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A study on the behavior of various foundations during earthquake and liquefaction

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ABSTRACT

In an effort to develop the reclaimed city of Saemangeum as a global frontrunner of green growth, renewable energy generation facilities are to be constructed. To structurally support the renewable energy facilities, various types of foundations are to be utilized. Hence, in this study, a scale model shaking table test was conducted to investigate and compare the behavior of different foundations such as skin-friction piles (SFP), helical piles (HP), end-bearing piles (EBP) and shallow foundations (SF) during earthquake and liquefaction. The results of the test showed that piles exhibit a tilting response during liquefaction, while for shallow foundations, a sinking behavior can be observed. The results of the test also showed that the relative displacement of the pile head with respect to the ground surface of the SFP was larger than both the HP and EBP before liquefaction. This is because the lateral resistance of the SFP was smaller due to its shorter length. However, as liquefaction occurred, the lateral resistance provided by the soil on the pile was reduced and resulted in the increase of inertial loading. The results showed that piles with longer lengths have larger relative displacements than piles with shorter lengths. Also, sharper vertical accelerations were observed for the SFP in comparison to the HP during liquefaction as a result of the decrease of the bearing resistance of its pile tip. Considering the results of the strain gauges, larger strains were observed for the piles with larger bearing resistances. In the end-bearing pile, simultaneous occurrence of positive and negative strains on opposite sides of the pile at a certain depth signifies the development of a couple that may be very significant especially in strong soil material or large diameter piles.

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1. INTRODUCTION

1.1 Energy sources and foundation technologies

In recent times, energy comes mainly from the petroleum and gas industry. However, due to increasing demand, it has become clear that petroleum and gas supply is not enough. One of the cheapest and fastest ways to produce energy is to tap into nuclear power. However, it is not always the safest. Hence, a lot of alternative power sources have been utilized over the years including hydropower, geothermal, biomass, wind, and solar resources.

The Saemangeum Development Project (SDIA 2015) is a national project that aims to build a global city and an industrial zone in Korea by means of land reclamation. In an effort to develop the reclaimed city of Saemangeum as a global frontrunner of green growth, renewable energy generation facilities are to be constructed. The renewable energy facilities are to be established offshore and onshore. Offshore facilities can be expensive but can deliver more energy. Onshore facilities, however, have a lower wind resource, but are cheaper since the local conditions are more consistent. To structurally support the renewable energy facilities, various types of foundations are to be utilized. Offshore facilities are usually supported by monopiles, tripods, gravity base foundations, and bucket foundations. Commonly used foundations for onshore facilities are piles and gravity base foundations.

In recent years, the use of helical piles to support a variety of loads has increased for its many advantages such as ease of installation, relatively small equipment, rapid installation speed, suitability in very limited access conditions, removable, and reusable. One of its many applications includes solar farms. In the Saemangeum Development Project, the solar farms are to be constructed using helical piles as its foundation. Load tests and solar farm mock installation have been conducted at a test site near Saemangeum, in preparation for the actual construction of the solar farms.

1.2 Liquefaction

The consequences of an earthquake are devastating. This includes ground rupture, landslides, fires, tsunami, floods, and soil liquefaction. Soil liquefaction occurs when a saturated or partially saturated soil substantially loses strength and stiffness in response to cyclic shear loading, in which a material that is ordinarily a solid behaves like a liquid. The phenomenon is most often observed in saturated, loose sandy soils. If loading is rapidly applied and large enough, or is repeated many times such that water does not flow out before the next cycle of load is applied, the water pressures may build up, and severe damage to structures could occur.

Due to the fact that reclaimed lands are known to be susceptible to liquefaction, a shaking table apparatus was developed in Gunsan, South Korea at Kunsan National University. To investigate the response of various foundations during earthquake and liquefaction, a scale model shaking table test was conducted. Four different foundations were used, and these are skin-friction piles (SFP), helical piles (HP), end-bearing piles (EBP) and shallow foundations (SF). Through the shaking table test, better understanding and design can be established.

