Centrifuge Modeling of Seismic Response of Pile-Raft System Subjected to a Long Duration Earthquake

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SUMMARY:
Singapore is historically considered a low seismic hazard area, and hence the current building code does not incorporate seismic design requirements. However, over the last few years, earthquake events arising from western Sumatra, Indonesia, have resulted in tremors that were felt in certain parts of Singapore, notably in the east and the central, where soft marine clays are commonly encountered. The behavior of pile foundations in soft soils under earthquake loading is an important factor affecting the performance of structures. Observations from past earthquakes have shown that piles in firm soils generally perform well, while those installed in soft or liquefiable soils are more susceptible to problems arising from ground amplification or excessive soil movements. The present experiments were carried out using the NUS geotechnical centrifuge. Several small-scale pile raft models were fabricated, ranging from a 2×1 to a 4×3 pile group. Each raft model was tested by placing it within a Kaolin clay bed contained in a laminar box, which was then subjected to controlled base excitation via a shaking table mounted on the centrifuge platform. A long duration earthquake of about 500 seconds is considered, this being representative of an event that may be triggered by a rupture along the Sunda subduction trench. The accelerations at selected locations within the model, as well as the bending strains at various depths along the piles, were measured during the simulated earthquake events.

Keywords: centrifuge test, bending moment, acceleration

1. INTRODUCTION

Numerous post-earthquake investigations have shown that pile damage is often encountered in areas severely influenced by seismic induced ground motion, such as the 1964 Niigata and 1995 Kobe earthquakes (Hamada et al., 1987; Bhattacharya et al., 2009). Besides, it has been established that seismic induced ground motion can be significantly amplified by soft soils (Tinawi et al., 1993; Pan, 1997; Mayoral et al., 2009; Banerjee, 2009). As a result of this, piles constructed in soft soils may be susceptible to some distress, or even damage, even under small or moderate earthquakes.

A considerable portion of the land in Singapore is underlain by soft soil deposits (Kallang formation), where pile foundations are commonly used to support the buildings and superstructure. Singapore is historically considered a low seismic hazard area, and hence the current building code does not incorporate seismic design requirements. However, over the last few years, earthquake events arising from western Sumatra, Indonesia, have resulted in tremors that were felt in certain parts of Singapore, notably in the central and the east, where soft marine clays are commonly encountered. These events occurred mainly along one of two active fault zones in this region: the Great Sumatran Fault and the Sunda Subduction Trench (Figure 1). The nearest distance between Singapore and the Great Sumatran Fault is about 350 km, while the Sunda Trench is about 600 km away (Megawati and Pan, 2002). The Sumatra fault is a strike slip fault and the energy stored by the shear interlock is limited. It is postulated that the magnitude of earthquakes generated along this fault should typically not exceed 7.6 on the Richter scale (Merati et al., 2000; Balendra et al, 2002). On the other hand, the Sunda subduction trench was formed by the convergence between the Indian-Australian and Eurasian plates (Pan et al., 2007). The relative movement between the Australian and Eurasian plates can be quite sudden and significant, giving rise to potentially much larger earthquakes (Balendra et al, 2002).

In this study, a series of centrifuge experiments were carried out using the National University of Singapore (NUS) geotechnical centrifuge. Several small-scale pile raft models were fabricated, ranging from a 2×1 to a 4×3 pile group. Each raft model was tested by placing it within a Kaolin clay bed contained in a laminar box, which was then subjected to controlled base excitation via a shaking table mounted on the centrifuge platform. A long duration earthquake of about 500 seconds is considered, this being representative of an event that may be triggered by a rupture along the Sunda subduction trench. The accelerations at selected locations within the model, as well as the bending strains at various depths along the piles, were measured during the simulated earthquake events.

