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STUDY ON P-Y CURVE FOR PILES SUBJECTED TO LATERAL FLOW OF LIQUEFIED GROUND

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ABSTRACT

Liquefaction-induced large ground deformation has caused severe damage to pile foundations of buildings, bridges, and waterfront structures. Several case histories have been reported in the literature from the 1964 Niigata, and 1995 Kobe earthquakes. Therefore, prediction of the force acting on piles due to liquefaction-induced large ground displacement is of major concern. The lateral response of piles is frequently evaluated using the p-y method, which defines the relation between lateral soil pressure and relative displacement of soil and piles. This approach requires that an appropriate p-y relationship be adopted considering soil conditions. This paper aims to study p-y relation for piles subjected to a large deformation of soil during liquefaction-induced lateral spreading which was derived by shaking table model tests on large pile groups, 6×6 and 11×11. Results show that the shape of the p-y curve is completely different from other recommended relations. The effect of group interaction on the p-y curve was investigated by establishing the curve for both single pile and the pile group. In addition, the effect of pile position in the pile group was found to be significant. Variation of soil lateral pressure showed a fairly good agreement with the velocity of soil lateral flow, confirming the viscous behavior of liquefied sand. Results from this study seem to suggest that liquefied soil could be perceived as a viscous fluid, and application of p-dy/dt relation is recommended for the numerical modeling of liquefied soil flow.

Keywords: Liquefaction, pile group, lateral force, p-y curve, velocity

INTRODUCTION

Deep foundations located in loose sandy ground near waterfront structures or sloped ground are susceptible to large ground displacement due to extensive liquefaction. Several examples have been reported in the literature from the 1964 Niigata, 1983 Nihonkai-Chubu and 1995 Kobe earthquakes (Hamada et al. 1986; Tokimatsu and Asaka 1998). Significant damage to pile foundations manifested the importance of the kinematic effect due to ground-lateral movement. Therefore, properly understanding the behavior of pile foundation during lateral soil flow is of major concern to both academicians and practitioners. Although the dynamic behavior of pile foundation in dry soil has been investigated in detail, their behavior has not been well studied in the case of a large ground flow of liquefied sand.

The lateral response of piles is frequently evaluated using p-y method, which defines the relation between lateral soil pressure and the relative displacement of soil and pile. This approach requires that an appropriate p-y relationship be adopted, considering soil conditions. Although appropriate methods have been developed to define p-y curves for non-liquefied sand (Reese et al., 1974), considerable uncertainty remains in dealing with liquefied sand. An application of the reduction factor to the p-y

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curve of non-liquefied soil or relations developed for soft clay is currently being used to model liquefied soil. Although, some recent studies (Tokimatsu and Suzuki 2004 and Rollins et al. 2005) were carried out to more fully understand the behavior of p-y curve in liquefied soil (Fig. 1), their studies were mainly concerned with either the cyclic behavior or smaller soil deformation, while, in reality, piles undergo large soil deformation in the case of liquefaction-induced lateral spreading. Orense et al. (2000) have run tests on piles utilizing a large laminar box, and have found that soil stiffness decreases as relative displacement between soil and pile increases.

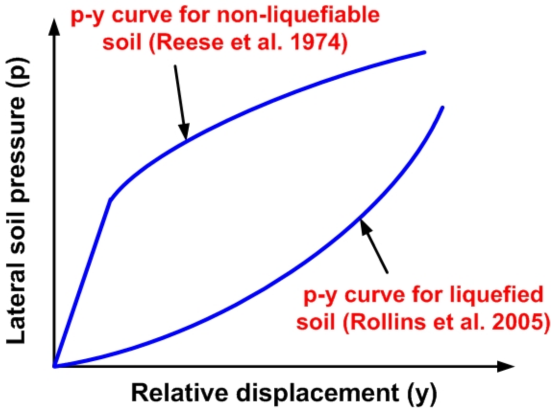


Figure 1. p-y curves for liquefied and non-liquefied soil

This paper aims to study p-y relation for piles undergoing large deformation of soil during liquefaction-induced lateral spreading which was derived by shaking table model tests on large pile groups, 6×6 and 11×11.

SHAKING TABLE MODEL TESTS

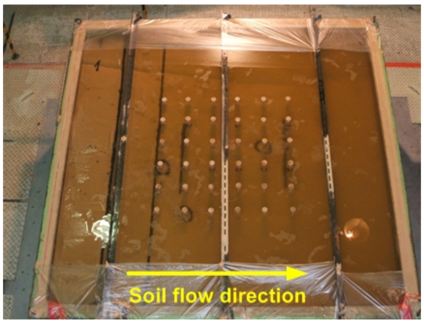
A series of shaking table model tests on pile foundation were carried out. Since the purpose of this study was to investigate the behavior of a large pile group in liquefaction-induced lateral soil movement, tests were run mainly on two pile group configurations, 6×6 and 11×11. In addition, a test was performed while some piles were removed to investigate the interaction effect. Test details are provided in Table 1 and the plan view of models are shown in Fig. 2. In test 1, pile spacing was 5 times the pile diameter (D), while in test 2, it was reduced to 2.5D. As a result, the number of piles was increased from 6×6 to 11×11. In test 3, only instrumented piles were remained and other dummy piles were removed. Hence, front row piles could be considered as single piles.

