EFFECTIVE STRESS ANALYSIS OF SEISMIC BEHAVIORS OF INCLINED MICROPILES ON LIQUEFIABLE SOILS

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ABSTRACT :

Seismic performance of inclined micropiles on the liquefiable soils is a complex problem. The traditional analytical closed from solutions is often difficult to meet the need of seismic design of micropiles on liquefiable soils. Herein an effective stress analysis method using a multiple shear plasticity model and a concept of liquefaction front was used to investigate dynamic behaviors of micropiles on liquefiable soils. The numerical simulations for the micropile with inclination of 0°, 15°, 25° to the vertical and different motion intensity of sine wave and El Centro earthquake motion were presented to study the effects of independent variables on the deflections, bending moments, accelerations and pile-soil relative lateral displacement along buried micropile length. Moreover, the results were also further compared. The numerical predications show that stronger input motion intensity results in higher responses at the micropile head. The maximum amplitude of deflection is lower in the inclined micropile groups than in the vertical micropile groups. And the values of deflection and bending moments of micropiles, lateral displacements difference between the micropile and soil in liquefiable soils are much bigger than in non-liquefiable soils. The inclined micropiles behave smaller lateral displacements and accelerations at micropile head as compared to the vertical micropiles. Inclination of micropiles results in asymmetrical distribution among the micropile groups during earthquake. These results provide a reference for the seismic design of micropiles founded on liquefiable soils.

KEYWORDS: liquefiable soil, seismic behavior, effective stress analysis, micropile

1. INTRODUCTION

Micropiles are traditionally used in foundation retrofit and rehabilitation projects due to their high flexibility ductility, capacity to withstand extension forces and a good performance during earthquakes. However, the seismic behavior of inclined micropile is not fully understood up to now because the behaviors of micropiles during earthquake are significantly influenced by the nonlinear characteristics of liquefiable soils and pile-soil interaction. Consequently, many tests and simulations have been conducted to study this problem. Sadek et al. investigated the influence of connection conditions at the head and tip of micropiles on their response to seismic loading using a finite element modeling. Misra et al presented a reliability-based design methodology for micropiles at their service limit state. Centrifuge tests carried by Wang et al. show that liquefiable soil contributes to an increase in both the pile cap displacement and the bending moments. However, seismic behaviors of micropiles are complex due to nonlinear characteristics of micropile-soil interaction and larger deformation of liquefiable soils. And number of full- and model-scale tests used to investigate the seismic behavior of micropiles, as well as the amount of numerical modeling studies for micropiles is limited. Many issues and considerable research work still need to be done in order to develop and assess seismic design guidelines for proper design of micropile systems. Numerical analysis is an effective way to study the behavior of micropiles as, once a model is verified, conditions can be changed with little effort to conduct a parametric study on the system variables. Therefore, this paper attempts to analyze the influence of micropiles inclination and shaking motion intensity on seismic response of micropile foundation by the means of numerical simulations. Analysis is conducted using a two-dimensional finite element analysis (FEM) with FLIP (Finite element analysis program for LIquefaction Process) program. The results obtained in this study will provide a basis for the seismic design of micropiles during earthquakes.

2. NUMERICAL MODELLING

2.1. Based Model for the Analysis Method FLIP

The program FLIP developed by Iai is used to analyze the seismic behaviors of inclined micropiles on liquefiable soils. The constitutive model incorporated in the FLIP is composed of a multiple shear plasticity model and a model for generating excess pore water pressure. The multiple shear plasticity model, which is composed of virtual simple shear mechanisms in arbitrary orientations, used for the analysis can take into account the effect of rotation of principal stress axis directions and can behave the seismic behaviors of micropiles in liquefiable soils during motions. The excess pore water pressure generation due to dilatancy is modeled using the concept of liquefaction front, which is defined in the normalized stress space with the isotropic stress ratio and the deviatoric stress ratio. The program has been verified in many numerical simulation works of structure damage induced by earthquakes and liquefaction (Iai et al, 1992; Wang et al. 2005a, 2005b; Li et al. 2007).

