Evaluation of Inertial and Kinematic Forces on Pile Foundations Under Seismic Loading by Centrifuge Tests

M.T. Yoo, I.W. Jung, S.Y. Kwon & M.M. Kim
Seoul National University, The Republic of Korea

SUMMARY:
Pile foundations supporting superstructures are frequently found to have been damaged or to have failed during earthquakes. Recent research has confirmed that not only the inertial effects of pile foundation superstructures, but also the kinematic effects by ground movement, have a considerable influence on the damage to the pile foundations in liquefiable soils where lateral ground movement occurred. Therefore, it is necessary to investigate the inertial and kinematic effects on the behavior of piles during earthquakes. In this research, a series of dynamic centrifuge tests was carried out under a seismic loading condition, to analyze the effect of inertial and kinematic forces on a pile foundation, and to evaluate the influence of various input parameters on each component. The tests were conducted in dry sand and liquefiable saturated sand deposit. Based on the test results, the effects of inertial and kinematic forces on pile foundations were evaluated.

Keywords: Inertial effect, Kinematic effect, Pile foundation, Centrifuge test.

1. INTRODUCTION

Pile foundations supporting superstructures are frequently found to have been damaged or to have failed during earthquakes. From recent research, it was confirmed that not only the inertial effects of pile foundation superstructures, but also the kinematic effects by ground movement, had a considerable influence on the damage to the pile foundations. However, pseudo static analysis, which is a widely-used method for seismic design, cannot adequately consider the kinematic effect, by converting only the inertial force of a superstructure to a pseudo-static lateral force. In addition, little is known concerning the degree of contribution of the two effects, although much research on pile behavior under seismic loading has been performed. Therefore, it is necessary to investigate the inertial and kinematic effects on the behavior of piles during earthquakes. According to Dezi et al. (2010), pile displacement by kinematic effect was similar to ground displacement. Tokimatsu et al. (2005) suggested that the pressure acting on a pile may be determined as the sum of the two forces caused by the two effects, or the square root of the sum of the squares of the two forces. However, this previous research was performed using 1-g shaking table tests, which could not reproduce the in-situ confining pressure, or was conducted only by numerical analysis.

In this research, a series of dynamic centrifuge tests were carried out, with different pile diameters installed in dry and loose saturated sand deposit (liquefiable sand), for various conditions of input acceleration and upper mass. The effects of inertial and kinematic force on a pile foundation were analyzed, and the influence of various conditions on each effect was evaluated.

2. CENTRIFUGE TEST SET-UP & PROGRAM

In this study, centrifuge tests were performed with the KAIST dynamic centrifuge facility in Korea, which has a 5m radius, 2.5ton payload, and up to 100g centrifugal acceleration geotechnical centrifuge. All tests in this study were carried out at a centrifugal acceleration of 40g. The model container was an Equivalent Shear Beam (ESB) box, and the dimensions of the box were 49cm x 49cm x 63cm. The box was fabricated to reduce reflection waves from the sides of the box during shaking, and was connected by 6cm thick rigid bands with rubber buckles, and was deformed with soil in the box (Kim et al. 2010).

Three model piles were fabricated from a close-ended aluminum pipe of 2.5cm, 2.2cm and 1.8cm external diameters and a 0.1cm wall thickness. The embedment depth of piles was 57cm, and they were installed to be longer than the infinite depth. Therefore, the three model piles simulated prototypical piles of 72cm, 88cm and 100cm diameters, with an embedment depth of 22.8m. The properties of the piles are summarized in Table 1.

Table 1. Pile Properties

	Scaling factor	Diameter (cm)	Flexural stiffness (kg · cm^2)
Model 1	40	1.8 (72*)	133889 (3.43E+11*)
Model 2	40	2.2 (88*)	252080 (6.45E+11*)
Model 3	40	2.5 (100*)	376083 (9.63E+11*)

* Prototype

Jumoonjin sand, characterized as clean and uniform sand (SP sand), was used in these tests. The properties of Jumoonjin sand are shown in Table 2. The diameter of the model pile (D) was 47~65 times the effective particle size (D_{10}) of the silica sand, which concurred with the result by Ovesen (1979), which demonstrated that particle size had no effect on a pile.