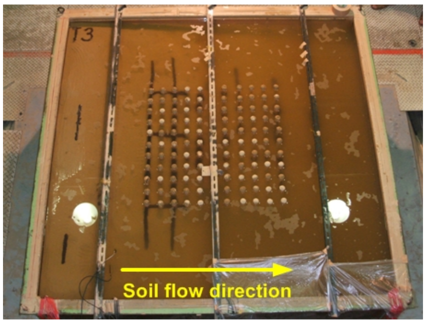
Configuration of the ground model was a gently sloped liquefiable soil deposit made of Toyoura sand with the relative density of around 35%. Piles, which were used in this study, are made from Poly Carbon (Table 2). Piles were fully instrumented by strain gauges and several sensors were embedded in the ground model including accelerometers, pore water pressure transducers, and inclinometers.

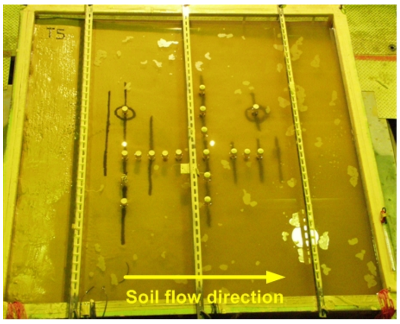
Table 1. Configuration of shaking table model tests

Test	Ground model	Pile configuration	Spacing
Test1	Single liquefied layer	6×6	5D
Test2	Single liquefied layer	11×11	2.5D
Test3	Single liquefied layer	17 piles	varying

Many strain gauges were pasted onto piles to record bending moments during the tests. Piles were fixed at the base, while free at the top, being similar to a cantilever beam. Hence, the profile of the bending moment along the pile was fitted using a polynomial function. Then, pile deflection and lateral soil pressure were calculated as the second integration and derivative of the bending moment by applying boundary conditions described above. Hence, p-y curve was obtained at a given depth. Cross section of model test is shown in Fig. 3. The size of the container was 1.95m×1.95m and the input motion was applied in the direction which was perpendicular to the soil flow. Hence, loads applied to the piles were mainly generated by the kinematic effect of lateral soil movement.







(a)Test1 **(b)Test2** **(c)Test3**

Figure 2. Plan view of pile group models

Table 2. Properties of pile

Specification	Poly Carbon pile
Height (cm)	53
Outer/inner diameter (cm)	3.2/2.7
EI (N.cm2)	532810

TEST RESULTS AND ANALYSIS

Soil and Pile Deformations

Three inclinometers were used to measure the time history of soil displacement at three different positions: in front of the first row of piles, between piles inside the pile group, and beside the pile group as a free-field motion. Profiles of soil displacement inside and outside the pile group are presented in Figs. 4(a) and 4(c). In addition, pile deflection was calculated by double integration of bending moment and is shown together with the soil displacement in Fig. 4(a). As shown in Fig. 4, the maximum soil deformation occurred at the ground surface, and was much larger than pile deflection. This observation is same as was reported during field investigations after 1964 Niigata and 1995 Kobe earthquakes (Hamada et al., 1986 and Tokimatsu and Asaka 1998).

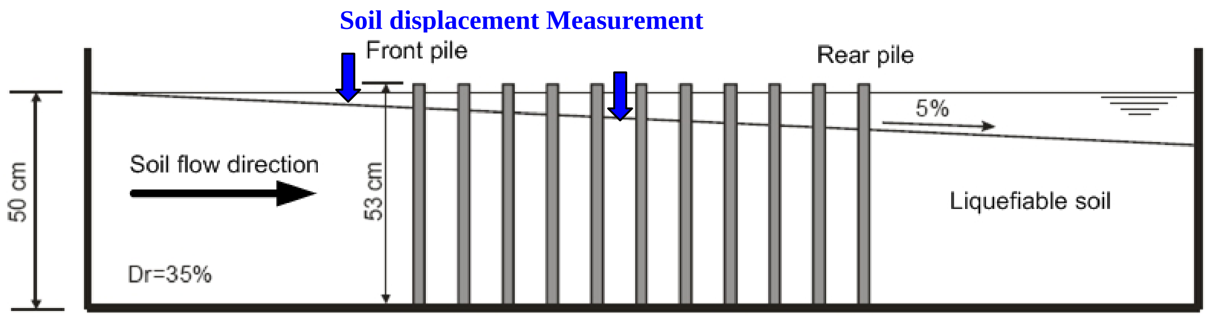


Figure 3. Cross section of model 6×6 pile group

Free-field ground lateral deformation is depicted in Fig. 4(c) and the deformation pattern is similar to what was observed between piles (Fig. 4a); however, soil displacement decreases inside the pile group. The time history of lateral soil displacement is presented in Figs. 4(b) and 4(d) and shows a steady increase during shaking, approaching a residual value at the end.

