, De and Ee, according to AS 1170.4 have been utilised in this research. Characteristics of the used soil shown in Table 1 have been extracted from various geotechnical reports. Therefore, these parameters have merit over the assumed parameters which may not completely conform to reality.

The shear wave velocity shown in Table 1 was 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 (λ),(ξ) which both vary with the cyclic shear strain amplitude, change relatively. These nonlinearities in soil stiffness and damping ratio (Hysteretic damping) for cohesionless soils were elucidated by Vucetic and Dobry (1991) as two ready to use curves. The represented relation between G/G_{max} and damping ratio versus cyclic shear strain (γ_c) and soil plasticity (*PI)* for normally and over consolidated cohesionless soils are illustrated in Figure 2.

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 γ_c curve, for a wide variety of cohesive soils. As the soil plasticity index increases, G/G_{max} increases and damping ratio decreases. This is true for both normally and over consolidated soils.

Table 1: Geotechnical characteristics of the utilised soft soil

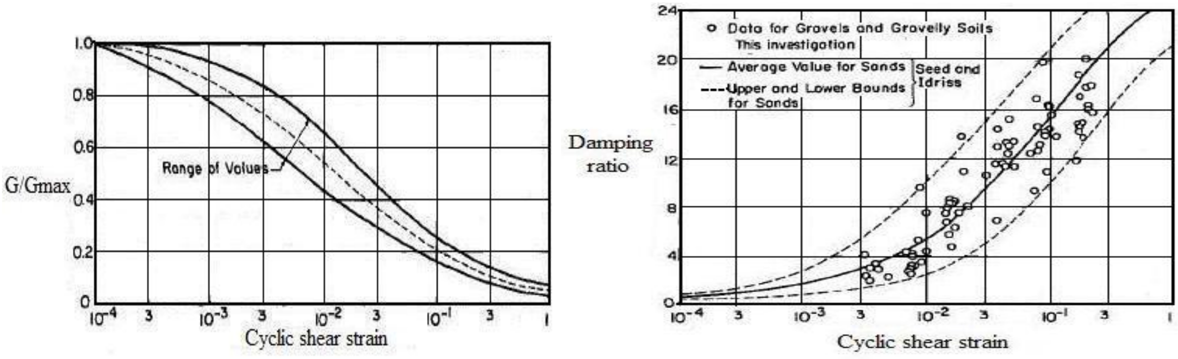
Soil Type (AS1170)	Shear wave velocity *Vs* (m/s)	Unified classification	Shear Modulus G_{max} (kPa)	ρ (Kg./m^3)	Poisson's Ratio	SPT	Plastic Index (*PI*)	C (kPa)	Φ (Degree)
Ce	600	GM	623409	1731	0.28	N>50	-	5	40
De	320	CL	177304	1731	0.39	30	20	20	19
Ee	150	CL	33100	1471	0.40	6	15	20	12



(a) (b)

Figure 2: (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 (Vucetic and Dobry, 1991)

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 3). Based on the results, they concluded that damping ratio for gravel is very similar to damping ratio for sand but the curve for gravel is a little flatter than the curve for sand. In cohesionless soils as the cyclic shear strain increases, G/G_{max} decreases and damping ratio increases.



(a) (b)

Figure 3: (a) Relations between G/G_{max} versus shear strain; (b) Relations between material damping ratio versus shear strain (Seed and Idriss, 1986)

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

5 MODELLING THE SOIL-STRUCTURE SYSTEM USING FLAC2D

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 in this study to model the soil-structure system and solve these equations for complex geometries. *FLAC* (*F*ast *L*agrangian *A*nalysis of *C*ontinua) is a two-dimensional explicit finite difference program for engineering mechanics computation. This program simulates the behaviour of structures built of soil, rock, steel, concrete or other materials. Materials are represented by elements, or zones, which form a grid that is adjusted by the user to fit the shape of the object to be modelled. 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.

The soil-structure model, as shown in Figure 4, is composed of beam elements to model structural elements, two dimensional plane strain grid elements to model the 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 the seismic excitation. Horizontal distance between soil boundaries is assumed five times the structure width (60 m) and bedrock depth is assumed 30 m according to Rayhani and Naggar (2008) research results.