Table 2. Soil Properties

D_{10}	D_{50}	C_u	G_s	$\gamma_{d,max}$	$\gamma_{d,min}$
0.38mm	0.57mm	1.58	2.65	15.99 kN/m^3	13.05 kN/m^3

The layout of the test is shown in Figure 1. The model piles were fixed at the bottom of the soil box, in order to simulate the rock-socketed pile, and a concentrated mass of 1.5kg and 2.5kg (96ton and 160ton on the prototype scale), respectively, was located 11cm above the subsurface. Eight pairs of strain gauges were attached on both sides of the pile, to calculate the bending moment in the pile during vibration. Eight accelerometers were installed in the soil at the same depth as each strain gauge, to calculate the displacement of soil, and one accelerometer was attached to the pile head, to measure the acceleration responses of the pile. In addition, eight pore water pressure transducers were installed in the soil at the same depth as other instrumentation for the saturated sand deposit. The three model piles were installed together in an ESB box. The spacing between the piles was over 10 times the pile diameter (D), which concurred with the result obtained by Remaud (1999), which demonstrated that there was no interactional effect between the piles when the pile spacing was over 10D. In addition, the piles were placed perpendicular to the direction of shaking, in order to avoid being affected by the adjacent piles.

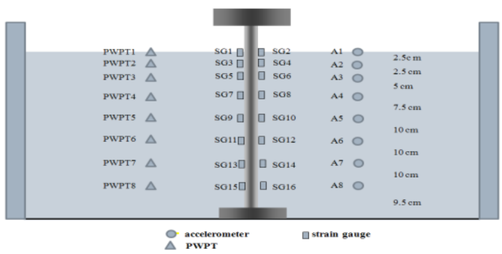


Figure 1. Layout of test (in model scale)

The test programs are summarized in Table 3. In order to analyze the effect of inertial and kinematic force according to ground condition, the tests were conducted in both dry sand and liquefiable saturated sand deposit. In the case of dry sand deposit, sand pluviation was conducted with an automatic pluviation facility, to prepare a uniform sand layer with a relative density of 80%. In the case of saturated sand deposit, the sand deposit was prepared by water-pluviating sand to a relative density of approximately 30%, and saturating with viscous fluid, whose viscosity was adjusted to be 40 times that of water. The viscous fluid was made of HPMC (HydroxyPropylMethylCellulose). A sine wave was selected as the input base motion. In the case of dry sand deposit, the loading amplitude of the input sine wave ranged from 0.05g to 0.2g on the prototype scale. In order for liquefaction to occur, an input sine wave with input acceleration of 0.3g was applied to the loose saturated sand deposit. The frequency of input motion was 1Hz on the prototype scale.

Table 3. Test Programs (Prototype Scale)

No. of test	Input acceleration	Input frequency	Relative density	Ground condition	Upper mass
1	0.05g ~ 0.2g	1 Hz	80%	Dry	none
2	0.05g ~ 0.2g	1 Hz	80%	Dry	96 ton
3	0.05g ~ 0.2g	1 Hz	80%	Dry	160 ton
4	0.3g	1 Hz	30%	Saturated	none
5	0.3g	1 Hz	30%	Saturated	96ton

The presence of upper mass means the presence of inertial force. When the upper mass is none, only a kinematic effect was applied to the soil-pile system, and when there is an upper mass, both inertial effect and kinematic effect are applied.

3. EXPERIMENTAL RESULTS

The bending moments mobilized in the pile were calculated by substituting the strains measured by the strain gauges, and y_{pile} can be derived based on simple beam theory (Eqn.(3.1)). In order to obtain a continuous bending moment profile along the pile, the cubic spline method (Dou & Byrne, 1996; Scott, 1980) was used as a curve-fitting technique.

$$y_{pile} = \iint \frac{M(z)}{EI} dz \tag{3.1}$$

where, *EI* : flexural rigidity of the pile, *z* : depth below the ground surface, *M(z)* : measured bending moments along the pile

The soil displacement (y_{soil}) was calculated by double integration of the free field acceleration of each depth.

3.1. Dry Dense Sand

3.1.1. Kinematic effect

The kinematic effect of the pile was evaluated by the test case without upper mass. Results from the experiments were converted to the prototype scale, using a scaling factor. Figure 2 shows the input motion, ground acceleration, and pile head acceleration-time history for an input acceleration of 0.1g. In this figure, if there is no upper mass, amplification on the ground surface and the pile head is relatively less than the input motion. The measured acceleration of the ground surface and the pile head was in-phase with the input motion. This kind of phenomenon implies that small soil deformation is generated in dense sand, and the deformation pattern of the soil and the pile is the same, when only a kinematic effect is generated by the soil deformation. Figure 3 shows the maximum displacement at the ground surface, according to the input acceleration. As shown in Figure 3, as the input acceleration increases, the soil deformation increases linearly in dense sand. This means a linear behavior of the free field response in dry sand.

