SHAKING MODEL TESTS ON BEHAVIOR OF GROUP PILES UNDERGOING LATERAL FLOW OF LIQUEFIED SUBSOIL

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ABSTRACT :

This study addresses shaking model tests which concerns group pile models subjected to lateral flow of liquefied soil. The main objective of this research was on the magnitude of lateral load exerted by the soil flow, with emphasis on the distribution of the load to individual piles. Model tests employed three kinds of group pile which consisted of 3×3, 6×6, and 11×11 piles. They revealed the following important points. Firstly, the displacement of the ground surface around a pile decreases within a few times of the pile radius. Hence, due to the overlapping of the range of pile influence between two adjacent piles, the entire lateral load decreases as the pile spacing becomes smaller. What is important is that the magnitude of the lateral load on individual piles in the front row (the upstream side of the group pile) as well as on the most downstream side (rear row) takes the maximum value. In contrast, the piles inside the group pile undergo less magnitude of lateral load. Then, a practical distribution of lateral loads on individual piles is proposed. Consequently, it becomes possible to protect existing group pile from lateral pile by installing additional rows of piles in front and back. Next, the variation of the lateral load with the relative displacement and the velocity between piles and soil was studied. Both small and large pile group model tests showed better correlation between the load and the velocity than the displacement. This implies the viscous nature of liquefied sand. This experimental finding strongly supports the analytical method in which the seismic performance of liquefied soil and mitigative measures are assessed by the idealization of liquefied sand as viscous liquid.

KEYWORDS: Liquefaction, Large Lateral Flow, Pile Groups

1. INTRODUCTION

Pile groups embedded in a loose sandy ground near waterfront structures or sloping ground are susceptible to large ground displacement due to extensive liquefaction during earthquakes. Several examples of significant damage in pile foundation 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). Although the dynamic behavior of pile foundation in dry soil has been investigated in detail, their behavior has not been fully understood in the case of a large ground flow of liquefied sand. Tokimatsu and Suzuki (2004) conducted several large shaking table tests on pile groups in liquefied ground, and focused on the cyclic behavior of a soil-pile-structure model. However, the lateral force caused by liquefied soil was out of scope. Centrifuge experiments have been used to study this phenomenon. For example, McVay et al. (1998) conducted centrifuge experiments on two pile groups models (3×3 and 7×3) in sandy ground and found that an individual pile row's contribution to a group's lateral resistance did not change with the size of the group, but only with its row position. Moreover, it was shown that the leading row is subjected to the greatest lateral load, and that the middle pile in each row receives slightly less lateral force than side piles. Similarly, Kimura et al. (2002) demonstrated group effect in centrifugal model tests. Their results illustrated that the percentage of lateral load decreased as it moved in a downstream direction in the sloping ground, while this trend was not valid for the pile at the downstream edge (fourth pile row) that received a greater load than the third row for the monotonic force.

Comparable results were also reported by Rollins et al. (2005) through field testing on a pile group. The rate-dependent behavior of liquefied soil has been studied by several researchers through element testing (Nishimura et al. 2002 and Gallage et al. 2005), 1-g shaking table model tests (Towhata et al. 2006 and Motamed et al. 2007), and large scale shaking table tests (Tokimatsu et al. 2001). Generally, their findings are in close agreement indicating the correlation between the lateral pressure of liquefied soil and the velocity of soil flow while excess pore water pressure maintains high values.

2. SHAKING TABLE TESTS

In total, twenty five experiments were performed on pile groups in sloping ground models; however, due to page limitation some of the results are presented hereafter, and Table 1 summarizes the characteristics of the presented experiments. Model tests are classified into two main categories: small pile group models (3×3) and large pile groups (6×6 and 11×11). Schematic cross sections and plan views of some of the experiments are illustrated in Figures 1 and 2.

Table 1 List of shaking table model tests

Test ID.	Soil condition	Relative density (%)	Frequency (Hz)	Amplitude (Gal)	Remarks
Test L1	Liquefiable	40	10	300	Large pile group (6×6). Single liquefiable sand layer. 5% slope
Test L3	Liquefiable	40	10	300	Large pile group (11×11). Single liquefiable sand layer. 5% slope
Test L5	Liquefiable	40	10	300	Single pile model. Single liquefiable sand layer. 5% slope
Test 6	Liquefiable	30	10	300	Single layer sand. 5% slope.