2.2. Numerical Modelling of Practical Example

The soil layer for numerical model of practical example is assumed horizontal homogeneous stratums. The water table is at the elevation of -2.0 m. The main features and parameters of each model are listed in the Table 1 and labeled as sine wave model and earthquake wave model. The stratum for all models is same and composed of a dry sand deposit and liquefiable sand deposit and dense saturated sand, as show in Figure 1. The sine wave models are used to investigate the influence of the input motion intensity on the micropile with inclination of 15° to the vertical. The frequency for input sinusoid wave is 1.5 Hz. And the earthquake models are used to simulate seismic behaviors of micropile with an inclination of 0°, 15°, and 20°during El Centro earthquake motion of 30 second shaking duration.

Table 1 Numerical model

Label of model	Inclination of micropile	Peak of input motion
Sine wave model	15°	0.1 g
	15°	0.2 g
	15°	0.3 g
Earthquake wave model	0°	0.32 g
	15°	0.32 g
	25°	0.32 g

Table 2 Parameters of soil layers

Soil layer	Thickness	K_{ma}	G_{ma}	φ_f	S_1	p_1	p_2	w_1	c_1
Dry soil	2.0 m	151.4 MPa	58.3MPa	38.59°	—	—	—	—	—
Saturated soil	3.0 m	151.4 MPa	58.3 MPa	38.59°	0.005	0.5	1.106	1.368	1.643
Dense saturated soil	5.0 m	282.3MPa	108.3 MPa	40.56°	—	—	—	—	—

K_{ma}: initial bulk modulus of soil skeleton at at confining pressure of 98 kPa; G_{ma}: initial shear modulus at confining pressure of 98 kPa; φ_f: effective friction angle; S_1, p_1, p_2, w_1, c_1: parameters for excess pore water pressure accumulation model. The detailed illumination of parameter definition was expounded in the reference (Iai et al, 1992).

The finite element mesh for the sine wave model used in the analysis, are similar to the earthquake wave model as shown in Figure 1 that used in. The finite element model consists of 2 796 nodes and 4 666 elements. The soil profile is consisted of three soil layers. The soil layers 2 are liquefiable soils. The soils are simulated with multiple spring elements. The thickness and mechanical properties of the soil are summarized in Table 2. The length and diameter of micropile are 5.7 m and 0.2 m, respectively. The micropiles are simulated with linear beam elements. Analysis was carried out with the following characteristics for the pile material: Shear modulus of the micropile G_s=770 MPa; Poisson's ratio μ=0.3; The density ρ=2.5 g/cm^3; and I= 7.86×10^{-4} m^{-4}. The super-structure mass is treated as a rigid body, and is represented by a concentrated mass. The soil-pile interaction spring element is used to simulate the pile-soil interaction. The pore water pressure is modeled with pore water element.