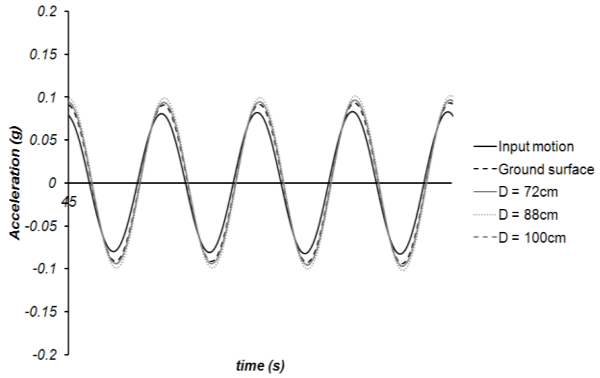


Figure 2. Acceleration-time history
(Upper mass = None, input motion = 0.1g)

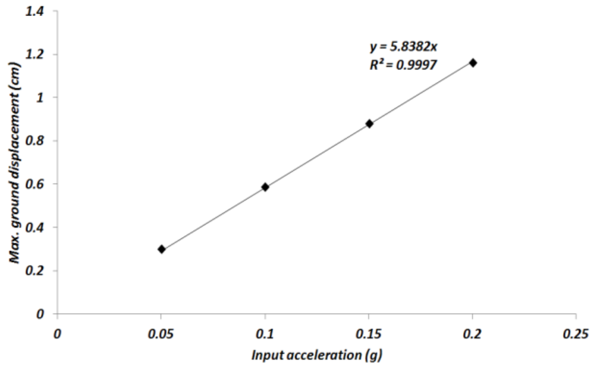
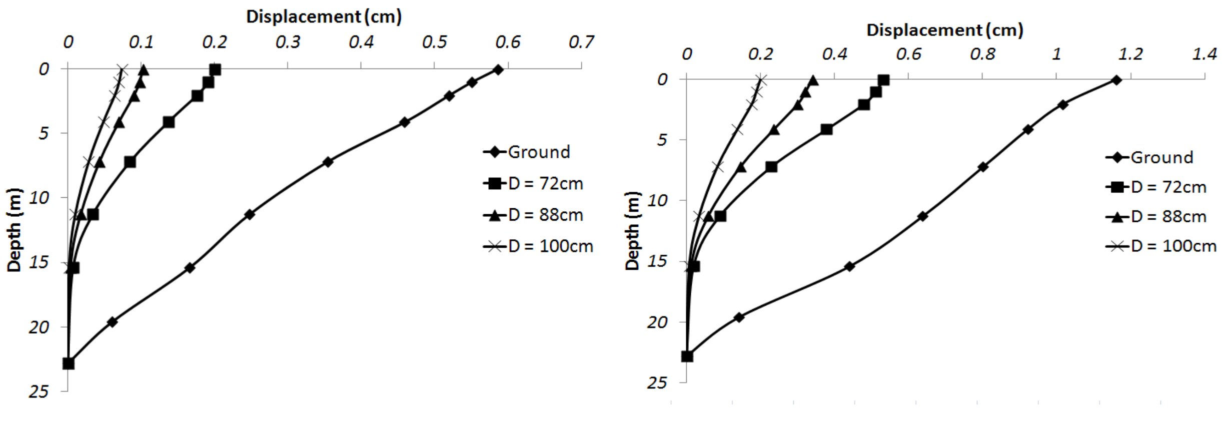


Figure 3. Relation between input acceleration and maximum displacement of ground surface

Figure 4 shows pile displacement and soil deformation along depth, which is evaluated at the moment when maximum displacement of ground surface is occurring. As shown in Figure 4, the pile displacement generated by the kinematic effect was 11% ~ 45% of the soil deformation. As the pile diameter and horizontal stiffness increase, the pile displacement decreases. These results are contrary to Dezi et al. (2005), which report the pile displacement by kinematic effect to be identical to the soil deformation. In the case of a pile embedded in soil, the pile stiffness is relatively greater than the soil stiffness, and the pile displacement is less than the soil deformation, due to the horizontal stiffness of the pile when only a kinematic effect is generated. Also, the pile displacement was inversely proportional to the pile stiffness, when identical kinematic forces acted on each pile. This results in a small displacement for a pile that has a large stiffness and large diameter. In Figures 4 (a) and (b), when the input motion doubles, the soil displacement doubles, but the pile displacement is greater than double. Such difference between the pile displacement and the soil deformation is due to the nonlinearity in horizontal behavior of the soil-pile system. When horizontal loads acted on a pile embedded in soil, the horizontal stiffness of the soil-pile system, which is representative of a nonlinear p-y curve, becomes smaller as the pile displacement and horizontal load increase. Therefore, as horizontal loads and horizontal displacement increase by the kinematic effect, the horizontal soil stiffness of the back ground of the pile decreases. Finally, the increase of pile displacement becomes more than that of the soil displacement. Figure 5 shows the relationship between soil displacement and pile displacement, which is the cause of kinematic force. In this figure, the nonlinear relation between soil displacement and pile displacement is identified.