As can be seen, the models were prepared in a large rigid box, and the piles (see Table 2 for the material properties) were fixed at the bottom to prevent any rotation or displacement, while being free at the top. Spacing between piles in the group was 2.8D (D is pile diameter=3.2 cm) for small pile group tests (Figure 1), 5D for the case of 6×6 pile group (Figure 2), and 2.5D for tests with the configuration of 11×11 piles. The configuration of the model ground was a sloping liquefiable soil deposit made of Albany Silica and Toyoura sands (see Table 3 for properties) with the relative density of 30% and 40%, which was prepared by the water sedimentation method.
The main objective of this study was to investigate the behavior of pile groups subjected to liquefaction-induced large ground deformation. As a result, in order to reproduce the in-situ stress-strain behavior of the liquefied soil, model grounds were prepared with much lower density in 1-G shaking table model tests than the prototype density (Towhata, 2008).

3. EXPERIMENTAL RESULTS

The models were densely instrumented with numerous sensors such as accelerometers, pore water pressure transducers, inclinometers, laser transducers and a shapetape (Figures 1 and 2). In addition, many strain gauges were pasted on the piles to measure bending strain. It should be noted that since the main objective of this study concerns the kinematically induced-lateral force of liquefied soil, monotonic components of the some of the recorded parameters, e.g. pile bending moment and soil displacement, were focused on after filtering out the cyclic components.

3.1. Pile Bending Moment

In order to measure bending moment, piles were densely instrumented with several strain gauges at different levels. The strain data were then converted into bending moment using calibration factors (see Motamed 2007 for calibration details). Since the piles were fixed at the bottom while free at the top, the maximum bending moment was observed at the base of piles, being similar to a cantilever beam.

