Evaluation of dynamic pile group effect by shaking table tests

Évaluation d'effet de pile groupe dynamique par le test de secouage table

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ABSTRACT: Shaking table tests are performed on model pile groups to investigate the mechanics of dynamic pile-soil interaction, and to evaluate the dynamic pile group effect. Tests are executed on a single pile as well as group piles(3×3) varying a pile spacing from 3D to 8D. A lumped mass is located on top of piles to simulate a superstructure. Dynamic p-y curves of the single pile and the group piles are obtained from the tests and compared with the backbone slopes of API cyclic p-y curves. From the comparisons, dynamic pile group effects are evaluated in terms of a pile depth, a shaking frequency, and a shaking intensity.

RÉSUMÉ: Le test de secouage table s'exécute sur maquette de pile groupe pour examiner le mécanisme d' interaction de pile-sol dynamique et évaluer l' effet de pile groupe dynamique. Test s'exécute sur seul pile et pile groupe(3×3) de l' espace de 3D a 8D. Substance trés lourde est située en haut de pile pour simuler superstructure. P-y courbe dynamique de seul pile et pile groupe est obtenue par test et elle est compare avec colonne pente de courbe d' API cyclique p-y. En conséquence de la comparaison, l' effect de pile groupe dynamique est evalué à l' égard de profondeur de pile, fréquence de secouage et intensité de secouage.

1 INTRODUCTION

The group piles under dynamic loads are believed to exhibit some softening behavior due to the pile-soil interaction phenomena. This group pile effect would be a function of the characteristics of shakings, soils, piles, and pile arrangements.

Finn & Gohl(1992) investigated the influence of the pile spacing on the pile group effect executing shaking table tests on a single pile and 2× 2 group piles embedded in a dense sand layer. They analyzed the test results using SPASM8(Matlock et al. 1979). It was observed that the dynamic pile group effect would be negligible when the center-to-center pile spacing is larger than 6D.

Dou & Byrne(1996) utilized the hydraulic similitude technique to run the shaking table tests on a single pile in dense sands and obtained the experimental p-y curves from the moment distribution curves using a simple beam theory, where they observed the API p-y curves underestimate the soil resistance at shallow depths for the case of strong shakings.

In this research, 1-g shaking table tests are executed on a single pile and group piles(3×3) embedded in dense sands to observe the pile group effects in terms of the characteristics of input shakings and pile-soil systems. To this end, the experimental p-y curves are obtained from the test results using a simple beam theory, and compared with API p-y curves.

2 SHAKING TABLE TEST PROGRAMS

A test box is made of 2.0cm thick plexi-glass, whose size is 1.5m long, 1.0m wide and 0.7m deep. The minimum distance between the sidewall of the test box and the pile shaft was 63D, so that the friction between the wall and soils can be neglected. 5.5cm thick sponges are attached to the inside faces of the box to reduce the rigid boundary effects, and sandpapers are attached to the bottom of the box to prevent the slip between soils and the bottom.

Hollow aluminum pipes are used as model piles. The physical properties of model piles are: outer diameter 14mm, thickness 1mm, and length 70cm. The flexural rigidity(EI) is 6.19×10^5 N·cm^2, and the elastic modulus(E) is 70Gpa. The embedded pile length was average 60cm.

Pile tips were inserted in the test box to prevent the rotation and the translation. The piles were bolted to the pile cap, which was designed to arrange the center-to-center pile spacing to be 3, 6, or 8 pile diameters. A lumped mass was put on top of piles to simulate the inertial force caused by a superstructure. In the case of a single pile, the weight of the lumped mass was 0.86kg and for 3×3 group piles, the weight of it was 7.7kg(0.86kg× 9 piles), so that each pile would support the same weight.

In total, 36 strain gauges, 4 accelerometers, and 2 LVDTs are instrumented as shown in Figure 1. Strain gauges are attached at the outside of piles to obtain the time varying moment distribution curves along the pile shaft. The electrical wires of strain gauges are pulled out through the inside hole of the pile. In the case of group piles, three selected piles are instrumented. Instrumented piles have 6 pairs of strain gauges placed at 0, 5, 10, 17.5, 25 and 40 cm depth from the ground surface. In this paper, all the discussions are made for the measured data of the center pile.