(a) Input acceleration = 0.1g

(b) Input acceleration = 0.2g

Figure 4. Soil & pile displacement along depth (Upper mass = None)

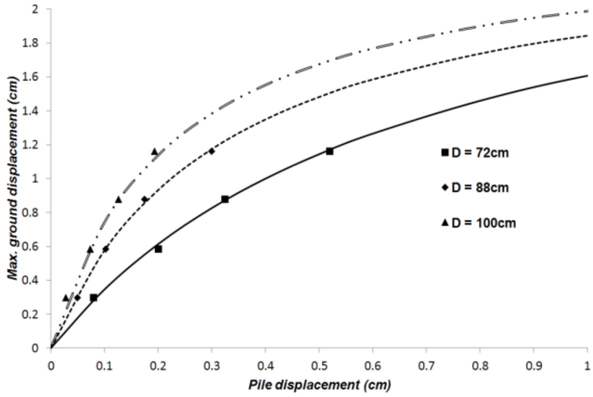
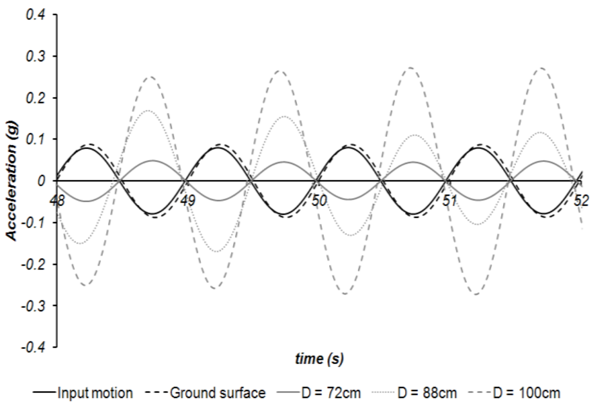


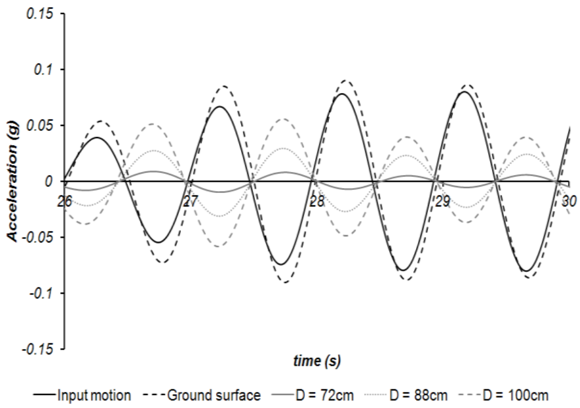
Figure 5. Relation between maximum soil displacement and pile displacement

3.1.2. Inertial effect

To investigate the inertial effect acting on the pile foundation, experiments were performed for an upper mass of 96ton, and 160ton, respectively, on the prototype scale. Figure 6 shows the input acceleration, ground acceleration and acceleration of each pile head, for an upper mass of 96ton, and 160ton, respectively, and input acceleration of 0.1g. As shown in Figure 6, all accelerations measured at the upper mass are out-of-phase with the input acceleration and soil acceleration. This means that the inertial force generated by the upper mass, and the kinematic force generated by the soil movement, act in opposite directions. Moreover, acceleration measured at the upper mass of each pile shows a large difference, according to the pile dimension. This is because of the difference between the input frequency and natural frequency of each structure. Table 4 shows the natural frequency distribution, according to the pile diameter and upper mass. As shown in Table 4, as the natural frequency approaches 1Hz, which is the input frequency, the upper mass acceleration becomes large.