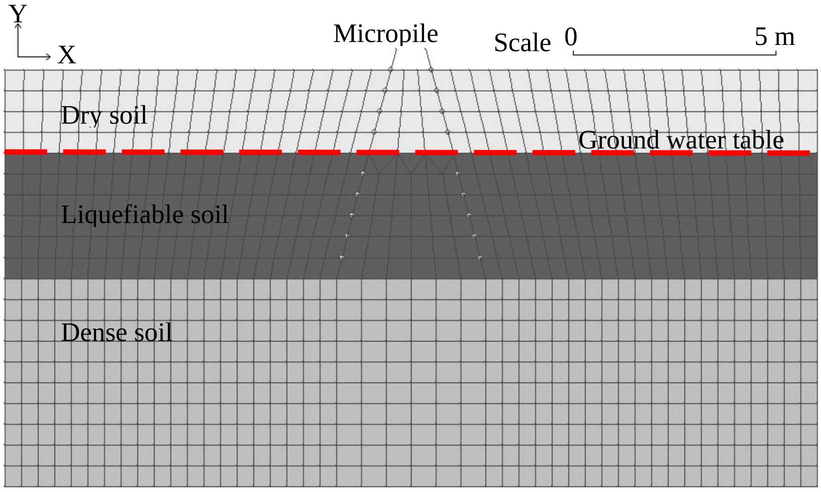


Figure 1 Mesh for earthquake wave model

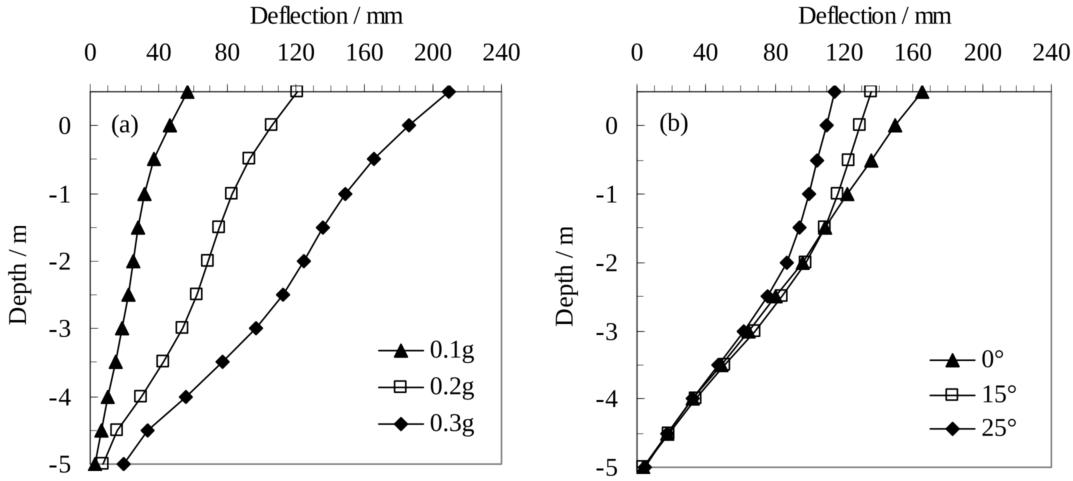
To simulate the conditions of site, the bottom boundary of the analytical domain was set at the base of soil layer 3. The ground motions were applied at the fixed bottom boundary. A viscous condition was assigned for the both side boundaries for dynamic analysis. The numerical integration is done by Wilson-θ method (θ=1.4) at time step of 0.01 seconds. Rayleigh damping (α=0.000, β=0.003) was used for ensure the stability of the numerical solution process. Before the dynamic response analysis conducted under undrained condition, a static analysis was performed with gravity to simulate the initial stress acting in situ.

3. RESULTS AND DISCCUSIONS

The results from numerical predications are presented below in prototype scale and compared with each other.

3.1. Lateral Displacement

The maximum lateral displacements along buried micropile length are depicted in Figure 2. It may be seen from the Figure 2(a) that the deflection of micropile increased with the increase of sine wave intensity. And the deflection of micropile decrease with the buried depth. For the earthquake wave model, the deflection decreased with increase of inclination of micropile at the same buried depth. It is worth noting in Figure 2 that the deflection of micropile changed obviously at the interface between the dry sand and the liquefiable soil. The increasing ratio is larger in liquefiable soil than in dry sand. These curves clearly illustrate the effect of pile inclination and input motion intensity on the micropile deformation responses during simulated earthquakes.