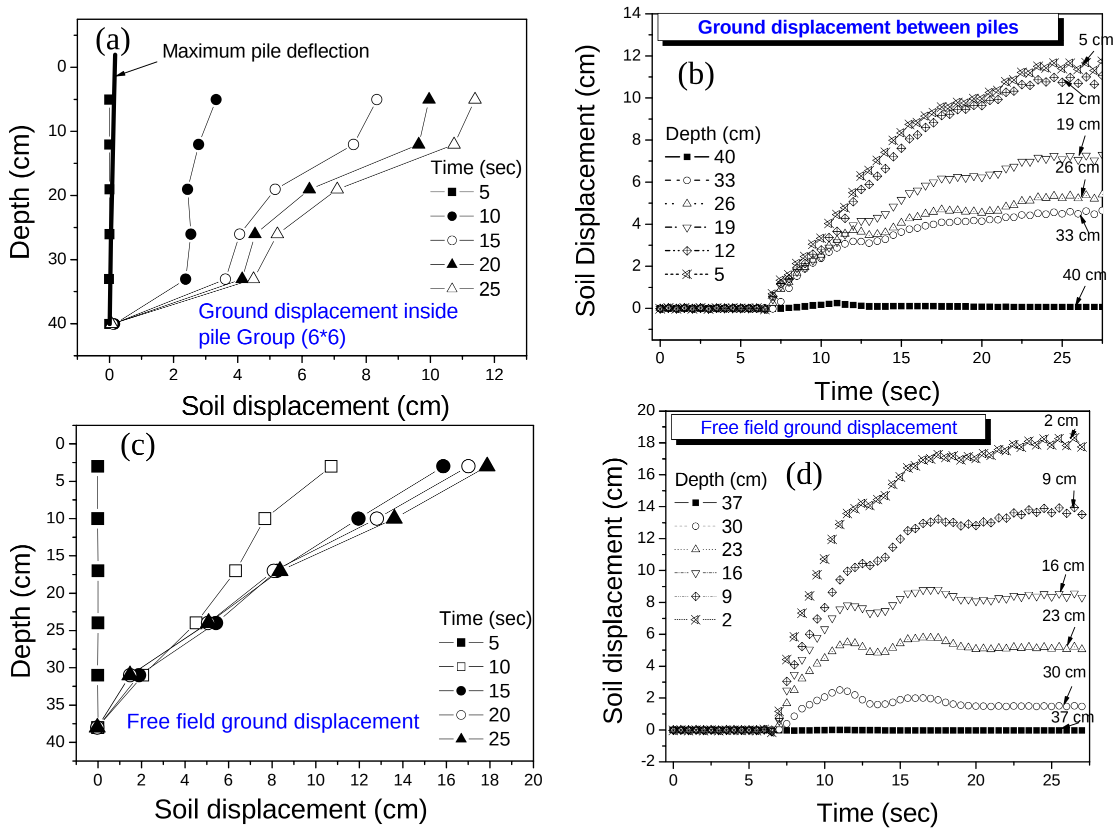


Figure 4. Profile and time history of soil deformation in 6×6 pile group

Furthermore, colored sand was used for marking surface ground to ensure the values measured by inclinometers (Fig. 5). This direct observation validated the accuracy of measured soil displacement. For instance in Fig. 5(b), the position of the inclinometer is compared with the colored sand, and it is illustrated that inclinometers are able to measure the permanent soil deformation with sound accuracy. According to the deformation pattern of surface colored sand (Fig. 5a), when a single pile is subjected to liquefaction-induced large ground deformation, a zone about 6 times the pile diameter is influenced by the presence of the pile. This observation could suggest that when pile spacing is greater than 6D, piles would be perceived as single piles, since interaction between piles would be neglected.

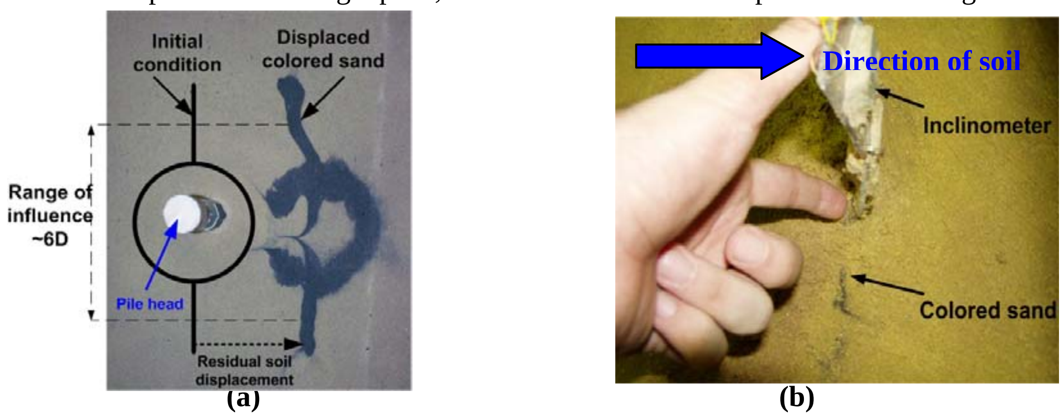


Figure 5. (a) Relative displacement of soil surface and pile head (b) comparison between measured soil displacement by inclinometer and colored sand

Lateral Soil Pressure

In this section, lateral soil pressure exerted on piles is discussed. Lateral soil pressure was calculated as the second derivative of the bending moment. As is shown in Fig. 6, the lateral soil pressure increased in the early stage of the test, while it decreased suddenly after attaining the peak. This drop is observed in both the front and middle row of piles; however, it is more significant in the front piles. In addition, the amplitude of the lateral soil pressure in the front row is two times larger than the middle piles. A similar trend was observed for single piles and the 11×11 pile group.

