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Settlement and load sharing behaviour of a piled raft subjected to strong seismic motion

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ABSTRACT

This paper offers a case history of a low-rise building supported by a piled raft foundation on medium to dense sand underlain by overconsolidated silty soil. To confirm the validity of the foundation design, field measurements were performed on the foundation settlement and the load sharing between the raft and the piles to 56 months after the end of construction. During the monitoring period, 44 months after the end of construction, the 2011 Tohoku Pacific Earthquake struck the site of the building located in Ibaraki Prefecture. The peak horizontal ground acceleration of 3.24 m/s^2 was observed at the site 0.9 km south from the building. Although the ground settlement just below the raft was increased 4 mm to 25 mm, no significant changes in the load sharing between the raft and the piles were found after the strong seismic motion.

Keywords: building, piled raft, settlement, load sharing, measurement, seismic loading

1 INTRODUCTION

In recent years there has been an increasing recognition that the use of piles to reduce raft settlements can lead to considerable economy without compromising the safety and performance of the foundation (Poulos 2001). Detailed investigations of many high-rise buildings founded on piled rafts in Germany, mainly in Frankfurt, have been carried out (Katzenbach et al. 2000; Mandolini et al. 2005). Piled rafts have been used in Japan for a large number of buildings including tall buildings in excess of 150 m and the settlement and the load sharing behaviour have been carefully investigated for the selected buildings (Yamashita et al. 2011a; Yamashita et al. 2011b). At present, it is required to develop more reliable seismic design method for piled rafts in Japan and other countries where major earthquakes occur frequently.

This paper offers a case history of a low-rise building, located in Ibaraki Prefecture, supported by a piled raft foundation on medium to dense sand underlain by overconsolidated silty soil. To confirm the validity of the foundation design, field measurements were carried out on the foundation settlement, the axial loads of the piles, the contact pressures of the raft and the pore-water pressures beneath the raft from the beginning of construction to 56 months after the end of construction. During the monitoring period, 44 months after the end of construction, the 2011 Tohoku Pacific Earthquake struck the building site. In this paper, the field measurement results on the settlement and the load sharing of the piled raft before and after the strong seismic motion are presented and the effects of the earthquake on the foundation behaviour are discussed. In addition, a part of the results of the field measurements presented in this paper have been previously published (Yamashita et al. 2011a).

2 BUILDING AND SOIL CONDITIONS

The hadron experimental hall is located at J-PARC (Japan Proton Accelerator Research Complex) in Ibaraki Prefecture (Figure 1). The J-PARC is a joint project between KEK (High Energy Accelerator Research Organization) and JAEA (Japan Atomic Energy Agency) to study material and life science, hadron and particle physics using high-intensity and high-energy proton beam. Figure 2 shows a schematic view of the building and the foundation with a soil profile. The experimental hall, 19 m in height above the ground surface, is a steel reinforced concrete structure. The subsoil consists of loose to dense sand with SPT *N*-values of 7 to 40 to a depth of 6 m from the ground surface, underlain by diluvial dense sand-and-gravel with SPT *N*-values of 60 or higher and medium to dense sand with

