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Study on Dynamic Behavior for Pile-Soil-Bridge Structure Seismic Interaction in Liquefying Ground under Strong Earthquake

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Abstract
Pile foundations for bridge usually built in different types of liquefiable soils and might suffer from the severe damage in destructive earthquakes. Therefore, it's necessary to investigate the problems related to seismic response of single-pile foundation in liquefiable soils with different soil layers. For these purposes, shaking table test that involved seismic soil-pile-bridge structure interaction (SSPSI) in liquefiable three-layer ground had been conducted, subjected to a series of El Centro earthquake events with varying shaking level and duration. Three-layer ground consisted of a middle horizontal saturated the sand layer with a surface non-liquefaction clay layer, underlain by a non-liquefaction clay layer. The tests were conducted using the laminar shear box with depth of 2 m and plan dimensions of 2 m and the single-pile foundation which was prefabricated by galvanized iron wire and micro-concrete was used. Superstructures were simulated as the mass. In the note, the macroscopic phenomena displaying the critical information of seismic design of bridge foundations were introduced firstly, and then the important features on time histories of seismic pile-soil interaction systems in different soil profiles were obtained, finally the peak bending moment of the pile were presented for soil profiles.

Keywords: pile - soil - bridge seismic interaction; pile bridge damage response; liquefied sites; strong earthquake, shaking table test

INTRODUCTION

Since the 20th century, China, the United States, Japan and other earthquake-prone countries have been more than devastating earthquake occurred. Earthquake, liquefaction piles a few examples of bridge damage, resulting in great economic losses and casualties. 1906 San Francisco earthquake, the emergence of multi-site liquefaction resulting from the destruction of pile bridge damage cases (Wilson D W, Boulanger R W, Kutter B L.1997), Gonzalez was no damage to the northeast of the bridge, but the south west of the bridge since liquefaction led to large areas of the cracking and larger tilt ; Salinas South Terminal has two highway bridges, bridge 26 pile deformed and moved south to 1.2m ~ 2.1m, pile in at the surface is not damaged, but the bridge has greatly because liquefaction tilt; Salinas railway bridge fluid of the soil pile, much to the Salinas River direction of movement, eventually leading to the bridge collapse.

Pile Foundation Liquefaction Damage Case

Haicheng 1975 earthquake, there are many bridge pile damage occurred because the instances of liquefaction (Wilson D W, Boulanger R W, Kutter B L, 2000). Earthquake, pier piles as soil liquefaction and sliding into the river heart damage caused by winding two-stage liquefaction River Bridge Pier 3 in broken bridge at the top and bottom of the level of dislocation occurs, the distance of 1.5m as much as . A lot of Tangshan earthquake in 1976 caused the bridge foundation liquefaction instance structural damage (Liu L, Dobry R. 2001). Strong earthquake in Tangshan area, damaged large and medium type of reinforced concrete highway bridges are 130, liquefaction caused damage to these bridges is one of the important reasons, and the collapse of the bridge has 18 bridges, 15 caused the liquefaction. For example, the Victory Bridge in a liquefaction zone, the earthquake process, the bridge site near the sand surface water appears to take the phenomenon of simultaneous bank slip, channel distortion, such as surface cracking and subsidence, leading to occurrence of one-way bridge pile pier tilted bottom of the crack and break; Beijing Changping County, Luding Bridge, the earthquake due to liquefaction caused subsidence in central pier and bridge deck caused paralysis down. Loma, California in 1989, a large number of seismic liquefaction ETA Puri lateral expansion flow structure, bridge foundation damage caused by case(Matlock H, Foo S, Tsai C, et al, 1978); to Manchester Rufus Marsh bridge damage, for example, the bridge since the earthquake liquefaction cause of column and the surrounding soil of about 0.08m ~ 0.3m between the cracks, leading to the apparent top of the bridge column with the bottom of the plastic distortion and lateral relative displacement occurs; and responsible for the bridge northbound liquefaction occurs because the pitch buttress lateral displacement. Seismic liquefaction of

bridge foundation becomes a hot field of geotechnical earthquake engineering problems.