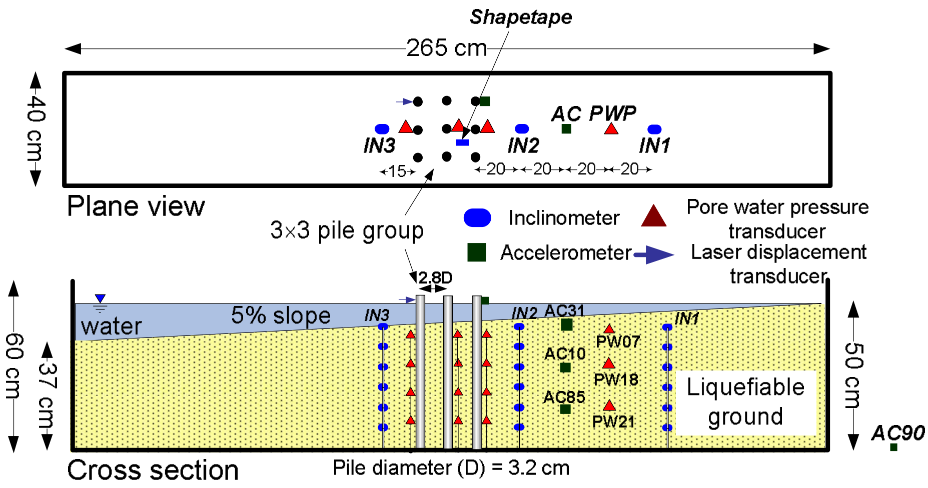

Figure 1 Configuration of small (3×3) pile group tests

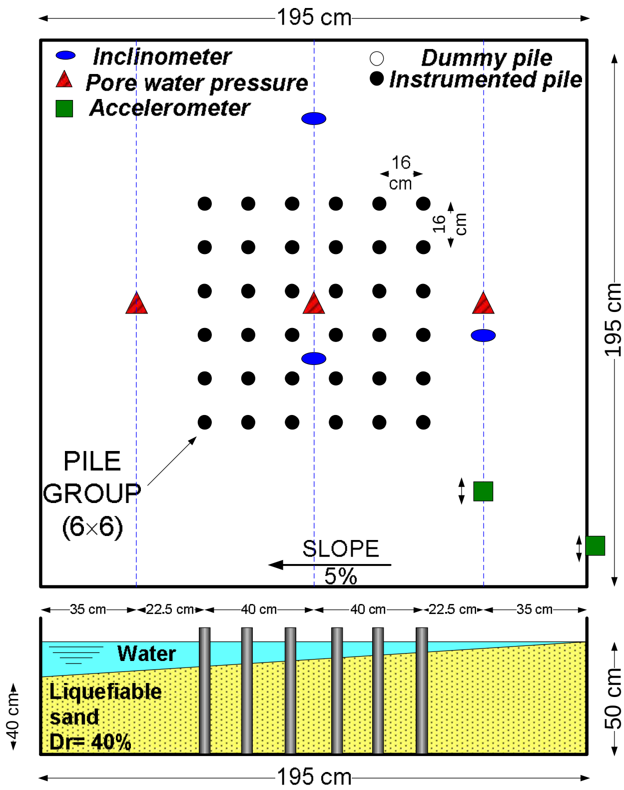

Figure 2 Configuration of large (6×6) pile group tests

3.2. Lateral Soil Displacement

In order to study the liquefaction-induced large ground displacement, appropriate measures should be employed to record soil deformation. In this study, two different approaches were implemented to precisely record the lateral soil movement. An example of model before and after shaking is displayed is Figure 3, and as can be seen, the sloping ground became almost horizontal after the shaking.

1. Instrumental measures: two types of sensors were employed to record the time history of lateral soil displacement: three inclinometers and a shapetape. This method provides the time history of soil deformation at three different positions: in front of the pile group in upstream (IN1), among piles inside the group (ST), and behind the pile group in downstream (IN3). (Figures 1 and 2). Velocity of soil flow was also evaluated by a time derivative of lateral soil displacement.

2. Non-instrumental measures: colored sand and surface tags were utilized to directly observe the deformation pattern of the liquefied sand during lateral spreading. These data were employed to confirm the accuracy of recorded data by instrumental tools. It should be noted that this approach is only able to provide residual soil displacement.

Table 2 Material properties of pile foundation in model tests

Material	Polycarbonate
Height (cm)	53
Outer/Inner diameter (cm)	3.2/2.7
E (N/cm^2)	2.7×105
I (cm^4)	2.5385

Table 3 Properties of Albany Silica sand and Toyoura sand

Materials =>	Albany Silica	Toyoura
Specific gravity (g/cm3)	2.6463	2.651
Maximum void ratio, (emax)	0.741	0.971
Minimum void ratio, (emin)	0.470	0.615
Mean grain size, D50	0.302	0.204
Coefficient of uniformity, Uc	2.237	1.233

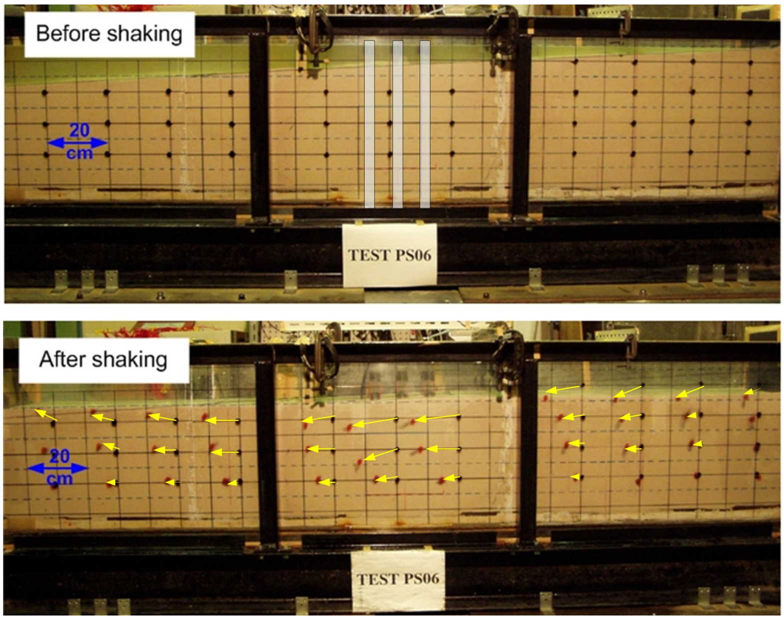

Figure 3 Model ground before and after shaking – Test6 (arrows pointing lateral deformation)

3.3. Lateral Pressure of Liquefied Soil

The lateral pressure of the liquefied soil flow exerted on piles was back calculated using the bending strain data. In this back calculation procedure, first a polynomial function of the third order was fitted for the recorded bending moment along the entire length of the pile. Then, the lateral soil pressure was obtained as its second derivative (Eq. 1).

$$P(x) = -\frac{d^2M}{dx^2} = -\frac{M(x+\Delta x) - 2M(x) + M(x-\Delta x)}{(\Delta x)^2} \qquad \text{(Eq. 1)}$$

in which:

P : Lateral pressure of soil (N/cm).

