CENTRIFUGE MODELING FOR SEISMIC BEHAVIORS OF PILE GROUPS ON INCLINED LATERALLY SPREADING SOILS

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ABSTRACT :

The assessment of liquefaction hazard and the seismic design for the pile foundation in the inclined liquefiable soil layer is potentially very significant. Centrifuge tests of 50g are conducted to investigate the seismic behaviors of pile groups on the inclined liquefiable soils during earthquakes. The scenario input motions with peak shaking amplitudes of 0.24g and 0.99g (at prototype scale) were adopted in centrifuge tests. These centrifuge experiments simulate an inclined saturated layer of slope angle = arctg(1/2), and relative density of 89 % and 60%. The soil profile resting on stiff bedrock is made by de-aired dry sand saturated by de-aired motolose solution of 50 times the viscosity of water such that the deposit has the prototype permeability of sand. The model pile foundation consists of structure supported by a 2×2, 10 times diameter spacing pile group. A relative large crest residual lateral displacement of over 0.85m at prototype scale was measured after the test of strong shaking of 0.99g. It is found that the lateral displacement and bending moments of pile groups are much larger in laterally spreading soils than in non-liquefied soils. And the location for the max bending moment during shaking and residual bending moment transfer further down with the liquefaction and lateral spread of soils. The dynamic centrifuge tests proposed in this paper are applicable and reliable for simulating seismic performance of pile groups on the inclined liquefiable foundation.

KEYWORDS: liquefaction, dynamic centrifuge modeling, earthquake, lateral spread

1. INTRODUCTION

Extensive damage to pile foundations due to earthquake-induced liquefaction and lateral spreading has been observed around the world (Wang et al, 2008). As we known, saturated soils develop high pore water pressures or liquefy during strong earthquake shaking, which would results in almost a complete loss of stiffness and strength of the liquefied soil, and consequent large ground deformation and lateral spreading. Consequently, the excessive lateral movement of the liquefied soil and significant stiffness reduction in the liquefied layer are key features that need to be considered when evaluating the seismic performances of pile foundation found on the liquefiable soils. Lateral spreading can be a governing factor of reliability of pile foundation in liquefiable soils subject to strong motion. Hence, the research of this topic is potentially very significant. However, they are very difficult to predict reliably because predicting the behavior of a pile foundation in liquefying ground during an earthquake requires consideration of design motions, free-field site response, superstructure response, and soil-pile-superstructure interaction. Although in recent years a limited number of physical model studies of pile groups in liquefied and laterally spreading ground have been performed (e.g., Wilson et al. 2000, Finn et al. 2002; Abdoun et al. 2003; Kagawa et al. 2004; Wang et al. 2005), which have helped to clarify and characterize certain aspects of soil-pile interaction and seismic behaviors of pile foundation in liquefied sand, the actual loading mechanisms between laterally spreading ground and pile foundations are only approximately understood. The objective of this study is to investigate the performance of pile foundation in an inclined liquefiable soil layer subjected to different level strong scenario motion with centrifuge tests, and to provide a basis for the seismic design of pile foundation subjected to a strong motion in the inclined liquefiable soils.

2. CENTRIFUGE MODELLING

2.1. Testing Equipment

All centrifuge tests are conducted at the DPRI centrifuge using the rigid container box and model piles and silica sand as research tools. The DPRI centrifuge has an in-flight radius of 2.5m, and its max centrifugal acceleration for static test is 200 g, and for dynamic test is 50 g. A rectangular rigid container with internal dimensions of 150(W) ×450(L) ×300 mm(H) was used in the centrifuge tests, including the instrumentations used for all the centrifuge models presented in Figure 1. The arrangement and instrumentation is shown in Figure 1. For each test (See Figure 1), a complete set of response time histories were recoded during and after shaking, in the form of acceleration at 3 locations, pore pressures at 2 locations, pile strain at 22 locations, and horizontal displacement at 1 location by the side of pier surface. A data acquisition system was installed on the centrifuge to minimize electric noise. Digitals signals from the on-board computer were transferred to the computer in the controlled room via wireless communications.

