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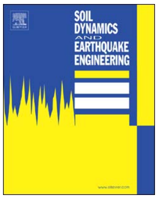

Seismic response of clay-pile-raft-superstructure systems subjected to far-field ground motions

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ABSTRACT

A series of three-dimensional (3D) finite element analyses incorporated with a hyperbolic-hysteretic soil model were performed to investigate the seismic response of pile-raft-superstructure systems constructed on soft clay stratum, focusing on the seismic pile bending moment and superstructural responses. The seismic pile bending moment results suggested that using a lumped mass to represent the superstructure, which has been widely used in many other studies, could only perform well for a relatively low-rise superstructure; on the other hand, the seismic response of superstructure was found to be significantly affected by the soil-structure interaction, and both the detrimental and beneficial effects of dynamic soil-structure interaction were observed. Hence, coupled soil-foundation-superstructure analyses were primarily performed in this study. The influences of peak base acceleration, pile flexural rigidity and the configuration of superstructure on both the pile bending moment and superstructural responses were studied. Furthermore, some correlations were derived to relate the maximum pile bending moment to the influencing factors, which can be used as useful tools for obtaining preliminary and first-order estimates of the maximum pile bending moment for pile-raft-superstructure systems constructed on soft clay deposits.

1. Introduction

It is a common practice to assume that the structure is fixed at the base and to apply the free-field ground motion at the base (e.g. [40]) when investigating the seismic response of a structure. In so doing, the influence of dynamic soil-structure interaction (SSI) is neglected, which may induce large prediction errors as the seismically-induced motion at ground surface is not likely to be the same as that at building foundation level [43,45,46]. The seismic SSI tends to increase the fundamental resonance period and damping of the system in comparison with the fixed-base assumption; as a result, the effect of seismic SSI is conventionally considered beneficial and hence neglected as recommended in many seismic codes such as ATC-3-06 [3] and NEHRP [16]. However, the detrimental effect of dynamic SSI was also reported in many published studies (e.g. [41,27]); the effect of seismic SSI can have either beneficial or detrimental effects on the seismic response of a structure, depending on the factors of earthquake type, soil type, foundation configuration and dynamic characteristics of the structure (e.g. [28,36]). In fact, the seismic SSI has been recognized as being important and the coupled soil-foundation-superstructure analysis has been recommended by many researchers [21,28,36,38].

Pile foundations have been widely used for buildings built on thick layers of soft clays. The performance of the pile-superstructure system against seismic shaking is an important area of study, which involves complex dynamic soil-pile-superstructure interaction (SPSI) mechanisms. During an earthquake, piles are subjected to kinematic and inertial forces respectively imposed by the surrounding soils and the superstructure that they support, which may result in the piles being subjected to structural distress leading to cracking or the formation of plastic hinges as observed in many postearthquake investigations (e.g. [9,17,26]). Besides, a major concern in seismic SSI is the amplification of ground motion induced by the soft soil layer [8,34,39,47], which may result in the piles and the superstructure being subjected to amplified loading even under small to moderate earthquakes. Furthermore, the performance of pile-superstructure system constructed on soft clay stratum against earthquake is also an important consideration under many national design codes, e.g. NEHRP [16], GB50011-2010 [37] and Eurocode 8 [14].

Significant works have been done in the area of seismic soil-pile-structure interaction over the past decades. Most of the laboratory experiments including centrifuge tests (e.g. [1,10,11,19,22,50]) and 1-g shaking table tests (e.g. [4,18,23,24,25,30,48]) were focused on the seismic response of soil-pile-superstructure installed in predominantly sandy (liquefiable or dry) soil, while the relevant studies involving soft

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clays are still relatively limited. One significant work in this area was carried out by Meymand [35], who conducted a series of large scale 1-g shaking table tests to study the seismic interaction of soft clay-pile-superstructure; Hokmabadi et al. [27] also performed a series of 1-g shaking table tests to investigate the seismic response of superstructure supported by a 4×4 pile group installed in a synthetic clay bed. Banerjee [7] and Banerjee et al. [8] performed a series of centrifuge tests to study the dynamic response of pile-raft system embedded in soft kaolin clay subjected to short-duration far-field earthquakes. In their work, the pile spacing along the shaking direction was 10 times the pile diameter or more, and their test results were largely representative of the seismic response of single piles embedded in soft clay. Zhang [51], Zhang et al. [52,53] also performed a series of centrifuge tests to investigate the influence of pile group configuration on the seismic response of clay-pile-raft systems subjected to both long- and short-duration far-field ground motions. With the exception of the studies by Ayothiraman et al. [4] and Hokmabadi et al. [27], most of the aforementioned experimental studies treated the superstructure as either a lumped mass or a simplified single degree of freedom oscillator and hence the effect of higher modes of the superstructure was not accounted for in these studies. On the other hand, in order to fully account for the nonlinear behaviour of the soil under seismic loadings, numerical simulations such as finite element analysis (e.g. [8,21,33]) and finite difference analysis (e.g. [27,29]) are commonly performed in time domain to investigate the seismic SPSI. In addition, beam-on-dynamic-Winkler-foundation model or dynamic p-y method is also a popular approach to account for the dynamic SPSI (e.g. [12,38]), for which the parameters assigned to the springs and dashpots used for the p-y curve are usually back-calculated from the measured pile response.