(a) Upper mass = 96ton



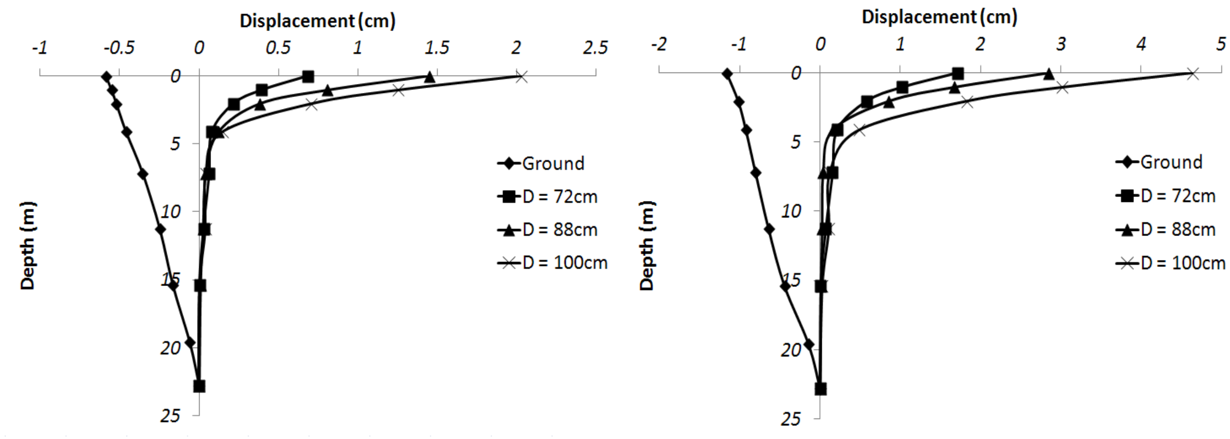
(b) Upper mass = 160ton

Figure 6. Acceleration-time history (Upper mass = 96ton, Input acceleration = 0.1g)

Table 4. Natural Frequency of Soil-Pile Model

	Upper mass = 96ton	Upper mass = 160ton
Diameter: 72cm	0.6 Hz	0.4 Hz
Diameter: 88cm	0.75 Hz	0.55 Hz
Diameter: 100cm	0.9 Hz	0.7 Hz

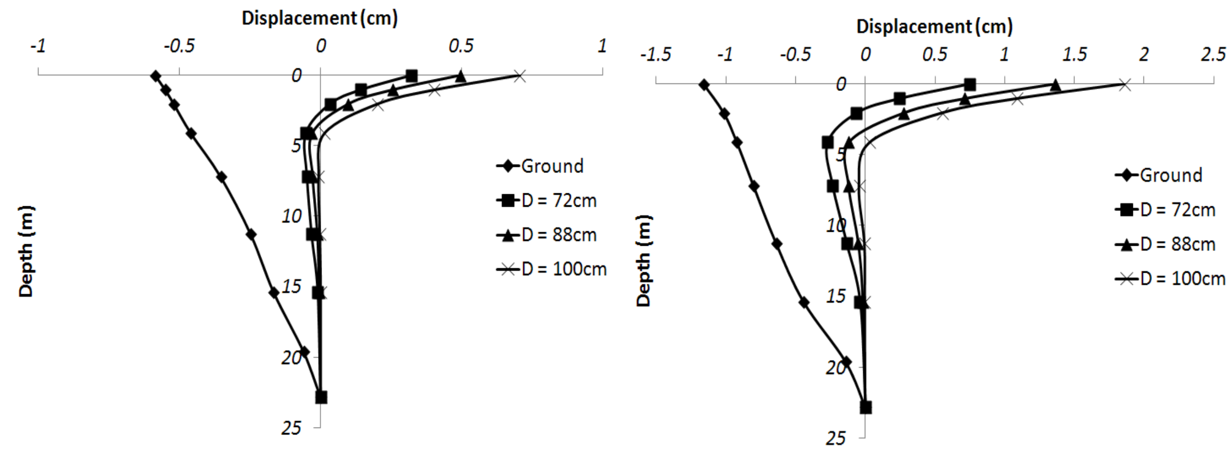
Figures 7 and 8 show the soil and pile displacement, when maximum displacement is occurring for an upper mass of 96ton, 160ton, respectively. Pile displacement was transcribed with positive sign, while soil displacement was transcribed with negative sign, because pile displacement and soil displacement are out-of-phase with each other. As shown in the figures, pile displacement was large when the upper mass was small. This is because amplification of the acceleration at the upper mass largely occurred for an upper mass of 96ton, due to the influence of natural frequency. The magnitude of inertial force, which multiplies the upper mass and the acceleration, was greater for the upper mass of 96ton than for the upper mass of 160ton. This implies that inertial force generated in soil-pile system is largely affected not only by the upper mass, but also by the relation between the input frequency and the natural frequency of the soil-pile system. In the case that both kinematic and inertial effect were generated, pile displacement occurred in the direction of the inertial force, and the maximum pile displacement occurred 5 ~ 25 times greater, than in the case that only kinematic effect was generated. This means that inertial force is dominant for soil-pile interaction in dry sand. Also, in the case that only kinematic effect was generated, pile displacement occurred relatively large at a relatively deep depth (deeper than 10m). However, in the case that both the kinematic and inertial effect occurred, pile displacement either hardly occurred, or occurred in the direction of the inertial force, which was the opposite direction to the kinematic force, in a depth that was deeper than 5m. This implies that inertial force largely has an affect in a relatively shallow depth, and the influence sharply decreases as the depth increases. On the other hand, the kinematic effect applies even at a relatively deep depth. Therefore pile displacement in the lower part of the ground occurred in the opposite direction to inertial force for the case of an upper mass of 160ton, where the inertial force was small, because the influence of kinematic force was dominant.



