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Experimental Behavior of a Reinforced Concrete Pile During Liquefaction-Induced Lateral Spreading

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Abstract. Past earthquakes have revealed that lateral spreading induced by liquefaction may cause excessive movement, and large localized plastic demands may be generated in the piles. A one-g shake-table experiment using a medium-size laminar soil container was conducted to investigate the mechanism of liquefaction-induced lateral spreading effects on pile foundations. A single reinforced concrete pile of 25 cm diameter was tested under an earthquake excitation in a mildly inclined soil profile. Pile response was characterized using curvature profiles coupled with bending moment estimation and post-test physical observations. In this paper, testing layout is presented along with post shaking observations. Soil and pile lateral displacement as well as excess pore pressure are discussed. Such a pile-ground interaction mechanism is of consequence for analyses that correlate pile bending moments to the accumulated lateral soil deformation as in the conventional p-y soil spring approach.

Keywords. Reinforced concrete, pile, shake table, liquefaction, lateral spreading.

1. Introduction

Lateral Spreading induced by liquefaction may cause excessive movement and possible failure of pile foundation [1]. This presents a complex loading situation as the soil undergoes a significant change in its dynamic properties [2].

Physical modelling is a valuable resource to complement the field investigations. Centrifuge experiments were conducted to study pile kinematic effects during liquefaction and lateral spreading mechanisms in mildly inclined ground. Studies by Abdoun [3] and Dobry [4] in a laminar box with multi-layered soil found the largest bending moment at the interface be-tween liquefied and underlying non-liquefied soil layers. Conclusions from tests by Brandenberg [5] show that lateral load direction from different soil layers depend on the incremental and total relative displacement between pile and soil. Brandenberg [6] continue discussing the softening of crust load transfer mechanism during the passive failure.

In addition to the above, large scale one-g shake table experiments were performed. He [7] and He [8,9] discuss four experiments in mildly inclined laminar box with different single pile and pile group configurations. These experiments discuss the

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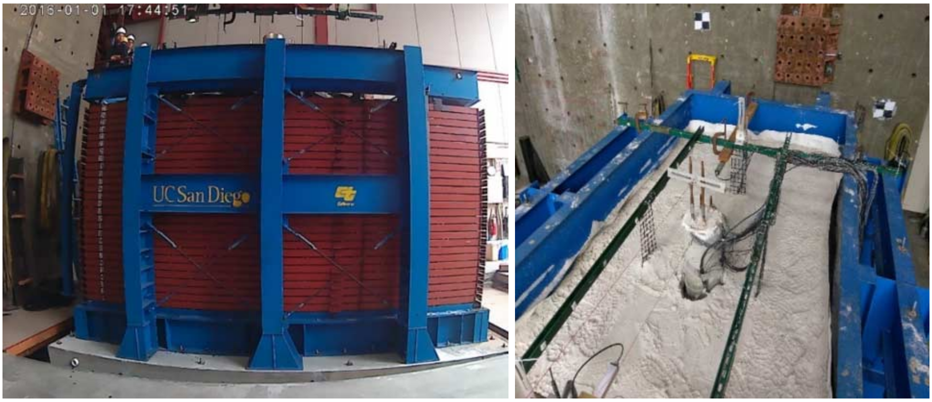
evolution of pore-water pressures, total pressures and displacements on steel pipe piles. This paper discusses testing of a 2 m reinforced concrete pile embedded in a multi-layered profile inside a mildly inclined laminar soil box. This document is part of a larger study discussed by Ebeido [10].

2. Experimentation program

Figures 1 and 2 show pictures and schematic layout of the experiment using the medium size laminar box at the University of California, San Diego. The soil stratum was constructed by sand deposition in water. Ottawa F-65 sand [11] was used having an estimated relative density of 50-60% and saturated density was about 1950 kg/m^3 for the liquefiable layer.

Box inside dimensions were 3.9 m long, 1.8 m wide and 1.8 m high with 28 laminates. The box was inclined at 4° to the horizontal. Test setup was a single reinforced concrete pile in 2-layer soil strata. Water table was 0.7 m below the downslope ground surface. The bottom layer was a saturated loose layer (55% relative density), with a 1.1 m height. The top layer was a 0.7 m stiff crust (85% relative density). Input motion (Figure 3) was in the form of a sinusoidal acceleration with a 2 Hz frequency and 0.15g peak amplitude. Duration of motion was 30 cycles with the amplitude building up steadily in the first 10 cycles followed by a constant 0.15g amplitude for 10 cycles then ramping down for the last 10 cycles.



a) b)

Figure 1. Laminar box on the shake table at UC San Diego a) elevation view b) plan view.