Model Pile and Test Procedure

Shaking table experiments were conducted at the State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China, using MTS shaking table facility. The table is three-dimensional and has six degree-of-freedom motion. The dimension of the table was 4 m×4 m, and the maximum payload was 25, 000 kg. The shaking table could vibrate with two maximum horizontal accelerations of 1.2 g and 0.8 g, with a maximum acceleration of 0.7 g vertically. Its frequency ranged from 0.1 to 50 Hz and there were 96 channels available for data acquisition during the testing progress.A large-scale laminar shear box was designed to study the seismic pile -soil-bridge structure interaction (Wu *et al*., 2002). The box is 1.5m × 2m × 2m (in the major shaking direction); its moving parts weigh approximately 0.7 t. It is typically 5% of the weight of the entire test model including the shear box. The shear box was designed to be sufficiently light when compared to the model. Therefore, the shear box can produce an approximate one-dimensional wave propagation field. The soil profiles, consisted of a horizontally saturated sand layer overlaid with a silty clay .The laminar shear box was partially filled with water in advance, and after that, the unwashed sand was directly placed into it, using a free fall method for the saturated sand layer (Ling *et al*., 2005), i.e., the sand was lifted to a pre-specified height and dropped into the box through a cone. The dropping height was determined according to the required relative density. Special attention was given so that the sand layer was as homogeneous and loose as possible. The height of the lower sand layer was 1.2 m .This method for the saturated sand has been used successfully in previous model studies (Ling *et al*., 2004). The 0.3 m thick upper layer was normally consolidated silty clay and the lower layer about 0.4 m, soil physical parameters for the foundation as shown in Table 1. In order to ensure that the sand layer was completely submerged, the water table was approximately at the interface between the upper clay layer and lower saturated sand layer. The reinforced concrete Pile of 2.52m length and with 0.1m diameter. With 12Φ2 steel reinforcement and Φ1 @ 20 stirrups, which pile at the top of 0.22m, the bottom of the hoop is taken to be within 0.2m Φ1 @ 15, concrete cover thickness 5mm, reinforcement shown in Figure1. super structure in the tests was represented by an individual mass of 120 kg on the top of the pier to characterize the interial effect of the bridge structure. Pile geometry and physical parameters in Table2 .Test body design and sensor layout shown in Figure2.

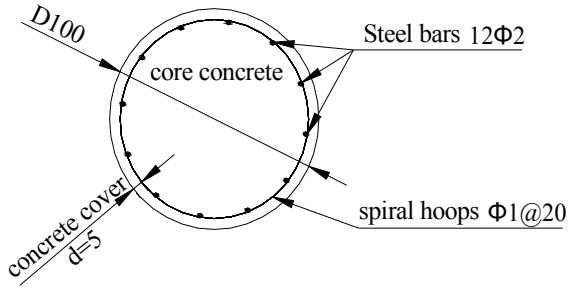


Figure1: Cross section of single pile (Unit: mm)