The accelerometers are installed at the center of gravity of the lumped mass to obtain the inertial force acting on piles, and at the various depth in the free field to measure the ground accel-

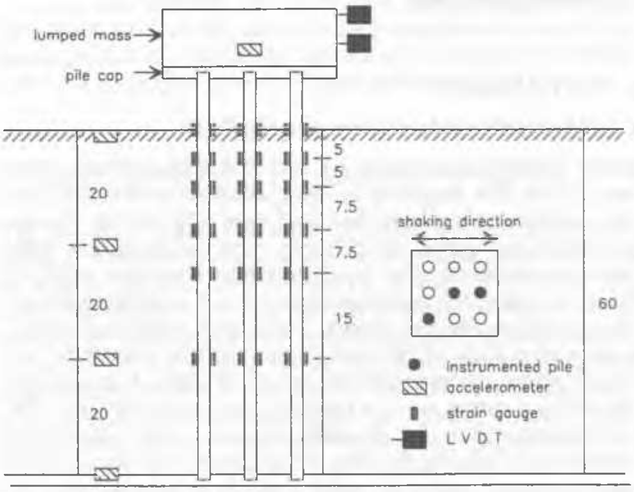


Figure 1. Schematic drawing of test set-up

eration response. 2 LVDTs are installed to measure the lateral displacement and the rotation of the lumped mass.

The average particle size of model sands(D_{50}) is 0.58mm(with the coefficient of uniformity(c_u) of 1.68) and the maximum and the minimum dry densities of the sand are 1.66 ton/m^3 and 1.33 ton/m^3, respectively. Dense sand ground was formed using the vibration compaction. The piles were placed according to the desired center-to-center pile spacing, which were fixed to the pile cap to prevent the relative displacement during vibration. Model grounds were vibrated with the sine wave of frequency 20Hz and amplitude 0.4g for 4 minutes after sands were poured in the box. The vibrating compaction process was repeated 7 times, and each time, the same weight of sands were poured. The relative density of sand grounds was 70% in average. After each test, the settlement of ground was measured, and the residual density of the ground was recalculated. The change in the density of the ground before and after tests was minimal.

The center-to-center pile spacing of 3× 3 pile groups are varied to be 3, 6 and 8 pile diameters. The frequency of input acceleration was varied from 5 to 20Hz, and the amplitude of the peak acceleration was varied from 0.1g to 0.4g .

3 EXPERIMENTAL P-Y CURVES

Experimental p-y curves at a certain time step can be obtained from moment distribution curves along pile shafts using a simple beam theory. Pile deflection y_{pile} can be obtained by a double integration of the moment distribution curve, and soil resistance p by a double differentiation as shown in Equation 1.

$$y_{pile} = \iint \frac{M(z)}{EI} dz, \qquad p = \frac{d^2M(z)}{dz^2} \qquad (1)$$

where EI=flexural rigidity, M(z)=bending moment at the depth of z.

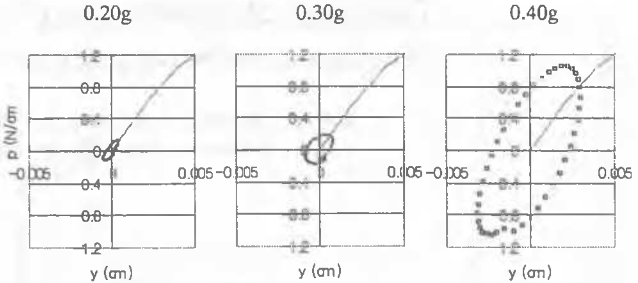
Measured bending moments are only known at certain discrete locations so that a curve-fitting technique is necessary to obtain the continuous data of the pile deflection and soil resistance. In this research, the cubic spline fitting method(Yan & Dou 1991) was used. The noises in moment data were removed using the bandpass filtering method. The constraints imposed in the fitting process are that there is no translation and rotation at the pile tip and the soil resistance at the soil surface is zero. From the double integration and the double differentiation of the fitted curves, the p and the y_{pile} are obtained, respectively.

The y of the p-y curve is the relative displacement between soils and pile. Therefore, the soil displacement around the pile y_{soil} must be subtracted from y_{pile} to obtain the y. The y_{soil} can be obtained by the double integration of acceleration data at each depth in the free field. The resulting y_{soil} was, however, almost the same as the input displacement of the shaking table, thus the y_{soil} was neglected here.