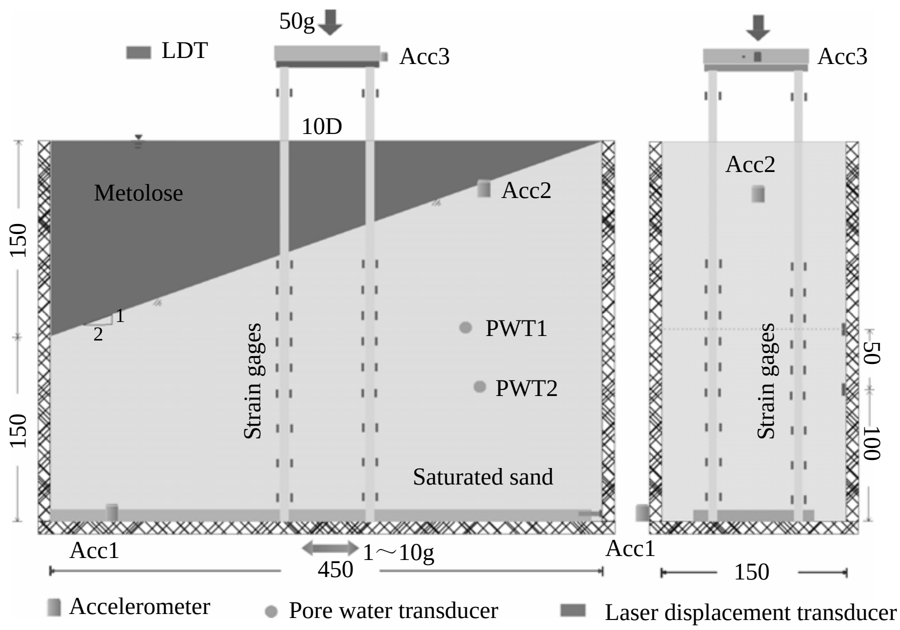

Figure 1 Schematic figure of the centrifuge model (Unit: mm)

2.2. Model Pile and Model Soil

As shown in Figure 1, group piles were lined up 2 by 2 with a spacing of 10 times a pile diameter. The model pile was made of brass pipe of an outside diameter 7.0 mm, length 360 mm and thickness 0.9 mm, clamped to a pile cap at pile head. A pile plate of 0.78 kg fixed on the top of pile cap has dimensions of 83(W)×83(L)×12mm(H) in model units. Both the pile top and bottom were set in rotation fixed condition.

The soil profile is comprised of one layer silica sand of about ranging from 7.5 m to 15 m thick resting on stiff bedrock at prototype scale. The sand is a uniformly grade fined sand with coefficient of uniformity of 1.8 and mean grain size of 0.15 mm. The specific gravity of the sand is G_s=2.63. The maximum and minimum porosity is 1.2 and 0.7, respectively. In both cases, the soil is saturated with de-aired metolose solution, having 50 times the viscosity of water such that the deposit has the prototype permeability of sand. This solution is obtained by mixed a very small portion of metolose powder in water to obtain solution of 50 times of water viscosity.

2.3. Centrifuge Models and Input Motions

The main features and parameters of each test are listed in the Table 1 and labeled case 1, 2. The sand relative density of case 1 is 89 %, and the maximum acceleration amplitude of applied base motion exited by a scenario input wave parallel to the base of the container, is 0.24 g at prototype scale (See Figure 2). In the case 2, the sand relative density is 60 %, and the crest value of scenario input wave is 0.99 g at prototype scale. The particular experimental configuration shown in Figure 1 was adopted for case 1. The configurations of case 2 were very similar to case 1.

