Dynamic behavior of single pile from 1g shaking table tests

Hyunsung Lim[1], and S. Jeong[1]

[1] School of Civil and Environmental Engineering, Yonsei University, 50, Yonsei-ro, Seoul 03722, Republic of Korea.

ABSTRACT

In this study, the dynamic behavior of a single pile in dry sand was investigated based on 1g shaking table tests. The studies were performed by controlling loading frequencies, acceleration amplitudes, pile head mass and soil conditions. Based on the test results, the resonant frequency of a soil-pile system varies depending on the acceleration amplitude, the relative density of the soil and superstructure mass. Also, it was found that inertia force like acceleration amplitude and superstructure mass, and relation of the resonant frequency of soil-pile system and loading frequency have a great influence on dynamic *p-y* curve.

Keywords: 1g shaking table test, loading frequency, resonant frequency, soil-pile systems, dynamic *p-y* curve

1 INTRODUCTION

The number of large-scale earthquakes has increased worldwide, resulting in many human injuries and substantial property damage. Earthquake-resistance design has become increasingly important to reduce the threat. The behavior of pile foundations under earthquake loading is an important factor affecting the performance of many essential structures.

In the earthquake-resistance design of pile foundation, pseudo-static approach which analyzes the inertial force acting on the pile due to seismic load as an additional load is mainly used, and *p-y* curve method which can consider the nonlinear behavior of the soil in the pseudo-static approach is widely used. The *p-y* curves were developed based on an experiment in which static or cyclic loading was applied to the pile head under various soil conditions (Matlock 1970; Cox et al. 1974, Reese et al. 1974, 1975; API 1987; Murchison and O'Neil 1984). However, the *p-y* curves don't suitably consider soil stiffness and soil inertia effects under seismic loads. Because the *p-y* curves derived from field tests applying static and cyclic loads at the pile head (Rovithis et al. 2009; You et al. 2013).

In this study, the dynamic behavior of soil-pile systems was investigated in dry sand from 1g shaking table tests. The studies were performed by controlling loading frequencies, acceleration amplitudes, pile head mass and soil conditions.

2 1G SHAKING TABLE TESTS

2.1 Testing apparatus

The shaking table has a platform width of 1,500 mm and a platform length of 1,500 mm. The maximum sample weight, acceleration and frequency are 2 tons, 1.1 g and 50 Hz, respectively. A soil box 1,200 × 600 × 800 mm in size was constructed with transparent polycarbonate and aluminum plates. Sponge pads 50 mm thick were placed on the sidewalls of the soil box to reduce the reflection waves in the shaking direction. Fig. 1 shows the 1g shaking table and soil box.

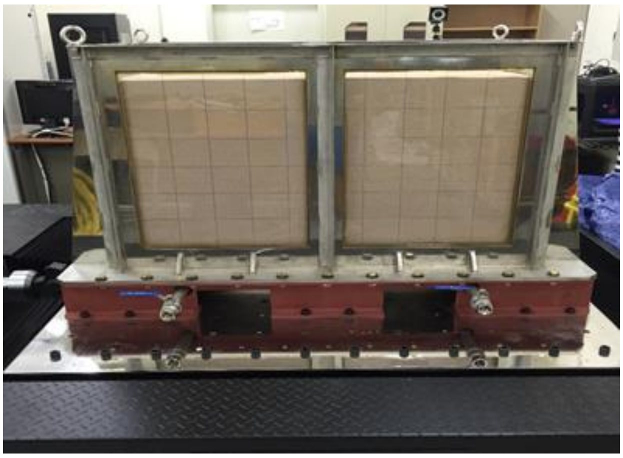

Fig. 1. 1g shaking table and soil box

2.2 Model soil and pile

Jumoonjin sand classified as SP (poorly graded sand, according to the Unified Soil Classification System), with a specific gravity G_s 2.65, an effective grain size D_{10} = 0.38 and a uniformity coefficient C_u = 1.59, was used for the 1g shaking tests. the properties of the test soil are shown in Table 1.