2.1. Pile details

The circular reinforced concrete pile (Figure 4) was constructed from regular strength concrete with 6-Grade 60 #4 US longitudinal reinforcement and #4 spiral reinforcement spaced at 100 mm. The #4 rebar corresponds to a 12.7 mm rebar diameter. The pile was casted with a base pedestal which was then bolted to the base of the container. Rotational and translational fixity were preferred for the base, however the connection flexibility allowed for some rotation of the pile. This connection was tested and characterized to have a rotational flexibility of 1500 kN.m/rad. Unconfined compression strength of the concrete was tested at 28 days and was found to be 24.1 MPa. The pile was 2.2 m long with 25.4 cm diameter and 2.54 cm cover. Concrete compressive strength and steel reinforcement stress-strain properties were used to calculate the moment curvature for the section (Figure 4). The theoretical first yield values were determined using the software Opensees [12]. The yield moment and curvature were 14.25 kN m and 0.004 rad/m respectively.

2.2. Instrumentation

Model was instrumented with a large number of accelerometers, pore pressure sensors, pressure transducers, strain gauges and LVDTs (Figure 2). Instrumentation was placed along the pile shaft and along the depth of the ground stratum. Strain gauges were densely deployed along the pile longitudinal reinforcement to aid in back-calculation of the bending moment during shaking. Strain gauges were placed on both sides of the pile with a 10 cm spacing giving a total number of 40. A total of 16 displacement transducers were mounted on the laminar box exterior wall to measure lateral displacements of approximately every other laminate. Piles were also instrumented with transducers to measure pile head displacements above the ground surface. Total number of 25 pore pressure transducers were placed on the piles in addition to being embedded in free field soil.

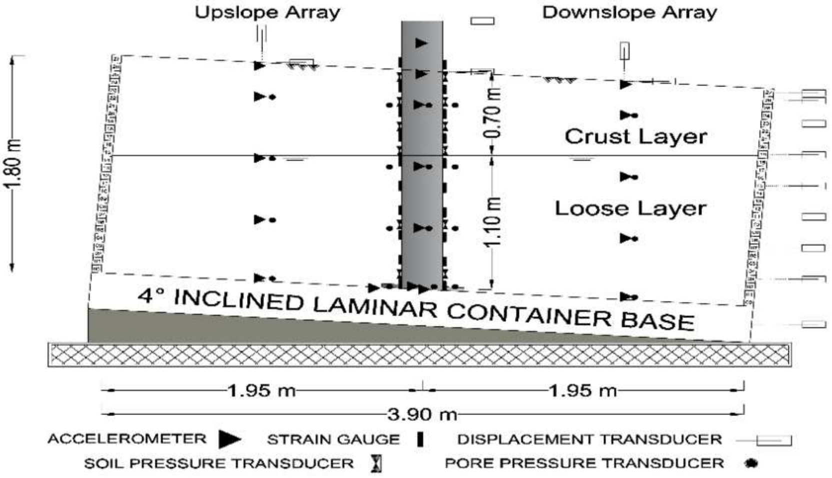


Figure 2. Schematic experiment layout with instrumentation locations.

