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Effects of soil-pile-structure interaction on seismic response of moment resisting buildings on soft soil

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ABSTRACT: Dynamic response of structures sitting on soft soils is influenced by the soil properties, and the response is significantly different to the fixed base condition owing to the interaction between the ground and the structure. In order to study this effect, a fifteen storey moment resisting building frame, representing a conventional type of regular mid-rise building frame, resting on soil type Ee according to Australian Earthquake action code with the shear wave velocity equal to 150 m/s is adopted. The numerical analysis using FLAC2D software is carried out for three different cases, namely: (1) fixed-base structure representing the situation excluding the soil-structure interaction (SSI); (2) structure supported by shallow foundation on soft soil; and (3) structure supported by pile foundation in soft soil. Benchmark earthquakes including the 1995 Kobe, the 1994 Northridge, the 1968 Hachinohe, and the 1940 El Centro earthquakes are adopted. Results indicate that considering soil-structure interaction in both cases with shallow and pile foundations is vital, and the conventional design procedure excluding soil-structure interaction is not adequate to guarantee the structural safety for the moment resisting buildings resting on the soft soil.

1 INTRODUCTION

Numerous mid-rise and high-rise buildings have been built in earthquake prone areas supported by pile foundations. Deep foundations consisting of frictional or end bearing piles are routinely employed to transfer structural loads through soft soils to deeper layers in order to increase the bearing capacity and reduce the settlement of the superstructure. These foundation elements may also be subjected to the transient or cyclic lateral loads arising from earthquake, wind, wave, blast, or loading. The coincidence of major pile-supported structures siting on soft soils in regions with high earthquake hazard, results in significant demands of understanding the seismic behaviour of these systems consisting of soil, pile foundation, and the structure.

Despite the fact that the seismic waves may travel through tens of kilometres of rock and often less than 100 meters of soil, the soil plays a very important role in determining the characteristics of the ground surface motion. If the ground is stiff enough, the dynamic response of the structure will not be influenced by the soil properties during the earthquake, and the structure can be analysed under fixed-base conditions. However, the same structure behaves differently if it is constructed on the soft soil deposit. Firstly, the foundation is not able to follow the deformation of the free field motion due to its stiffness. Secondly, the dynamic response of the structure itself would induce deformation to the supporting soil. This process, in which response of the soil influences the motion of the structure and vice versa is referred to as the soil-structure interaction (Kramer, 1996). According to the simplified model suggested by Wolf (1985), soil-structure interaction has four basic effects on the structural response: (1) increase in the natural period of the system; (2) increase in the damping of the system; (3) increase in the lateral displacement of the structure; and (4) change in the base shear depending on the dynamic characteristics of the structure and the soil, and frequency content of the input motion.

Several researchers (e.g. Tajimi 1969; Ukaja 1975; Han and Cathrio 1997; Gazetas 1991; Shiming and Gang 1998; Inaba et al. 2000; Hayashi and Takahashi 2004; Hokmabadi et al. 2011; Carbonari et al. 2011) have been studied the seismic soil-pile-structure interaction (SSPSI) and effect of this phenomena on the seismic response of the structures. The developed analytical methods for studying the soil-pile-structure interaction may be categorised in to three groups: (1) Substructure Methods (or Winkler methods), in which series of springs and dashpots are employed to represent the soil behaviour; (2) Elastic Continuum Methods which are based on Mindlin (1936) closed form solution for the application of point loads to a semi-infinite elastic media; and (3) Numerical Methods. The substructure methods are the simplest and most commonly used methods, however, the methods using substructuring rely on the principle of superposition and, consequently, are limited to either the linear elastic or the viscoelastic domain (Pitilakis et al., 2008).

Numerical methods, adopting finite element or finite difference methods, have become more popular to study the complex and complicated interactive behaviours giving the researcher the ability to model complicated conditions of the ground with high degree of accuracy by considering effects such as nonlinear stress-strain behaviour, heterogeneous material conditions, and material and radiation damping using two or three dimensional elements. Another advantage of employing numerical methods is the capability of performing the SSPSI analysis of pile groups in a *fully-coupled manner*, without resorting to independent calculations of site or superstructure response, or application of pile group interaction factors (Meymand, 1998).