2. SCALE MODEL TEST SETUP AND MATERIALS

The materials and gauges used in the test are arranged in the manner as shown in Fig. 1. Further details on the placement and labels of the strain gauges are shown in Fig. 2. Accelerometer A1 was installed at the bottom of the tank to measure the input acceleration while accelerometers A2, A3, A4, A5, and A6 were installed on top of the pile head, ground surface, and the shallow foundation to measure the relative displacement. Soil pressure gauges B1, B2, and B3 were installed to be able to measure the bearing capacity of the pile tips and helix. The pore pressure rise during shaking was monitored using pore pressure gauges (PP1, PP2, PP3), as shown in Fig. 1.

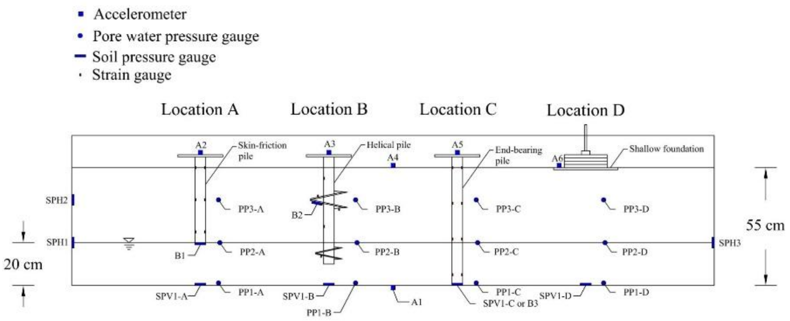


Fig. 1. Scale model test setup

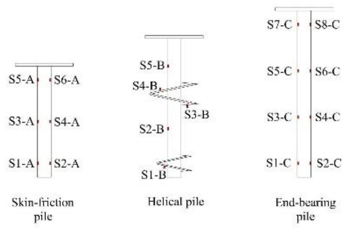


Fig. 2. Strain gauge placement and label

The piles were made of aluminum to be able to measure the strain along the length of the pile and the strain of the helix during shaking. If stiffer materials were used, strain readings might be misleading since strain quantities are significantly small. The axial load applied on the piles was 3 kg while 4 rectangular plates weighing 4.54 kg each were placed on top of the shallow foundation. Saemangeum silty sand, which is classified as most liquefiable soil, was used in the experiment. The soil sample was placed in the tank by buckets in a step by step manner. The saturated lower layer is 20 cm thick while the moist upper layer is 35 cm thick. The properties of the Saemangeum dredged soil are listed in Table 1. Increasing cyclic loading having frequencies of 1 Hz, 1.33 Hz, 1.67 Hz, and 2 Hz, were applied to the shaking table, as shown in Fig. 4.

Table 1. Properties of Saemangeum dredged soil

Property	Unit	Quantity
Specific gravity, G_s	NA	2.71
Percent passing #200 sieve	%	26.2
Soil classification (USCS)	NA	SM
Void ratio in loosest state, e_{max}	NA	1.37
Void ratio in densest state, e_{min}	NA	0.68

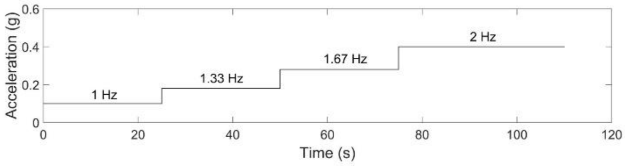


Fig. 3. Cyclic loading applied to the shaking table

3. RESULTS

Data obtained from the accelerometers are shown in Fig. 4. As shown in Fig. 4a, input cyclic loadings of 1 Hz, 1.33 Hz, 1.67 Hz, and 2 Hz have gravity accelerations equal to about 0.10g, 0.18g, 0.28g, and 0.40g, respectively. Based on the results, the pile head of the helical and end-bearing piles have the largest horizontal peak accelerations while the pile head of the skin-friction pile has a similar horizontal peak acceleration with the ground surface acceleration. The shallow foundation had the least horizontal peak acceleration since the load on the shallow foundation was larger, which resulted in the sinking motion of the foundation rather than sliding motion. Looking at the data obtained from the pore pressure gauges, as shown in Fig. 5, the results show that pore pressure rise was insignificant at cyclic loadings having frequencies of less than 1.66 Hz. It should be noted that peak excess pore pressure is highest at location D. Based on the accelerometer and pore pressure gauge data, ultimate soil weakening occurred at about t > 70 s.