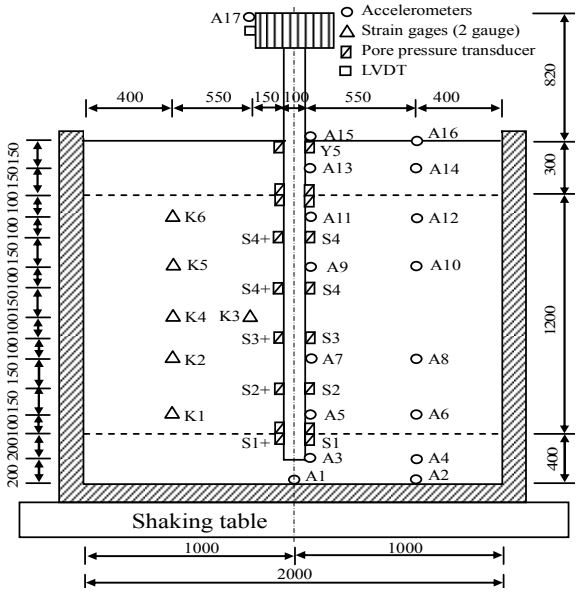


Figure2: Layout of sensors for shaking table test

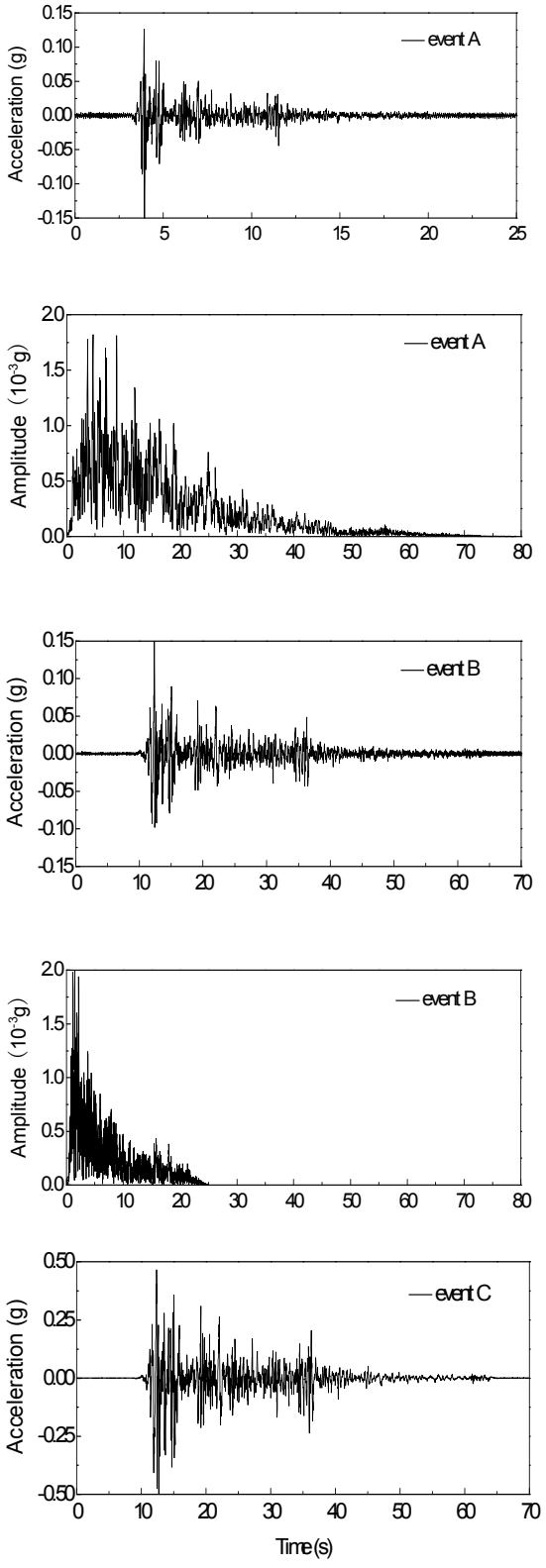
Table1: Physical properties of soil layer

Clay Layer	γ (kN/m^3)	ω (%)	φ (°)	C (kPa)	P.L (%)	L.L (%)	Void ratio	D_r (%)
	18.5	23.8	13	18	15.3	28.4	0.913	/
Sand Layer	19.0	/	30	/	/	/	/	40%

Table 2. Design data of test pile

Material	Dia (m)	E (×10^{3}MPa)	I (×10^{-6}m^4)	Density(kg/m^3)	υ
Reinforcement concrete pile	0.1	8.24	4.91	2350	0.2

In order to investigate the effect of earthquake, Figure 3 shows the excessive earthquake events went against the successful execution of shaking table test involved soil liquefaction. The container base was only excited by three earthquake events orderly i.e. event A, B and event C in turn.