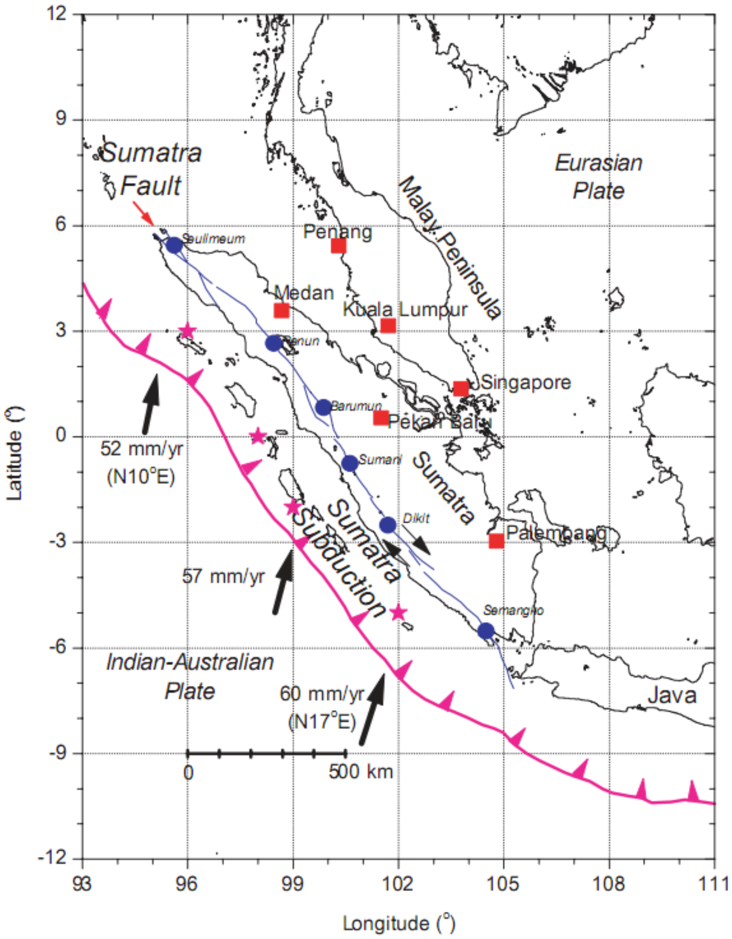


Figure 1. Regional tectonic setting (after Pan et al., 2007)

2. EXPERIMENTAL PROCEDURE

2.1. Centrifuge Set-up

The centrifuge tests in this study were carried out using the centrifuge facility at the National University of Singapore (NUS). The NUS centrifuge has a radius of 2 m, a payload capacity of 40,000 g-kg and a maximum working g-level of 200 g (Lee et al., 1991). As shown in Figure 2, the NUS centrifuge consists of a conical base, rotating arms, drive shaft, payload and counterweight buckets, among others. When the buckets are fully swung up, the distance between the rotation center and the platform of the payload bucket is about 2 m.

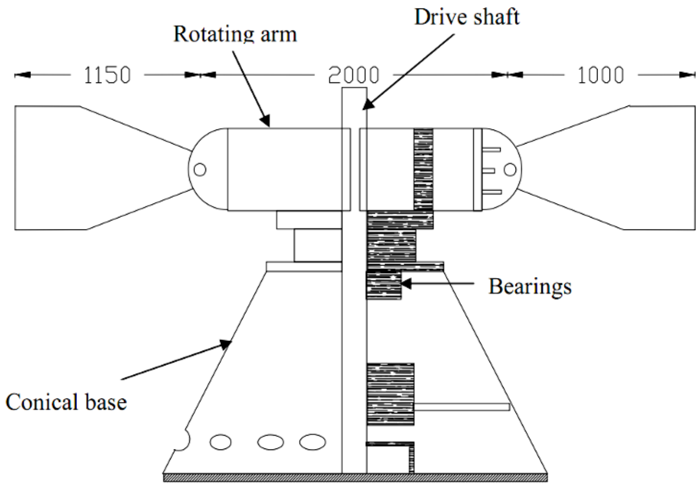


Figure 2. Schematic view of NUS geotechnical centrifuge (after Banerjee, 2009)

The key components of the centrifuge shaker are the slip table, servo-actuator, servo-valves and built-in displacement transducer (Figure 3). The servo-controlled actuator connected to the base plate drives the shaker based on the incoming control signal. The reaction mass used to develop the motion force is provided by the swing platform and the fixed base of the shaking table. One unique feature of the shaker is the placement of the hydraulic power source on the arm of the centrifuge, which obviates the need for expensive high-pressure rotary joints whilst allowing an almost unlimited number of tests to be performed without swing-down.

