EXPERIMENTAL MODELING OF LARGE PILE GROUPS IN SLOPING GROUND SUBJECTED TO LIQUEFACTION-INDUCED LATERAL FLOW: 1-G SHAKING TABLE TESTS

RAMIN MOTAMED\(^1\), VLATKO SESOV\(^2\), IKUO TOWHATA\(^3\) and NGO TUAN ANH\(^4\)

ABSTRACT

A series of 1-g shaking table model tests were carried out to study the behavior of pile groups embedded in sloping ground subjected to lateral flow of liquefied soil. Two different configurations of pile groups: large (6×6 and 11×11) and small (3×3), were considered. The models were subjected to the liquefaction-induced large ground deformation to investigate the effect of several parameters on the response of pile groups and mechanism of lateral flow. These parameters comprise amplitude, frequency, and direction of input motion; density and slope of ground; and the thickness of non-liquefiable layer at the surface. The outcome of this parametric study reveals the importance of above mentioned factors which should be taken into account for analysis and design purposes. In addition, the results from the experiments clearly illustrate that in sloping ground configuration, both front (in upstream) and rear (in downstream) row piles receive greater lateral forces than middle row piles. This finding is attributed to the distribution of soil motion (displacement and velocity) of the liquefied soil in the model. As a result, installation of additional pile rows in front and behind an existing pile foundation can be considered as an effective retrofitting technique. Finally, soil-pile interaction was evaluated by running experiments with different pile spacings, and reliability of the JRA 2002 design manual in estimation of liquefaction-induced lateral force on piles is evaluated.

Key words: large pile group, liquefaction-induced large ground deformation, shaking table (IGC: D7/E8/E12)

INTRODUCTION

Pile groups embedded in a loose sandy ground near waterfront structures or in sloping grounds are susceptible to large ground displacement due to extensive liquefaction during strong earthquakes. Several examples of significant damages in pile foundations have been reported in the literature from the 1964 Niigata, 1983 Nihonkai-Chubu and 1995 Kobe earthquakes (Hamada et al. 1986; Hamada and O’Rourke 1992; Tokimatsu and Asaka 1998). The behavior of pile foundation subjected to the liquefaction-induced large ground deformation has been investigated by several researchers through large shaking table tests (Motamed et al., 2009; Tokimatsu and Suzuki, 2004; Tokimatsu et al., 2001 and 2005; Yao et al., 2004; Orense et al., 2000), field tests (Rollins et al., 2005; Ashford et al., 2006; Weaver et al., 2005), centrifuge experiments (Abdoun et al., 2003; Dobry et al., 2003; Okamura et al., 2001; Imamura et al., 2004), small 1-g shaking table model tests (Motamed and Towhata, 2009; Towhata et al. 2006), and numerical modeling (Cubrinovski et al., 2008; Uzuoka et al., 2008). However, they have been mainly concerned the behavior of single or small pile groups in the liquefied and laterally spreading ground.

Toyota et al. (2004) reported the results of a series of 1-g shaking table model tests on lateral flow of a sandy slope undergoing high excess pore water pressure built-up and explored the effect of several parameters on the extent of lateral spreading such as intensity of shaking, frequency of base excitation, slope angle, and density of sand. 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. A comprehensive review on the behavior of pile foundations in seismically liquefiable soils can be found in Bhattacharya and Madabhushi (2008).

Nevertheless, most of the present knowledge about the behavior of pile groups in liquefied soil is based on studies on single pile or small pile groups, and information on the behavior of large pile groups during lateral flow of liquefied soil is very limited. Therefore, the present study investigates the behavior of large pile groups embedded in sloping ground model subjected to lateral flow of liquefied soil by performing a series of shaking table tests. Furthermore, extensive experiments were conducted on small pile groups, and the results were compared to those of large group tests.