Figure 1. Hadron experimental hall

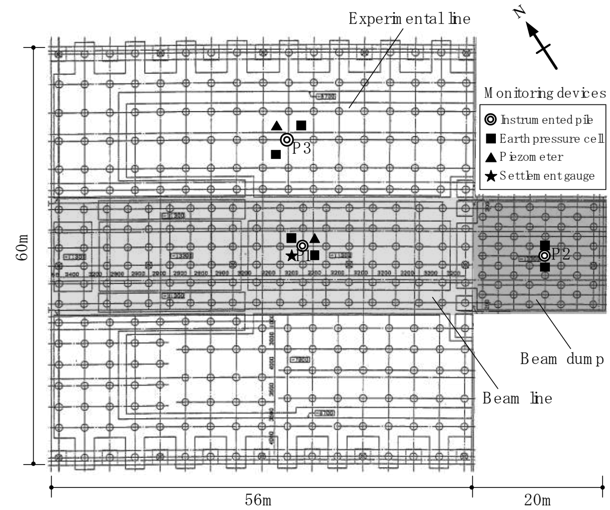


Figure 3. Layout of piles with locations of monitoring devices

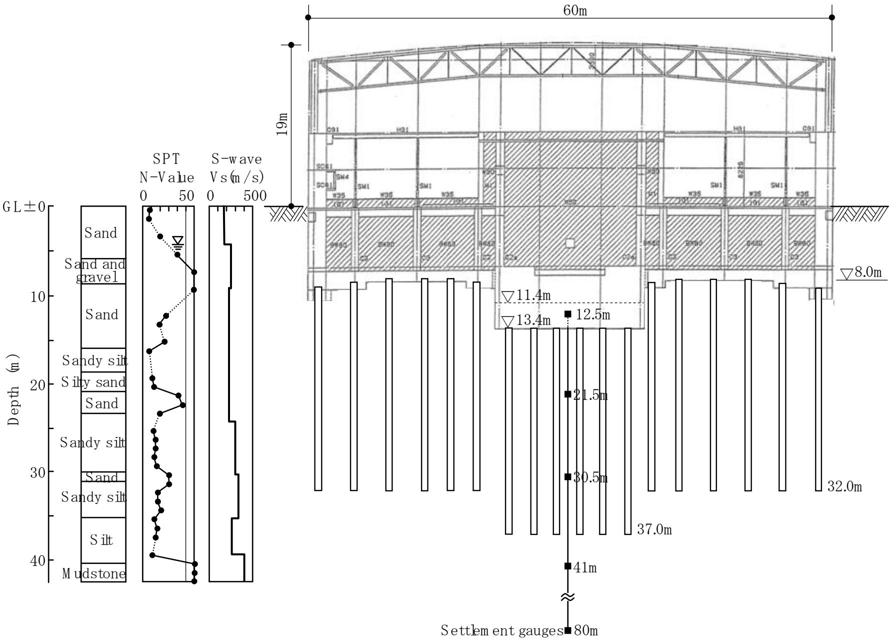


Figure 2. Schematic view of the building and foundation with soil profile

SPT *N*-values of 20 to 60 to a depth of 16m. Between the depths of 16 to 23 m, lie medium sandy silt, loose silty sand and dense sand. Between the depths of 23 and about 40 m, lie cohesive layers with unconfined compressive strengths of 180 to 480 kPa, underlain by a weathered sandy mudstone. The groundwater table appears about 4 m below the ground surface.

3 FOUNDATION DESIGN

The hadron experimental hall consists of a primary proton beam line, secondary beam line and experimental facilities and a beam dump. Figure 3 shows the foundation plan with a layout of the piles. The average contact pressures over the raft were 259 kPa (196 kPa) in the experimental line, 350 kPa (294 kPa) in the beam line and 442 kPa (294 kPa) in the beam dump: the figures in the parentheses are the live loads. The live loads were relatively large (67 to 84% of the total load), because a lot of iron and concrete shielding blocks were to be set up after the end of construction. The foundation levels are between depths of 8.0 to 13.4 m. A reinforced concrete mat was founded on the dense sand-and-gravel and medium to dense sand, so that the allowable bearing capacities at the foundation levels were much higher than the average contact pressures. If a raft foundation were used, the overall settlement would be estimated to be greater than the allowable value of 40 mm due to the compression of the cohesive layers below a depth of 23 m. Therefore, to reduce the settlement of the raft foundation, a piled raft foundation consisting of 371 precast concrete piles (PHC piles) was proposed. The PHC piles (pre-tensioned spun high-strength concrete piles) are 22.0 to 25.5 m in length and have diameters varying from 0.60 to 0.80 m. The piles were constructed by inserting a couple of 9 to 15 m long PHC piles into a pre-augered borehole filled with mixed-in-place soil cement.

4 INSTRUMENTATION

Field measurements were performed on the vertical ground displacements below the raft, the axial loads of the piles and the contact pressures between the raft and the soil, as well as the pore-water pressures beneath the raft from the beginning of the construction to 54 months after the end of construction. The locations of the monitoring devices are shown in Fig. 3. The LVDT-type transducers were installed near the centre of the foundation at depths of 12.5, 21.5, 30.5 and 41.0 m to measure the relative displacements to a reference point at a depth of 80 m from the ground surface. The three piles, P1, P2 and P3, were installed with a couple of LVDT-type strain gauges at the pile head and the pile toe. A pair of LVDT-type earth pressure cells was installed beneath the raft near the instrumented piles. The LVDT-type piezometers were installed near the piles P1 and P3.