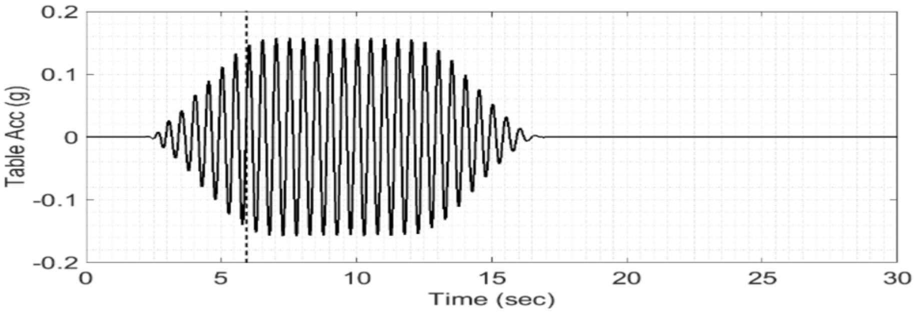
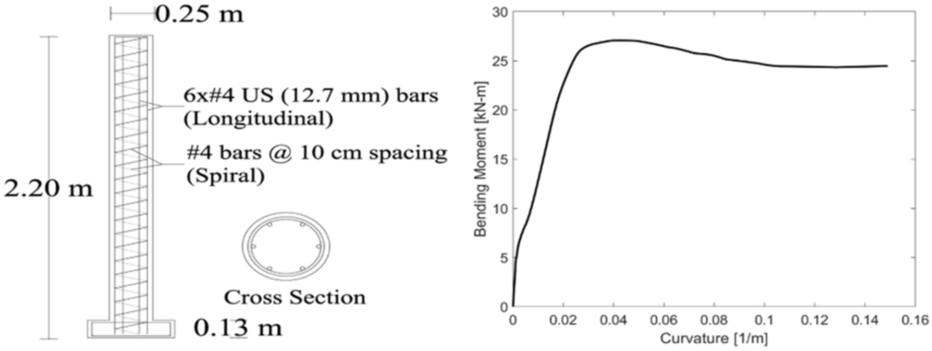


Figure 3. Input table acceleration.



a) Reinforced Concrete Pile Details b) Reinforced Concrete Moment-Curvature

Figure 4. Reinforced concrete pile details and moment-curvature relation.

3. Results

3.1. Analysis protocol

Focus is placed on system response mainly discussing excess pore-water pressure, displacements and pile bending moments. Thus, representative time histories were chosen to identify that response along with the peak bending moment. Bending moment was calculated based on strain gauge readings placed on the pile reinforcement. Bending moment is an indication of pressures acting on the pile. For ease of analysis, the time corresponding to the peak bending moment was identified and represented as a dashed line on all time history plots.

As the box was mildly inclined at 4°, the soil box started moving downslope when the shaking begun. Liquefaction of the saturated soil layer was observed during the test. Both soil box and pile head exhibited permanent displacements. Cracking and settlement of the crust layer was also observed. A large gap was formed between the pile and the downslope ground.

3.2. Soil response

Input motion (Figure 3) was a 15 second 2Hz sinusoidal wave with gradual increase and decrease in amplitude. Liquefaction did not occur early during shaking but happened about midway through the 15 second shaking. Representative time history for acceleration (Figure 5) and excess pore water pressure ratio (Figure 6) were chosen to support this. The vertical line in these figures denotes the time corresponding to the instant of maximum pile bending moment at about 5.95 seconds and is included on all time histories for ease of tracking.

Accelerations were chosen along the depth of the upslope array. Three locations were chosen at 1.70 m and 1.30 m within the saturated stratum and at 0.30 m in the middle of the liquefied crust. The bottommost location shows the same trend as the input excitation. At the beginning of shaking, with the soil not liquefied, base excitation was gradually increasing recording a small amplitude. However, the upper location recorded an amplification to the input excitation. This amplification was 4 times for the soil at 1.30 m beneath the surface and 10 times for the upper-most location at 0.30 m beneath the ground surface. This indicates a stiff soil that is able to amplify the accelerations. The max bending moment recorded on the pile was during this part of shaking.

As the shaking continued, the soil got weaker losing its stiffness. This can be observed in the acceleration plots, as accelerations decrease with height in the saturated layer. Accelerations in the non-liquefied crust decreased, however it remains larger than the ones in the saturated layer.

3.3. Excess pore-water pressures

Figure 6 shows a representative excess pore water pressure ratios. The figure presents the recording in 2 locations, upslope and downslope of the pile. Transducers chosen were located at a depth of 1.30 m and are placed 1.0 m away from the pile in both directions. Liquefaction ($r_u = 1.0$) occurred gradually and approximately midway through shaking at 11.51 seconds. The maximum pile response denoted by the vertical line occurs at 5.95 seconds with $r_u = 0.40$.

The general trend of the pore pressure data shows dips in values in the downslope side more than the upslope. This shows the dilative tendency of the soil. Small dips in the upslope pore pressures suggested that soil is moving towards the pile and away from the container boundary. Larger dips in the downslope array indicates the soil moving away from the pile.