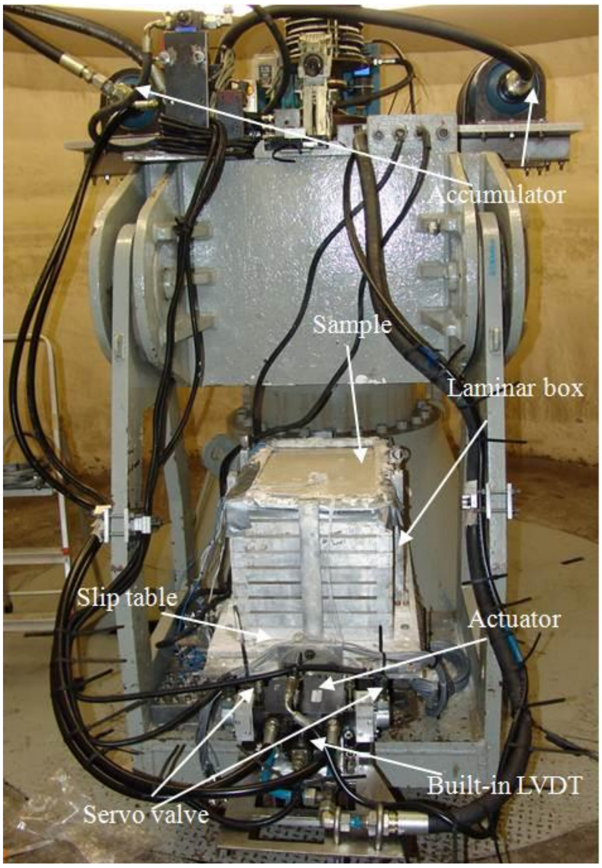


Figure 3. Centrifuge shaking table with test model on swing platform

2.2. Experimental Procedure

2.2.1. Sample preparation

The clay beds used in the centrifuge model tests were prepared using Kaolin powder. The geotechnical properties of the Kaolin clay used in this study are given in Table 2.1 (Goh, 2003). White Kaolin powder was first mixed with water in a mass ratio of 1: 1.2 to form the clay slurry which would be transferred into the rubber-lined laminar box in several pours. The completed slurry mixture in laminar box was then subjected to both 1-g and 50-g consolidation processes to develop the representative strength profile and stress history. The 1-g consolidation was carried out first to pre-compress the clay beds, so as to reduce the time required for the subsequent in-flight consolidation. Dead weights were applied in stages, up to a total load of about 100 kg, which corresponds to an effective overburden stress of about 5 kPa at the top of the clay bed. The 1-g consolidation usually lasts for about 2 weeks, following which the sample was mounted on the centrifuge together with the shaker and other accessories. It was then subjected to in-flight centrifuge consolidation under 50 g until the degree of consolidation along the entire depth of clay layer was 90% or more, which is a process that requires at least 18 hours of continuous spinning.