The model pile was made considering the similitude law proposed by Iai (1989). In this study, Type 2 of Iai's similitude law was adopted, because the model ground of dry sand was expected to show cyclic mobility behavior (Choi et al. 2015). The prototype is assumed to be a general steel pipe pile with a diameter of 0.981 m, a thickness of 0.014 m and a length of 17

m. The pile is a flexible and long pile condition. The model pile was made of aluminum alloy (6061-T6) and had a hollow circular section with an outer diameter of 2.0 cm. The embedment depth of 64 cm. The properties of the model pile are summarized in Table 2. The 1g shaking table test device is illustrated in Fig. 2.

Table 1. Physical properties of test soil

Physical properties	Symbol	Properties
Specific gravity	G_s	2.65
Max. dry density	γ_{dmax}	16.2 kN/m^3
Min. dry density	γ_{dmin}	13.6 kN/m^3
Effective particle size	D_{10}	0.38
Uniformity coefficient	C_u	1.59
USCS	-	SP

Table 2. Pile properties

Pile	Scaling factor (λ = 26.72)	Prototype	Model pile
Diameter (cm)	λ	91.44	2.0
Thickness (cm)	λ	1.4	0.2
Pile depth (cm)	λ	1,710	64
Flexural rigidity (kg□cm^2)	$\lambda^{4.5}$	8429.83	0.0032

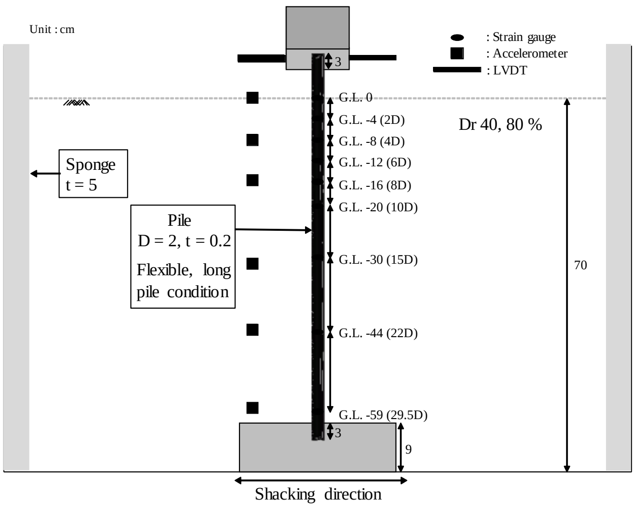

Fig. 2. Sectional of model tests

2.3 Testing program

Sweep tests were conducted to evaluate the resonant frequencies of the soil-pile systems under various acceleration amplitude. The resonant frequencies were derived from the measured accelerations at the superstructure mass.

The input wave was as a sine wave. Because the acceleration amplitude and loading frequency can be easily changed. The input wave was applied at the base of the soil box for approximately 5 seconds. The loading frequencies used in the tests were calculated from the resonant frequencies (f_r) of the soil-pile systems. The loading frequencies range from 0.4f_r Hz to 1.6f_r Hz. The test programs are summarized in Table 3.

Table 3. Test program

Case	Relative density of soil (%)	Acceleration Amplitude (g)	Loading Frequency (Hz)
1	40	0.098, 0.154, 0.22, 0.3	Sweep test (1~20 Hz)
2	80	0.098, 0.154, 0.22, 0.3, 0.4	Sweep test (1~20 Hz)
3	40	0.098, 0.154, 0.22, 0.3	0.4f_r ~ 1.6f_r
4	80	0.098, 0.154, 0.22, 0.3, 0.4	0.4f_r ~ 1.6f_r

*Note: f_r = resonant frequency of soil-pile system

3 TEST RESULTS AND ANALYSES

3.1 Resonant frequency of soil-pile systems

The resonant frequency of the soil-pile systems was estimated by analyzing the acceleration response of the superstructure mass after the model test by applying the chirp signal of 1 ~ 20 Hz for 200 seconds.