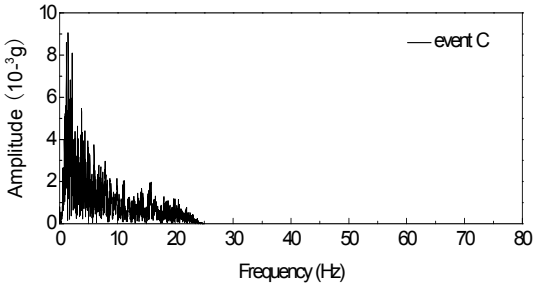


Figure3: Time histories and its Fourier spectrum from events A, B and C

DISCUSSION THE RESULTS

The excessive earthquake events went against the successful execution of shaking table test involved soil liquefaction. In order to avoid the disadvantageous effect for the tests, the container base was only excited by three earthquake events orderly i.e. event A, event B and event C in turn. Event A was scaled by the time scaling factor of $1/\sqrt{10}$ relative to event B. Time histories and its Fourier spectrum of the input shaking acceleration in events A and B are depicted in Figure3. And the acceleration frequency band in event A was far broader than that in event B. The acceleration frequency content in event A dominated in the range from 0 to 20 Hz and represented more than 60% of total acceleration amplitude. The frequency component of the input shaking acceleration from event B dominated within the lower 5 Hz band. Events B and C had the peak amplitude of 0.15g and 0.5g occurring at the same time, respectively.

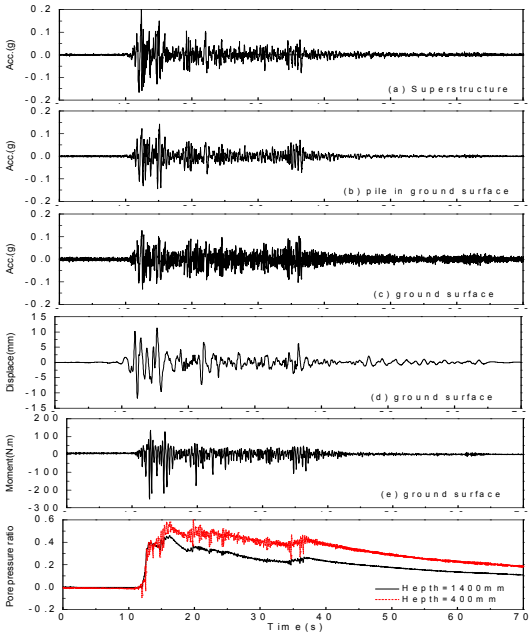
Therefore, the input shaking acceleration between event A and event B had only the amplitude change and almost kept the same frequency content. The frequency content of the input shaking acceleration between events B and C was almost consistent and only is the amplitude at any frequency is different. The interval between two shaking events was long enough to dissipate the excess pore pressure generated in the last event. The phenomena regarding the damage of single pile were obtained from the test, shown in Figures4. Surface and the pile vibrated slightly and waterspouts on the ground surface didn't occur from event A. In event B, the upper sand liquefied slightly; a little of water perspired around the local ground surface; the vibration amplitude of the pile top was still very small but it became bigger and the vibration frequency relatively decreased than that in event A, which might be related that excess pore pressure ratios of the sand in event B increased more than those in event A, showed time histories of excess pore pressure ratios in Figure6, and the sand layer gradually weaken. in event C, the sand layer liquefied completely and then sandboils and waterspouts occurred strongly and lasted for a long time, in addition, the settlement of ground surface ranged from 5 cm to 8 cm (15-18 cm for the parts);

lots of sandy hillocks formed by sandboils distributed on the ground surface after draining; some cracks on the pile were observed at the depth of about 1 m, which showed that the inertial effect of the mass from superstructure and kinetic pile-soil interaction had significant effect on the dynamical performance of the pile in liquefied ground; the pile around the soil interface between non-liquefaction soil layer and the sand layer with 0.3 m depth was entirely broken off; the large transverse fracture region appeared in the transition zone of soil interface which suggested that the pile was moving all the time and the breakage region gradually expanded with soil liquefaction, and most of the main steel bars in the pile were snapped when the input shaking acceleration reached the peak.