**DESCRIPTION OF 1-G SHAKING TABLE TESTS**

This paper presents the results of twenty-five experiments on large and small pile groups embedded in sloping ground models. In this section, experimental program, test procedures, model configurations, material properties, preparation of models, and experimental set up are

<table>
<thead>
<tr>
<th>Table 1. Experimental program of 1-g shaking table model tests on large pile groups in sloping ground</th>
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<tr>
<td><strong>Test no.</strong></td>
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<tr>
<td>Test L1</td>
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<td>Test L2</td>
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<tr>
<td>Test L3</td>
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<td>Test L4</td>
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<tr>
<td>Test L5</td>
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<td>Test L6</td>
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Y: shaking in direction perpendicular to slope of ground

<table>
<thead>
<tr>
<th>Table 2. Experimental program of 1-g shaking table model tests on small pile groups (3 × 3) in sloping ground</th>
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<tr>
<td><strong>Test no.</strong></td>
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<tr>
<td>Test 1</td>
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<td>Test 3</td>
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<tr>
<td>Test 5-R</td>
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<td>Test 6-R</td>
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<tr>
<td>Test 7-R</td>
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<td>Test 8</td>
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<td>Test 9</td>
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<td>Test 11</td>
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<td>Test 12</td>
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<td>Test 13</td>
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<td>Test 14</td>
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<td>Test 15</td>
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<td>Test 16</td>
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<td>Test 17</td>
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<tr>
<td>Test 18</td>
</tr>
<tr>
<td>Test 19</td>
</tr>
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X: shaking parallel to slope of ground
Y: shaking in direction perpendicular to slope of ground
introduced in detail.

This study attempted to cover a wide range of number of piles in a group to properly reproduce the behavior of pile groups constructed in the practice. This objective was achieved by running tests on $6 \times 6$, $11 \times 11$, and $3 \times 3$ pile groups. The features of these tests are summarized in Tables 1 and 2, respectively. According to Table 1, six tests were conducted on large pile groups ($6 \times 6$ and $11 \times 11$) and single pile models; while, nineteen tests were performed on small pile group models ($3 \times 3$). Schematic cross sections and plan views of some of the experiments are illustrated in Figs. 1 to 4. The first two figures display the model of large pile groups ($6 \times 6$ and $11 \times 11$) in single layer of liquefiable soil models. As can be seen, these models were prepared in a large rigid container ($1.95 \, \text{m} \times 1.95 \, \text{m} \times 0.6 \, \text{m}$) with transparent side walls, and the piles (see Table 3 for the material properties) were fixed at the bottom to prevent any rotation or displacement, while being free at the top. By fixing the piles at the bottom, it is assumed that their behavior can be regarded as end-bear-

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**Fig. 1.** Layout of experiment on $6 \times 6$ pile group in single liquefiable soil model—Test L1

**Fig. 2.** Layout of experiment on $11 \times 11$ pile group in single layer soil model—Test L3

**Fig. 3.** Layout of experiment on $3 \times 3$ pile group in single liquefiable soil layer model
Spacing between piles in the large group tests was five pile diameters \((5D = 5 \times 3.2 = 16 \text{ cm})\) for the case of \(6 \times 6\) pile group (Fig. 1); however, it was reduced to 2.5D for the tests with configuration of \(11 \times 11\) piles (Fig. 2). The configuration of the model ground was a sloping liquefiable soil deposit made of Toyoura sand (see Fig. 5 and Table 4 for properties) with the relative density of 40% which was prepared by the water sedimentation method. In addition to the tests with single liquefiable soil layer, two tests were carried out with two layer soil configuration which included a top non-liquefiable soil layer overlying the liquefiable layer. The thickness of this non-liquefiable layer was 10 cm and consisted of the dry Toyoura sand. The water migration from the underlying liquefiable soil during the shaking was prevented by placing impermeable sheets on the saturated soil layer. In this regard, appropriate thin sheets were employed to eliminate the interaction with the lateral soil displacement or the pile response. Moreover, to fully understand the soil-pile interaction phenomenon in pile groups, two tests (Tests L5 and L6) were run on single pile models which were reproduced by removing the dummy (non-instrumented) piles.