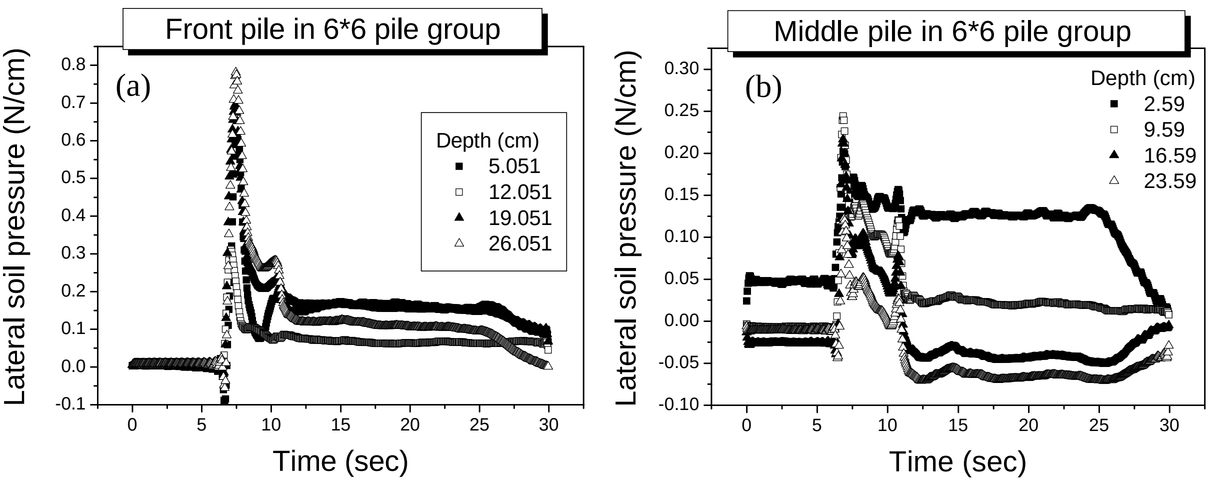


Figure 6. Time history of lateral soil pressure (a) front row pile, (b) middle row pile

The total lateral force, which is applied to piles, is obtained by integrating the lateral soil pressure along the pile (Fig. 7a). Then, the total lateral force for each row is calculated by adding the values of each pile, and finally the total lateral force in the pile group is determined by adding the values of each row. Variations of total lateral force in the pile group, both 6×6 and 11×11, are shown in Fig. 7(b), and as are illustrated, the front and rear row of piles receive much larger values compared to middle row piles. This is an important finding that piles in a pile group are distressed by different forces based on their position. However, it should be noted that this finding was observed in the model tests in which there was neither pile cap nor superstructure. Hence, more studies are suggested to generalize this behavior.

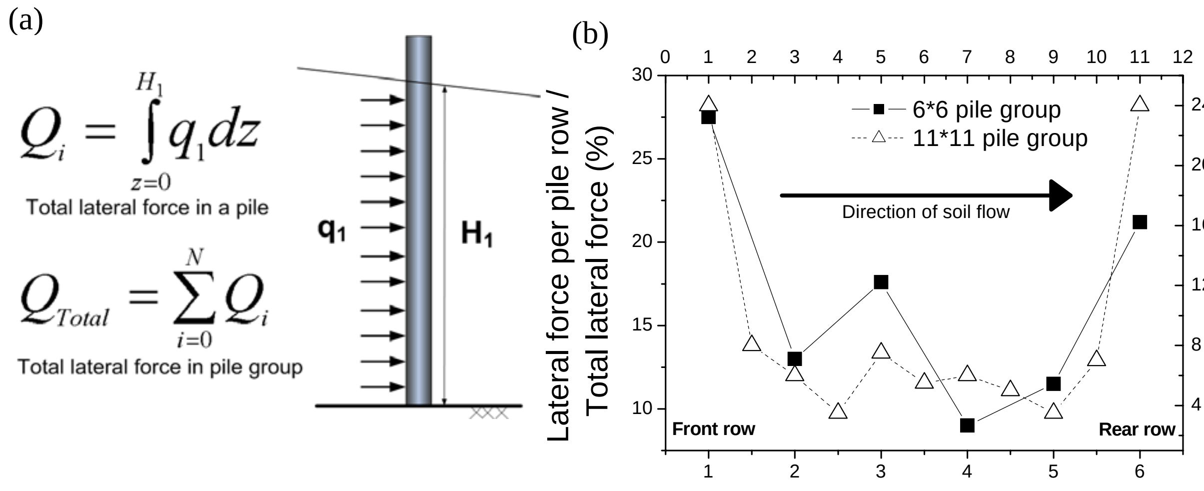


Figure 7. (a) definition of total lateral force, (b) variation of total lateral force in pile group