Table 2.1. Basic properties of Kaolin clay (Goh, 2003)

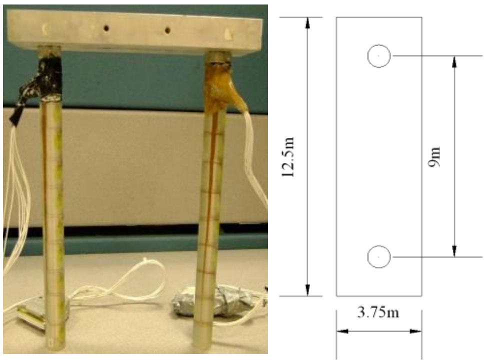
Property	Average value
Bulk unit weight (kN/m^3)	16
Water content	66%
Liquid limit	80%
Plastic limit	35%
Compression index	0.55
Recompression index	0.14
Coefficient of permeability (m/s)	2×10^{-8}
Initial void ratio	2.54
Angle of friction	25^o

Several small-scale pile raft models ranging from a 2×1 to a 4×3 pile group were fabricated, as shown on Figure 4. Each pile-raft was carefully inserted into soil sample before the high-g consolidation.

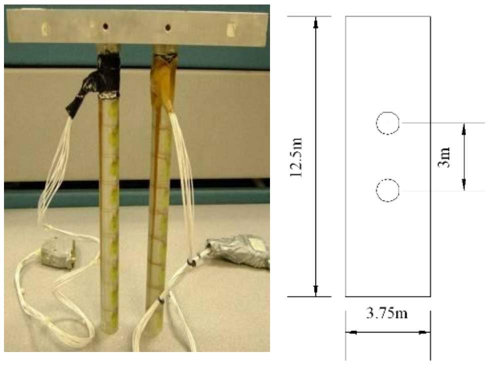
2.2.2. Centrifuge testing

Figure 5 shows the schematic layout for the centrifuge model with the 2×1 sparse pile group. The configurations of the other pile-raft models are quite similar and hence will not be presented. The piles have prototype lengths of 14 m and diameters of 1 m, and are rigidly connected to a 1.2 m thick raft. The pile-raft was fully embedded in a 15.5 m thick uniform Kaolin clay bed with a clay cover of 0.3 m above the raft surface. There are three accelerometers labelled A1, A2 and A3, which were employed to measure the acceleration responses at the clay base, clay surface and raft top, respectively. Three pore pressure transducers (PPTs), embedded at 4m, 8m and 12m below the clay surface respectively, were employed to monitor the variation of pore water pressure of the soil sample during the 50-g consolidation. For the 2×1 sparse and 2×1 compact pile groups, only the front pile of each group was instrumented and monitored with 9 strain gauges. The strain gauges were located at prototype spacings of 1.3 m along the pile length, with the top strain gauge located 3 m beneath the pile raft. The pile bending moment responses during the earthquake event were obtained by converting the strain measurements using a calibrated constant. At the bottom of sample there is a 10 mm (0.5 m prototype) layer of sand, which was air-pluviated to form a thin drainage layer at the bottom of the clay bed.

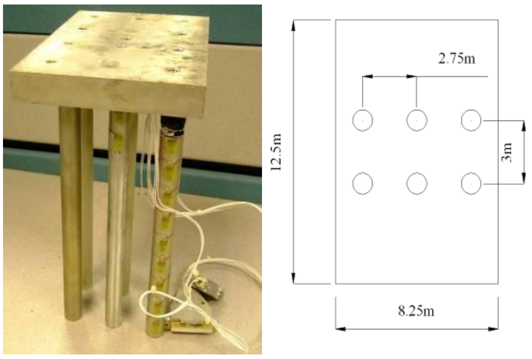
After consolidating for more than 18 hours under 50-g to achieve an average consolidation degree of 90% or more, a T-bar test was performed to obtain the soil strength profile with depth. This was followed by approximately another 3 hours of 50-g consolidation to dissipate the excessive pore water pressure induced by the T-bar disturbance. After that, the soil sample was subjected to the in-flight earthquake shaking via the centrifuge shaker.