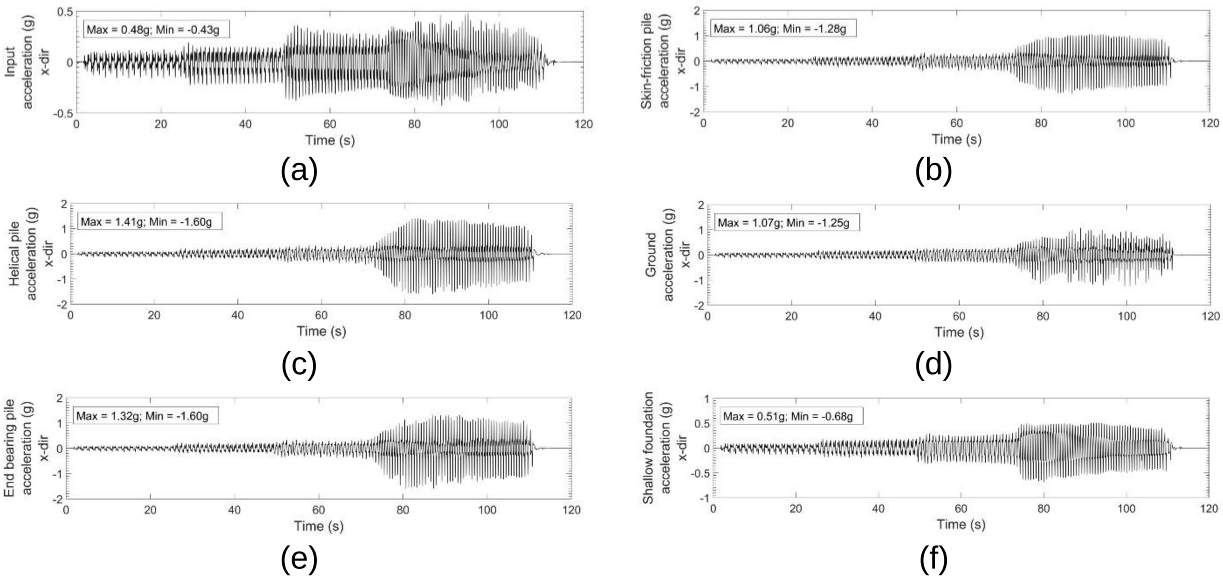
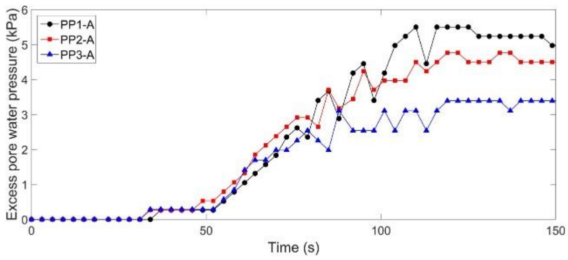
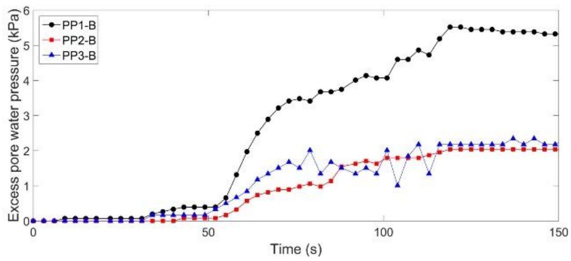


Fig. 4. Horizontal acceleration: a) Input acceleration, b) SKP pile head, c) HP pile head, d) ground surface, e) EBP pile head, f) SF

