Seismic Response of Superstructure on Soft Soil Considering Soil-Pile-Structure Interaction

Influence de l'Interaction sol- pieu- structure sur la réponse sismique de la superstructure sur sol mou

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ABSTRACT: This paper presents results of shaking table tests and three dimensional numerical simulations to investigate the influence of Soil-Pile-Structure Interaction (SPSI) on the seismic response of mid-rise moment resiting buildings supported by end-bearing pile foundations. Three different cases have been considered, namely: (i) fixed-base structure representing the situation excluding the soil-structure interaction; (ii) structure supported by shallow foundation on soft soil; and (iii) structure supported by end-bearing pile foundation in soft soil. Comparison of the numerical predictions and the experimental data shows a good agreement confirming the reliability of the numerical model. Both experimental and numerical results indicate that soil-structure interaction induces significant increase in the lateral deflections and inter-storey drifts of the structures on both shallow and end-bearing pile foundations in comparison to the fixed base structures. This increase in the lateral deformations and in turn inter-storey drifts can change the performance level of the structure during earthquakes which may be safety threatening.

RÉSUMÉ : Cet article présente les résultats des essais sur table vibrante et trois dimensions simulations numériques pour étudier l'influence de l'Interaction sol-pieu-structure (ISPS) sur la réponse sismique des bâtiments pris en charge par les fondations sur pieux. Trois cas différents ont été examinés, à savoir: (i) la structure de base fixe sans interaction sol-structure; (ii) la structure soutenue par la fondation superficielle sur sol mou; et (iii) la structure soutenue par la fondation sur pieux dans le sol mou. Les prédictions numériques et les données expérimentales montrent un bon accord. Résultats expérimentaux et numériques indiquent que l'interaction sol-structure augmente les déflexions latérales et les dérives inter étage des structures en comparaison avec les structures de base fixes. Cela peut changer le niveau de performance de la structure lors de tremblements de terre qui peuvent être un problème d'innocuité.

KEYWORDS: soil-pile-structure interaction, seismic response, shaking table test, FLAC3D, end-bearing pile foundation

1 INTRODUCTION

The problem of soil-pile-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. Influence of the underlying soil on seismic response of the structure can be ignored if the ground is stiff enough, and the structure can be analysed considering fixed-base conditions. However, the same structure behaves differently when it is constructed on the soft soil deposit. Earthquake characteristics, travel path, local soil properties, and soil-structure interaction are the factors affecting the seismic excitation experienced by structures. The result of the first three of these factors can be summarised as free-field ground motion. However, the foundation is not able to follow the deformation of the free field motion due to its stiffness, and the dynamic response of the structure itself would induce deformation of the supporting soil (Kramer 1996).

Over the past decades, several researchers (e.g. Tajimi 1969, Gazetas 1991, Shiming and Gang 1998, Hokmabadi et al. 2011, Carbonari et al. 2011, Tabatabaiefar et al. 2013) have studied the seismic soil-pile-structure interaction (SSPSI) and the effect of this phenomena on the response of the structures. The developed analytical methods for studying the soil-pile-structure interaction may be categorised into three groups: (i) Substructure Methods (or Winkler methods), in which series of springs and dashpots are employed to represent the soil behaviour (e.g. Hokmabadi 2012); (ii) 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 (iii) Numerical Methods. The substructure methods are the simplest and most commonly used methods, however, these methods adopting the substructuring concept rely on the principle of superposition, and consequently, are limited to either the linear elastic or the viscoelastic domain (Pitilakis et al. 2008).