(a) Sine wave (b) El Centro wave

Figure 2 Deflections along buried micropile length

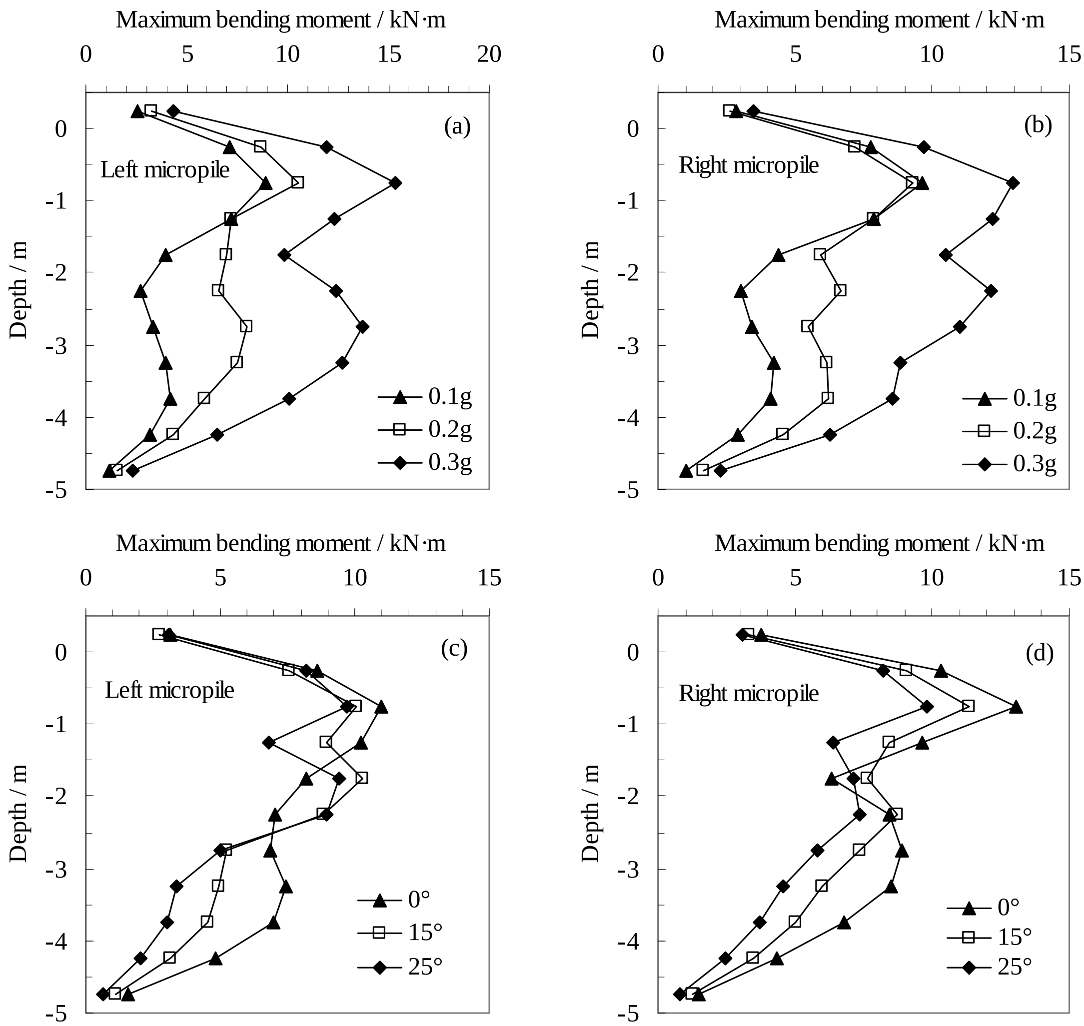


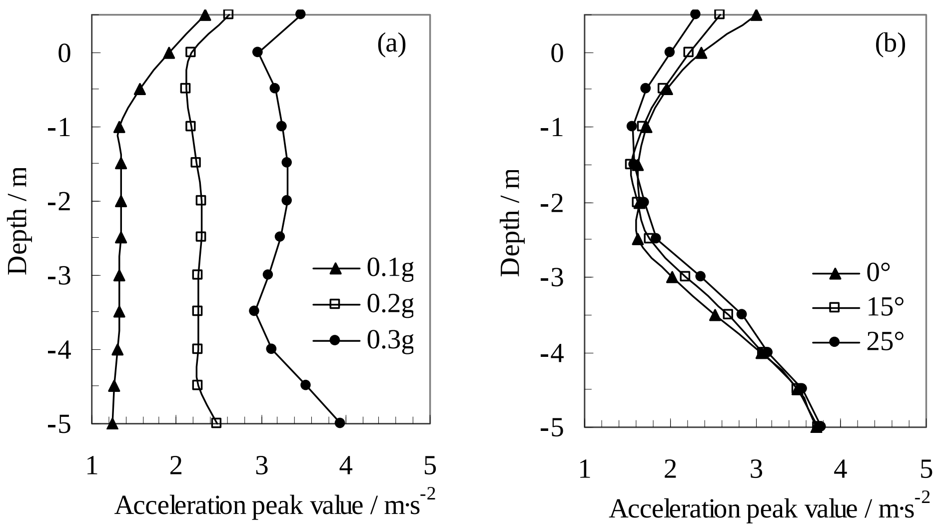
Figure 3 Relationship between the maximum bending moments of pile and buried length: (a), (b) Sine wave; (c), (d) El Centro wave