M : Bending moment obtained from strain gauge records (N.cm).

The total lateral force, which was applied to a pile, was calculated by integrating the lateral soil pressure along a pile using Eq. 2. As a result, the time history of total lateral force for each pile, $Q_i(t)$, was obtained. This procedure was performed for all piles in the group, giving the total lateral force in the pile group, $Q_{total}(t)$ (Eq. 3). The average lateral force per pile, $Q_{average}(t)$, was then derived by dividing the maximum total lateral force of the group by the number of piles in the group (Eq. 4).

$$Q_i(t) = \int_{z=0}^{H1} p dz \quad \text{(Eq. 2)}, \qquad Q_{total}(t) = \sum_{i=0}^{N} Q_i(t) \quad \text{(Eq. 3)}, \quad Q_{average} = \frac{Q_{total}^{\max}}{N} \quad \text{(Eq. 4)}$$

where

p: Lateral soil pressure back calculated from strain gauges records (N/cm)
H: Height of pile (cm)
N: Number of piles in group
Q_i (t): Time history of total lateral force in a pile (N)
Q_{total}(t): Time history of total lateral force in group pile (N)
$Q_{average}$: Average total lateral force per pile (N)

4. KEY OBSERVATIONS AND DISCUSSIONS

In this section the key observations of the experiments are presented and related discussions are addressed. First the general results of small pile groups (3×3) and those of large pile groups (6×6 and 11×11) are given, then the specific finding are delivered.

Figures 4 and 5 display the time histories of some of the parameters. According to acceleration time histories, the response acceleration amplitude inside the soil decreased after the onset of shaking; as a result of excess pore water pressure built-up and consequent liquefaction. Pore water pressure records show that high excess pore water pressure developed at the early stage of shaking and was maintained during shaking. Time histories of soil displacement demonstrate a steady increase during the shaking, approaching residual value at the end. Comparison between time histories of soil displacement at the ground surface exhibits that the lateral soil deformation behind the pile group on downstream was greater than that in front of pile group on upstream, and the soil movement inside the pile group was the smallest because of soil-pile interaction.

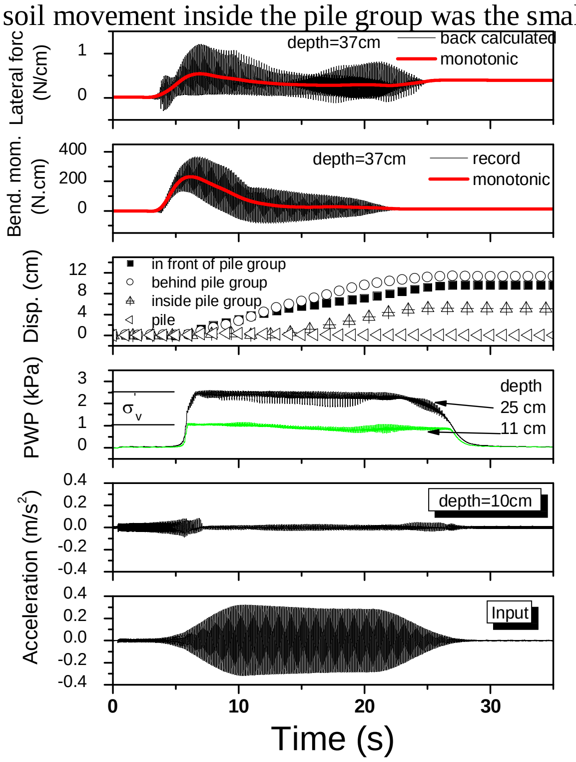

Figure 4 Representative time histories from Test 6 (3×3 pile group)