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

$$[M]\{\ddot{u}\}+[C]\{\mathring{u}\}+[K]\{u\}= -[M]\{m\}\ddot{u}_g+\{F_v\} \qquad (1)$$

where, $\{u\}$, $\{\mathring{u}\}$, and $\{\ddot{u}\}$ are the nodal displacements, velocities and accelerations with respect to the underlying soil foundation, respectively. [M], [C] and [K] are the mass, damping, and stiffness matrices of the structure, respectively. It is more appropriate to use the incremental form of Equation (1) when plasticity is included, and then the matrix [K] should be the tangential matrix and $\{\ddot{u}\}$ is the earthquake induced acceleration at the level of the bedrock. For example, if only the horizontal acceleration is considered, then $\{m\}=[1,0,1,0,....1,0]^T$. {Fv} is the force vector corresponding to the viscous boundaries. This vector is nonzero only when there is a difference between the motion on the near side of the artificial boundary and the motion in the free field (Wolf 1985).

The present research aims to study the effects of SSPSI on the seismic response of the superstructure by employing the fully nonlinear method in which main components of the interaction including subsoil, pile foundation, and superstructure are modelled simultaneously. For this purpose, a three-dimensional explicit finite-difference program, FLAC3D (Itasca 2009), is used to numerically model and examine the influence of the soil-structure interaction on the seismic response of a 15-storey moment resiting building. Two types of foundations including shallow foundations and end-bearing pile foundations have been considered. The proposed numerical soil-structure model has been verified and validated against experimental shaking table test results.

2 SHAKING TABLE EXPERIMENTAL TESTS

2.1 Prototype characteristics and scaling factors

In order to provide a calibration benchmarks for the numerical simulation and to make quantitative predictions of the prototype response several of shaking table tests have been conducted. Previous researchers (e.g. Meymand 1998, Chau et al. 2009) modeled the superstructure as a simplified single degree of freedom oscillator in which the behaviour of the soil-structure system may not be completely conform to reality and the higher modes would not be captured. In the current model tests, unlike the previous efforts, a multi-storey frame for the superstructure is adopted representing most of the dynamic properties of the prototype structure such as natural frequency of the first and higher modes, number of stories, and density. The experimental model tests have been carried out utilising the 3×3 m shaking table facilities located at structures laboratory of the University of Technology Sydney (UTS).

The selected prototype structure is a fifteen-storey concrete moment resisting building frame with the total height of 45 m and width of 12 m consisting of three spans, representing the conventional types of mid-rise moment resisting buildings. The spacing between the frames into the page is 4 m. Natural frequency of the prototype building is 0.384 Hz and its total mass is 953 tonnes. The soil medium beneath the structure is a clayey soil with the shear wave velocity of 200 m/s and density of 1470 kg/m3. The horizontal distance of the soil lateral boundaries and bedrock depth has been selected to be 60 m and 30 m, respectively. The building is resting on a footing which is 4 m wide and 12 m long. For the pile foundations case, a 4×4 reinforced concrete pile group with equal spacing and pile diameter of 1.25 m and 30 long are considered. The piles are embedded into the bedrock representing typical end-bearing pile foundations.

In order to achieve a reasonable scale model, a dynamic similarity between the model and the prototype is applied as described by Meymand (1998). Dynamic similarity governs a condition where homologous parts of the model and prototype experience homologous net forces. Although small scale models could save cost, the precision of the results could be substantially reduced. Considering the specifications of UTS shaking table, scaling factor of 1:30 is adopted for experimental shaking table tests on the scale model which provides the largest achievable scale model with rational scales, maximum payload, and overturning moment meeting the facility limitations.

2.2 Shaking table tests model components

The developed soil-structure model for shaking table tests possesses four main components including the model structure, the model pile foundations, the laminar soil container, and the soil mix. Employing geometric scaling factor of 1:30, height, length, and width of the structural model are determined to be, 1.50 m, 0.40 m, and 0.40 m, respectively. In addition, the required natural frequency of the structural model is 2.11 Hz. The model structure has been designed employing SAP2000 (CSI 2010) software to meet the required characteristics, and finally a 500×500×10 mm steel plate as baseplate, fifteen 400×400×5 mm horizontal steel plates as the floors and four 500×40×2 mm vertical steel plates as the columns are adopted. The completed structural model is shown in Figure 1.