In the present study, finite difference approach using FLAC2D software is employed to investigate the effects of SSPSI on the seismic response of mid-rise moment resisting buildings. For this purpose, the seismic behaviour of the superstructure supported by two types of foundations including shallow and pile foundations are compared with the fixed-base assumption in which the effects of soil-structure interaction is excluded.

2 PERFORMANED-BASED ENGINEERING ASSESSMENT

Performance-based seismic design is a modern approach to earthquake-resistant design. Seismic performance (performance level) is described by considering the maximum allowable damage state (damage performance) for an identified seismic hazard (hazard level). Performance levels describe the state of structures after being subjected to a certain hazard level, and based on FEMA273/274 (BSSC, 1997) are classified as: fully operational, operational, life safe, near collapse, or collapse. Overall lateral deflection, ductility demand, and inter-storey drifts are the most commonly used damage parameters. The above mentioned five qualitative 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 (BSSC, 1997).

In addition, most of the force-based design codes employ an additional check in terms of limiting inter-storey drifts to ensure that particular deformation-based criteria are met. For example, ASCE (2010) defines allowable storey drift for structures considering type and risk category of the structure. Australian Code (2007) indicates 1.5% as the maximum allowable storey drift. It is believed that the inter-storey drift is the most acceptable parameter to control the displacement, resulting damage, and in turn performance of the structure. In the present study, the structure is designed to stay in the life safe zone, and effects of soil-structure interaction in increasing the lateral deformation and inter-storey drifts of the superstructure are investigated.

3 GEOTEHCNICAL AND STRUCTURAL CHARACTRISTICS OF THE MODELS

A fifteen-storey concrete moment resisting building frame with total height of 45 meters and width of 12 meters consisting of three spans, representing the conventional type of buildings in a relatively high risk earthquake prone zone, is selected. Structural sections are designed according to Australian Standard for Concrete Structures (AS3600, 2009) after undertaking dynamic time-history analysis based on equivalent elastic response of the structural system under influence of four earthquake ground motions, as a fixed-base model. The characteristics of the earthquake ground motions are summarised in Table 1. The frame is considered as moderately ductile and the equivalent linear approach is used to capture the non-linear cyclic behaviour of the structure during the time-history analysis by reducing the stiffness of both vertical and horizontal elements due to cracking (ACI318-08, 2008) and by allocating 5% damping ratio to the structure. In addition, geometric nonlinearity (p-Δ effects) is incorporated in the numerical analysis. The specified compressive strength of the concrete is assumed to be f'_c=32 MPa, the specific yield strength of the steel rebar f_y= 400 MPa, and the concrete density γ_c=25 kN/m^3 is used to design the structure. Performance level of the structural model is considered as life safe in the design indicating the maximum inter-storey drift of the model being less than 1.5% according to FEMA273/274 (BSSC, 1997).

Table 1. Earthquake ground motions used in this study

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

The mentioned frame rests on soft soil type Ee according to the Australian Earthquake action code (AS1170.4, 2007) with 40 m depth to the bedrock. Characteristics of the utilised soil are shown in Table 2. Since the subsoil properties have been extracted from the actual in-situ and laboratory tests (Rahvar, 2006), they have merit over the assumed parameters which may not be completely conforming to the reality. The watertable is assumed to be well below the ground surface.

Table 2. Geotechnical characteristics of the utilised subsoil

Soil Type (AS1170)	Shear wave velocity (m/s)	Unified classification	Shear modulus G_{max} (kPa)	Poisson's ratio	SPT	Plasticity Index (PI)	c' (kPa)	φ' (kPa)	C_u (kPa)

Ee	150	CL	33100	0.40	6	15	20	12	50

The shear wave velocity value shown in Table 2 has been obtained from down-hole test generating low cyclic shear strain (approximately 10^{-4}) resulting in G_{max}. During the earthquake, soil particles experience different levels of cyclic shear strain, and due to the nonlinear behaviour of the soil, both stiffness and damping ratio of the soil vary with the amplitude of the cyclic shear strain. The backbone curve suggested by Sun et al. (1988) for cohesive soils indicating the variation of the shear stiffness and damping ratio versus cyclic shear strain is adopted in this study.