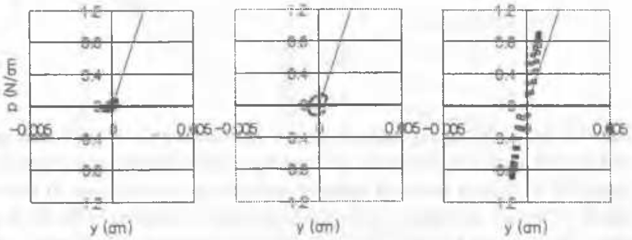
4 TEST RESULTS

4.1 *The experimental p-y curves of a single pile*

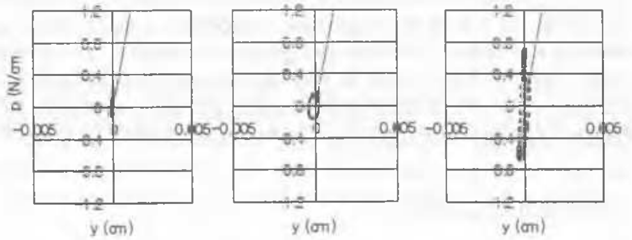
Figure 2 shows experimental p-y curves at depths of 5cm, 10cm and 17.5cm. The frequency of input accelerations was 5Hz, and the amplitude of accelerations varied from 0.2g to 0.4g. The experimental p-y curves are obtained from the oscillation cycle when the amplitude of an input acceleration becomes stable. In the same figure, the backbone slopes of API recommended cyclic p-y curves are also shown, which were computed using a peak friction angle of 38° and the soil modulus parameter k of 61,000 kN/m^3 recommended for dry dense sands. It is seen that the API p-y curves are in a relatively good agreement with the experimental curves for all depths for low to mid acceleration levels(0.2g-0.3g). For the case of 0.4g peak acceleration, however, the cyclic curves are softer than those deduced from the experiments. It is noticed in the experimental curves that the hysteresis loop becomes larger as the peak input acceleration increases or the soil depth gets shallower, which may reflect larger dissipation of energy under those conditions.



(a) Depth 5cm



(b) Depth 10cm



(c) Depth 17.5cm

Figure 2. Experimental p -y curves of a single pile (input frequency: 5Hz)

4.2 *The experimental p-y curves of group piles*

4.2.1 *The influence of the amplitude of input accelerations*

Figure 3 shows the experimental p-y curves of group piles for various level of peak input accelerations at depths of 5cm, 10cm and 17.5cm. The center-to-center pile spacing was 3D, and the frequency of input accelerations was 5Hz. At the shallow depth of a pile with 5cm(3.5xpile diameter), group pile effect appears clearly even under the relatively low level of acceleration(0.2g), the experimental p-y curves becoming softer than the API curves which represent the behavior of single piles. At the depth of 10cm, the group pile effect appears for the tests under mid to high levels of shakings(0.3g-0.4g), while it appears only under the strong shaking(0.4g) at the depth of 17.5cm(14.5xpile diameter).

Brown et al.(1988) suggested the p multiplier factor concept to obtain the p-y curve of group piles from the p-y curve of a single pile. Table 1 shows p multiplier factors obtained from the p-y curves in Figure 3. The p multiplier was determined dividing the slope of an experimental p-y curve by the backbone slope of API p-y curve. The maximum value of p multiplier was set to be 1. The multiplier being less than one means that the group piles

Table 1. p multiplier factors

Amplitude of Input accelerations	p multiplier factor		
	Depth 5cm	Depth 10cm	Depth 17.5cm
0.1g	1.00	1.00	1.00
0.2g	0.54	1.00	1.00
0.3g	0.32	0.70	1.00
0.4g	0.20	0.44	0.60

