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Assessment of soil–pile–structure interaction influencing seismic response of mid-rise buildings sitting on floating pile foundations

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ABSTRACT

The role of the seismic soil–pile–structure interaction (SSPSI) is usually considered beneficial to the structural system under seismic loading since it lengthens the lateral fundamental period and leads to higher damping of the system in comparison with the fixed-base assumption. Lessons learned from recent earthquakes show that fixed-base assumption could be misleading, and neglecting the influence of SSPSI could lead to unsafe design particularly for structures founded on soft soils. In this study, in order to better understand the SSPSI phenomena, a series of shaking table tests have been conducted for three different cases, 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 floating (frictional) pile foundation in soft soil. A laminar soil container has been designed and constructed to simulate the free field soil response by minimising boundary effects during shaking table tests. In addition, a fully nonlinear three dimensional numerical model employing FLAC3D has been adopted to perform time-history analysis on the mentioned three cases. The numerical model adopts hysteretic damping algorithm representing the variation of the shear modulus and damping ratio of the soil with the cyclic shear strain capturing the energy absorbing characteristics of the soil. Results are presented in terms of the structural response parameters most significant for the damage such as foundation rocking, base shear, floor deformation, and inter-storey drifts. 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 amplifies the lateral deflections and inter-storey drifts of the structures supported by floating pile foundations in comparison to the fixed base structures. However, the floating pile foundations contribute to the reduction in the lateral displacements in comparison to the shallow foundation case, due to the reduced rocking components.

1. Introduction

The seismic design of buildings has been undergoing a critical reappraisal in recent years, with change of emphasis from "strength" to "performance". The development of capacity design principles in the 1970s [1] was an expression of the realisation that the distribution of strength through a building was more important than the absolute value of the design base shear which can be identified as the key point in the performance-based seismic design [2], where the overall performance of the building is controlled during the seismic design process.

For determining the seismic response of structures, it is a common practice to assume the structure is fixed at the base. In fact, if the ground is stiff enough (e.g. structure founded on solid rock) it is reasonable to assume that the input motion of the structure due to a design earthquake is essentially identical to the motion of the free field, which is defined as the motion experienced at the same point before the structure is built. However, for structures constructed on soft soils, two modifications need to be considered for determining the seismic response. First, the imposed motion to the structure differs from the free field motion due to the presence of the structure. Secondly, additional dynamic deformations are induced within the structure due to the underneath soft soil. The process, in which 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* [3].

The dynamic equation of the motion for the structure (Fig. 1) can be written as:

$$[M]\{u\} + [C]\{\dot{u}\} + [K]\{u\} = -[M]1u_g + F_v \tag{1}$$

where $[M]$, $[C]$ and $[K]$ are the mass, damping, and stiffness matrices of the structure, respectively. $\{u\}$, $\{\dot{u}\}$, and $\{\ddot{u}\}$ are the relative nodal

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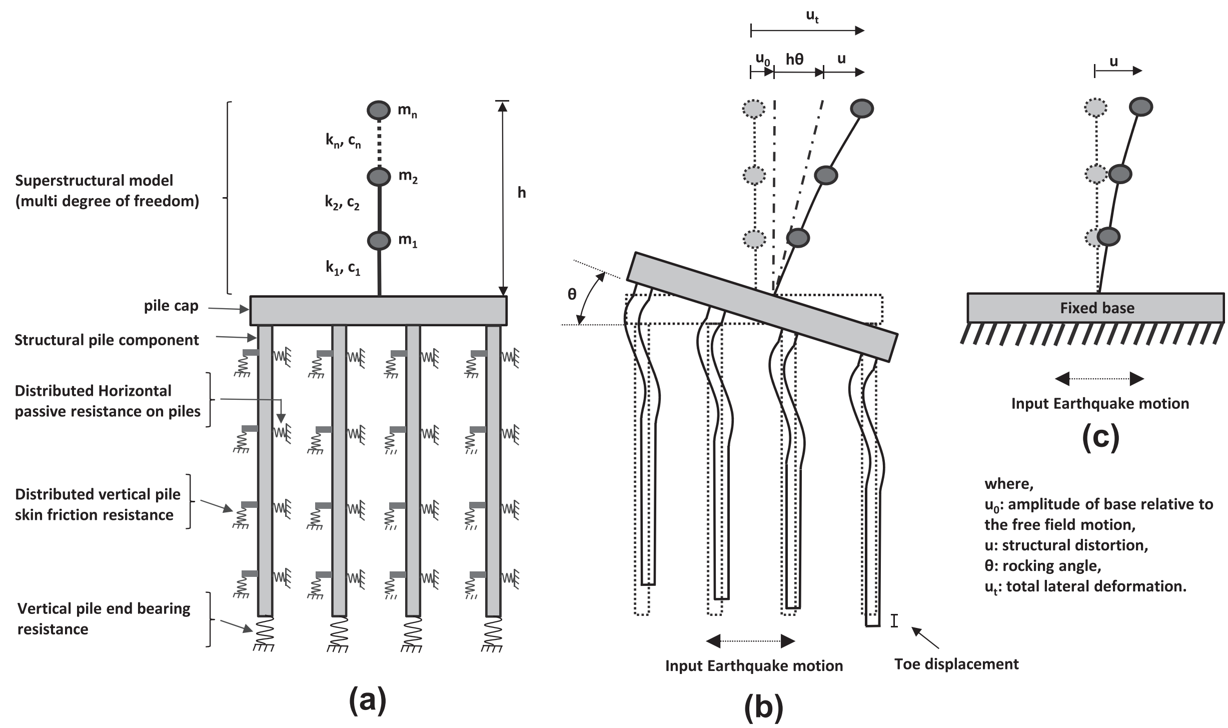