4 NUMERICAL SIMULATION OF SOIL-PILE-STRUCTURE INTERACTION

FLAC2D finite difference software is utilised to model the soil-structure interaction and to solve the governing equations of the system including equilibrium and compatibility equations. The developed numerical model can capture the cyclic non-linear behaviour of the soil following the actual stress-strain path during cyclic loading as suggested by Sun et al. (1988). This method has merit over the equivalent linear methods which cannot capture directly any nonlinearity effects and the strain-dependent modulus of the soil and damping functions are only taken into account in an average sense. In addition, as suggested by Rayhani & El Naggar (2008), Mohr-Coulomb criteria is implemented in the model to capture the elastoplastic behaviour of the subsoil during the earthquake. Furthermore, appropriate boundary conditions accurately representing the real situation for both static and dynamic parts of the analysis are employed.

The shallow foundation is considered as reinforced concrete footing with 1 m depth. The pile foundation has four reinforced concrete piles with 1 m diameter and 20 m embedment length designed based on the Australian national code for piling, design, and installation (AS2149, 2009). Same properties of concrete as used for the superstructure are assumed for both pile and shallow foundations. Piles are modelled as two-dimensional elements with three degrees of freedom (two displacements and one rotation) at each node. A pile element segment is treated as a linearly elastic material with no axial yielding. Piles interact with the surrounding grid via shear and normal coupling springs, which are nonlinear connectors transferring forces and the motion between the pile elements and the grid (Itasca, 2008).

The pile formulation simulates a row of equally spaced piles in plane-strain condition. Reducing 3D problems (with regularly spaced piles) to 2D problems involves averaging the effect in 3D over the distance between the elements. Donovan et al. (1984) suggest that linear scaling of the material properties is a simple and convenient way of distributing the discrete effect of elements over the distance between elements in a regularly spaced pattern. In FAC2D model the relation between the actual 3D properties and the scaled properties is demonstrated by considering the stiffness properties for regularly spaced piles. In the present study, dynamic analysis is carried out for three different cases: (1) fixed-base structure to represent the situation without soil-structure interaction; (2) structure supported by shallow foundation resting on the mentioned soft soil; and (3) structure supported by the pile foundation resting on the same soil. Figure 1 depicts the FLAC2D model for the case with the pile foundation.

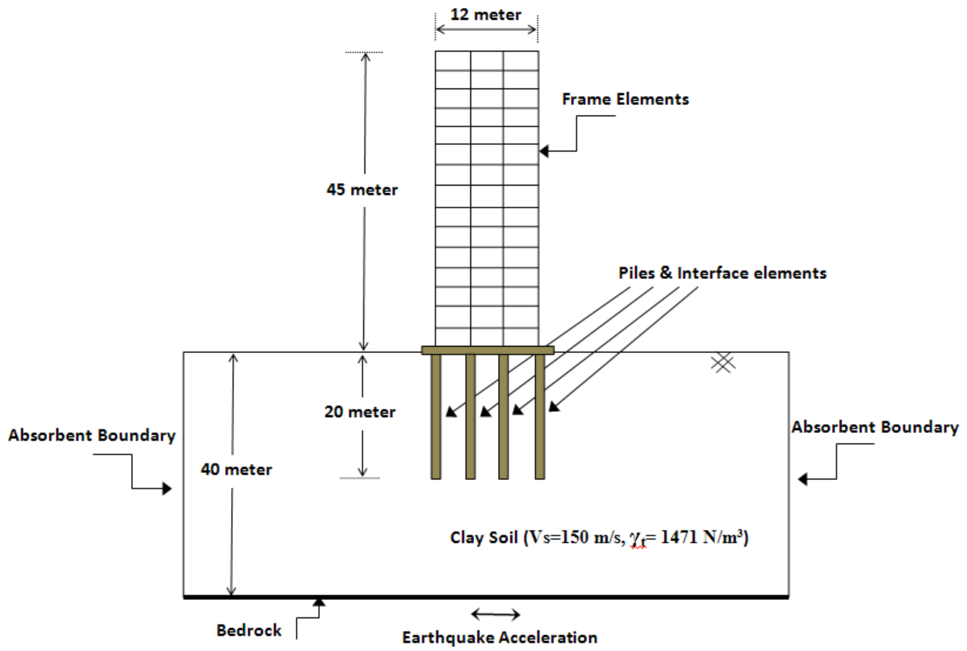

Figure 1. Components of soil-pile-structure model in FLAC2D

5 RESULTS AND DISCUSSION

Table 3 compares the structural demand of the superstructure in terms of base shear under the influence of four earthquakes. In general, the ratio of the base shear for cases including soil-structure interaction ($\tilde{V}$) to that of fixed-base (V) is less than one, demonstrating the effect of soil-structure interaction in reducing the base shear of the structure. In addition, it may be concluded that presence of pile foundation increases the base shear and in turn demand of the superstructure, in comparison with the case supported by shallow foundation. For example, in the case of Northridge earthquake, the structure on the pile foundation attracts more than twice base shear (300 kN) in comparison to the structure on the shallow footing (137 kN).