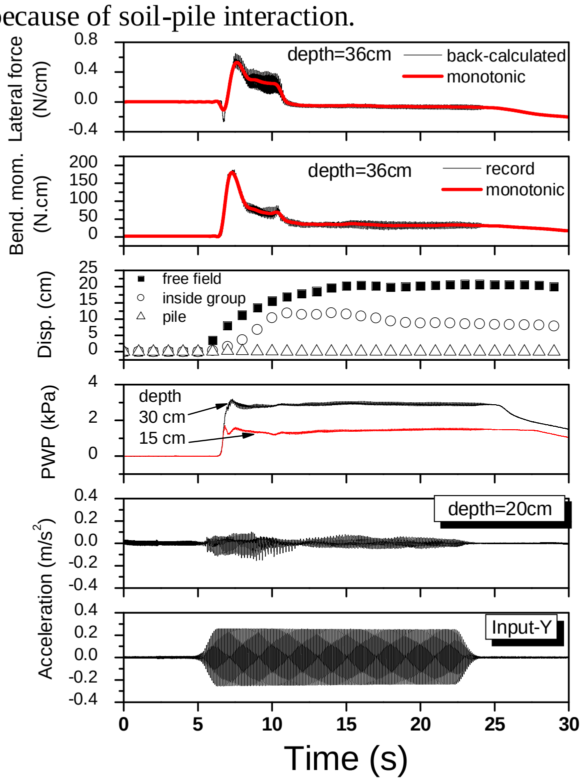

Figure 5 Representative time histories from Test L1 (6×6 pile group)

Furthermore, an example of recorded bending moment by strain gauges is depicted in Figures 4 and 5. As can be seen, the bending moment record could be decomposed into cyclic and monotonic components, and the monotonic component is highlighted by the thick curve. Since the main objective of this study was on the kinematical aspect of liquefaction-induced lateral spreading, the monotonic component was considered for further investigation. In addition, the back-calculated lateral forces exerted on piles are presented in Figures 4 and 5. So far, the results delivered were representing the all experiments, and it was attempted to provide readers the general observations during the experiments. Next, the key findings from these series of tests are elaborated in detail.

4.1. Distribution of Maximum Soil Displacement and Velocity

Distribution of maximum lateral soil displacement is illustrated in Figure 6 including the data from several tests. As can be seen, the maximum lateral soil deformation occurred behind pile groups on downstream side, and the soil displacement inside pile group was the smallest.

The distribution of maximum velocity of soil flow is displayed in Figure 7, and it is clearly understood that lateral soil flow of the liquefied soil also exhibits a similar behavior like soil displacement.

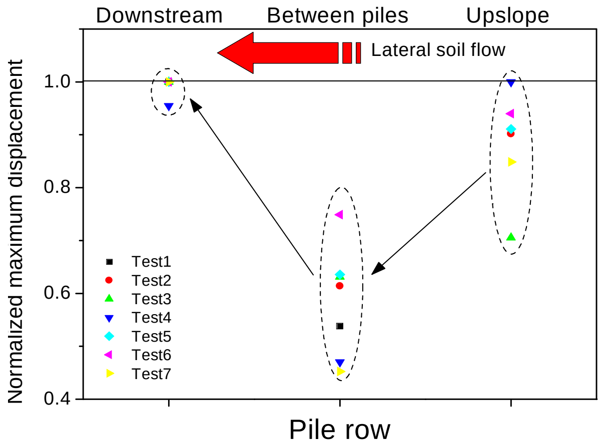

Figure 6 Distribution of normalized maximum surface ground lateral displacement in sloping ground models

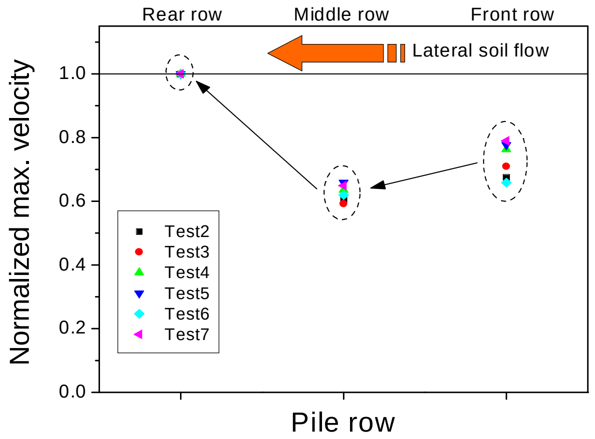

Figure 7 Distribution of normalized maximum velocity of soil flow in sloping ground models

4.2. Distribution of Maximum Total Lateral Force in Pile Groups

The distribution of the maximum total lateral force for the group piles in sloping ground was carefully studied, and two examples of the results are given in Figures 8 and 9 for the small (3×3) and large (6×6) pile groups, respectively. These distributions demonstrate that in the sloping ground model both front row (in upstream) and rear row piles (in downstream) carry larger lateral forces in the group than middle row piles (inside pile group). This behavior is caused by the displacement/velocity trend of the soil which was explained in Section 4.1. Moreover, the distributions show that the center piles in each row are distressed less than the side piles.