5 RESULTS OF MEASUREMENTS

Figure 4 shows the measured vertical ground displacements relative to the reference point. The ground displacement at the depth of 12.5 m was approximately equal to “foundation settlement” if it was initialized just before the casting of the foundation mats. The foundation settlement near the center of the hall was 12.4 mm at the end of construction. Thereafter, the settlement increased due to the setting up of the shielding blocks and reached 20.7 mm just before the 2011 Tohoku Pacific Earthquake. Figure 5 shows the measured axial loads of the piles. As for pile P1, the measured pile-head load increased considerably after the end of construction due to the setting up of the shielding blocks. Figure 6 shows the measured contact pressures and pore-water pressure beneath the raft. The contact pressures increased gradually after the end of construction and the pore-water pressures were almost constant.

Figure 7(a) shows the time-dependent load sharing among the piles, the soil and the buoyancy in the tributary area of pile P1. Figure 7(b) shows the ratio of the load carried by the pile to the effective load versus time together with that to the total load versus time. Here, the total load was the sum of the measured pile-head load and the raft load, which was derived from the mean value of the measured contact pressures, and the effective load was the total load minus the buoyancy. Figures 8(a) and 8(b) show those in the tributary area of pile P2. The ratios of the load carried by the piles to the effective load in the tributary area were estimated to be 0.85 on pile P1 and 0.67 on pile P2 just before the earthquake. At that time, the ratios of the load carried by the piles to the total load were estimated to be 0.67 on pile P1 and 0.45 on pile P2.

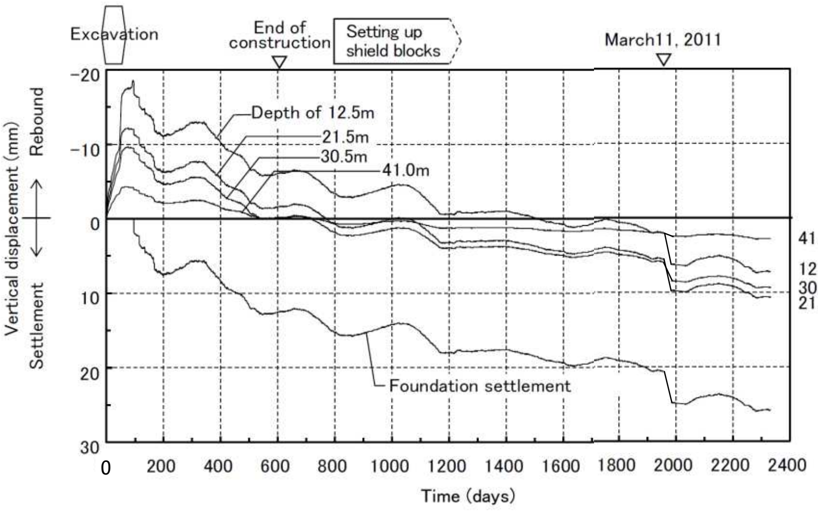
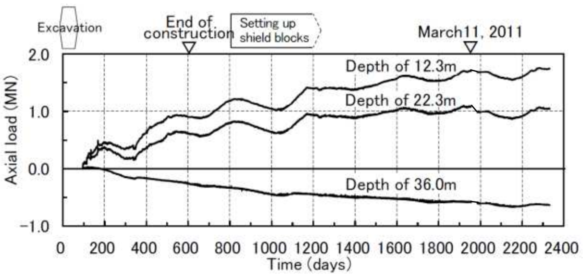
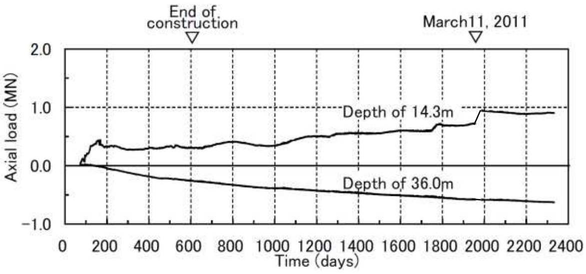