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

Earthquake	**Fixed-base**	**Shallow foundation**		**Pile foundation**	
	V (kN)	$\tilde{V}$ (kN)	$\tilde{V}/V$	$\tilde{V}$ (kN)	$\tilde{V}/V$
Kobe	1131	168	0.148	326	0.288
Northridge	675	137	0.203	300	0.444
Hachinohe	291	141	0.484	216	0.742
El Centro	393	112	0.285	201	0.511

Figures 2 to 5 compare the inter-storey drifts of three mentioned cases in conjunction with four sets of input motions. In order to capture the critical inter-storey drifts, the total maximum inter-storey drifts are recorded considering all time steps during the earthquakes (Hokmabadi et al., 2012).

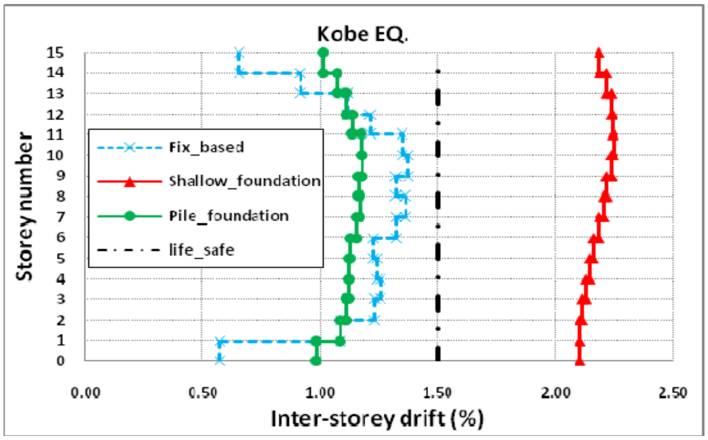

Figure 2. Inter-storey drifts for the fixed-base and flexible-base models imposed by Kobe earthquake, 1995.

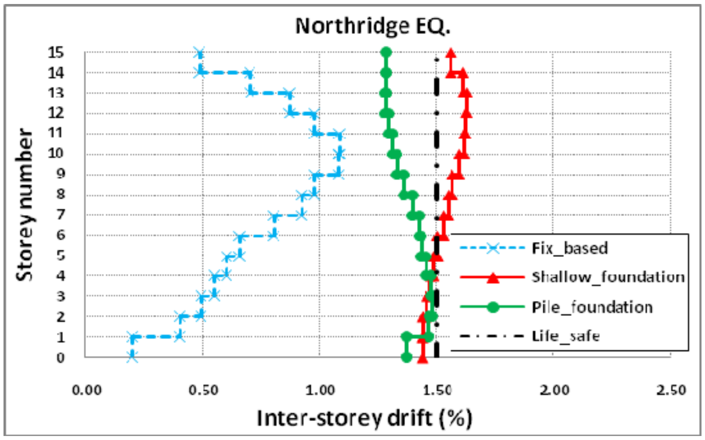

Figure 3. Inter-storey drifts for the fixed-base and flexible-base models imposed by Northridge earthquake, 1994.

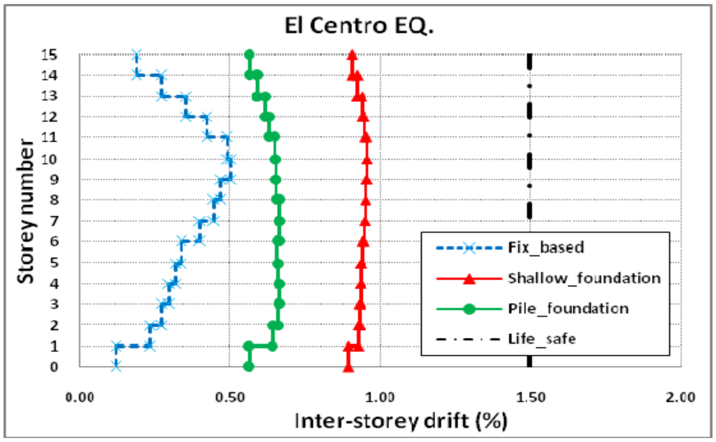

Figure 4. Inter-storey drifts for the fixed-base and flexible-base models imposed by El Centro earthquake, 1968.