Table 1 Centrifuge model tests

Label	Input motion		Relative density of soil
	Wave form	Peak amplitude	
Case 1	Scenario wave	0.24 g	89 %
Case 2	Scenario wave	0.99 g	60 %

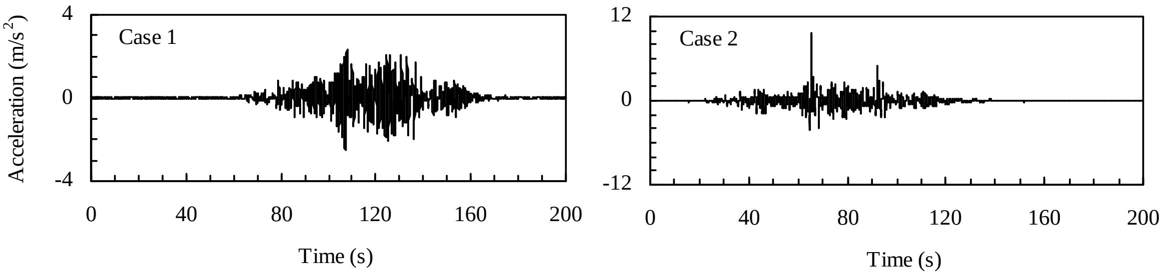

Figure 2 Input motions of centrifuge tests

3. RESULTS AND DISCCUSIONS

The results from tests and comparisons are presented below at prototype scale.

3.1. Lateral displacement

Figure 3 shows the measured time histories of lateral displacement at the pile head of each case. The displacement time history at the pile top recorded by the LDT placed on the top of the container indicates that the maximum displacement of the pile head is 0.33 m during shaking, and the permanent prototype lateral displacement of test is about 47 mm for the case 1. And the prototype lateral displacement of case 2 was much more than 0.55 m during shaking for the LDT is overflow. The measured permanent lateral displacement at the pile top is about 0.85 m after the centrifuge test. It clearly shows that the value of displacement in case 2 is much more than that of case 1. This may be due to the laterally spreading of liquefied soil during shaking in case 2. The transient lateral displacements of the clay layer were greater than the residual lateral displacements in the case 1, but in the case 2, the both value are approximately same.

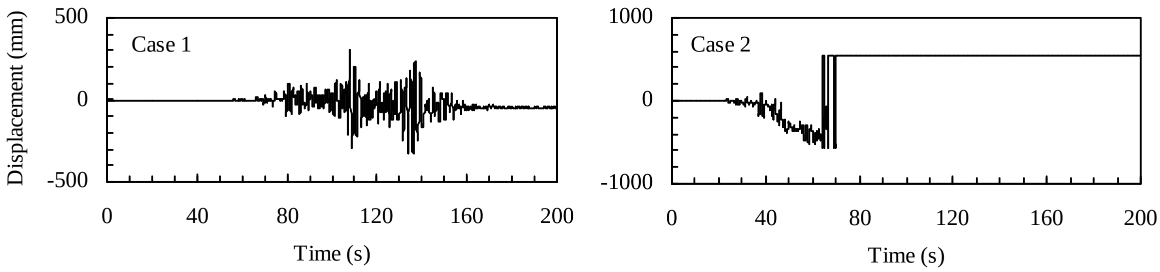

Figure 3 Lateral displacement response at pile head during shaking

3.2. Accelerations

The horizontal acceleration responses at pile head and ground surface are illustrated in Figure 4. As expected, the crest acceleration amplitude at pile head increased with the increasing intensity. The recorded acceleration amplitude at the ground surface as respect to the input motion (See Figure 2) increases significantly during shaking for the case 1. It suggests that the soil does not liquefy after 200 s of shaking for the case 1. However, the measured acceleration waveforms of the pile head and ground surface for the case 2 decreased as the soil sand generated significant pore water pressure during the motion, as shown in Figure 4. The maximum lateral acceleration at the pile top and ground surface are 4.06 and 4.78 m/s^2 in case 2, which are reduced about 42% and 49 % compared with the input motion of 9.68 m/s^2, respectively.