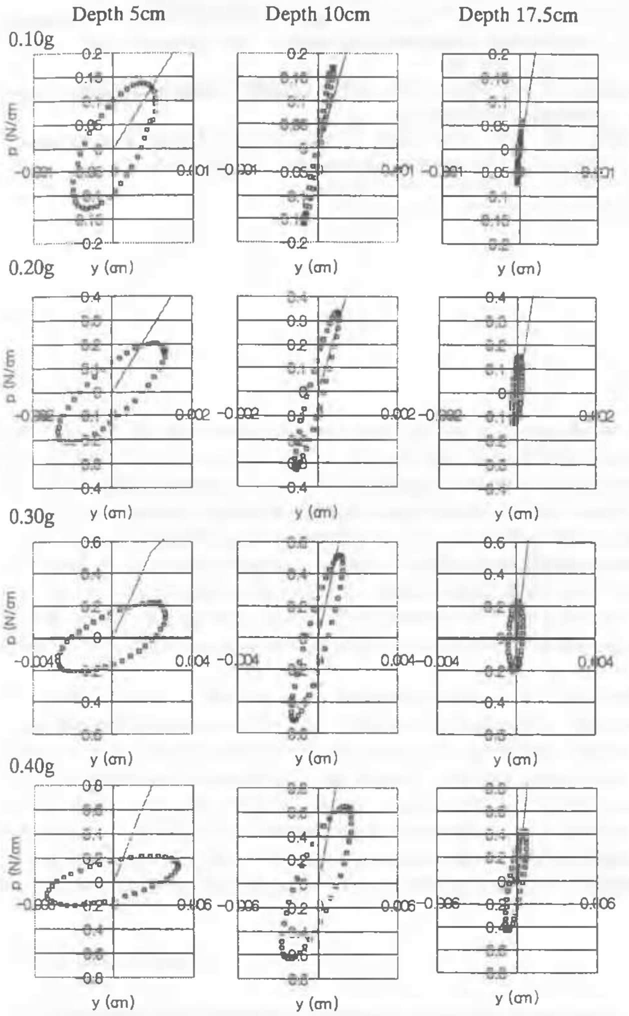


Figure 3. Experimental p-y curves of group piles for various level of peak accelerations (s=3D, input exciting frequency: 5Hz)

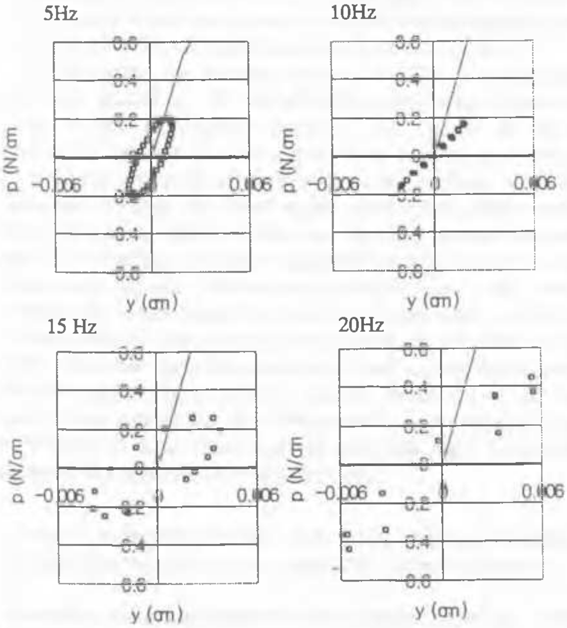
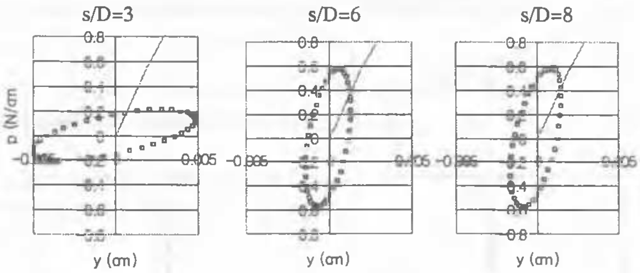
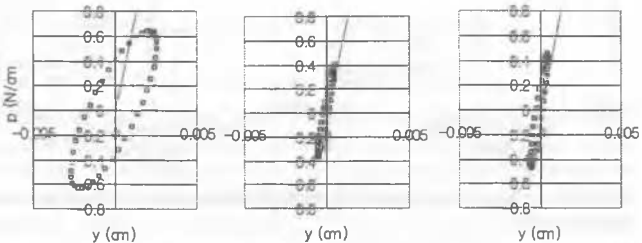


Figure 4. Experimental p-y curves of group piles for different frequency of input accelerations (s=3D, Depth: 5cm, peak acceleration: 0.20g)



(a) Depth 5cm



(b) Depth 10cm

Figure 5. Experimental p-y curves of group piles (input acceleration: 5Hz, 0.40g)

behave softer than the single pile. As the peak input acceleration increases, or the soil depth becomes shallower, the p multiplier decreases due to the increment of the pile group effects.

4.2.2 Tthe influence of the frequency of input accelerations

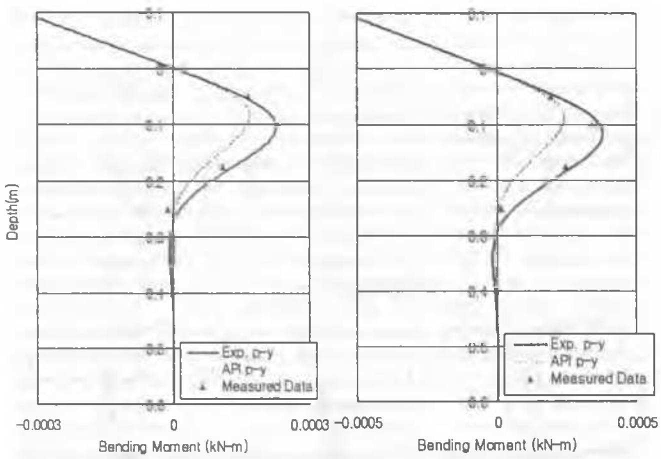
Figure 4 shows the p-y curves for the various frequencies of input accelerations. The amplitude of peak base acceleration was 0.20g, and the frequency of input acceleration varied from 5Hz to 20Hz. It is observed that the maximum pile deflections(y) and, thus, the maximum soil reactions(p) increase as the acceleration frequency increases toward the natural frequency of the pile-soil system which was estimated, by a sweep test, to be around 20Hz.