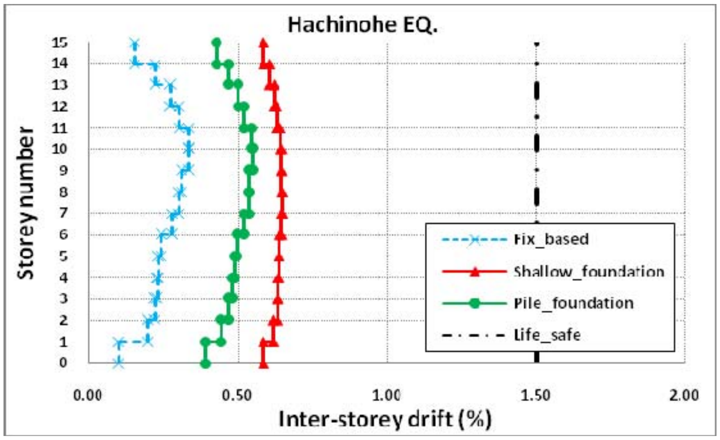

Figure 5. Inter-storey drifts for the fixed-base and flexible-base models imposed by Hachinohe earthquake, 1940.

According to Figures 2 to 5, it is obvious that including the effect of soil-structure interaction in the analysis increases the inter-storey drifts of the structure resting on the soft soil significantly, and consequently the performance level of the structure may change from life safe level to near collapse level. For example, in the case of Northridge earthquake, the maximum inter-storey drift of the structure supported by pile foundation (1.48%) is 135% more than the fix-based situation (1.09%) in which the effects of soil-structure interaction are excluded. For the same earthquake, the maximum inter-storey drift of the structure for the shallow foundation case (1.63 %) is 149% more than the fix-based situation.

Pile foundations reduce the lateral drifts in comparison to the shallow foundation case. This is due to presence of stiff pile elements in the soft soil increasing the stiffness of the ground influencing the dynamic properties of the whole system such as the natural frequency and damping. However, in comparison with the fix-based case, soil-pile-structure interaction tends to increase the lateral deformation and in turn inter-storey drifts of the structure. It should be noted that in some cases although the total lateral deflection is increasing due to soil-pile-structure interaction, the maximum inter-storey drift may decrease due to the frequency content of the input motion and dynamic properties of the system including soil, pile, and the superstructure.

6 CONCLUSIONS

According to the results of the numerical investigations conducted in this study for the 15 storey moment resisting building resting of soft soil class Ee (V_s=150 m/s), it is observed that the base shear of the structure while considering the effect of soil-structure interaction, for both shallow and pile foundations, are less than the base shear of the structure modelled as fixed-base excluding the effects of soil-structure interaction. In other words, construction of pile foundations increases the structural demand of the system in comparison with the case sitting on the shallow foundation.

Moreover, considering the effect of soil-structure generally interaction increases the inter-storey drifts of the superstructure. This effect is more severe particularly for the earthquakes with high PGA in which it causes the performance level of the model to exceed the life safe level and shift to near collapse zone. For the structures resting of pile foundation, effects of soil-structure interaction are less than the cases with shallow foundation. However, in both cases the inter-story drifts increase in comparison with the fix-based situation. Consequently, considering soil-structure interaction in both cases with shallow foundation and with pile foundation is vital, and conventional design procedures excluding soil-structure interaction are not adequate to guarantee the structural safety for the moment resisting buildings resting on soft soils.

REFERENCES

ACI318-08 (2008) Building Code Requirements for Structural Concrete and Commentary. In, American Concrete Institute, pp. 473.

AS1170.4 (2007) Structural design actions—Earthquake actions in Australia. In, Standards Australia, NSW, Australia, Vol. AS 1170.4-2007.