Figure 4. Measured vertical ground displacements

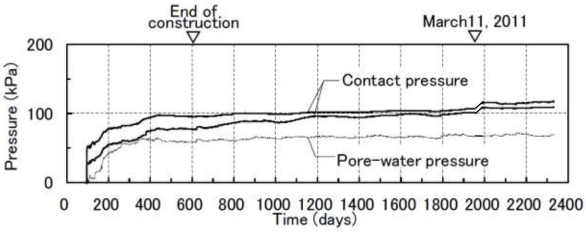


(a) Pile P1 in beam line

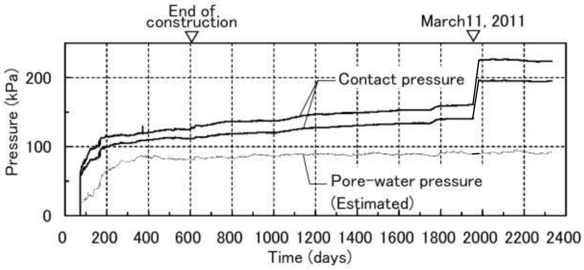


(b) Pile P2 in beam dump

Figure 5. Measured axial loads of piles

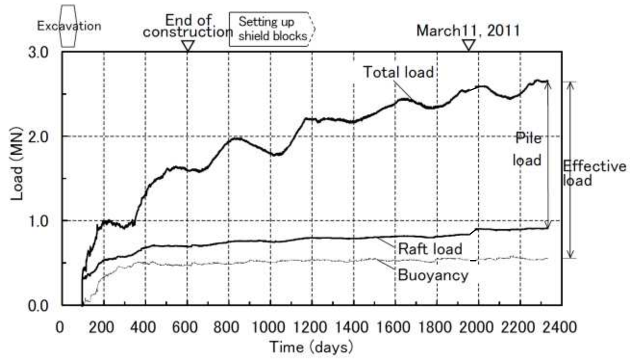


(a) Near pile P1

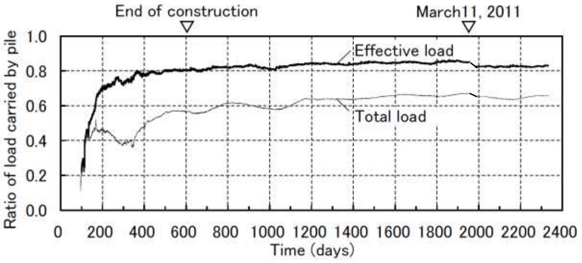


(b) Near pile P2

Figure 6. Measured contact pressures and pore-water pressure

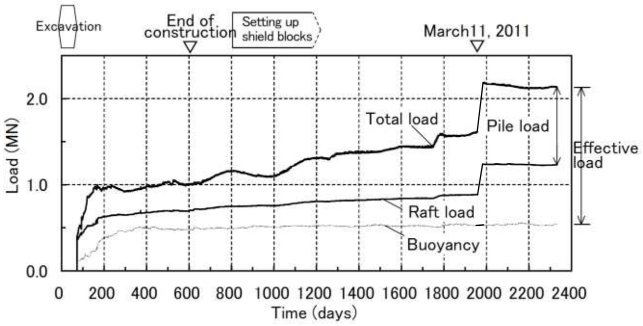


(a) Load sharing between raft and pile

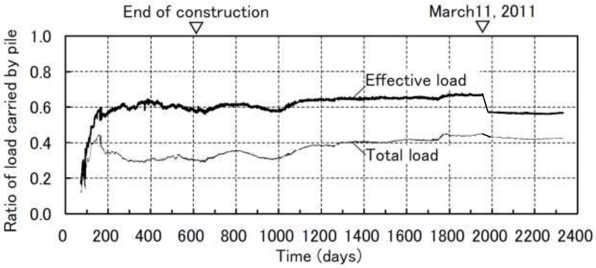


(b) Ratio of load carried by pile

Figure 7. Load sharing between raft and piles on tributary area of pile P1



(a) Load sharing between raft and pile



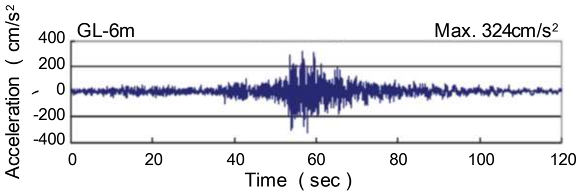
(b) Ratio of load carried by pile

Figure 8. Load sharing between raft and piles on tributary area of pile P2

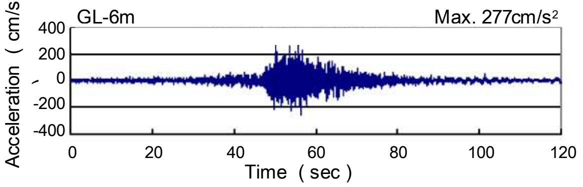
6 EFFECT OF EARTHQUAKE ON FOUNDATION BEHAVIOUR