In order to perform parametric study, several tests were carried out on small pile groups \((3 \times 3)\) which were embedded in a similar ground configuration. Figures 3 and 4 depict the \(3 \times 3\) pile group models in a single liquefiable and two-layer soil models, respectively. As can be seen, the models were constructed in a rigid container \((2.65 \text{ m} \times 0.4 \text{ m} \times 0.6 \text{ m})\) with transparent side walls, and the piles had the identical material properties and boundary conditions to the large pile group tests. Pile spacing in the group was 2.8 pile diameters, and configuration of the

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**Table 3.** Material properties of pile foundation

<table>
<thead>
<tr>
<th>Material</th>
<th>Polycarbonate</th>
</tr>
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<tbody>
<tr>
<td>Height (cm)</td>
<td>53</td>
</tr>
<tr>
<td>Outer/Inner diameter (cm)</td>
<td>3.2/2.7</td>
</tr>
<tr>
<td>(E) (N/cm²)</td>
<td>(2.7 \times 10^5)</td>
</tr>
<tr>
<td>(I) (cm⁴)</td>
<td>2.5385</td>
</tr>
</tbody>
</table>

**Table 4.** Properties of Albany silica sand, Toyoura sand, and Chiba gravel

<table>
<thead>
<tr>
<th>Materials(\Rightarrow)</th>
<th>Albany silica sand</th>
<th>Toyoura sand</th>
<th>Chiba gravel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity (g/cm³)</td>
<td>2.6463</td>
<td>2.651</td>
<td>2.74</td>
</tr>
<tr>
<td>Maximum void ratio, (e_{max})</td>
<td>0.741</td>
<td>0.971</td>
<td>0.99</td>
</tr>
<tr>
<td>Minimum void ratio, (e_{min})</td>
<td>0.470</td>
<td>0.615</td>
<td>0.48</td>
</tr>
<tr>
<td>Mean grain size, (D_{50}) (mm)</td>
<td>0.302</td>
<td>0.204</td>
<td>1.93</td>
</tr>
<tr>
<td>Coefficient of uniformity, (U_c)</td>
<td>2.237</td>
<td>1.233</td>
<td>2.2</td>
</tr>
</tbody>
</table>
model was a sloping ground prepared from Albany silica sand (see Fig. 5 and Table 4 for properties) mainly with the relative density of 30%. The liquefiable soil layer was prepared by the water sedimentation method; while, in the case of two-layer soil models (Fig. 4), the top non-liquefiable soil layer, which was made of Chiba gravel (see Fig. 5 and Table 4 for properties), was placed over the liquefiable layer with the dry deposition approach. In order to reproduce the in-situ stress-strain behavior of the liquefied soil, in this study, the model grounds were prepared with much lower relative density than the prototype (Towhata, 2008). Verdugo and Ishihara (1996), showed that the dilatancy of sand, development of excess pore water pressure, and the consequent softening are governed by the combined effects of density and effective stress level. Therefore, the in-situ stress-strain behavior of liquefied soil can be reproduced in the small scale models by preparing the ground with lower density, compensating for the effect of low confining stress.

According to Tables 1 and 2 which list the specifications of the experiments, the effect of following parameters on the response of pile groups were investigated: pile spacing; group effect; existence of top non-liquefiable layer; amplitude, frequency, and direction of input motion; relative density of soil; slope of surface ground; and thickness of top non-liquefiable layer. It should be noted that prior to conducting the main experiments, three tests were run under identical conditions to satisfy repeatability and reliability of the data whose results can be found in Motamed (2007). In addition, further details of the model preparation, materials, and instrumentations can be found in Motamed (2007).

DATA MEASUREMENTS AND ANALYSES

The models were densely instrumented with numerous sensors such as accelerometers, pore water pressure transducers, inclinometers, laser displacement transducer, and a shapetape (Figs. 1 to 4). The shapetape is an array of fiber optic bend and twist sensors mounted on a ribbon, usually made of spring steel. The data obtained are first bend and twist, and then converted to Cartesian data at many points along the ribbon (Measurand, 2004). In addition, many strain gauges were attached to the piles to measure bending strain. Hence, the time histories of several parameters were recorded throughout the shaking.