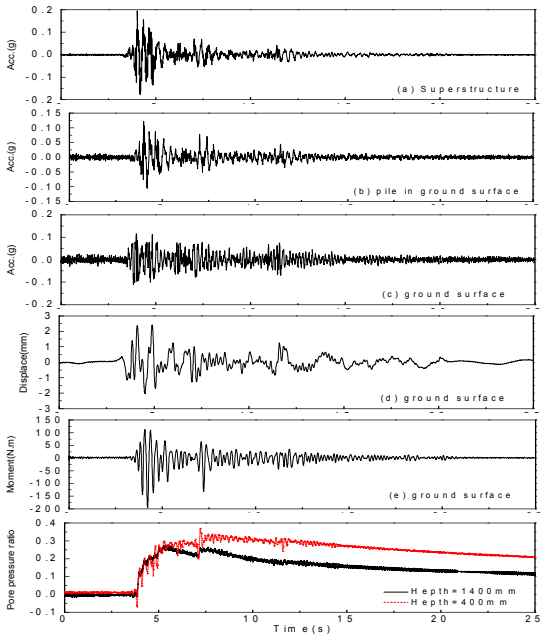
Despite the fact that a large factor of safety is apparently employed in the design of bridge piles, but many cases of damage and failure in liquefied soil during earthquakes still happened. These suggest that the single-pile foundation of bridge are easy to be damaged and are not suitable to be employed in liquefiable ground in seismic zone. Moreover, it was found from test after the earthquake that not only the upper parts of the pile but also the lower parts of the pile had cracked or failed, which were similar to that many pile foundations have been severely damaged during the 1995 Hyogoken-Nambu Earthquake. This phenomenon indicates that both the inertia force from the superstructure and kinematic pile-soil interaction played important roles in the mechanical behavior of the piles. In particular, when the ground surrounding a structure liquefies due to seismic excitation, the behavior of the pile becomes more and more complicated.

Figure4: Macro phenomena of test

variation regarding the amplification factors on the peak acceleration of the pile with depth is described in Figure 6 in events A and B and the magnification factors of the peak acceleration are defined as the ratio of the responded peak acceleration of the pile to the peak input acceleration. The datum in the brackets of Figure 7 was the peak oftime of bending moment on the pile (Unit: seconds). In event A, the magnification factors of the peak acceleration of the pile presented the regulation of "increase-decrease-increase" from bottom to top.



a) Event A



b) Event B

Figure5: Time histories of pile-soil systems in event A,B

The magnification factors of the pile peak acceleration bottom-up in ground gradually increased all the time in event B. All the acceleration of the pile had different degree of magnification effect on input shaking acceleration in events A and B and the magnification effect was more obvious in event B than that in event A, which might be related to the gradually intense pile-soil interaction effect as the result of sand liquefaction. In events A and B, the

acceleration of the pile in the soil presented the damping action on input shaking acceleration, on the contrary, the acceleration on the pile above the soil presented the magnification effect on input shaking acceleration in three-layer ground, which was caused by the restriction to the pile tip embedded in clay layer that could decrease the acceleration of the pile effectively.