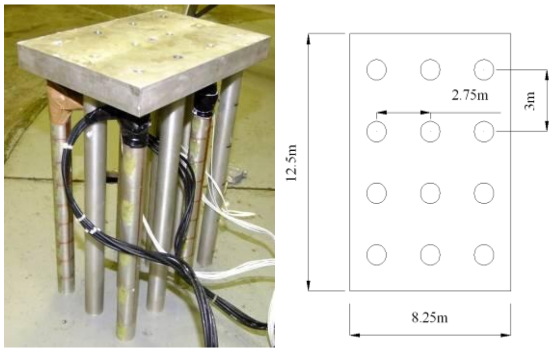
(a) 2×1 sparse pile group



(b) 2×1 compact pile group



(c) 2×3 pile group



(d) 4×3 pile group

Figure 4. Photo and schematic plan view of pile-raft system (prototype dimensions)

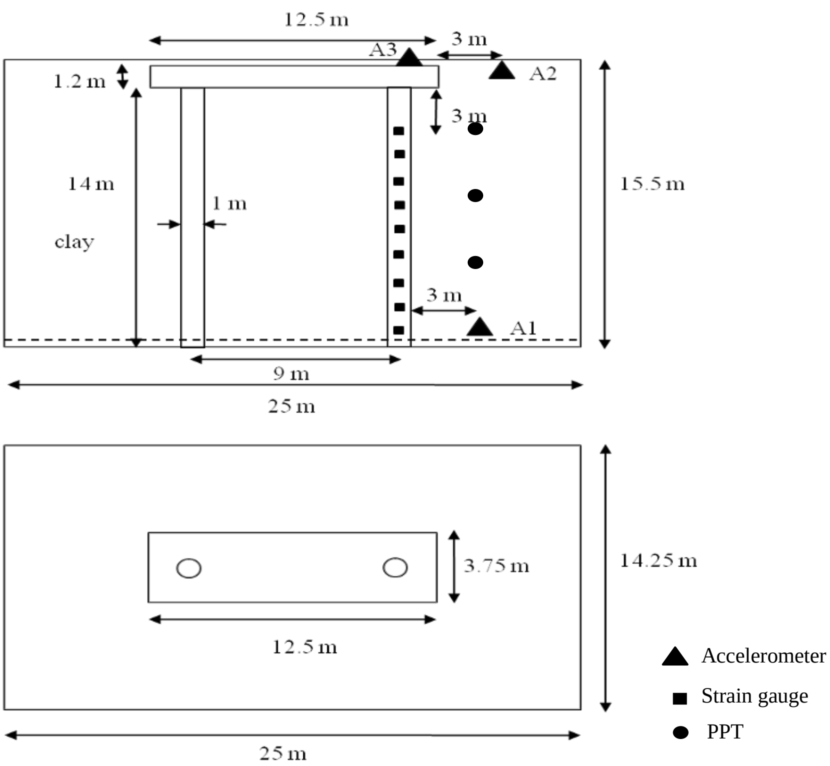


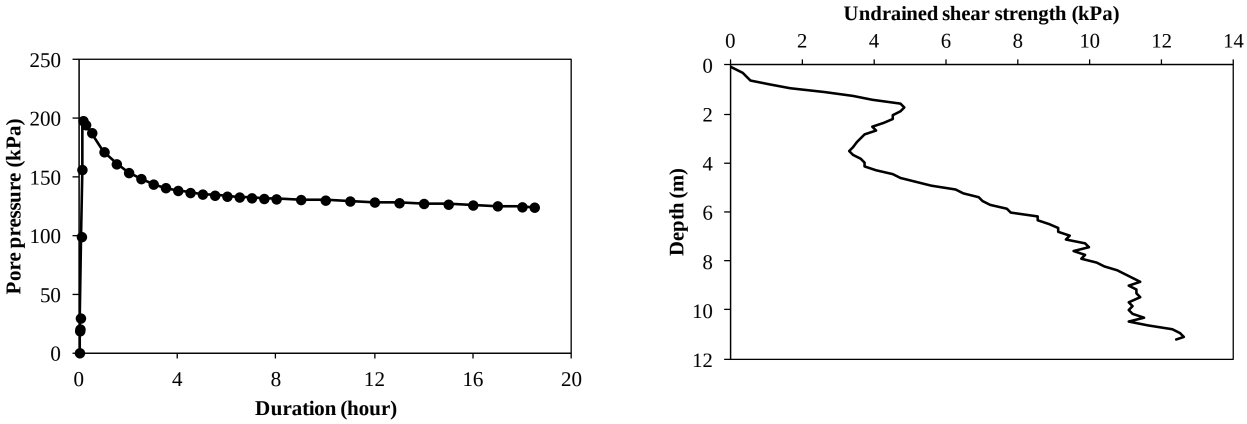
Figure 5. Schematic layout for the sample of 2×1 sparse pile group (prototype dimensions)