Furthermore, it should be noted that since the main objective of this study concerns the kinematically induced lateral force of the liquefied soil, monotonic component of some of the recorded parameters, e.g., pile bending moment and soil displacement, were focused on after discarding the cyclic component. This separation procedure will be discussed in the section related to lateral force calculation. Sign convention in this study is depicted in Fig. 6 and, as can be seen, horizontal ground displacement and lateral force of liquefied soil are considered positive in the down-slope direction, while acceleration is assumed to be positive in the up-slope direction. In the remaining part of this section, measurement method and data analysis approach of each parameter are described.

Acceleration

Acceleration was recorded at different positions in the model such as inside the ground at different depths and at the base of the model. The input acceleration was sinusoidal and had a taper shape. The amplitude of input motion was mainly 300 Gal with the frequency of 10 Hz.

Pore Water Pressure

Generation of excess pore water pressure during the shaking was monitored by positioning several pore water pressure sensors at different locations: far from pile group in the upstream, in front of a pile group in upstream, between piles in the group, and in the downstream side of the group (Figs. 1 to 4). In each position, transducers were placed at different depths below the ground surface.

Pile Bending Moment

In order to measure bending moment, piles were densely instrumented with strain gauges at different elevations. The strain data were then converted into bending moment using appropriate calibration factors. The calibration procedure details have been elaborated in Motamed (2007). Since the piles were fixed at the bottom to prevent rotation and displacement while free at the top, maximum bending moment was observed at the base of the piles.

Lateral Soil Displacement

In order to study the liquefaction-induced large ground displacement, appropriate measures should be employed to accurately record the soil deformation. In this study, two different approaches were implemented to precisely record the lateral soil movement:

- Instrumental measures: two types of sensors were employed to record the time history of lateral soil displacement: three inclinometers and a shapetape. These sensors have no lateral rigidity, hence can move with the liquefied soil. This method provided the time history of soil deformation at different depths.
- Non-instrumental measures: colored sand and small tags were utilized to directly observe the deformation pattern of the liquefied sand during lateral spreading.
This approach was able to provide the magnitude of residual soil displacement.

**Back-Calculated Lateral Force**

The lateral force of liquefied soil flow exerted on the piles was calculated by using the bending moment data as follows. First, a polynomial function of third order was fitted for the recorded bending moment along the entire length of the pile. Then, the lateral force of liquefied soil was obtained as its second derivative.

**GENERAL OBSERVATIONS OF PILE GROUP BEHAVIOR IN SLOPING GROUND**

In this section, first the general observations from shaking table tests on large and small pile groups are presented. Then, in-depth discussions are provided on the key findings based on the results from all the shaking table tests. For example, Fig. 7 depicts a model before and after shaking with arrows pointing the trend of the lateral soil movement.

In this study, special attention was paid to carefully record the lateral soil displacement because understanding the mechanism of liquefaction-induced large ground deformation was one of main objectives in this research. Figures 8 and 9 show instrumental and non-instrumental measures employed in this study for the above mentioned goal. In this regard, the residual displacement of the soil at surface was directly measured after each test, and it was then compared with the results obtained from instruments, and the results are given in Fig. 10. According to this figure, the inclinometers were able to provide a precise estimation of the lateral soil displacement, and the shapetape sensor could also provide valuable information of the soil displacement with an acceptable level of accuracy. Therefore, shapetape sensor could be utilized to measure soil displacement in places where no inclinometer can be installed, e.g., between piles inside the group.

Figures 11 and 12 present time histories of some of the recorded parameters in the large pile group experiments. According to the acceleration time histories, the amplitude of response acceleration inside the soil decreased after the onset of shaking; as a result of excess pore water pressure build-up and the consequent liquefaction. Pore water pressure records show that high excess pore water pressure accumulated in the early stage of shaking and was maintained for the duration of shaking. Time histories of lateral soil displacement demonstrated a steady increase during the shaking, approaching a residual value at the end. Comparison between soil displacement data inside and beside pile group implies that soil inside the group deformed laterally to a smaller extent than soil beside the pile group. The latter soil movement represented a free field displacement without any group effect. Figure 13 provides further data on the lateral soil deformation from single and two layer ground configurations. As can be seen, in the single layer soil model (Fig. 13(a)), maximum soil deformation developed at the ground surface, and pile deflection was much smaller than the soil displacement. However, in two layer soil model (Fig. 13(b)), the existence of the top non-liquefiable soil layer significantly reduced the soil lateral movement at the surface.