Moreover, the total lateral force exerted on piles was assessed from the Specifications for Highway Bridges Seismic Design (Japan Road Association, 2002) and results are compared with the measured values in shaking table model tests (Fig. 8). The JRA manual specifies that 30% of total overburden pressure in liquefied sand and 100% of passive earth pressure in the surface non-liquefiable layer be multiplied by the total width of a group pile is assigned as total lateral force. As can be seen, JRA could reasonably estimate average lateral force per pile when pile spacing is 5D. However, when pile spacing decreases (2.5D), JRA underestimates the force. Although, JRA recommends lateral force for the pile group, the authors attempted to calculate lateral force per pile by considering pile diameter as width of affected zone. Fig. 8 shows that JRA's value in the case of single pile is much smaller than the experimental results. Hence, it can be suggested that this design code could only well evaluate the force for 6×6 pile group. However, the general trend is in compliance with the experimental data. The reason is that number of piles or pile spacing is not considered in the design code. Results from this study shows that average force per pile declines as spacing decreases, resulting in a larger interaction between piles. The important finding from this section is the suggestion that either the number of piles or pile spacing should be implemented in the design code.

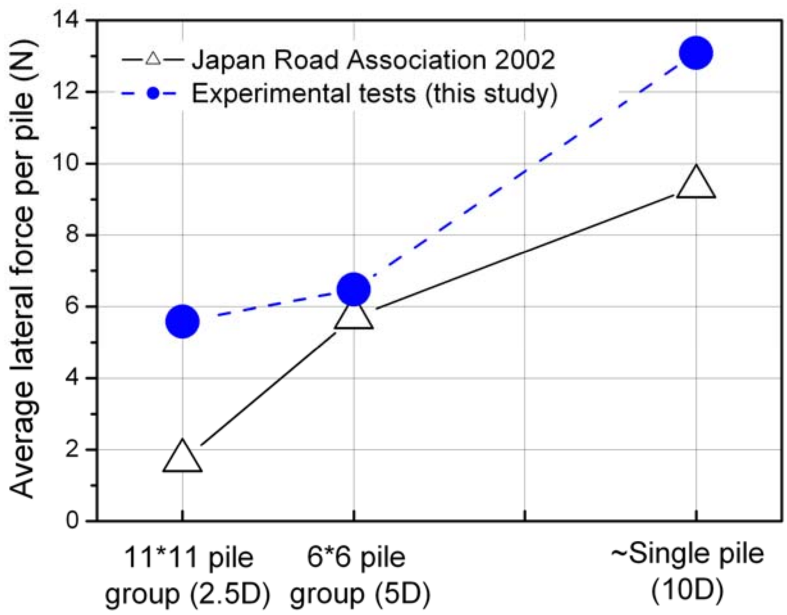


Figure 8. Average lateral force per pile by JRA and shaking table experiment

Evaluation of p-y Curve

The relationship between lateral soil pressure and relative displacement between soil and pile, p-y curve, was calculated based on the results obtained in previous sections. This curve was established for piles in different positions in a group (Fig. 9). As can be seen, the calculated curves are different from what have been recommended for liquefied soil (Rollins et al. 2005). Generally, there is a sudden increase in lateral soil pressure, followed by a drop. However, this declination strongly depends on two parameters. According to Figs. 9(a) to 9(c), group interaction significantly affects the shape of the p-y curve. In the case of single pile (Fig. 9a), lateral soil pressure maintains large values to a relatively large soil displacement, 3 cm; while, in 6×6 pile group, a drop in pressure occurs in smaller displacements, 1 cm. Furthermore, by increasing interaction effect, a sharp drop of pressure happens in very small displacement, 0.5 cm. Therefore, interaction effects could lead to a sharper reduction in lateral soil pressure. The effect of position on p-y curve can be understood from Figs. 9(c) and 9(d). While in front row pile, pressure decreases significantly after attaining the peak, in the middle row pile, pressure maintains a high value in a relatively large displacement.

According to results from this section, in the case of piles subjected to liquefaction-induced large ground displacement, lateral soil pressure does not show any correlation with the relative displacement (Fig. 10). However, several studies have previously shown that in the non-liquefiable ground, lateral soil pressure correlates well with the relative displacement. (Reese et al., 1974). This finding declares that the p-y method could not be applied to the piles distressed by liquefaction-induced large ground deformation.