The resonant frequencies of the soil-pile systems were analyzed under various conditions. Fig. 3 shows change in the resonant frequency with the acceleration amplitude of the soil-pile systems. It was found that the resonant frequency of the soil-pile-systems as the acceleration amplitude increases. This is similar to the results reported by Yang et al. (2010), showing a decrease in the resonant frequency for each acceleration amplitude due to the reduced elastic modulus of the soil. In addition, the resonant frequency of the soil-pile systems for the relative density of 40 %, is smaller than that for the relative density of 80 % due to the increased stiffness in the soil with a higher relative density.

Fig. 4 shows change in the resonant frequency with the superstructure mass of the soil-pile systems. As shown in Fig. 4, the resonant frequency decreases as the superstructure mass increases. In general, the mass of an object and its natural frequency are known to be inversely proportional, and therefore, the resonant frequency is considered to decrease because the mass of total system increases.

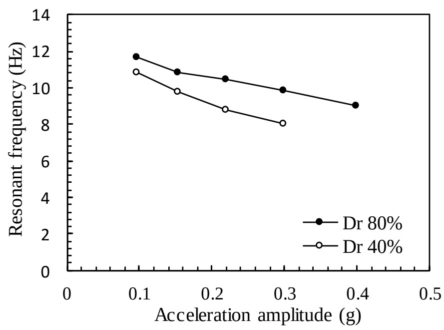

Fig. 3. Resonant frequency of soil-pile systems at various acceleration amplitude

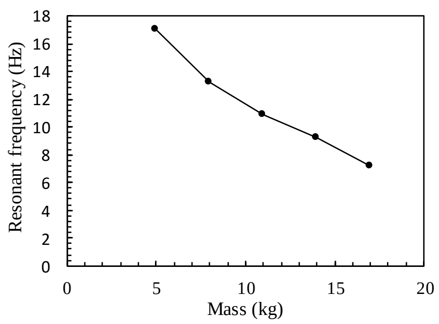

Fig. 4. Resonant frequency of soil-pile systems at various superstructure mass

3.2 Typical experimental dynamic *p-y* curves

Fig. 5 shows typical dynamic *p-y* curves in dense sand (D_r 80%) at different depths. The input acceleration was 0.154 g, and the input frequency was the resonant frequency (1.0 f_r Hz). As shown Fig. 5, The curves show nonlinear hysteric shapes. The curves are flat near the surface and become stiffer with depth. The reason is that the soil confining stress is low near the surface, and the soil confining stress increases as the depth is deepened. The soil resistance is dramatically decreased under unloading condition due to soil-pile separation. It is that the movement of the soil does not follow the movement of the pile.

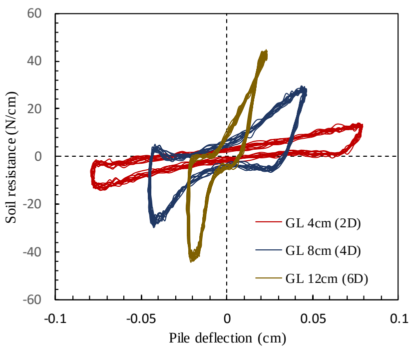

Fig. 5. Dynamic *p-y* curves at depths

3.3 Effect of loading frequencies

Characteristics of dynamic *p-y* curve for various loading frequencies was investigated by 1g shaking table tests. Fig. 6 and 7 show the experimental dynamic *p-y* curves for different loading frequency in dense sand. Figure 6 shows the dynamic *p-y* curves when the acceleration amplitude is 0.154 g, and Fig. 7 shows the time when the acceleration amplitude is 0.4 g. As the frequency ratio approaches 1.0, soil resistance increases under low-level shaking (0.154g) and does not increase further when a large displacement beyond some limit displacement occurs under strong shaking (0.4g). As the frequency ratio approaches 1.0, the pile displacement further increases regardless of depth and the slope of dynamic *p-y* curve decreases. This phenomenon is considered to be due to the fact that resonance occurs due to the approach of the loading frequency to the resonant frequency, which causes a large response of the soil-pile-system.