AS2149 (2009) Pilling-Design and installation. In, Standards Australian, NSW, Australia, Vol. AS2159-2009.

AS3600 (2009) Concrete Structures. In, Standards Australia, NSW, Australia, Vol. AS 3600-2009.

ASCE7-10 (2010) Minimum Design Loads for Buildings and Other Structures In, American Society of Civil Engineers.

BSSC (1997) NEHRP Guidelines for the Seismic Rehabilitation of Buildings, 1997 Edition, Part 1: Provisions and Part 2: Commentary. In, Federal Emergency Management Agency, Vol. FEMA 273/274.

Carbonari, S., Dezi, F. and Leoni, G. (2011) Linear soil-structure interaction of coupled wall-frame structures on pile foundations. Soil Dynamics and Earthquake Engineering 31, 1296-1309.

Donovan, K., Pariseau, W.G. and Cepak, M. (1984) Finite Element Approach to Cable Bolting in Steeply Dipping VCR Stopes. In, Geomechanics Applications in Underground Hardrock Mining Society of Mining Engineers, New York, pp. 65-90.

Gazetas, G. (1991) Formulas and Charts for Impedances of Surface and Embedded Foundations. Journal of Geotechnical Engineering 117, 1363-1381.

Han, Y.C. and Cathro, D. (1997) Seismic behaviour of tall building supported on pile foundations. seismic analysis and design for soil-pile-strcutre interaction. In, Geotechnical Special publications, No. 70, ASCE, pp. 36-51.

Hayashi, Y. and Takahashi, I. (2004) Soil-structure interaction effects on building response in recent earthquakes. In, Third UJNR Workshop on Soil-Structure InteractionVallombrosa Center, Menlo Park, California.

Hokmabadi, A.S., Fakher, A. and Fatahi, B. (2011) Seismic strain wedge model for analysis of single piles under lateral seismic loading. Australian Geomechanics 46, 31-41.

Hokmabadi, A.S., Fatahi, B. and Samali, B. (2012) Recording inter-storey drifts of structures in time-history approach for seismic design of building frames. Australian Journal of Structural Engineering (In press).

Inaba, T., Dohi, H., Okuta, K., Sato, T. and Akagi, H. (2000) Nonlinear response of surface soil and NTT building due to soil-structure interaction during the 1995 Hyogo-ken Nanbu (Kobe) earthquake. Soil Dynamics and Earthquake Engineering 20, 289-300.

Itasca (2008) Fast Lagrangian Analysis of Continua, User's Manual. In, Itasca Consulting Group, Inc.

Kramer, S.L. (1996) Geotechnical earthquake engineering. Prentice Hall.

Meymand, P.J. (1998) Shaking table scale model tests of nonlinear soil-pilesuperstructure
in soft clay. PhD thesis in Civil Engineering Thesis, University of California, Berkley.

Mindlin, R.D. (1936) Force at a Point in the Interior of a Semi-Infinite Solid. Physics 7, 195-202.

Pitilakis, D., Dietz, M., Wood, D.M., Clouteau, D. and Modaressi, A. (2008) Numerical simulation of dynamic soil-structure interaction in shaking table testing. Soil Dynamics and Earthquake Engineering 28, 453-467.

Rahvar (2006) Geotechnical investogation and foundation design report of Mahshahr train station. P. O. Rahvar Pty Ltd, Iran Railway Authority, Mahshar, Iran.

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

Shiming, W. and Gang, G. (1998) Dynamic soil-structure interaction for high-rise buildings. In Zhang, C. and John, P.W. (eds.), Developments in Geotechnical Engineering, Elsevier, Vol. 83, pp. 203-216.

Sun, J., Golesorkhi, R. and Seed, H.B. (1988) Dynamic moduli and damping ratio for cohesive soils. UCB/EERC-88/15, University of California Berkeley-Earthquake Engineering Research Center.

Tajimi, H. (1969) Dynamic Analysis of a Structure Embedded in an Elastic Stratum. In, Proc. 4th World Conf. Earthquake Eng.Santiago, USA, Vol. 3, pp. 53-69.

Ukaja, K. (1975) Analysis of soil foundation structure interaction. 18, Stanford University, Department of Civil and Environmental Engineering.

Wolf, J.P. (1985) Dynamic soil-structure interaction. Prentice-Hall, Englewood Cliffs, New Jersey.