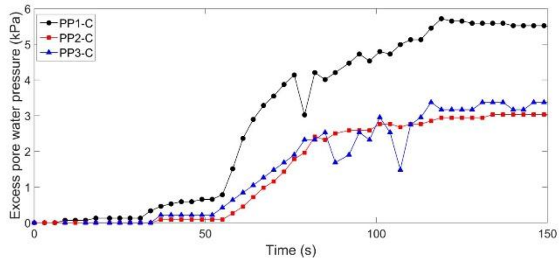
By filtering and double integration of the accelerometer data, the relative displacement of the pile heads were obtained, as shown in Fig. 5. Results show that the relative displacement of the skin-friction pile is larger than the helical and end-bearing piles at t < 70 s. At t > 70 s, it is noticeable that the relative displacement of the pile with the longer length is larger than the pile with the smaller length. The results show that the lateral resistance of the pile is governed by the pile length. Before liquefaction, the soil helped resist against tilting motion. However, as the soil started to behave like liquid, the lateral loading induced by the soil on the pile increases.



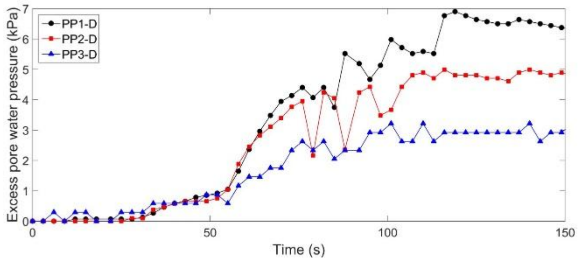
(a)



(b)

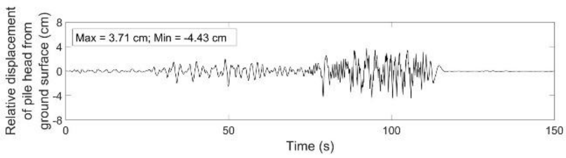


(c)

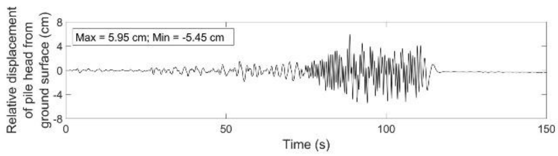


(d)

Fig. 5. Excess pore water pressures: a) Location A, b) location B, c) location C, d) location D



(a)



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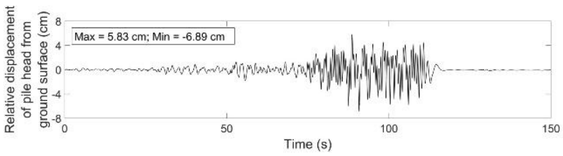
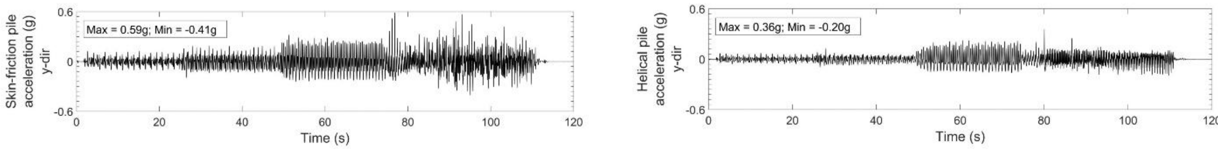


(c)

Fig. 5. Relative displacement of pile head: a) SKP, b) HP, and c) EBP

Shown in Fig. 6 is the vertical acceleration of the skin-friction pile and helical pile. Larger vertical accelerations are observed for the skin-friction pile. This can be attributed to the fact that its bearing capacity is smaller in comparison to the longer pile, which is supported by helices. A slight increase in the bearing pressure was observed for all piles before the onset of liquefaction, as shown in Fig. 7. However, a significant decrease in the bearing pressure was observed for the skin-friction pile as liquefaction occurred, which explains why the vertical acceleration was larger for the skin-friction pile. The helical pile held up well during liquefaction as the bearing pressure only slightly decreased and the vertical acceleration was not as significant in comparison to the skin-friction pile.