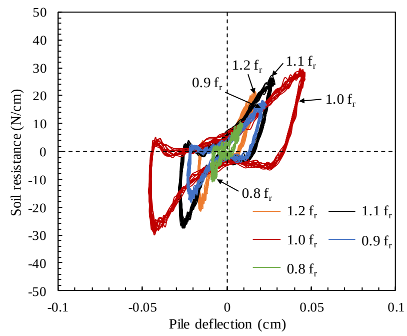

Fig. 6. Experimental dynamic *p-y* curve for various loading frequencies (D_r 80%, input acc. 0.154g, depth 8 cm)

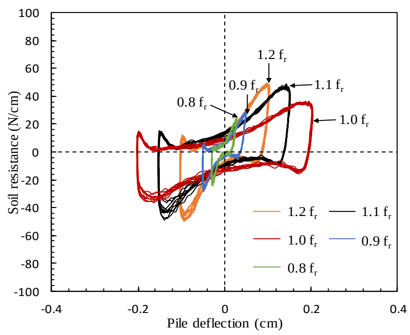

Fig. 7. Experimental dynamic *p-y* curve for various loading frequencies (D_r 80%, input acc. 0.4g, depth 8 cm)

3.4 Effect of acceleration amplitudes

Fig. 8 shows the experimental dynamic *p-y* curves for various acceleration amplitude with loading frequency of 1.0f_r Hz (resonant frequency). The larger the acceleration amplitude, the larger the relative displacement and soil resistance indicated due to the larger inertial force at the pile head. Soil resistance does not increase further regardless of the acceleration amplitude when a large displacement beyond some limit displacement occurs. It means that the soil resistance did not increase further when there was displacement large enough to generate the ultimate soil resistance.

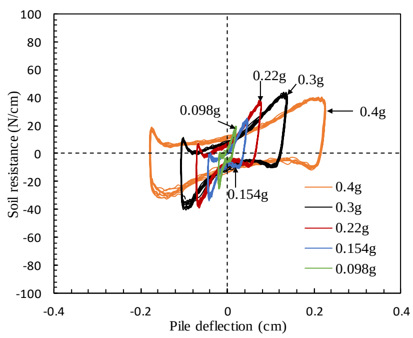

Fig. 8. Experimental dynamic *p-y* curve for various acceleration (D_r 80%, loading freq. 1.0f_r Hz, depth 8cm)

3.5 Effect of superstructure mass and soil conditions

Characteristics of dynamic *p-y* curve for different superstructure mass and soil condition were investigated by 1g shaking table tests. Fig. 9 shows dynamic *p-y* curve for various superstructure mass. It was found that the slope of the dynamic *p-y* curve decreases as the superstructure mass becomes heavy. Also, as the superstructure mass becomes heavy, the relative displacement of the soil and pile increases. the superstructure mass affects the inertia force applied to the pile. The larger the mass of the structure, the greater the inertia force, and therefore the slope of the dynamic curve and the relative displacement of the soil and pile become larger.

Fig. 10 shows dynamic *p-y* curve for soil conditions. As shown in Fig. 10, the soil resistance for the relative density of 40% is less than that for the relative density of 80% because the soil stiffness increases at higher relative densities. It can be seen that the slope of the dynamic *p-y* curve becomes more stiff in dense sand.