In this study, fully nonlinear time history dynamic analysis has been exploited using FLAC 2D to define seismic response of concrete moment resisting frame under the influence of SSI. Dynamic analyses are carried out for two different systems: (i) fixed-base structure on rigid ground (Figure 5), and (ii) frames considering subsoil (Figure 4) using direct method of soil-structure interaction analysis (flexible base).

Earthquake ground motions 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 in case of modelling the structure as fixed base (without soil), the earthquake records are applied to the base of the structural model. Three different sets of earthquake ground motions used in this study are summarised in Table 2.

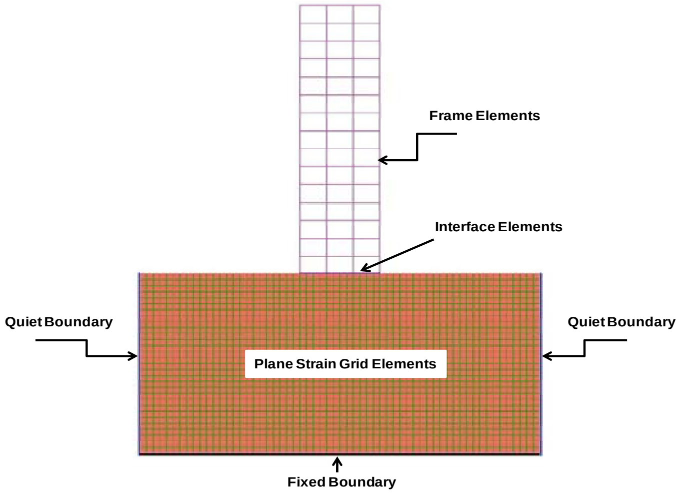


Figure 4: Components of the Soil-Structure model in FLAC

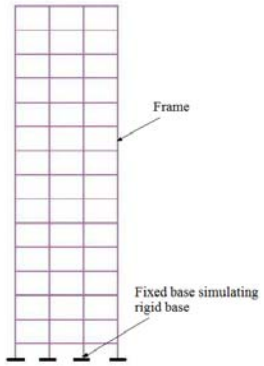


Figure 5**:** Fixed-base model

Table 2: Earthquake ground motions used in this study

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

In addition, the acceleration records of the above mentioned earthquakes, directly used in the numerical simulation, are illustrated in Figures 6, 7, and 8, respectively.

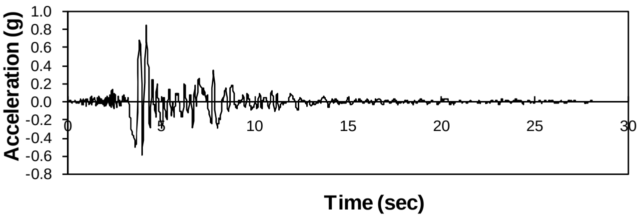


Figure 6: Acceleration record of Northridge earthquake (1994)

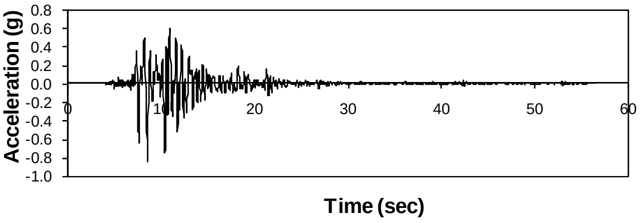


Figure 7**:** Acceleration record of Kobe earthquake (1995)

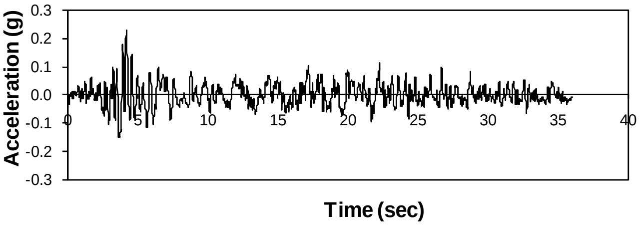


Figure 8: Acceleration record of Hachinohe earthquake (1968)

The foundation facing zone in numerical simulations is separated from the adjacent soil zone by interface elements. The interfaces between the foundation and soil is represented as a normal and shear stiffness between two planes contacting each other and is 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 estimates for 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.