(a) (b)

Fig. 6. Vertical acceleration: a) SKP pile head, and b) HP pile head

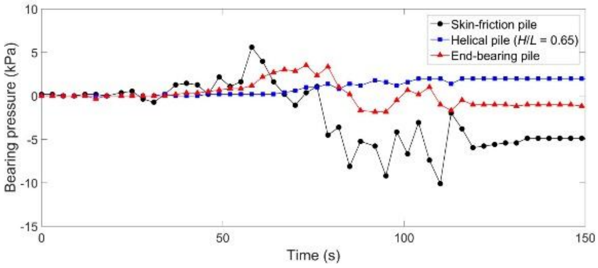


Fig. 7. Variation of bearing pressure with time

The axial loading during an earthquake is complex, with the structure having to carry the vertical loads which are applied under normal operating conditions, as well as additional axial loads arising from cyclic loading. For the shorter pile (SKP), a large amount of the added axial load (3 kg) is being carried mostly by the toe resistance and some by friction. However, during shaking and before liquefaction, dragload is induced and the load carried by friction decreases and the load carried by the pile tip increases, as shown in Fig. 7. However, as the soil started to liquefy, the effective stress of the soil decreases. As a result, the toe resistance greatly decreases. The capacity of the pile relies on friction, and this behavior results in a downward force at the pile tip and an upward force by friction near the pile tip. Hence, the pile behaves as if it is in tension, and this corresponds to a positive strain for the time range of t = 50 – 100 s. However, as the toe resistance stabilizes, a compressive behavior is observed and the strain on the pile decreases, as shown in Fig. 8.

For piles with larger toe resistance, the dragload induced by the earthquake is larger. The larger the end-bearing stiffness and resistance, the deeper the elevation of the neutral plane into the soil and the larger the dragload (Kim et al. 2018). As a result, the magnitude of the strain for the helical and end-bearing piles are larger in comparison to the strain experienced by the skin-friction pile, as shown in Figs. 9 and 10, respectively. Looking back at Fig. 7, the bearing pressure of both the helical and end-bearing pile did not decrease. However, due to the increasing dragload caused by cyclic loading, the pile behaves as if it is being compressed, and the strain on the pile is negative.