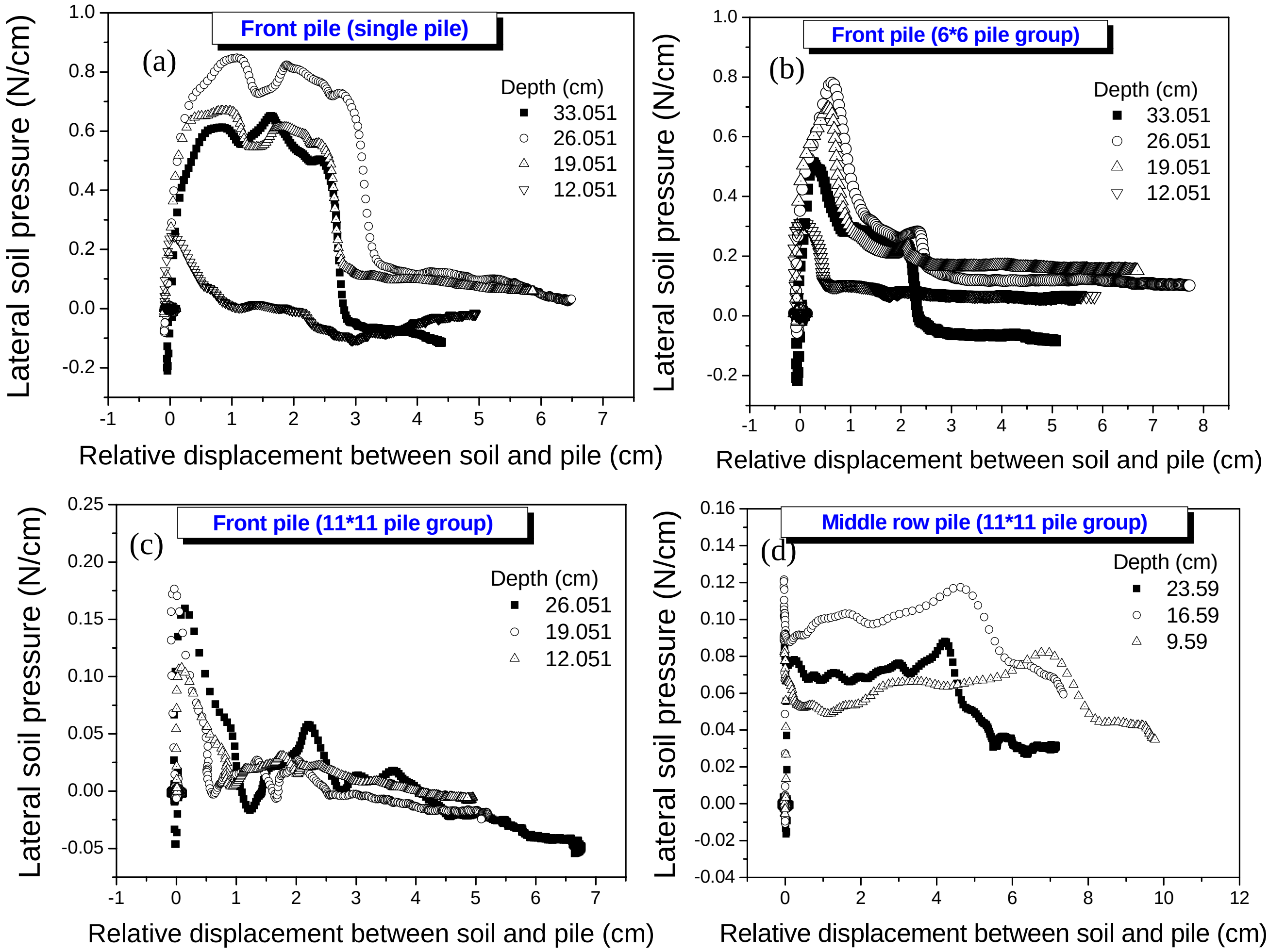


Figure 9. p-y curves for piles subjected to liquefaction-induced lateral spreading

Velocity of Soil Flow

For better understanding of the behavior of liquefied sand, the velocity of soil flow was evaluated. As can be seen in Fig. 11, the variation of the velocity of soil flow highly correlates with the lateral soil pressure. This correlation is presented in Fig. 12, while both axes were normalized to their maximum values. This observation is consistent with those by other researchers implying the viscous nature of liquefied sand. Gallage et al. 2005 have revealed the viscous behavior of liquefied sand using hollow cylindrical torsional shear apparatus, and Towhata et al. 1999 have shown the rate dependent behavior of liquefied sand through shaking table tests on buried pipe.

Results from this section show that in the case of laterally loaded piles by liquefaction-induced large soil displacement, soil pressure highly correlates with the velocity of soil flow, and this finding would suggest the application of the p-dy/dt curve for the numerical modeling. For this purpose, the velocity of soil flow could be calculated using Towhata's method (Kobayashi and Towhata 2005), and maximum lateral force could be evaluated through JRA's method (Japan Road Association, 2002). Results are presented in two categories; before and after the peak. Since evaluation of maximum lateral pressure is more important for design purpose, before the peak part could be applied to numerical modeling to estimate maximum lateral pressure. However, all data should be used if the time history of lateral pressure is demanded.