6 DYNAMIC ANALYSIS AND RESULTS

The results of dynamic analysis including base shear and the maximum lateral storey deflections have been determined and compared for fixed-base model and flexible-based models (for three types of mentioned soils) respectively, so as to clarify the effects of subsoil rigidity on seismic response of moment resisting frames. According to the results summarised in Table 3, the ratio of base shear of the flexible-base models ($\tilde{V}$) to that of fixed-base (V) in all models is less than one. Therefore, base shear of the structures modelled with soil as flexible-base are generally less than the base shear of structures modelled as fixed base. These results have good conformity to the NEHRP-1997 regulations.

Table 3: Base shear ratio of flexible-base to fixed-base models

Earthquake	Fixed-base model	Soil Type Ce		Soil Type De		Soil Type Ee	
	V (kN)	$\tilde{V}$ (kN)	$\tilde{V}/V$	$\tilde{V}$ (kN)	$\tilde{V}/V$	$\tilde{V}$ (kN)	$\tilde{V}/V$
Northridge	1,198	1,129	0.942	559	0.467	169	0.141
Kobe	1,639	1,578	0.962	872	0.532	271	0.165
Hachinohe	388	375	0.966	228	0.588	114	0.293

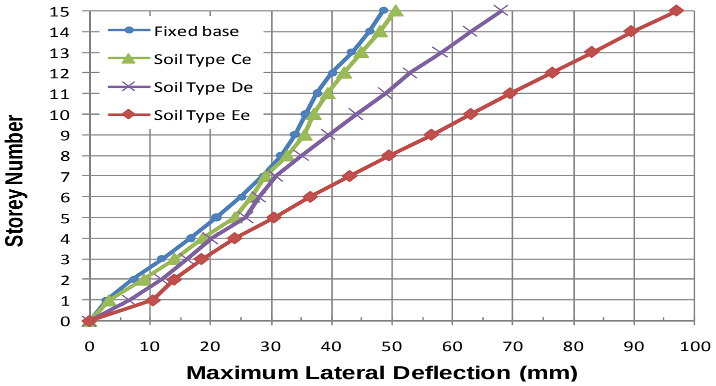


Figure 9: Maximum lateral deflection of the15 storey fixed- base and flexible base models (Northridge earthquake, 1994)

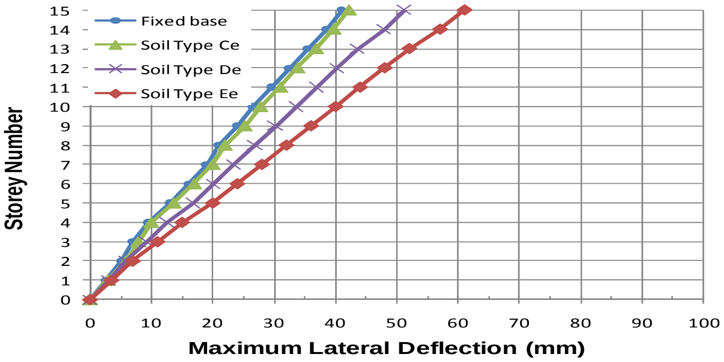


Figure 10: Maximum lateral deflection of the15 storey fixed- base and flexible base models (Kobe earthquake, 1995)

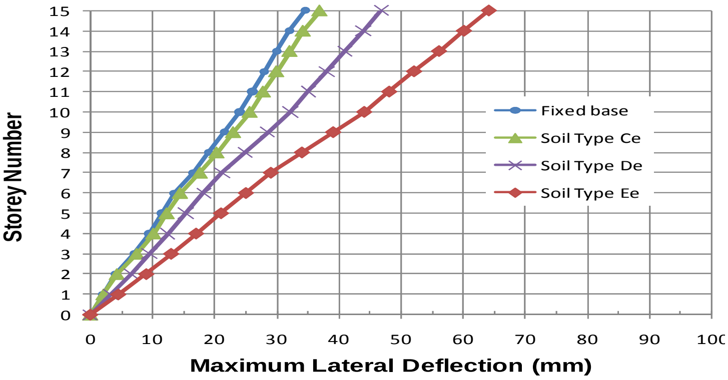


Figure 11: Maximum lateral deflection of 15 storey fixed- base and flexible base models (Hachinohe earthquake, 1968)