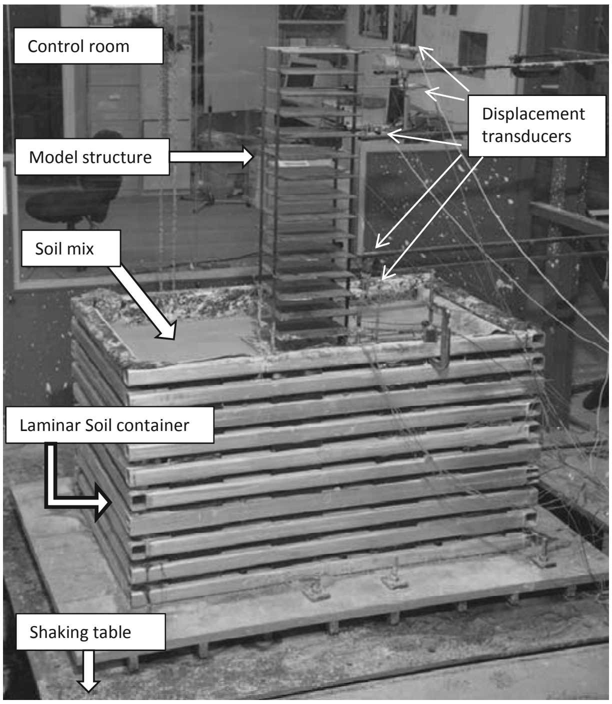

Figure 1. Final setup of the shaking table tests for the structure with end-bearing pile foundation

Similar to the model structure, the model pile is subjected to the competing scale model criteria. The model piles have a diameter of 40 mm with L/d ratio of 25. By selecting a commercial Polyethylene high pressure pipe with Standard Dimension Ratio (SDR) of 7.4 the model piles fall in the range of acceptable criteria with 5% deviation from the target value for EI.

The ideal soil container should simulate the free field soil response by minimising boundary effects. Since the seismic behaviour of the soil container affects the interaction between the soil and structure, the performance of the soil container is of the key importance for conducting seismic soil-structure interaction model tests successfully (Pitilakis et al. 2008). A laminar soil container with final length, width, and depth of 2.10m, 1.30m, and 1.10m, respectively, are designed and constructed for this study. The employed laminar soil container consists of a rectangular laminar box made of aluminium rectangular hollow section frames separated by rubber layers. The aluminium frames provide lateral confinement of the soil, while the rubber layers allow the container to deform in a shear beam manner.

A synthetic clay mixture was designed to provide soil medium for the shaking table testing considering required dynamic similarity characteristics. Several mixtures were examined and finally the desired soil mix (60% Q38 kaolinite clay, 20% Active-bond 23 Bentonite, 20% class F fly ash and lime, and water, 120% of the dry mix) produced the required scaled shear wave velocity of 36 m/s at the second day of its cure age. Accordingly, the soil density and undrained shear strength on the second day were determined to be 1450 kg/m^3 and 3.14 kPa, respectively.

The shaking table tests have been carried out in three stages: fixed-base condition, shallow foundations, and end bearing pile foundations. Since the properties of the designed soil mix is time depended, the second and third stages should be carried out in the same age in order to make the results comparable, without being interrupted by variation of the soil mix dynamic properties. Two scaled near field shaking events including Kobe, 1995, Northridge, 1994, and two scaled far field earthquakes including El Centro, 1940, and Hachinohe, 1968 are adopted. The characteristics of the mentioned benchmark earthquakes are summarised in Table 1. Displacement transducers (levels 3, 5, 7, 11, 13, and 15) and accelerometers (at levels 3, 5, 7, 9, 11, 13, and 15) were installed on the structure in order to monitor the dynamic response of the structure and to primarily measure the structural lateral displacements. The recorded accelerations can be used to check the consistency and accuracy of obtained displacements through a double integration in time domain. The final setup of the tests for the end-bearing pile foundation system on the shaking table is shown in Figure 1.