4.3. Soil-Pile Interaction

In order to investigate the soil-pile interaction, several experiments were conducted with different pile spacing: 5D, 2.81D, and 2.5D, including both large (6×6 and 11×11) and small (3×3) pile groups. In addition, one experiment was performed on a single pile model. As a result, the soil-pile interaction was studied in detail.

In this regard, the average total lateral force per pile ($Q_{average}$) was calculated using Eq. 4 for different pile spacing, and the results are illustrated in Figure 10. As is shown in Figure 10, average lateral force per pile decreased as pile spacing became smaller. This is because of what is called the group effect. The data in Figure 10 are mainly from the large pile group tests; however, one point data from the experiment on the small pile group is also included of which the values are slightly greater than the large group test data. This observation is because of differences in the direction of input motion as in the large group tests, models were shaken in the transverse direction to the ground slope, while in the small group experiments, the input motion was applied in the direction parallel to the slope of ground which intensified the lateral force to some extend.

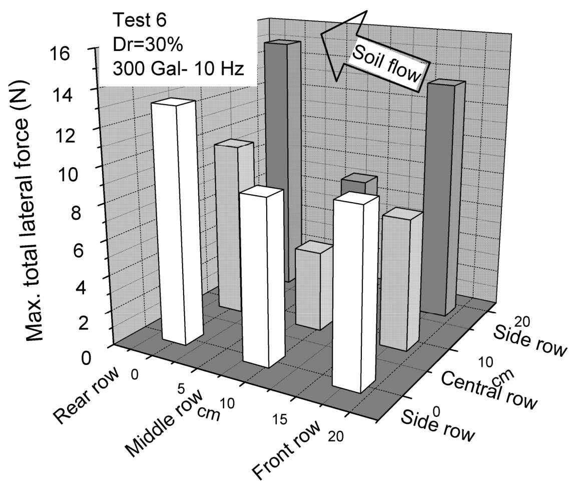

Figure 8 Distribution of maximum total lateral force in small pile group (3×3) – Test 6

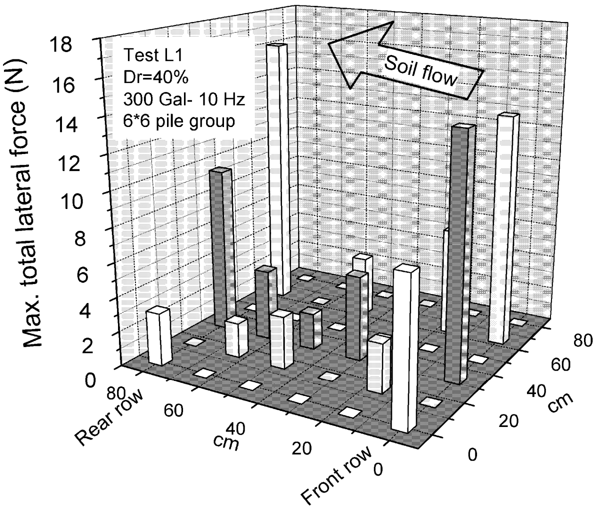

Figure 9 Distribution of maximum total lateral force in large pile group (6×6) – Test L1