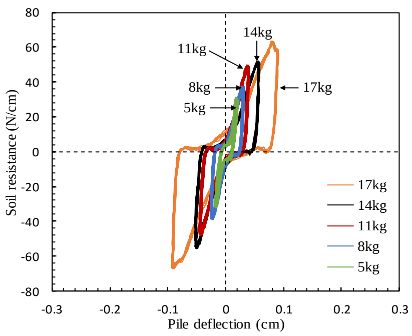

Fig. 9. Experimental dynamic *p-y* curve for various superstructure mass (D_r 80%, acc. 0.154g, freq. 1.0f_r Hz, depth 8cm)

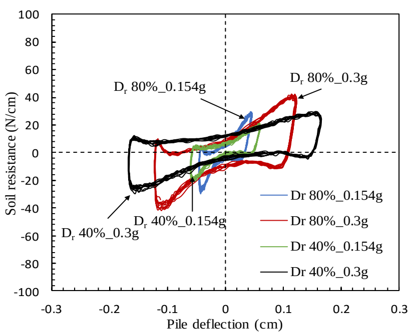

Fig. 10. Experimental dynamic *p-y* curve for soil condition (acc. 0.154g, 0.3g, freq. 1.0f_r Hz, depth 8cm)

4 CONCLUSION

In this study, a series of 1g shaking table tests were carried out on soil-pile systems under various conditions to analyze the dynamic behavior of the soil-pile systems. Based on the test results and these analyses, the results of the investigations are summarized below.

1) The sweep tests determined that the resonant frequency of a soil-pile system varies depending on the input acceleration and the relative density of the soil due to the change in the soil stiffness. It is also dependent on the superstructure mass.

2) Based on the model tests, the closer the loading frequency is to the natural frequency of the soil-pile system, the smaller the slope of the dynamic *p-y* curve due to the resonance. It was also found that the slope of the dynamic *p-y* curve becomes stiffer in dense sand.

3) In addition, it was found that as the acceleration amplitude and the mass of the superstructure increase, the slope of the dynamic *p-y* curve decreases due to the increased inertial force.

ACKNOWLEDGEMENTS

This work was also supported by a grant(code19SCIP-B119960-04) from Construction Technology Research Program funded by Ministry of Land, Infrastructure and Transport of Korean government.

REFERENCES

American Petroleum Institute (API) (1987). Recommended practice for planning, designing and constructing fixed offshore platforms, API Recommendation Practice 2A (RP 2A), 17th edition, pp. 68-71

Cox, W. R., Reese, L. C., and Grubbs, B. R. (1974). Field testing of laterally loaded piles in sand. Proc. of the 6th Offshore Technology Conference, Houston, Texas, Paper OTC 207

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

El Naggar, M. H., and Bentley, K. J. (2000). Dynamic analysis for laterally loaded piles and dynamic *p-y* curves. Canadian Geotechnical Journal, 37, pp. 1166-1183.

Iai, S. (1989). Similitude for shaking table tests on soil-structure-fluid model in 1g gravitational field. Soils and Foundations, 29(1), pp.105-118.

Matlock, H. (1970). Correlations for design of laterally loaded piles in soft clay. Proc. of the 2nd Annual Offshore Technology Conference, 1, Houston, Texas, pp. 577-594.

Murchison, J. M., and O'Neil, M. W. (1984). Evaluation of *p-y* relationships in cohesionless soils. Analysis and Design of Pile Foundations, ASCE, pp. 174-191.

Reese, L. C., Cox, W. R. and Koop, F. D. (1974). Analysis of laterally loaded piles in sand. Proc. of the 6th Offshore Technology Conference, Houston, Texas, 2, No. 2080, pp. 473-484.

Reese, L. C., Cox, W. R., and Koop, F. D. (1975). Field testing and analysis of laterally loaded piles in stiff clay. Proc. of the 6th Offshore Technology Conference, Houston, Texas, pp. 671-690.

Rovithis, E., Kirtas, E., and Pitilakis, K. (2009). Experimental *p-y* loops for estimating seismic soil-pile interaction. Bulletin of Earthquake Engineering, 7(3), pp. 719-736.

Yoo, M. T., Choi, J. I., Han, J. T., and Kim, M. M. (2013). Dynamic *p-y* curves for dry sand from centrifuge tests. Journal of Earthquake Engineering, 17, pp. 1082-1102.