Table 1. Utilised earthquake base motions

Earthquake	Year	PGA (g)	Mw (R)	Duration (S)
Northridge	1994	0.843	6.7	30.0
Kobe	1995	0.833	6.8	56.0
El Centro	1940	0.349	6.9	56.5
Hachinohe	1968	0.229	7.5	36.0

3 DEVELOPMENT OF 3D NUMERICAL MODEL

Three-dimensional explicit finite-difference based program called FLAC3D (Itasca 2009) has been employed to develop the numerical model for the shaking table tests and to simulate the response under the seismic loading. Three cases including fixed-base conditions, the structure supported by shallow foundations, and the structure supported by end-bearing pile foundations have been modelled separately and the results are compared. The dimensions of the numerical models were chosen similar to the experimental tests. The reason for choosing the soil deposit thickness of 30 m for the both experimental and numerical models is that most amplification occurred within the first 30 m of the soil profile, which is in agreement with most modern seismic codes calculating local site effects based on the properties of the top 30 m of the soil profile (Rayhani and El Naggar 2008).

Experience gained from the parametric study helped to finalise the adopted mesh size and the maximum unbalanced force at the grid points to optimize the accuracy and the computation speed simultaneously. The numerical grid and model components in FLAC3D are shown in Figure 2.

Adjusting the boundary conditions, in the static analysis in which the system is under the gravity loads only, the bottom face of the mesh is fixed in all directions, while the side boundaries are fixed in the horizontal directions. During the dynamic time-history analysis, the earthquake acceleration is applied horizontally at the entire base, while free-field boundary conditions are assigned to the side boundaries.

Solid elements are used to model the soil deposits, and Mohr-Coulomb failure criterion is adopted. In addition, Hysteretic damping of the soil is implemented using the built-in tangent modulus function as developed by Hardin and Drnevich (1972). The pile elements and superstructure are modelled with solid elements considering elastic-perfectly plastic behaviour with yielding criteria for the elements to control the possibly of inelastic behaviour in both superstructure and piles. As a calibration, a FLAC3D analysis was first conducted on a cantilever pile while the pile was fixed at one end into ground without the surrounding soil and the different lateral loads were applied on the free end of the cantilever pile. The recorded deflection from the FLAC3D model shows less than 2% difference from analytical predictions, confirming the accuracy of the model. It should be noted that using the structural elements such as beam and shell elements in FLAC3D (version 4.0) for modelling the superstructure increases the execution time dramatically and leads to less accurate results.

Because of the different characteristics of the soil and the superstructure/piles, sliding and separation may occur at the soil–structure interfaces. Two sets of interface elements are modelled in this study. For the shallow foundation case, the interface elements are placed between the foundation and the soil surface. However, for the pile foundation case, the interface elements were attached to the outer perimeter of the piles. It should be noted that in the pile foundation case, there is no interface or attachment between the foundation and the surface soil as some gap in the shaking table tests is considered to avoid any pile-raft behaviour. Therefore, there is not any direct stress transfer between the foundation slab and the subsoil in the pile foundation cases. The interfaces were modelled as linear spring–slider systems, while the shear strength of the interfaces was defined by Mohr–Coulomb failure criterion. The lateral and axial stiffness of the interface elements are estimated for both sets separately based on the recommended method given by Itasca (2009) to ensure that the interface stiffness has minimal influence on system compliance. Finally, fully nonlinear time-history analysis is conducted under the influence of the scaled earthquake records and results in terms of maximum inelastic lateral deflections, determined for the three mentioned cases, are recorded.