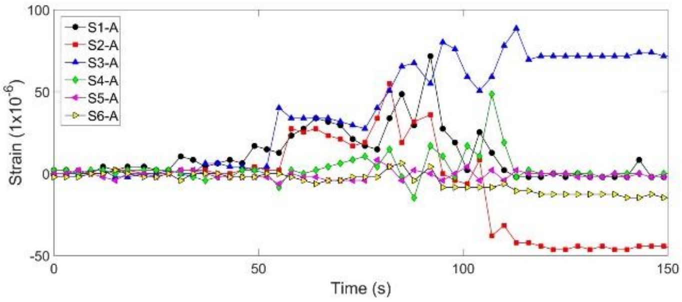


Fig. 8. Variation of strain with time for skin-friction pile

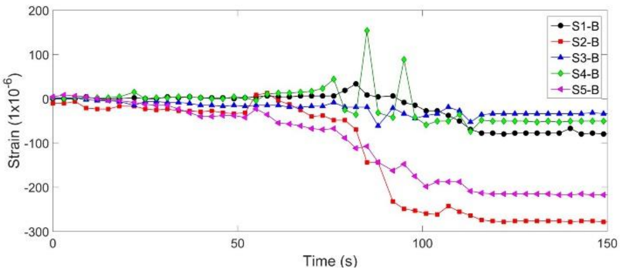


Fig. 9. Variation of strain with time for helical pile

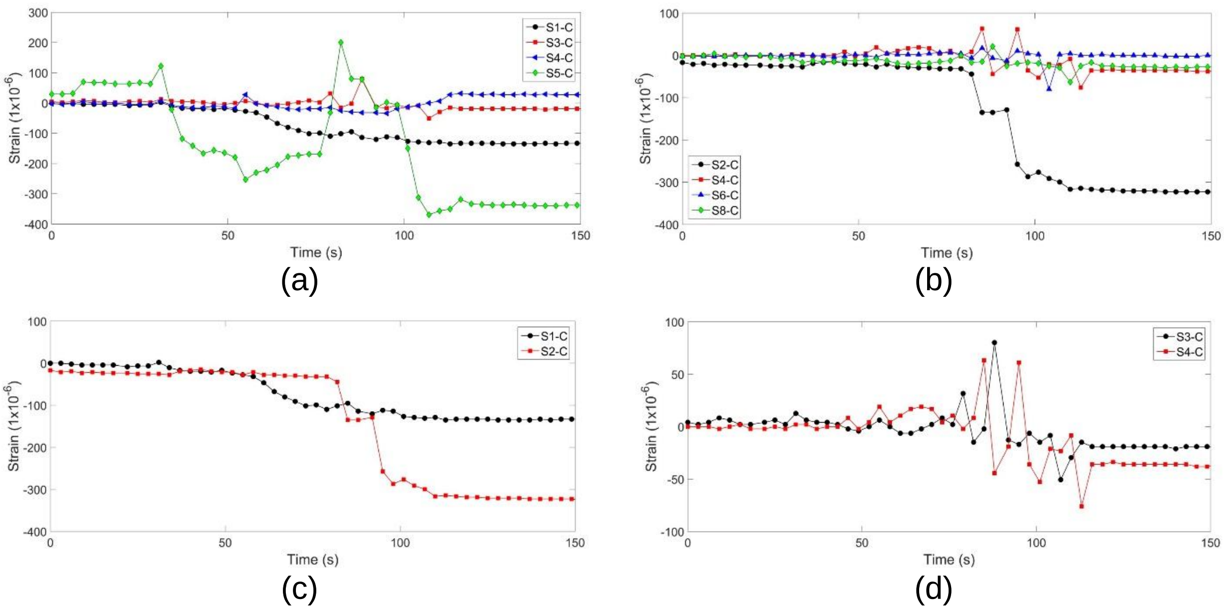


Fig. 10. Variation of strain with time for end bearing pile: a) left side of pile, b) right side of pile, c) strain near pile tip, d) strain near the center of the pile showing simultaneous positive and negative strains on opposite sides

In Fig. 9, S1-B is the strain gauge on the bottom helix, S2-B is the strain gauge on pile shaft located between the two helices, S3-B and S4-B are the strain gauges on the top helix, and S5-B is the strain gauge on the pile shaft located above the top helix. As shown, strain on the helices are small while strain on the pile shaft is larger. For the end-bearing pile, the strain is large at the pile tip as shown in Fig. 10c. However, in Fig. 10d, simultaneous positive and negative strains on opposite sides of the end-bearing pile near the mid-depth is observed, which signifies the development of a couple that may be very significant especially in strong soil material or large diameter piles.

4. CONCLUSIONS

To investigate the response of various foundations during earthquake and liquefaction, a scale model shaking table test was conducted. Based on the results of the experiment, the following conclusions are drawn:

- The shallow foundation exhibited a sinking behavior during liquefaction while the piles exhibited a tilting behavior.
- Pore pressure rise was insignificant at low frequency cyclic loadings.
- The relative displacement of the pile with the longer length is larger than the pile with the smaller length.
- The lateral resistance of the pile is governed by the pile length. Before liquefaction, the soil helped resist against tilting motion. However, as the soil started to behave like liquid, the lateral loading induced by the soil on the pile increases.
- The skin-friction pile experienced tension during liquefaction as upward force by friction near the pile tip and downward force at the pile tip was induced due to the decrease of the toe resistance.
- The magnitude of the strain for the piles with larger bearing resistances (helical and end-bearing piles) are larger in comparison to the strain experienced by the skin-friction pile. These piles experienced a compressive behavior near due to dragload.
- Simultaneous positive and negative strains on opposite sides of the end-bearing pile near the mid-depth is observed, which signifies the development of a couple that may be very significant especially in strong soil material or large diameter piles.

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REFERENCES

Kim, H.J., Mission, J.L., Park, T.W., and Dinoy, P.R. (2018), “Analysis of negative skin-friction on single piles by one-dimensional consolidation model test”, *Int. J. Civ. Eng.,* **16**(10), 1445-1461.