4.2.3 The influence of the center-to-center pile spacing

Figure 5 shows the p-y curves(measured at center piles) for different center-to-center pile spacings. The amplitude and the frequency of input acceleration was 0.4g and 5Hz, respectively. For the pile spacing of 3D, the group effect is clearly observed from the softened experimental p-y curves compared with the backbone slope of the API cyclic p-y curves. For the pile spacings of 6D and 8D, however, the group pile effects do not appear. Therefore, it can be said here that the group piles with larger pile spacings than 6D would not experience the group pile effect, even if it is not clear from what spacing it is so.

5 APPLICATION OF EXPERIMENTAL P-Y CURVES

The nonlinear response of a pile to lateral loading can be computed in terms of moment, shear, and deflection using the finite difference program LPILE(Reese & Wang 1997). Figure 6 shows the prediction of pile bending moment distribution along the length of pile for the tests under 0.3g and 0.4g peak base accelerations. It may be seen that the API recommended p-y curves underestimate bending moments for the both of tests by a significant amount. In the same figure, the bending moment distribution calculated by the LPILE program using modified API p-y curves which are constructed by multiplying the p-multipliers to the original API p-y curves are shown, where it is seen to agree well with the measured values.



(a) 0.3g (b) 0.4g

Figure 6. Computed and measured bending moments (s=3D, input acceleration: 5Hz)

6 CONCLUSIONS

The following conclusions are drawn from the comparisons of the shaking table test results on a single as well as group piles with the calculated results obtained by API recommended procedures.

1. The backbone slopes of API cyclic p-y curves of a single pile subjected to a dynamic loading are in a good agreement with the experimental p-y curves of a single pile for all depths for low to mid acceleration levels(0.2g-0.3g). However, for strong shakings(0.4g), the API p-y curves are estimated to be softer than the experimental p-y curves.
2. At the shallow depth of a pile(3.5xpile diameter), the group pile effect appears clearly even under the relatively low level of acceleration(0.2g). As a result of it, the experimental p-y curves of group piles become softer than the API p-y curves. At the depth of 7 pile diameters, the group effect appears under the strong shaking(0.3g-0.4g), while it appears only under the strong shaking(0.4g) at the deeper depth(14.5xpile diameter) of a pile.
3. The magnitudes of the maximum pile deflections and the maximum soil reactions of piles increase rapidly as the shaking frequency increases toward the natural frequency of the pile-soil system.
4. For the center-to-center pile spacings of 6 pile diameters or bigger, no pile group effects are observed.
5. It is found that the response of group piles in terms of bending moments under the dynamic lateral loading is significantly underestimated if the API recommended p-y curves are used for the calculation, while the bending moments, which are calculated along the pile length using the modified API p-y curves which are constructed by multiplying p-multipliers to the original API p-y curves, agree well with the measured values. Thus, it is recommended to use the concept of p-multipliers in the process of the API p-y curve construction to include the pile group effects.

REFERENCES

Brown D.A., Morrison C. & Reese L.C. 1988. Lateral Load Behavior of Pile Group in Sand. *Journal of Geotechnical Engineering* 114(11): 1261-1276.

Dou H. & Byrne P.M. 1996. Dynamic Response of Single Piles and Soil-Pile Interaction. *Canadian Geotechnical Journal* 33: 80-96.

Finn W.D. & Gohl W.B. 1992. Response of Model Pile Groups to Strong Shaking. In Prakash S.(ed.), *Piles under Dynamic Loads*: 27-55. ASCE.

Matlock H., Foo S., Tsai C. & Lam I. 1979. *SPASM 8 – A Dynamic Beam-Column Program for Seismic Pile Analysis with Support Motion*. Fugro Inc.

Reese L.C. & Wang S.T. 1997. *LPILE*^{PLUS}*3.0 for Windows User's Manual*. Ensoft Inc.

Ting J.M. 1987. Full Scale Cyclic Dynamic Lateral Pile Response. *Journal of Geotechnical Engineering* 113(1): 30-45.