6.1 The 2011 Tohoku Pacific Earthquake

The 2011 Tohoku Pacific Earthquake struck the East Japan on March 11, 2011. Hashimura et al. (2011) has reported about the response characteristics of the five-story base-isolated building located 0.9 km south from the hadron experimental hall. Figure 9 shows the time histories of accelerations



(a) Horizontal（nearly NS direction）



(b) Vertical

Figure 9. Time histories of accelerations at Tokai (Hashimura et al. 2011)

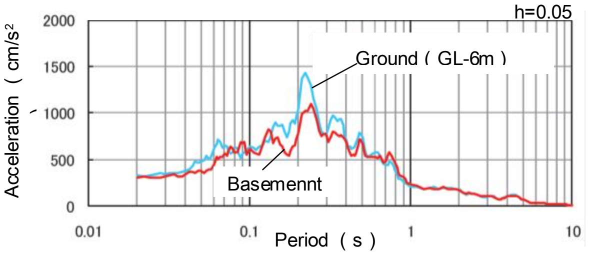


Figure 10. Response spectra of horizontal accelerations at Tokai (Hashimura et al. 2011)

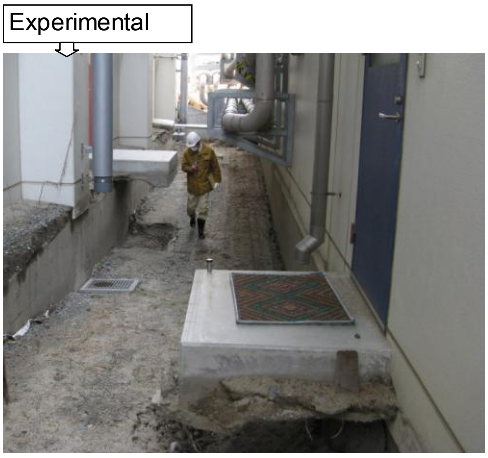


Figure 11. Ground subsidence around the building

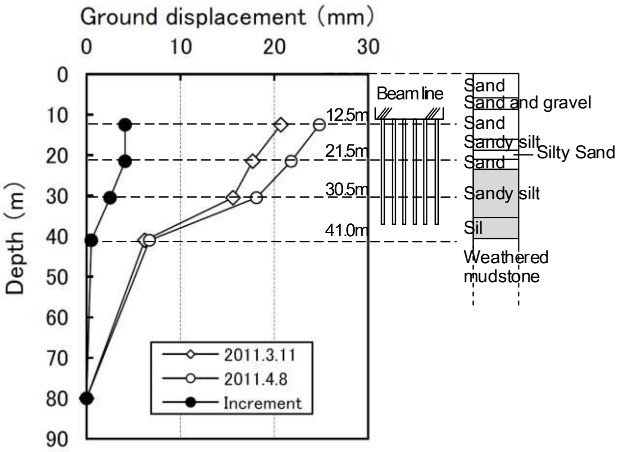


Figure 12. Profiles of vertical ground displacements

observed at a depth of 6 m below the ground surface near the building. The peak horizontal and vertical ground accelerations of the earthquake were 3.24 m/s^2 and 2.77 m/s^2, respectively. Figure 10 shows the response spectra with a 5% damping ratio of the horizontal acceleration of the ground and that of the basement. It can be seen that the predominant period of the horizontal ground acceleration was 0.22 s.

Figure 11 shows the ground subsidence along the northeast side of the experimental hall near the north corner. The ground subsidence reached a maximum of 1.2 m, which was presumed to be caused by compaction of the back-filled sand due to the strong horizontal and vertical ground motion. Although the monitoring system was suspended immediately after the earthquake because of power outage, the system was restored 28 days after the earthquake.