3. RESULTS AND DISCUSSION

This paper presents the results from the 2×1 sparse and 2×1 compact pile groups. All the results are presented in prototype unit otherwise stated. As shown in Figure 4, the only difference between the 2×1 sparse and 2×1 compact pile group is the pile spacing along the shaking direction. The pile spacing for the 2×1 sparse pile group is 9 times the pile diameter (s/d=9) while that for the 2×1 compact pile group is 3 times the pile diameter (s/d=3).

3.1. High-g Consolidation Phase

Figure 6a shows the PPT measurement obtained at 12 m beneath the clay surface, which indicates that the degree of consolidation at this depth is greater than 90% after the 18-hour consolidation phase. Figure 6b shows the undrained shear strength profile from the T-bar test, in which the soil strength generally increases with depth. The small hump near the upper part of the soil layer, in which the strength increases rapidly within the top 2 m, may be attributed to the overconsolidated nature of the soil caused by the initial dead-weight preloading applied under 1-g condition.



(a) Pore pressure history at 12 m beneath clay surface (after 50-g consolidation)

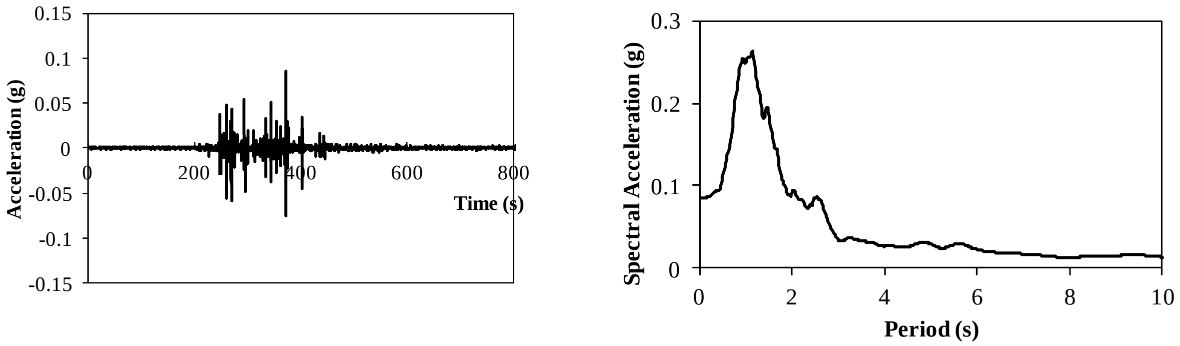
(b) Undrained shear strength profile from T-bar test (after 50-g consolidation)

Figure 6. Pore Pressure History and Shear Strength Profile after 50-g Consolidation Phase

3.2. Earthquake Test

3.2.1. Acceleration Response

A typical acceleration time history measured at the base of the Kaolin clay layer and its corresponding response spectrum are shown in Figure 7. It shows that the input earthquake has a strong motion duration of about 300 seconds, with a peak bedrock acceleration of approximately 0.08 g and dominant period of 1.14s.