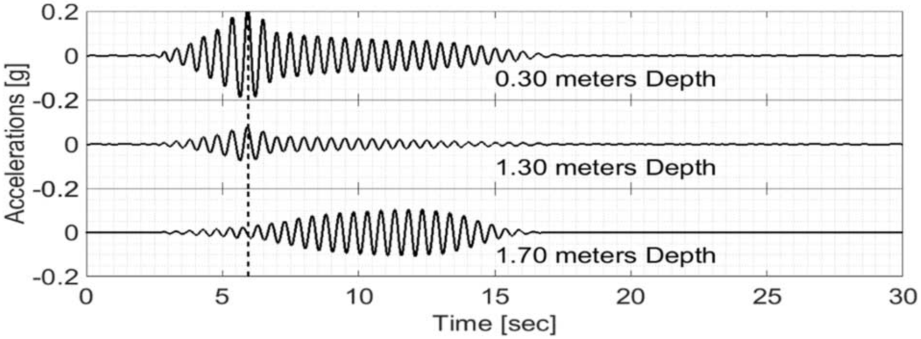


Figure 5. Representative acceleration time histories along the upslope array.

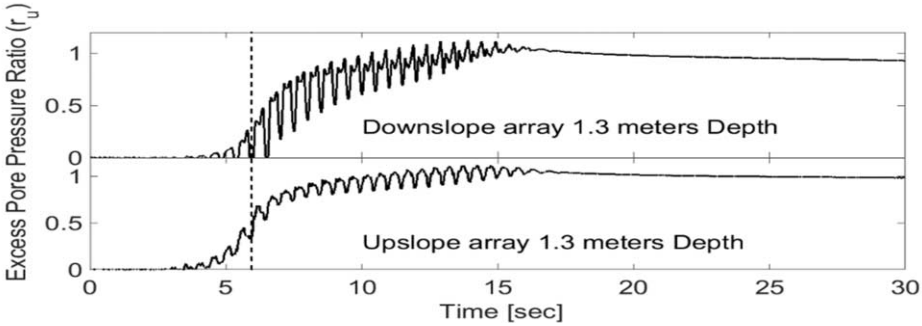


Figure 6. Representative excess pore pressure ratio (r_u) time histories for the upslope and downslope arrays at 1.30 m depth.

3.4. Pile response

Peak bending moment was observed early on during shaking (Figure 7) as indicated by the strain gauge readings placed on the longitudinal reinforcement. Bending moment measured is a reflection of the pressures and loads exerted on the pile. Thus, maximum pressure experienced by the pile happened before liquefaction of soil.

Figure 7 shows representative time histories from the bending moments along the pile shaft height. Locations chosen were at 1.60 m depth before the enlarged pedestal at the base, 1.30 m and 0.90 m depths. Maximum bending moments along the height occurred at the same time instance. Figure 7 shows a quick increase in the bending moment at the beginning of shaking followed by a constant part where the acceleration was constant. Although, this part was constant, it was slightly lower than the maximum value. The last part of the time histories shows a gradual decrease in values, however bending moments did not rebound to zero but was left at a lower residual value.

Maximum bending moment was recorded at the base of the pile shaft indicating that maximum moment will occur at the interface between liquefied soil and the underlying dense stratum. Maximum bending moment was 18 kN-m. This shows that the pile passed the first yield point and entered in to the plastic region. Local plastic demand was recorded at the pile base and observed along a 3 pile diameter length (0.75 m). All strain gauges in the lower 0.75 m region passed the first yield as calculated by the moment curvature diagram (Figure 7).

3.5. Displacements

Figure 8 shows the downslope deformation for the soil box, and single pile. Soil displacements kept increasing during the shaking phase recording 6.73 cm. However, the single pile reached a maximum displacement of 4.25 cm at the peak time instant gradually rebounding to 37% of that value at the end of shaking. From the beginning of shaking till the maximum time instance (time = 5.95 seconds), the pile was displacing more than the soil indicating that the pile is pushing on the soil. After the maximum instance, the soil started displacing more than the pile with the relative displacement increasing with each cycle.