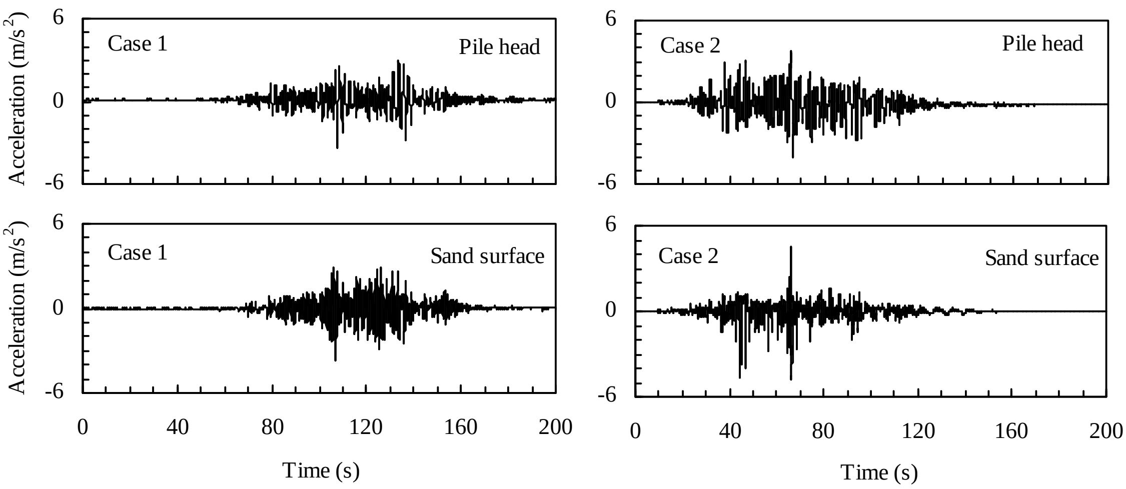

Figure 4 Acceleration response at pile head and ground surface

3.3. Bending Moment

Figure 5 shows the measured maximum bending moments profile of left pile during shaking and residual bending moment profile after shaking, whose locations are shown in Figure 1. The values of bending moments generally increase with increasing intensity. It is clearly seen that the characteristics of bending moments for the two cases behave different. There is a peak bending moment of 4100 kN·m at an elevation of -7.1 m for case 1. However, the peak bending moment of 820 kN·m occurred at an elevation of -10.25 m for case 2. The location for the peak bending moment becomes deeper with increasing input motion intensity, suggesting that load is transferred further down the pile with the liquefaction of soil. The transient bending moments were greater than the residual bending moments in the piles. The residual bending moment of case 2 is much more than that of case 1. The residual bending moments for these piles in the case 1 were not significantly different. On the contrary, in the case 2, the residual bending moment increased with the increasing buried pile length. It suggests that the soil is liquefied and spreaded laterally after the strong motion of case 2. This result indicates that the extensive deformation along the pile results from laterally spread of liquefied soil. Those observations are of significant for the design of pile in liquefiable soils during earthquakes.