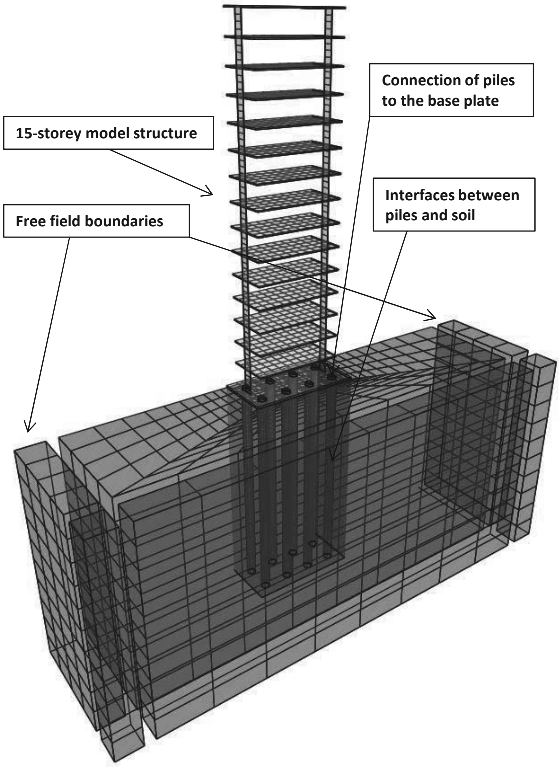

Figure 2. Numerical grid and model components in FLAC3D for the structure with end-bearing pile foundation

4 RESULTS AND DISCUSSION

The average values of the 3D numerical predictions versus experimental shaking table results for the maximum lateral displacements of the fixed-base, shallow foundations, and end-bearing pile foundations were determined and compared in Figure 3. Evaluation of the predicted and observed values of the maximum lateral displacements indicates that the trend and the values of the 3D numerical predictions are in a good agreement and consistent with the experimental shaking table test results. Therefore, the 3D numerical model can replicate the behaviour of the soil-pile-structure system with acceptable accuracy and is rational and appropriate for further studies of the soil-pile-structure interaction effects.

Accordingly, the maximum lateral deflection of the structure supported by end-bearing pile foundations is increased by 17% based on the experimental values and 19% based on the 3D numerical predictions in comparison to the fixed base structure. Moreover, the maximum lateral deflection of the structure supported by shallow foundation is increased by 55% based on the experimental values and 59% based on the 3D numerical predictions. Thus, pile foundations reduce the lateral drifts in comparison to the shallow foundation case. This is due to the presence of stiff pile elements in the soft soil which increase the stiffness of the ground and influences 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 of the structure.

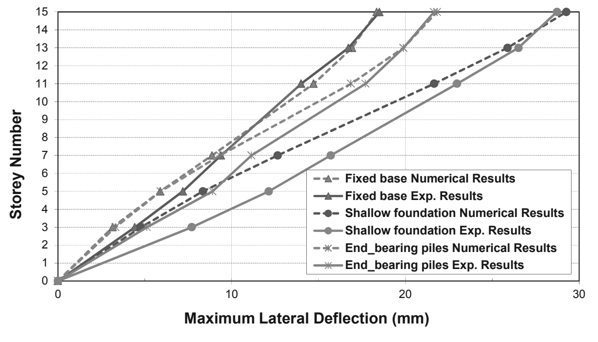

Figure 3. Average values of maximum lateral displacements: Shaking table experimental values versus 3D numerical predictions

The corresponding inter-storey drifts of the average values of 3D numerical model are plotted in Figure 4. Inter-storey drifts are the most commonly used damage parameters, and based on FEMA (BSSC 1997) maximum inter-storey drift of 1.5% is the defined border between life safe and near collapse levels. According to Figure 4, seismic soil-structure interaction tends to increase the inter-storey drifts of the superstructure from life safe zone toward near collapse or even total collapse.