(a) Input acceleration = 0.1g

(b) Input acceleration = 0.2g

Figure 7. Soil & pile displacement along depth (Upper mass = 96ton)



(a) Input acceleration = 0.1g

(b) Input acceleration = 0.2g

Figure 8. Soil & pile displacement along depth (Upper mass = 160ton)

3.2. Loose Saturated Sand Ground (Liquefiable Ground)

Figure 9 shows the excess pore pressures that occurred in liquefiable soils. As the figure shows, despite liquefaction generally occurring in shallow ground, where there was the condition of low confining pressure, liquefaction confirmed that the ratio of excess pore pressures was 1 at a depth of below 7m. This may have been because the relative density of the upper ground was greater than that of the lower ground, which was caused by using the sand pluviation method with viscous fluid. In addition, the upper ground may have not been fully saturated, so that liquefaction did not occur in the upper ground, but in the lower ground.

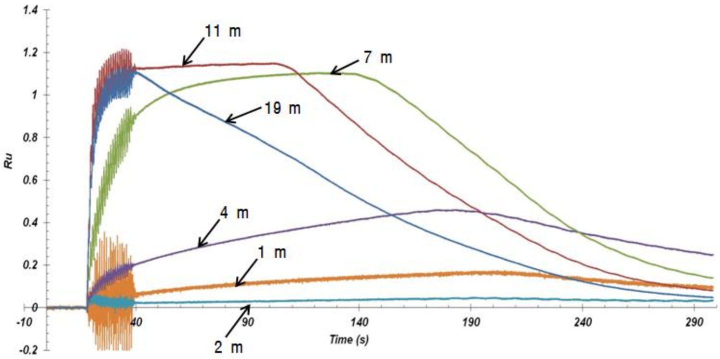


Figure 9. Excess pore pressure in saturated sand ground

3.2.1.Kinematic effect

Figure 10 shows the input acceleration, ground acceleration, and pile head acceleration-time history for an input acceleration of 0.3g in loose saturated sand ground, which is liquefiable ground. The ground acceleration is illustrated at the depth of 7m, which was liquefied. As shown in Figure 10, there were phase differences of 90° between the ground acceleration and the input acceleration in the liquefied ground. Furthermore, the pile head acceleration was in phase with the ground acceleration, and a similar acceleration time history was shown for all of the piles. From these results, it was found that phase difference occurred between input acceleration and ground acceleration in liquefied ground, and the ground displacements in the liquefied ground were greater than those that occurred in the dry sand ground. Moreover, when only kinematic effects were generated, it was found that there were also a similar acceleration time history between the ground and the pile in liquefied ground.

Figure 11 shows the pile and ground displacements in the liquefiable ground with depth, when the maximum ground displacement was occurring, in the condition of only kinematic effects, without inertial effects. As shown in Figure 11, it was found that the ground displacement of maximum 20cm in the liquefied ground was greater than that occurring in the dry sand ground. This is because ground acceleration and input acceleration are out of phase with each other, and thus the relative displacement increased between the ground acceleration and the input acceleration. The ground displacement increases largely until a depth of 7m; the rate of increment of ground displacement decreases in the upper ground, where liquefaction has not occurred. This shows that the upper ground behaved with the same acceleration time history between ground and pile as the dry sand ground. The pile displacement occurred significantly by up to 80%~95% of the ground displacement. Moreover, the differences of displacement between piles that occurred were not great. From the recent research of Yang et al. (2011), when lateral loading was applied to piles which are installed in saturated ground, the lateral subgrade resistance acting on the piles decreases with the rate of excess pore pressure, and subgrade resistance rarely occurs when liquefaction is generated. Therefore, when a large kinematic force was applied to piles in liquefied ground, subgrade resistance was rarely generated at the rear of pile. Thus, it is found that pile displacement was similar to ground displacement.

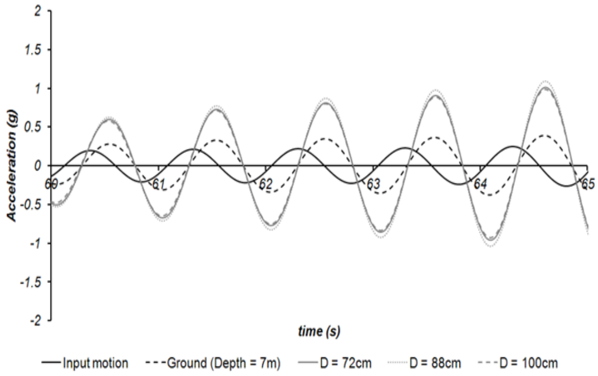


Figure 10. Acceleration-time history
(Upper mass = None, Input acceleration = 0.3g)