In this study, a total of 90 three-dimensional (3D) finite element analyses were performed using ABAQUS/Explicit to investigate the seismic response of different pile-raft-superstructure systems constructed on soft clay subjected to far-field ground motions. A newly developed VUMAT subroutine was incorporated to account for the hyperbolic-hysteretic soil behaviour that was proposed by Banerjee [7] on the basis of a series of resonant column and cyclic triaxial tests for soft clay. Two approaches, namely lumped mass and detailed modelling of the superstructure, which are respectively termed "added mass" and "detailed model", were used to account for the inertial effect imposed by a superstructure during the seismic shaking event. As Fig. 1 shows, the reference ground motion (PBA = 0.06 g) adopted in the present study is similar to that used by Banerjee et al. [8], which represents the type of shaking that may be experienced in Singapore due to a typical far-field earthquake arising from the strike-slip Great Sumatran Fault. In order to study the effect of different earthquake intensity, the reference ground motion was scaled down to two other different peak ground accelerations about 0.01 g and 0.03 g. In addition, some other influencing factors such as pile flexural rigidity, mass of the raft and storey number of the superstructure were varied in the numerical simulations. The computed results of pile bending moment, deflection of the superstructure, inter-storey drift ratio and shear force of the column of superstructure were presented. Given the fact that the relevant studies involving soft clays are still relatively few, the findings obtained from the present study can provide a useful reference for practical seismic design of pile-raft-superstructure systems constructed on soft clays subjected to far-field ground motions.

2. Numerical modelling procedure

2.1. General information

Fig. 2 shows the configuration of the clay-pile-raft-superstructure systems adopted in the present numerical study, which contains a superstructure with storey number ranging from 0 to 20 and supported by a 5×5 pile-raft system installed in a soft clay bed, the properties of which are shown in Table 1. The piles were embedded in a pure clay bed, with the toes sitting atop a 0.5 m-tick sand layer. The properties of the sand were adopted following Banerjee [7], which are listed in Table 2. As can be seen, these clay-pile-raft-superstructure systems are self-symmetrical with respect to the ground motion orientation, hence only a half 3D finite model of each system was set up using ABAQUS/Explicit 6.13. Fig. 3 shows the 3D finite element model of the 20-storey building supported by a clay-pile-raft system, which contains 19200 linear hexahedral elements, 5760 linear quadrilateral elements, and 3225 linear beam elements.

2.2. Soil model

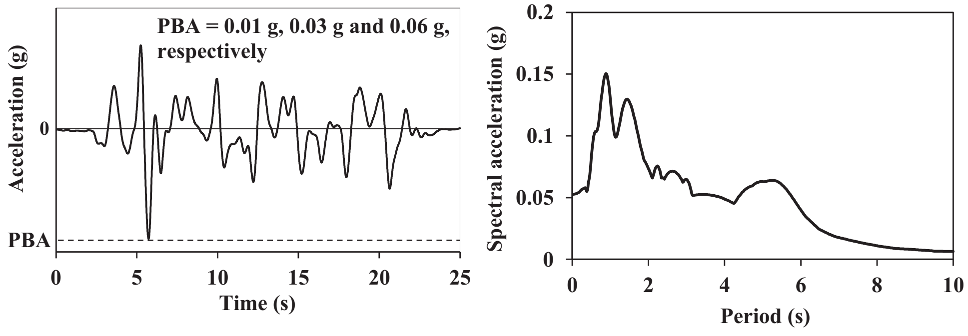
The behaviour of the soft clay was simulated using a hyperbolic-hysteretic soil model as shown in Fig. 4, which was proposed by Banerjee [7] and calibrated using laboratory test data from cyclic triaxial and resonant column tests on kaolin clay. The basic shear stress-strain relationship for this hyperbolic-hysteresis model is shown in Eq. (1).

$$q=\begin{cases} q_f-\dfrac{1}{3G_{\max}/q_f}\left[\dfrac{3G_{\max}}{1+3G_{\max}\varepsilon_s/q_f}\right] & \text{Initial loading (backbone) path}\\[2ex] -2q_f+\dfrac{2}{3G_{\max}/q_f}\left[\dfrac{3G_{\max}}{1+3G_{\max}(\varepsilon_{r1}-\varepsilon_s)/2q_f}\right]+q_{r1} & \text{Unloading path}\\[2ex] 2q_f-\dfrac{2}{3G_{\max}/q_f}\left[\dfrac{3G_{\max}}{1+3G_{\max}(\varepsilon_s-\varepsilon_{r2})/2q_f}\right]-q_{r2} & \text{Reloading path}\end{cases} \tag{1}$$

where q and ε_s are the current deviator stress and generalized shear strain, respectively;

q_{r1} and q_{r2} are the respective deviator stresses at the reversal points;
ε_{r1} and ε_{r2} are the respective generalized shear strains at the reversal points;
$G_{\max}$ is the small-strain shear modulus;
q_f is the deviator stress at failure.

For normally consolidated kaolin clay, the small-strain shear



(a) (b)

Fig. 1. Input base motions adopted in this study: (a) time history, (b) response spectrum for the base motion with peak base acceleration (PBA) of 0.06 g (5% damping).