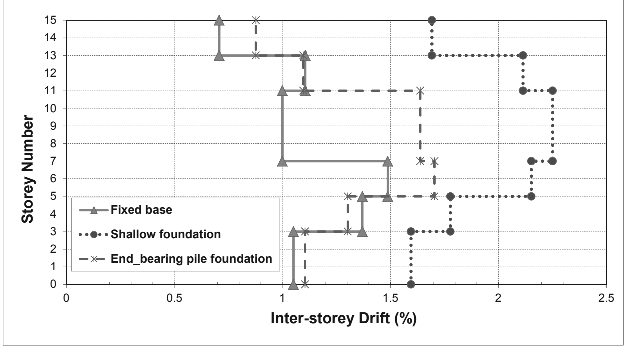

Figure 4. Average experimental inter-storey drifts for: (a) fixed-base structure; (b) Structure supported by shallow foundation; (c) structure supported by end-bearing pile foundation

The natural period of the system increases due to the soil-structure interaction. Therefore, such increases in the natural period considerably alter the response of the building frames under seismic excitation. This is due to the fact that the natural period lies in the long period region of the response spectrum curve. Hence, the displacement response tends to increase.

5 CONCLUSIONS

In this paper, a three-dimensional finite difference numerical model on a soil-pile-structure system has been conducted together with the experimental shaking table tests. By comparing predicted and observed results, it has been concluded that the numerical modelling method is rational and is suitable for the simulation of the soil-pile-structure interaction under strong ground motions.

In addition, based on the shaking table results and 3D numerical investigations it is observed that the lateral deflections of the structures siting on the end-bearing pile foundations amplified in comparison to the fixed base model (approximately 18% in this study). This amplification for the structure siting on the shallow foundations is more severe (approximately 57% in this study). Consequently, considering soil-structure interaction in both cases with and without pile foundations 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.

6 REFERENCES

BSSC. 1997. *NEHRP Guidelines for the Seismic Rehabilitation of Buildings, 1997 Edition, Part 1: Provisions and Part 2: Commentary*. In: Federal Emergency Management Agency.

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 (9): 1296-1309.

Chau, K.T., Shen, C.Y., and Guo, X. 2009. Nonlinear seismic soil-pile-structure interactions: Shaking table tests and FEM analyses. Soil Dynamics and Earthquake Engineering 29 (2): 300-310.

SAP2000 v14 Analysis Reference Manual. CSI (Computers and Structures Inc.), Berkley, California.

Gazetas, G. 1991. Formulas and Charts for Impedances of Surface and Embedded Foundations. Journal of Geotechnical Engineering 117 (9): 1363-1381.

Hardin, B.O., and Drnevich, V.P. 1972. Shear modulus and damping in soils: desing equations and curves. Journal of the Soil Mechanics and Foundations Division 98 (7): 667-692.

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 (1): 31-41.

Hokmabadi, A.S., Fakher, A., and Fatahi, B. 2012. Full scale lateral behaviour of monopiles in granular marine soils. Marine Structures 29(1): 198-210.

Tabatabaiefar, S., Fatahi, B., and Samali, B. Seismic Behaviour of Building Frames Considering Dynamic Soil-Structure Interaction. International Journal of Geomechanics (doi: 10.1061/(ASCE) GM.1943-5622.0000231).

FLAC3D version 4.00 Fast Lagrangian Analysis of Continua in three dimentions, User's Manual. Itasca Consulting Group, Inc, Minneapolis, Minnesota, USA.

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

Meymand, P.J. 1998. *Shaking table scale model tests of nonlinear soil-pile-superstructure in soft clay*. PhD PhD thesis in Civil Engineering University of California, Berkley.

Mindlin, R.D. 1936. Force at a Point in the Interior of a Semi-Infinite Solid. Physics 7 (5): 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 (6): 453-467.

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

Shiming, W., and Gang, G. 1998. *Dynamic soil-structure interaction for high-rise buildings*. In Developments in Geotechnical Engineering, eds. Chuhan Zhang and P. Wolf John: Elsevier. 203-216.

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

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