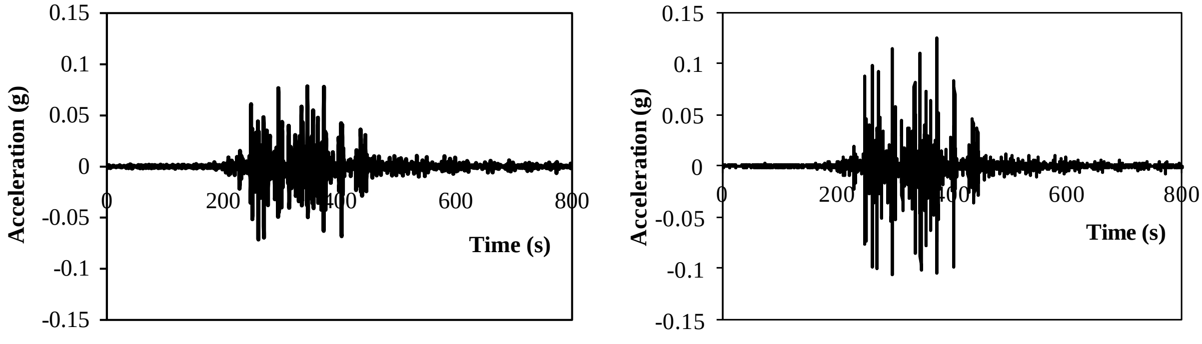


(a) Acceleration time history

(b) Acceleration response spectrum (5% damping)

Figure 7. Typical measured acceleration time history at the model base and its response spectrum

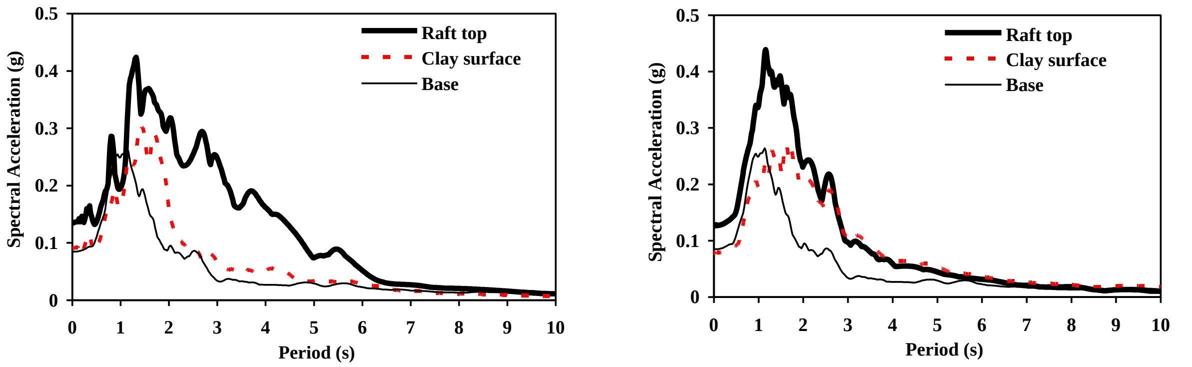
Figure 8 plots the measured acceleration histories at the clay surface and the raft top for the 2x1 compact pile group. The maximum acceleration values at the clay surface and raft top are approximately 0.08 g and 0.12 g, respectively. Though not shown (due to space constraint), the corresponding measurements for the 2x1 sparse pile group are quite similar.



(a) Clay surface (b) Raft top

Figure 8. Measured acclerations at clay surface and raft top for 2 × 1 compact pile group

Figure 9 plots the acceleration response spectra at the clay base, clay surface and raft top for both the 2×1 sparse and 2×1 compact pile groups. For the 2×1 sparse pile group the peak spectral accelerations at the raft top and clay surface are 0.42 g and 0.30 g, respectively; while the corresponding values for the compact pile group are 0.44g and 0.27g, repectively. The dominant periods for measured accelerations at the clay surface and raft top are 1.32s and 1.44s respectively for the 2 × 1 sparse pile group 1.16s and 1.62s respectively for the compact pile group. These results indicate that the dominant periods of the acceleration responses at the clay surface and raft top are generally lengthened compared to that measured at the base (1.14s).