3.2. Bending Moment

The max bending moment profile along the left and the right micropile buried length for various pile inclination and motion intensity is illustrated in Figure 3. The values of bending moments generally increase with increasing intensity (See Figure 3(a), (b)). And influence of micropiles inclination on the bending moment is observed in the earthquake wave model. The increase in inclination from 0 to 15° induces a decrease of the bending moment (See Figure 3(c), (d)). It may be seen that the value of bending moments for the right and left micropile are not same and not symmetric. This may be due to the inclination of micropile contributed to the unequal distribution of loads. Those observations are of significant for the design of micropiles in liquefiable soils during earthquakes.

3.3. Acceleration

The horizontal acceleration responses along the left micropile are illustrated in Figure 4. As expected, the crest acceleration amplitude increased with the increasing intensity in sine wave model with an inclination angle 15° (See Figure4 (a)). Figure 4(b) shows acceleration responses obtained for a group of micropiles with a inclination of 0°, 15°, and 20° to the vertical axis subjected to El Centro motion. It is clearly seen that the amplitude of acceleration decreased in the liquefiable soil layers during the motion, as shown in Figure 4 (b), then increased in the non-liquefiable soils. It can be observed that lateral acceleration is smaller in the inclined micropiles than that induced in the vertical micropile case. The amplification in the lateral acceleration at the pile top with a inclination of 25° is 0.74, which is about 23% smaller than the one induced in vertical micropiles subjected to El Centro earthquake motion.



(a) Sine wave (b) El Centro wave

Figure 4 Peak acceleration value along buried left micropile length

3.4. Relative Displacement Between Micropile and Soil

Figure 5 illustrated the relative lateral displacement between the micropile and soil. It may be seen that the relative lateral displacement behaves more complex in liquefiable soil than in the non-liquefiable soil. The bigger value occurred at the interface between the dry sand and liquefiable sand, and lower part of micropile.

The right and left micropile behaves different characteristics. The larger the value of relative displacement the stronger motion and the larger inclination of micropile are. The nonlinear behavior of the liquefiable soil and the micropile-soil interaction can greatly affect the seismic responses of the micropiles group.