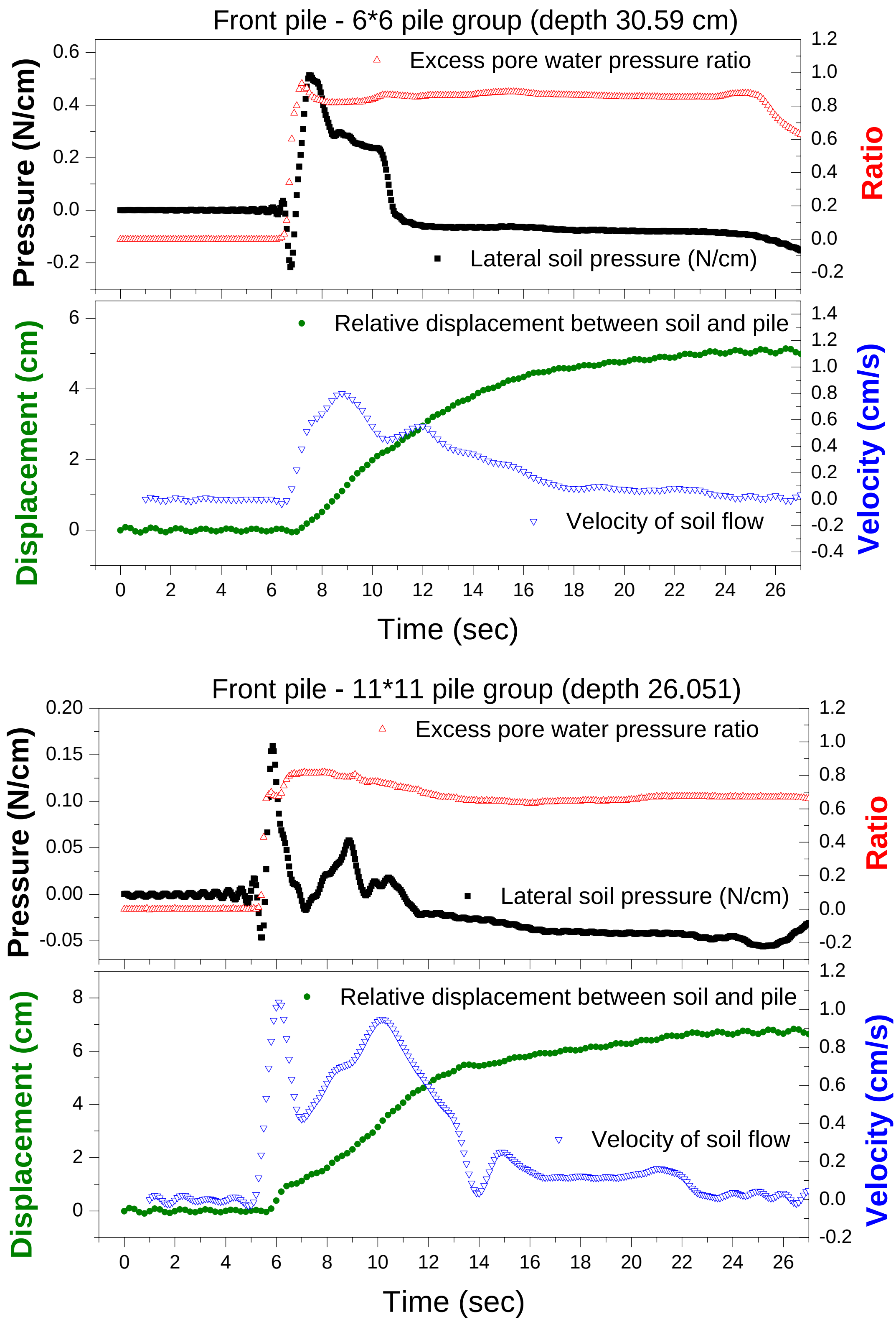


Figure 10. Time history of lateral soil pressure, excess pore water pressure, soil displacement, and velocity of soil flow for 6×6 and 11×11 pile groups