6.2 Effect of earthquake on settlement and load sharing

Figure 12 shows the profiles of the measured vertical ground displacements just before and after the earthquake, where the measured displacements were initialized just before the casting of the foundation mats. The foundation settlement increased 4.1 mm to 24.8 mm 28 days after the earthquake. It can be seen that the increments in the ground displacements occurred mostly by the compression of the silty soil between depths of 23 and 41m. The compression of the silty soil seemed to be caused by the vertical cyclic loading due to the inertial force acting on the building. Thereafter, the vertical ground displacements were stable and the foundation settlement reached 25.2 mm one year after the earthquake as shown in Fig. 4.

The axial loads of pile P1 decreased only slightly and the contact pressures near pile P1 increased slightly after the earthquake as shown in Figs. 5(a) and 6(a), respectively. On the other hand, the axial load of pile P2 at pile head increased 30% and the contact pressures near pile P2 increased 39% as shown in Figs. 5(b) and 6(b), respectively. One possible reason for the increase in the pile load and the contact pressures is that the frictional resistance at the interface of the outside wall of the structure and the back-filled sand was considerably reduced by the subsidence of the back-filled sand due to the strong seismic motion. So that, part of the structure load was transferred to the bottom of the raft and distributed to the soil beneath the raft and the piles. The increase in the pile load and the contact pressures appeared remarkably in the beam dump as the ratio of the perimeter to the planar area was relatively large. The pore-water pressures were not affected by the seismic motion as shown in Figs. 5(b) and 6(b).

The ratio of the load carried by the piles to the effective load in the tributary area of pile P1 decreased only slightly to 0.82 and that of pile P2 decreased slightly to 0.57 28 days after the earthquake. In one year after the earthquake, the ratios of the pile load to the effective load were quite stable. Meanwhile, the ratios of the pile load to the total load decreased only slightly to 0.65 on pile P1 and 0.43 on pile P2 28 days after the earthquake.

7 CONCLUSIONS

The settlement and the load sharing behaviour of a piled raft supporting a low-rise building were investigated by monitoring the soil-foundation system from the beginning of construction to 56 months after the end of construction. During the monitoring period, the 2011 Tohoku Pacific Earthquake struck the site of the building. Through the investigation before and after the earthquake, the following conclusions can be drawn:

1) The measured foundation settlement near the centre of the foundation reached 20.7 mm just before the earthquake. The ratios of the load carried by the piles to the effective load of the building in the tributary area of the instrumented piles were estimated to be 0.85 on pile P1 and 0.67 on pile P2.
2) The foundation settlement increased 4.1 mm to 24.8 mm after the earthquake. The ratio of the load carried by the piles in the tributary area of pile P1 decreased only slightly to 0.82 and that of pile P2 decreased slightly to 0.57. Consequently, the settlement and the load sharing behaviour of the piled raft were found to be stable after the strong seismic motion.

8 ACKNOWLEDGEMENTS

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REFERENCES

Hashimura, H., Uryu, M., Yamazaki, T., Nakanishi, R., Kirita, F. and Kojima, K. (2011): A study on the response characteristics of base-isolated structures for earthquake motion (Part 1 & Part 2), Proc. Annual Meeting of AIJ, 621-624 (in Japanese).

Katzenbach, R., Arslan, U. and Moormann, C. (2000): Piled raft foundation projects in Germany, Design applications of raft foundations, Hemsley J.A. Editor, Thomas Telford, 323-392.

Mandolini, A., Russo, G. and Viggiani, C. (2005): Pile foundations: Experimental investigations, analysis and design, Proc. 16th ICSMGE, Vol.1, 177-213.

Poulos, H. G. (2001): Piled raft foundations: design and applications, Geotechnique 51, No.2, 95-113.

Yamashita, K., Yamada, T. and Hamada, J. (2011a): Investigation of settlement and load sharing on piled rafts by monitoring full-scale structures, Soils & Foundations, Vol.51, No.3, 513-532.

Yamashita, K., Hamada, J. and Yamada, T. (2011b): Field measurements on piled rafts with grid-form deep mixing walls on soft ground, Geotechnical Engineering Journal of the SEAGS & AGSSEA, Vol.42, No.2, 1-10.