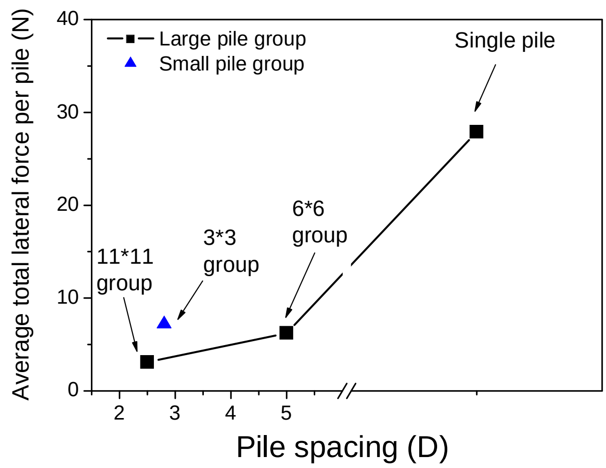

Figure 10 Average total lateral force per pile for different pile spacing

4.4. Rate-Dependent Behavior of Liquefied Soil

For better understanding the soil-pile interaction, rate-dependent behavior of liquefied sand was extensively investigated. It was shown that the lateral displacement of soil increased steadily during shaking, approaching the residual value at the end (Figures 4 and 5). However, lateral soil pressure followed a different pattern; a sudden rise at the early stage of shaking, then some fluctuations, and finally displaying a residual value. Figure 11 recalls these observations by giving an example of the large pile group tests. While lateral soil pressure showed no correlation with soil displacement during shaking, the relative velocity between soil and pile exhibited a better correlation with the pressure. These results seem to suggest the rate-dependent behavior of lateral soil pressure during shaking while pore water pressure maintains high excess pressure. Since there is an opinion that this apparent viscosity is due not to the nature of liquefied sand but the differences in pore water pressure between front and back sides of a pile, the pressure difference in a large scale test was examined, and it was understood that pore water pressure difference was too small to account for the measured lateral force. Details of this confirmation can be found in Motamed (2007).

5. CONCLUSIONS

This paper presented the results of a series of shaking table tests on pile groups in sloping ground models subjected to liquefaction-induced lateral spreading. Following conclusions are drawn from this study:

- Both lateral soil displacement and velocity of soil flow exhibited a similar distribution. Largest values were observed behind pile group (on downstream), while smallest ones occurred inside piles in group.
- Distribution of maximum total lateral force in the pile groups revealed that both upstream and downstream rows of piles carry larger lateral forces than middle row piles. In addition, it was observed that center piles in each row also are distressed less than side piles.
- Soil-pile interaction decreases as pile spacing increases in the group.
- Lateral force of liquefied soil illustrated a fairly well correlation with the velocity of soil flow, confirming the rate-dependent behavior of liquefied soil.

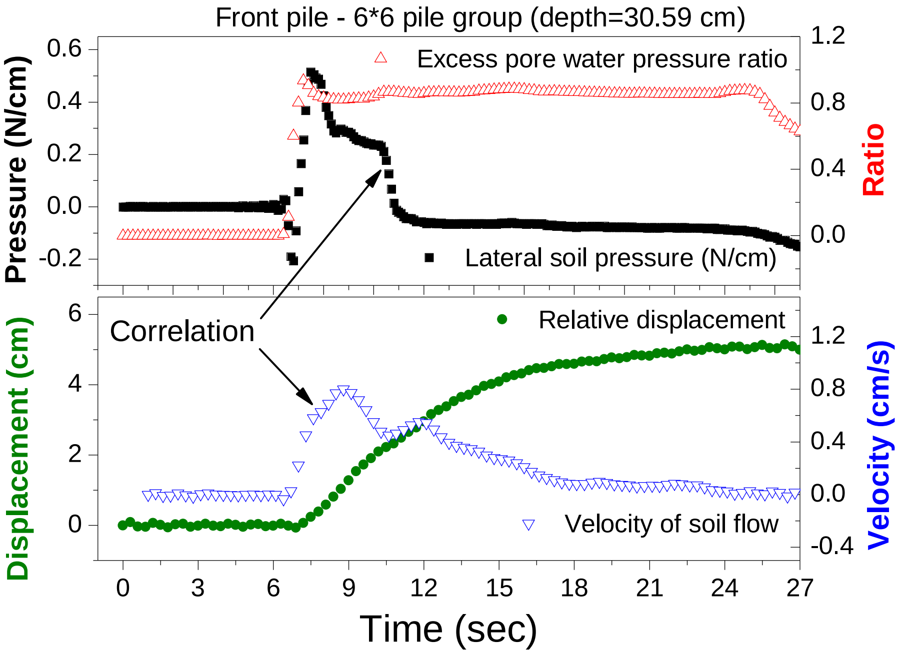

Figure 11 Rate-dependent behavior of liquefied sand in large pile group experiment

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