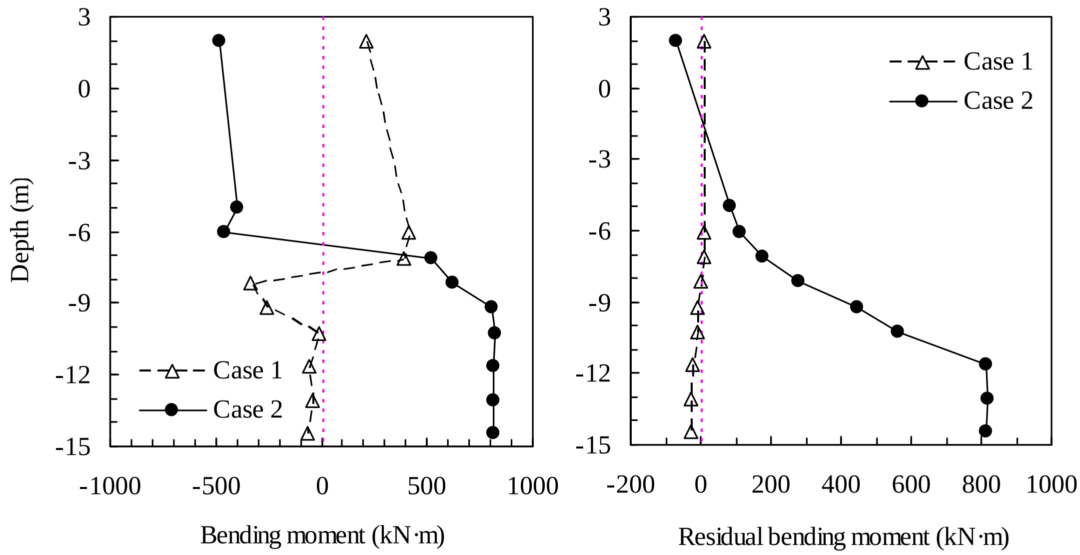

Figure 5 Maximum and residual bending moments along pile length

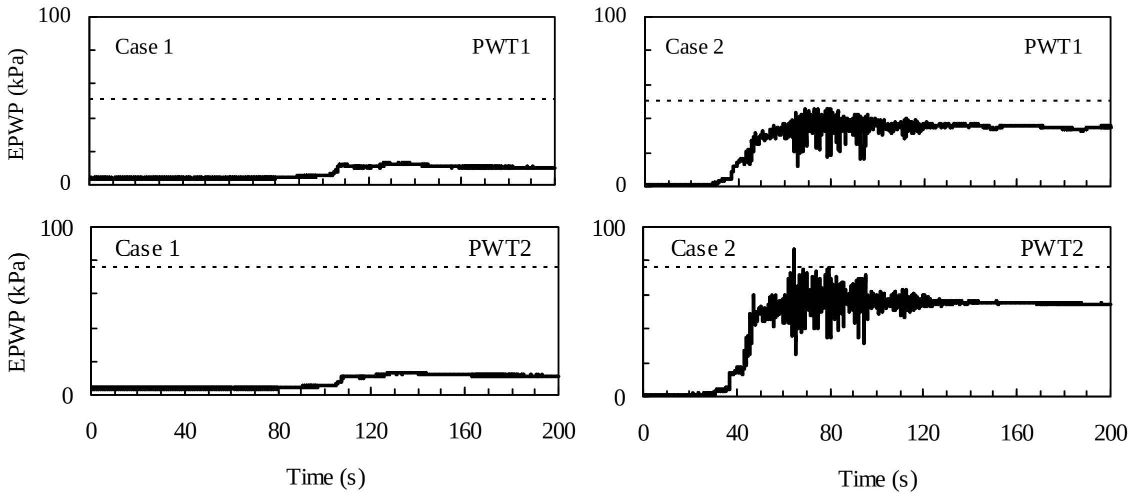

Figure 6 Express pore water pressure in the ground

3.4. Express Pore Water Pressure

Recorded excess pore pressures during the shaking respectively are shown in Figure 6 at prototype depths of 5.5 and 8.33 m in the soil profile. It is clearly seen that the sand layer in the case 1 does not liquefy for a small input wave although the measured excess pore pressure of the soil in the ground increase slowly and up to a smaller value after 100s shaking. On the contrary, in case 2, the saturated sand at two depths is shown to have completely liquefied when the pore water pressure reaches the initial effective stress of about 50 and 76 kPa after 60s period of shaking, and responding displacements are much larger. It is clearly seen that the stronger the motion, the larger EPWP is. It is also concluded that the triggering of liquefaction increases with the input motion and decreasing relative density. That also shows that the liquefaction occurs first near the surface and works its way downward.

4. CONCLUSIONS

This paper presents centrifuge model tests, which simulated the effect of strong ground shaking on the pile foundation structure in inclined liquefiable soils. Results as well as detailed interpretations and discussions are presented. Some major conclusions may be drawn from these results as follows:

1) The work presented demonstrates that centrifuge modeling can simulate realistically seismic response of soil-pile system in the inclined soil layer.

2) It is found that the lateral displacement, the maximum and residual bending moments of pile groups are much bigger in lateral spreading soils than in non-liquefied soils. And the location for the max bending moment during shaking and max residual bending moment transfer further down with the liquefaction and lateral spread of soils.

3) The problem of soil-pile interaction in inclined liquefiable soil is a very complex problem. Extensive and further studies are needed to evaluate further the performance and validity of centrifuge test, such as the comparison of seismic response between in a horizontal soil layer and the inclined soil layer.

ACKNOWLEDGEMENTS

Financial supports provided by Science and Technological Fund of Anhui Province for Outstanding Youth (No.08040106830) and National Natural Sciences Foundation, China (No.40702049) are gratefully acknowledged.

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