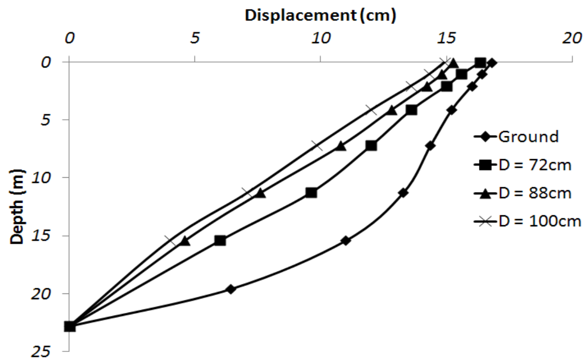


Figure 11. Soil & pile displacement along depth
(Upper mass = None, Input acceleration = 0.3g)

3.2.2. Inertial effect

To confirm the inertial effect in liquefiable ground, a test was conducted with an upper mass of 96ton in the same condition as the no upper mass case test. Figure 12 shows the input acceleration, ground acceleration, and pile head acceleration for an input acceleration of 0.3g, when the upper mass is 96ton. The ground acceleration is illustrated at a depth of 7m, which is liquefied. As shown in Figure 12, there were phase differences of 90° between the ground acceleration and the input acceleration in the liquefied ground. Furthermore, all of the pile head acceleration was out of phase with the ground acceleration, and a similar acceleration time history was shown for all of the piles. From these results, it was found that the inertial force by upper mass and the kinematic force by ground displacement act in opposite directions.

Figure 13 shows pile and ground displacements in liquefiable ground with depth, when the maximum ground displacement was occurring, in the condition of both kinematic effects and inertial effects being applied. As shown in Figure 13, it was found that pile displacement was generated in the same direction as ground displacement, which is the direction of the kinematic force at a depth of below 7m, where liquefaction occurred. On the contrary, pile displacement was generated in the opposite direction to ground displacement, which is the direction of the inertial force at the upper ground, where liquefaction has not occurred. The direction changes of ground displacement at the boundary between liquefied layer and non-liquefied layer correspond with recent research (Finn et al. 2002), which found that a large moment is generated at the boundary between the liquefied layer and the non-liquefied layer. Despite the inertial force and kinematic force acting in opposite directions, and liquefaction not occurring in the upper ground, overall pile displacement is generated in the direction of the kinematic force. From this result, it is found that the kinematic force is the more dominant factor for soil-pile-interaction in liquefied ground, than the inertial force. Therefore, it is found that the behavior of pile displacement was similar to the behavior when only the kinematic effect was generated (Figure 11), at a depth of below 7m, where liquefaction occurred. It means that the existence of inertial force is not a dominant factor for pile displacement in liquefied ground, and this result corresponds with recent research (Han et al. 2011). However, because liquefaction did not occur in the upper ground in this research, it is necessary to verify this result by another test, which generates liquefaction for the whole ground.

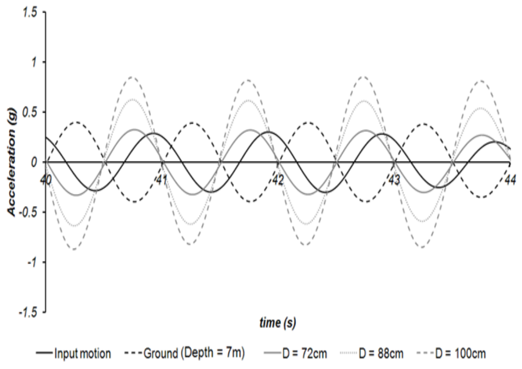


Figure 12. Acceleration-time history
(Upper mass = 96ton, Input acceleration = 0.3g)

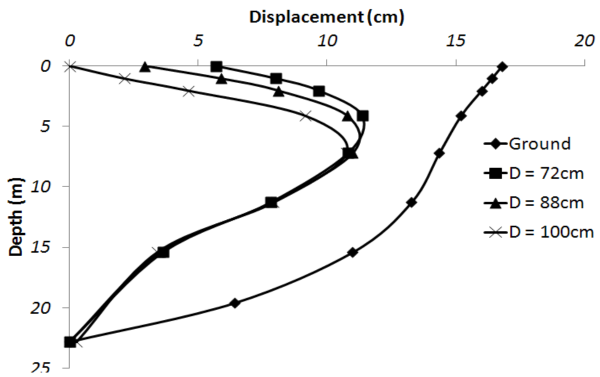


Figure 13. Soil & pile displacement along depth
(Upper mass = 96ton, Input acceleration = 0.3g)

4. CONCLUSIONS

In this research, a series of dynamic centrifuge tests were carried out with different pile diameters installed in dry and loose saturated sand deposit (liquefiable sand), for various conditions of input acceleration and upper mass. The effects of inertial and kinematic force on a pile foundation were analyzed, and the influence of various conditions on each effect was evaluated.