(a) 2×1 sparse pile group (5% damping) (b) 2×1compact pile group (5% damping)

Figure 9. Acceleration response spectra at different locations for 2×1 sparse and compact pile groups

3.2.2 Bending moment response

Figure 10 shows the measured maximum bending moment profiles for the 2×1 sparse and 2×1 compact pile groups. For depths greater than about 6m (or 6D), the measured bending moments in both piles are very similar, with negative bending moments developing between 9m depth and the pile tip. Near the surface, the maximum measured bending moments for the sparse and compact pile groups are 1316 and 998 kNm respectively, measured at the uppermost strain gauges located 3 m from the base of the raft. For the simple 2x1 pile group configuration considered in this study, the larger bending moment obtained from the sparse pile group (with the larger pile spacing) is consistent with previously published results indicating that pile spacing has a significant influence on the individual pile response within a group (Brown and Shie, 1990; Burr et al., 1994; Mostafa and El Naggar, 2002; Rollins et al., 2006; Chandrasekaran et al., 2010a & b; Manna and Baidya, 2010).

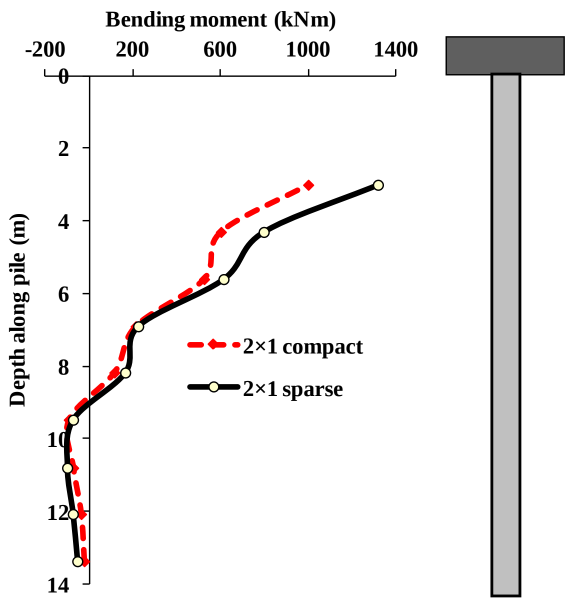


Figure 10. Measured maximum bending moment profiles for 2×1 sparse and 2×1 compact pile groups

4. SUMMARY AND CONCLUSIONS

This paper presents the results from centrifuge tests performed on two pile-raft systems embedded in a soft Kaolin clay layer, focusing on the acceleration responses at selected locations and bending moment responses measured from strain gauges mounted on selected piles. The only difference between these two pile-raft systems (sparse vs. compact) is the pile spacing along the shaking direction (9D vs. 3D).

In general, the acceleration responses at both the clay surface and raft top are amplified compared to that measured at the base of the clay layer, especially within the period spanning 0.2 to 1 sec. This suggests that the clay-pile-raft system has an overall amplification effect on the input earthquake or base motion. More specifically, it is noted that the raft accelerations are higher than those measured at the clay surface in both the 2×1 sparse and compact pile group models. This implies that the clay and the raft do not move in tandem even though both are amplified relative to the input base motion. Besides the magnitude, a comparison of the acceleration response spectra between the clay base, clay surface and the raft top shows that there is some lengthening of the dominant period in both the clay and the raft response as the earthquake motion propagates upward from the base of the model. The period lengthening effect appears to be more significant in the clay than the raft, which may be due to the higher frequency components being more significantly damped out in the much softer Kaolin clay.

The maximum bending moment in the 2×1 sparse pile group is higher than the corresponding value measured in the compact pile group. This suggests that, all other factors being the same, the maximum bending moment induced in a single pile would generally be higher than that induced within an individual pile in a pile-group. Hence, pile spacing is a crucial factor influencing the dynamic pile bending moment response under seismic shaking. In order to better understand the behaviour of pile group under seismic loading, more centrifuge tests involving complex pile groups (such as 2×3 and 4×3 pile groups) are currently being carried out.

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