Fig. 1. Schematic modelling of the multi degree freedom structure considering: (a) structure supported by floating pile foundation employing foundation springs; (b) lateral deformation and rocking of the structure supported by floating pile foundation; (c) lateral deformation of the fixed-base structure.

displacements, velocities and accelerations of the structure with respect to ground, respectively. $\{\ddot{u}_g\}$ is ground acceleration, and $\{F_v\}$ 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 [4]. The role of the seismic soil–pile–structure interaction (SSPSI) is usually considered beneficial to the structural system under seismic loading since it elongates the period of the structure and increases the damping of the structural system, so the consideration of SSPSI tends to reduce the base shear and in turn structural demand of the superstructure in comparison to the fixed-base condition. In contrast, as shown in Fig. 1, SSPSI may increase the overall displacement of the superstructure in comparison to the fixed-base condition due to translation and rotation of the foundation (e.g. Guin and Banerjee [5]; Yingcai [6]). The rocking stiffness is developed due to the resistance of the piles to vertical movement [7], as shown particularly in Fig. 1b. Ma et al. [8] showed that rocking may be the most critical mode of vibration for a foundation because of the very low hysteretic (material) damping, which will lead to high motion amplitude when the excitation frequencies are near the resonance state. The increase in the lateral deformation of the building can change the performance level of the structure and is especially important for tall, slender structures or for closely spaced structures that can be subjected to pounding when relative displacements become large [3]. Moreover, increase in the total deformation of the structure and in turn secondary $P-\Delta$ effect influences the total stability of the structure. The lessons learned from post seismic observations of the past earthquakes such as 1985 Mexico City, 1994 Northridge, and 1995 Kobe earthquakes provided sufficient reason to believe that the SSPSI effects should be investigated with greater rigour and precision (e.g. Mendoza and Romo [9]; Mizuno et al. [10]).

Pile foundations are usually employed to transmit foundation loads through soil strata of low bearing capacity to deeper soil or rock strata having a high bearing capacity and stiffness. End bearing piles terminate in hard, relatively impenetrable materials such as rock or very dense sand and gravel, while floating piles obtain a greater part of their capacity by skin friction or adhesion and are mostly employed in situations where the bedrock is deep. Determination of the pile foundation seismic response is a complex process involving inertial interaction between the structure and the pile foundation, kinematic interaction between piles and soils, and the non-linear response of soils to strong earthquake motions [7]. However, simple methods such as Winkler computational model are often used in engineering practice in which soil–pile interaction is modelled using either linear or non-linear springs. The reliability of these constitutive models has been questioned by many due to the simplifying assumptions regularly used [11,12]. At first, the applied earthquake motion in the time history analysis is derived from the free field motion ignoring the presence of superstructure and pile elements. Secondly, Winkler springs which have been developed initially to model single pile–soil interaction, are not directly applicable to simulate pile groups due to the overlapping displacement fields of piles affecting the individual pile stiffness [13]. The limitations of Winkler methods and availability of advanced computational tools lead the researcher to conduct fully-nonlinear analysis to study the seismic response of pile foundations. As mentioned by Chu [14], for systems with strong nonlinear behaviour, coupled soil–pile–structure response analysis is highly desirable which can explicitly express the relationship between the soil and the structural responses, especially when the stiffness of the pile foundation significantly affect the overall soil response.

Although a number of works dealing with the SSPSI effects on the seismic response of structures are available in the literature, most of them adopt simplified models (e.g. single degree of freedom system for superstructure or linear analysis) [15–19]. 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