The magnification factors of the peak acceleration of the pile tip in three-layer ground in events A and B were close to each other, which also demonstrated to the extent that the bottom clay layer had remarkable effect on the fixing to the pile. Noted that the magnification effect of the pile acceleration on input shaking acceleration was also relatively remarkable in event B than that in event A for three-layer ground. The magnification factors of the peak acceleration in event B were bigger than those in event A, magnification effect and accordingly would result in the greater displacement of superstructure with the development of soil liquefaction. It appeared that the magnification factors of the peak acceleration of the pile in the soil of three-layer ground had no obvious change in events A and B, and noted that compared with that in event A, the magnification effect of the peak acceleration of the pile tip in event B decreased to some extent in terms of the magnification factors of the peak acceleration of the pile top. It's concluded that the soil profile could greatly influent acceleration response of the pile top (superstructure) and the pile tip located in the bottom clay layer would be helpful to reduce acceleration response of the pile especially the pile top. It's necessary for the construction of bridge engineering that the pile usually penetrated through liquefiable sand and located in hard soil layer.

The acceleration of the pile top mainly depended on the rotation stiffness of foundation, translation stiffness and deformation stiffness of the pile. Since the pile tip in three-layer ground was fixed in the bottom clay layer, the rotation stiffness of the pile was relatively large, but the swing component and translation component caused by the rotated foundation would be relatively small; on the contrary, the pile tip was fixed in the sand layer of two-layer ground, so the rotation stiffness of the pile was relatively small and the swing component and translation component caused by the rotated foundation would be relatively bigger. At the same time, some factors, such as the input similar earthquake motion and the almost same deformation component of the pile in both tests, were taken into account.

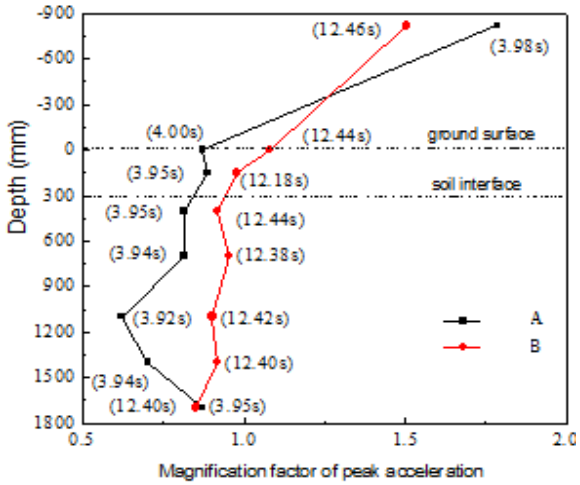


Figure6: Magnification coefficient for peak acceleration of the pile

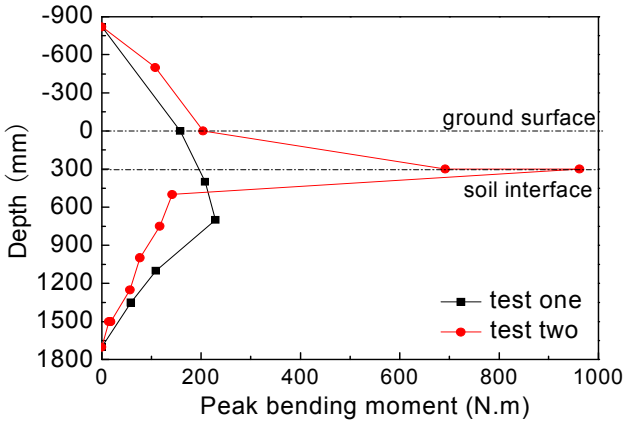


Figure7: Profiles of peak pile bending moment

CONCLUSIONS

The focus of this study was seismic response of single-pile foundation for bridge in liquefiable ground using shaking table test. The major conclusions are as following:

(1) As the results of soil liquefaction the single pile was broken off and the brittle failure appeared around the soil interface near ground surface of layered liquefiable ground with surface clay crust during strong earthquake, which was significant for the reinforcement design of pile in layered liquefiable ground.

(2) Excess pore pressure ratios strongly depended on soil depth and shaking duration and seemed to be related to the soil profiles.

(3) Whether the sand liquefies or not, the abrupt change of bending moment and the maximum bending moment was observed near the soil interface of different shaking events.

(4) The layered soil profiles could significantly affect the bending moment of the pile in liquefiable ground.

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