By comparing the lateral deflections of fixed-base model with flexible-base models resting on soil classes Ce, De, and Ee according to AS 1170.4 (Figures 9-11), it is observed that the maximum lateral deflections of the flexible base model resting on soil class Ce does not differ much from that of the fixed-base model, which is negligible, while maximum lateral deflections of the flexible base models resting on soil classes De and Ee substantially increase (especially for the flexible-base model resting on soil class Ee). Such a big difference in lateral deflections is not negligible; thus, the effect of soil-structure interaction must be precisely taken into account in dynamic analyses for the moment resisting frames resting on soft soils (classes De and Ee). In the case of the studied concrete moment resisting building frame resting on soft soil deposits, 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. Therefore, performance level of the structure may be changed from life safe to near collapse or total collapse. Based on the mentioned results, it is found that, by decreasing the dynamic properties of the subsoil such as shear wave velocity (*Vs*) and shear modulus (G_{max}), maximum lateral deflections of the moment resisting building frames increase relatively.

7 CONCLUSIONS

The following conclusions regarding to mid-rise concrete moment resisting building frames resting on soil classes Ce, De and Ee, according to AS 1170.4, can be drawn from the numerical investigation conducted in this study:

- Base shear of the structures modelled with soil as flexible-base are generally less than the base shear of the structures modelled as fixed-base.
- By decreasing the dynamic properties of the subsoil such as shear wave velocity (*Vs*) and shear modulus (G_{max}), maximum lateral deflections of the moment resisting building frames increase relatively.
- Considering SSI effects in seismic design of concrete moment resisting building frame resting on soft soils including classes De and Ee is essential as performance level of the structure similar to the model used in this study can be changed from life safe to near collapse or total collapse.

As the Australian Earthquake Standard AS1170.4 does not address the soil-structure interaction (SSI) explicitly, considering SSI effects in seismic design as a distinguished part of this standard is highly recommended. It is also suggested to engineering companies working in the Asia-pacific region, located in high earthquake risk zones, to consider SSI influences in dynamic analysis and design of moment resisting building frames on soft soils to ensure the designs are safe and reliable.

8 REFERENCES

AS1170. (2007). “Structural Design Actions”. Standards Australia. NSW, Australia.

AS3600. (2001). “Concrete Structures”. Standards Australia. NSW, Australia.

Byrne, P. M., and Wijewickreme, D. (2006). “Liquefaction Resistance and Post-Liquefaction Response of Soils for Seismic Design of Buildings in Greater Vancouver”, 59th Canadian Geotechnical Conference. pp. 1267-1278.

Dutta, C.H., Bhattacharya, K., and Roy, R. (2004). “Response of low-rise buildings under seismic ground excitation incorporating soil-structure interaction”, Soil Dynamic and Earthquake Engineering, 24(9), 893-914.

FEMA 440, (2005). “NEHRP Recommended Provisions for Improvement of Nonlinear Static Seismic Analysis Procedures”, ATC-55 Project, 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.

Itasca Consulting Group. (2008). “FLAC2D: Fast Lagrangian Analysis of Continua User’s manual”, version 6.0. 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”, New York : American Society of Civil Engineers.

Kramer, S.L. (1996). “Geotechnical Earthquake Engineering”, Prentice Hall civil engineering and engineering mechanics series.

NEHRP (1997). “Recommended Provisions for Seismic Regulation for New Buildings and Other Structures”, Part 2: Commentary FEMA 303. Washington DC : Federal Emergency Management Agency.

NewcastleCityCouncil(2010).http://www.newcastle.nsw.gov.au/discover_newcastle/local_history/newcastle_earthquake. Retrieved 2010-07-19, NSW, Australia.

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.

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”, Oxford : Elsevier.