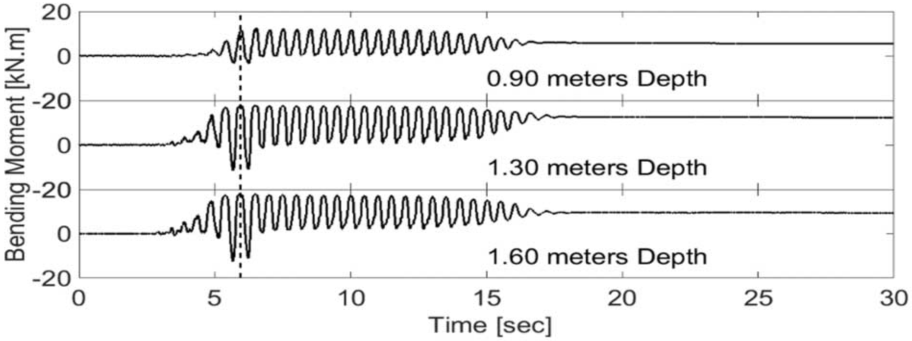


Figure 7. Representative bending moment time histories along the pile height.

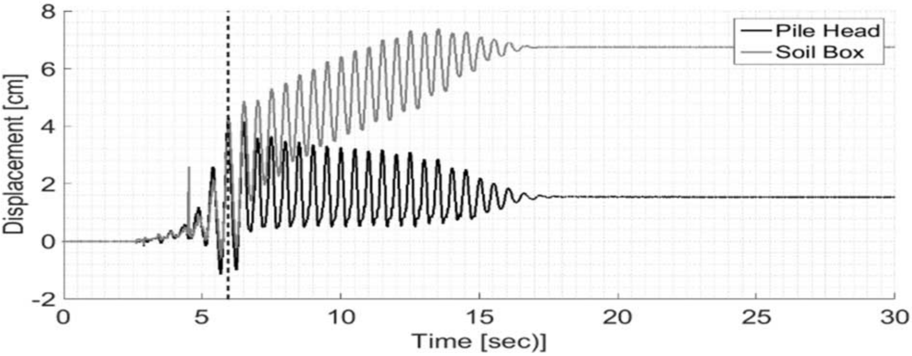


Figure 8. Soil surface and pile head displacement time histories.

4. Conclusions

A large scale one-g shaking table test was performed on a single reinforced concrete pile embedded in a multi-layer soil profile. The pile was tested in a sloped soil profile at 4°, to investigate the liquefaction induced-lateral spreading loading. Shaking was conducted using a 2 Hz sine wave with 0.15g peak amplitude.

Liquefaction of saturated soil layer, settlement and downward movement of the crust was observed. Dilative tendency of soil was detected as evident from dips in excess pore water pressure measurements. Upslope soil was flowing around the pile and downslope soil was moving away from the pile. This was also observed by soil heave and cracking of the crust upslope of the pile and a gap formation downslope of the pile (Figure 9). The decrease in pore water pressure points to an increased effective stress and stiffer soil.

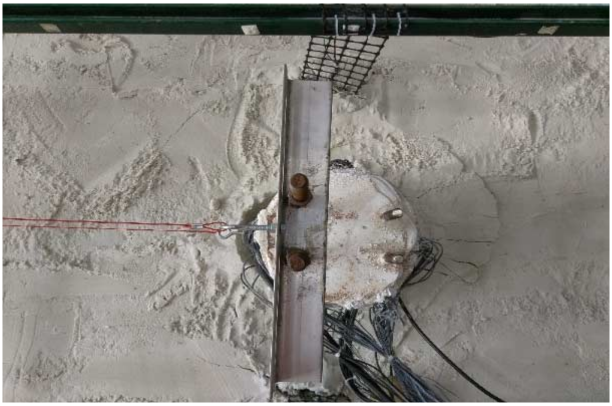


Figure 9. Cracking and gap formation in the crust post-earthquake.

Pressures acting on the piles along the depth were out of phase as evident from the shift in acceleration time histories along the depth. Amplification of the accelerations during shaking points to higher pressures exerted on the pile from the surrounding soils. In the beginning of shaking, pile displaced more than soil thus creating a gap in the upslope direction. Deformations stop after shaking indicating that lateral spreading discontinues when shaking stops.

Maximum bending moments occur at the base of the pile. Maximum bending moment was recorded early during shaking. Non-linear strains and local plastic behavior were measured at the base portion of the pile. Strain gauges in this region indicate post yield behavior. Residual bending moment and displacement of the pile indicate permanent deformation of the pile as would happen from non-linear response. Physical observations during post-test excavation show no cracks on the pile although micro cracking of the pile must have occurred.

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