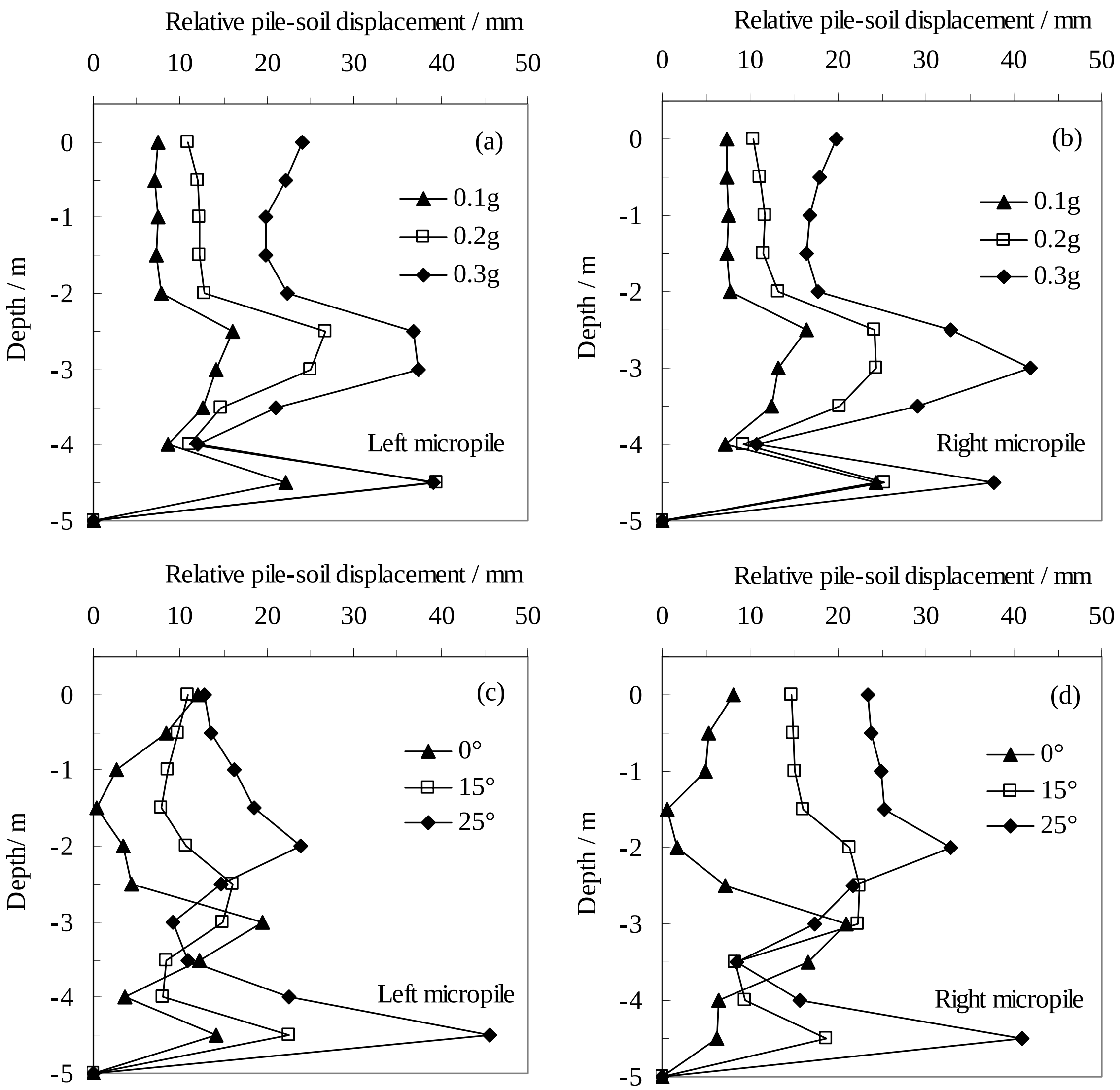


Figure 5 Relative soil-pile lateral displacements along buried micropile length: (a), (b) Sine wave; (c), (d) El Centro wave

4. CONCLUSIONS

This paper utilizes a finite element modeling to analyze the influence of micropiles inclination and motion intensity on seismic responses of micropile groups on liquefiable soils, and discussed the micropile-soil interaction mechanism subjected to motions. These results provide a foundation and reference for the seismic design of micropiles on a liquefiable soil foundation. The main results are presented as follow,

1) It is concluded that the presented analysis method is capable of predicting the behaviors of micropile during earthquakes. And it is very helpful to understand better the liquefaction process and seismic behaviors of micropile foundation.

2) The deflections and bending moments of micropile decrease with increase of the pile inclination to vertical, but the relative micropile-soil lateral displacement increase with the increasing motion intensity. And the deflection along the pile decreases with increasing he buried depth. The right and left micropiles behave different distribution.

3) The micropile-soil interaction during earthquakes is much more complex in liquefiable soils than in non-liquefiable soils. Thus these preliminary results needs to be further investigated in order to develop rational seismic design for micropile systems in liquefiable soils.

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