1. In the case of dry sand deposit, the ground acceleration was in-phase with the input motion, and small soil deformation was generated. The pile displacement generated by the kinematic effect was 11% ~ 45% of the soil deformation, and as the pile diameter and horizontal stiffness increased, the pile displacement decreased. In addition, as the input acceleration increased, the ratio of displacement to ground displacement increased. When horizontal loads were applied to the soil-pile system, the horizontal soil stiffness, which was applied at the rear of the pile, became smaller as the lateral load increased. Soil and pile displacement would tend to occur, due to this horizontal non-linearity of the soil-pile system.

2. In the case that both the kinematic and the inertial effect were generated in dry sand, the inertial force generated by the upper mass and the kinematic force generated by the soil movement were out-of-phase, and acted in the opposite direction. In this case, pile displacement occurred in the direction of the inertial force, and the maximum pile displacement was 5 ~ 25 times larger, than in the case where only a kinematic effect was generated. On the other hand, when the depth was greater than 10m, pile displacement either hardly occurred, or occurred in the direction of the kinematic force. This implied that while the effect of inertial force sharply decreased as the depth increased, the kinematic effect applied even at a relatively deep depth.

3. In the loose saturated sand ground, there were phase differences of 90° between the ground acceleration and the input acceleration. Moreover, the ground displacements in the liquefied ground were greater than those that occurred in the dry sand ground. By the kinematic effect, pile displacement occurred significantly by up to 80% ~ 95% of the ground displacement, because of the characteristic behavior in liquefied ground. Lateral subgrade resistance rarely occurred when liquefaction was generated in saturated sand ground. When kinematic force was applied to piles in liquefied ground, subgrade resistance was rarely generated at the rear of pile, and thus it was found that a large pile displacement was generated.

4. In loose saturated sand ground, when both kinematic force and inertial force were applied to a soil-pile structure, it was found that the inertial force by upper mass and the kinematic force by ground displacement were out of phase, and acted in opposite directions. In liquefied ground, pile displacement was generated in the direction of the kinematic force, whereas in non-liquefied ground, pile displacement was generated in the direction of the inertial force. The behavior of pile

displacement was also similar to the behavior when only the kinematic effect was generated, where liquefaction occurred. From this result, it could be found that in liquefied ground, the kinematic force was a more dominant factor for soil-pile-interaction, than the inertial force.

AKCNOWLEDGEMENT

This research was supported by the SNU SIR Group of the BK21 Research Program funded by the Ministry of Education, Science, and Technology of Korea, and by the National Research Foundation (NRF) grant funded by the Korea government (MEST) (No. 2011-0020414).

REFERENCES

Dezi, Francesca., Carbonari, Sandro., Leoni, Graziano. (2010). Static equivalent method for the kinematic interaction analysis of single piles. *Soil Dynamics and Earthquake Engineering Journal.* **30:** 679-690.

Dou, H., and Byrne, PM. (1996). Dynamic response of single piles and soil-pile interaction. *Canadian Geotechnical Journal.* **33:1,** 80-96.

Finn, W.D.L, and Fujita, N. (2002). Piles in liquefiable soils:seismic analysis and design issues. *Soil Dynamics and Earthquake Engineering Journal.* **22:9,** 731-742.

Han, J.T., Choi, J.I., Kim, S.H., Yoo, M.T., Kim, M.M. (2002). Analysis of Dynamic Earth Pressure on Piles in Liquefiable Soils by 1g Shaking Table Tests. *Journal of Korea geotechnical society*. **18:1**, 127-132.

Kim, Nam-Ryong and Kim, Dong-Soo. (2010). A Shear Wave Velocity Tomography System for Geotechnical Centrifuge Testing. *Geotechnical Testing Journal*. **33:6**, 434-444.

Kohji Tokimatsu, Hiroko Suzuki, Masayoshi Sato. (2005). Effects of inertial and kinematic interaction on seismic behavior of pile with embedded foundation. *Soil Dynamics and Earthquake Engineering Journal*. **25:** 753-762.

Ovesen, N. K. (1979). The Scaling Law Relationship. *Proceedings of the 7th European Conference on Soil Mechanics and Foundation Engineering*. **Vol. 4:** 319–323.

Remaud, D. (1999). Piles Under Lateral Forces: Experimental Study of Piles Group, University of Nantes, France.

Scott, R. F. (1980). Analysis of centrifuge pile tests; simulation of piledriving. Report for the American Petroleum Institute OSAPRProject 13. California Institute of Technology, Pasadena, California.

Yang, E.K., Choi, J.I., Kown. S.Y., Kim, M.M. (2011). Dynamic p-y Backbone Curves from 1g Shaking Table Tests. *KSCE Journal of civil engineering*. **15:5:** 813-821.