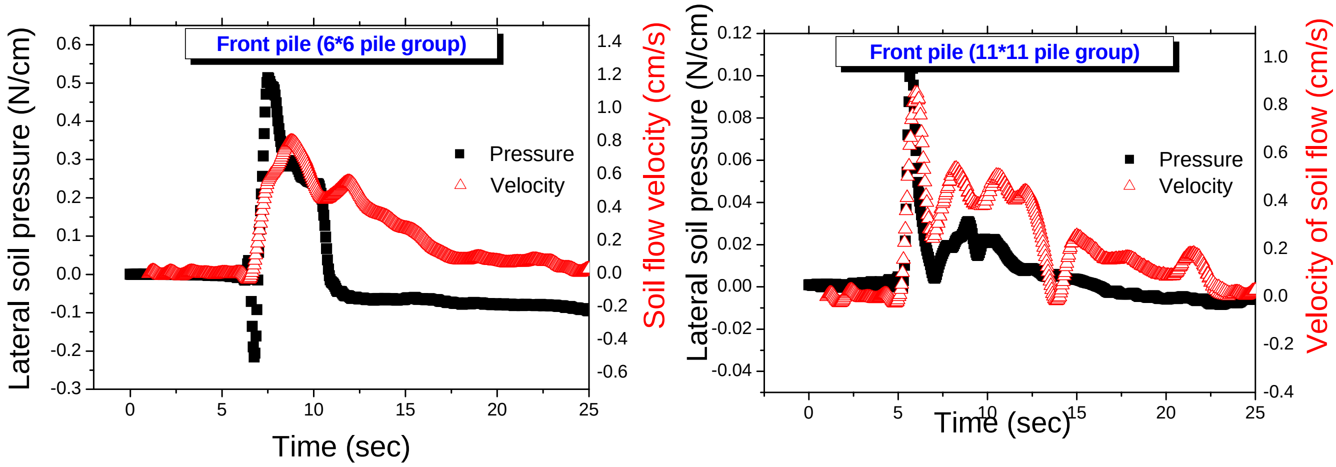


Figure 11. Time history of lateral soil pressure and velocity of soil flow

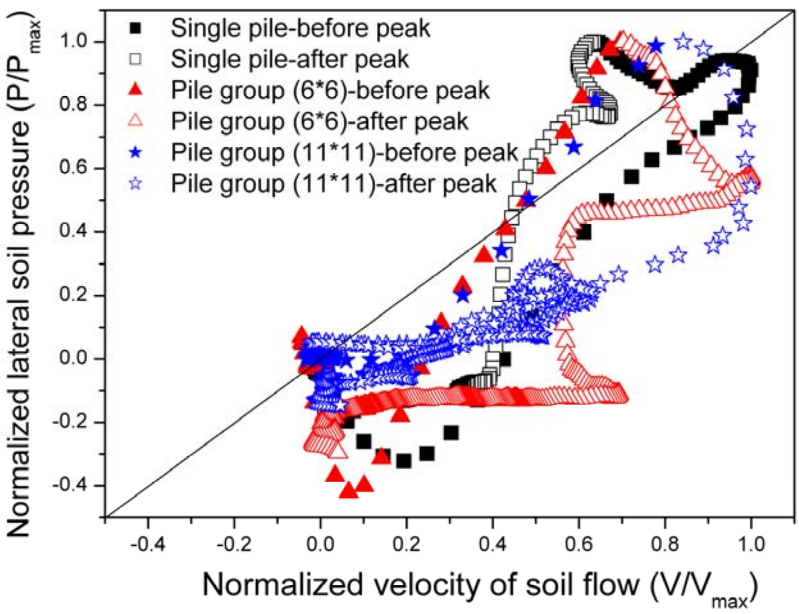


Figure 12. Correlation between lateral soil pressure and velocity of soil flow

Pore Water Pressure Distribution

Pore water pressure sensors were installed in different positions and levels and some of the results together with other parameters are presented in Fig. 10. Results show that high excess pore water pressure was developed just after shaking started and was maintained during shaking. Before the onset of liquefaction, soil lateral resistance saw a rapid rise, followed by a steep fall due to the generation of high excess pore water pressure ratio. As a result, soil lateral deformation was triggered, and piles were subjected to large lateral displacement of liquefied soil.

Conclusions

This study was performed to investigate the p-y relation of a large pile group in liquefaction-induced large ground displacement and the following conclusions are drawn.

1. Maximum soil deformation was observed at the surface of liquefied ground similar to observed field case histories during previous earthquakes, while soil displacement was much larger than pile deflection. The deformation pattern of colored sand on the surface ground illustrated that a zone about 6 times the pile diameter is affected by the presence of a pile. Hence, interaction effect would be neglected when pile spacing is larger than 6D.

2. Lateral soil pressure of liquefied ground was calculated, attaining a peak value at early stages of shaking and following with a significant drop. However, this declination strongly depends on pile position in a pile group. Front row piles face more significant reduction compared to middle row piles.
3. Variation of total lateral force in the pile group was investigated and it was shown that front and rear rows of pile are distressed more compared to middle rows. This finding could suggest that piles in a group should be assigned different loads based on their positions. However, it should be noted that this finding was observed in the model tests in which there was neither pile cap nor superstructure. Hence, more studies are suggested to generalize this behavior.
4. Based on the Japan Road Association manual, the average lateral force per pile was evaluated and compared to the results from this study. It was shown that JRA could precisely estimates the lateral force per pile only in the case of 6×6 pile group, i.e. 5D pile spacing. However, it underestimates for a single pile and 11×11 pile group, i.e. 2.5D pile spacing. This finding declares that JRA has limited capability to deal with pile groups, since the number of piles has not been considered in its equations.
5. The p-y relation was established for different piles and it was found that lateral soil pressure has no correlation with relative displacement between soil and pile. This implies that the application of p-y method to calculated laterally loaded pile undergoing liquefaction-induced large ground deformation is not appropriate.
6. The velocity of lateral soil displacement was estimated and a good correlation with the lateral soil pressure was found, implying a viscous nature of liquefied sand. As a result, application of p-dy/dt relation for numerical modeling of piles subjected to extensive liquefaction and soil deformation is highly recommended.

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