In addition, the bending moments recorded by strain gauges at two different depths are depicted in Figs. 11 and 12 for a front-row pile. As can be seen, bending moment at the deeper depth was greater which is reasonable con-
Fig. 9. Non-instrumental measures for lateral soil deformation measurement

Fig. 10. Comparison between residual soil displacement by direct observation and instrumental measures

considering the pile boundary conditions. In addition, the back-calculated lateral forces exerted on piles are presented in Figs. 11 and 12 and demonstrate a similar behavior to the bending moment records.

The distribution of maximum soil deformation at surface in the large pile group tests were investigated in more detail, and the results are presented in Fig. 14(a). As is shown, group effect (interaction between soil and pile) was remarkable in both single and two layer soil models, and the existence of top non-liqueifiable layer substantially reduced the surface soil movement. Moreover, the distribution of maximum lateral soil displacement on the ground surface in small pile group experiments, which
Fig. 13. Time histories and profiles of lateral soil displacement by inclinometers—6 × 6 pile group

(a) Single layer soil model – Test I.1, Dr=40%, 300 Gal, 10 Hz

(b) Two layer soil model – Test I.2, Dr=40&40%, 300 Gal, 10 Hz
was normalized by the largest value, is illustrated in Fig. 14(b). This figure indicates that soil lateral displacements in upstream and downstream were larger than inside the pile group. Furthermore, Fig. 15 displays an example of the displacement contour plot of the liquefied soil which was obtained by the colored sand and small tags. This visualization provides a clear understanding of the distribution of residual soil deformation in the entire ground model. This contour plot is consistent with the recorded data, demonstrating the largest soil displacement near the surface (in cross section view) and a larger magnitude of displacement in upstream and downstream sides than inside of the pile group (in plan view).

In addition, the distribution of normalized maximum velocity of soil flow is displayed in Fig. 16, and it is clearly understood that the velocity of the liquefied soil flow has a similar trend as the soil displacement.

Next, the profiles of bending moment in piles are ad-

![Fig. 14. Distribution of maximum soil displacement at ground surface](image)

![Fig. 15. Displacement contour plot of residual lateral soil displacement from non-instrumental tools](image)

![Fig. 16. Distribution of maximum velocity of soil flow at ground surface](image)
dressed. Figures 17(a) and 18(a) show the profiles of the monotonic component of bending moment in the case of a single soil layer model, while Figs. 17(b) and 18(b) for two layer soil models. By comparing them, the following points are made:

- Top non-liquefiable layer increased the bending moment in piles. This is because of the consequent passive earth pressure in this layer.
- Bending moment drastically increased at the boundary between liquefiable and non-liquefiable soil layers.

Both observations have been reported in the literature from field investigations after a number of recent destructive earthquakes (Hamada et al., 1986; Hamada, 2000, among others).

**PARAMETRIC STUDY ON SOIL DISPLACEMENT**

In this section, the effect of several parameters on the lateral soil displacement is comprehensively evaluated by performing a parametric study. First part of this section pertains to the effect of input motion characteristics as three different amplitudes of the input motion were applied: 150, 300, and 500 Gal; and for the frequency content, three frequencies were considered: 3, 5, and 10 Hz. In addition, input motion was applied to the model in two different directions: transverse and parallel to the slope of ground. In the second part of the section, the impact of the ground configuration is discussed by running tests with different soil relative densities, namely 18%, 30% and 60%, and slope inclinations which were 3° and 5°. Finally, the effect of existence of a top non-liquefiable layer is explored.

**Effect of Input Motion**

Figures 19 to 21 present time histories of the surface ground displacements which were measured in upstream and downstream sides of the pile group. Results from these figures clearly indicate the effect of input motion characteristics as follows:

- As the amplitude of input acceleration increased, the lateral soil movement increased as well (Fig. 19). However, this observation is valid until a certain level of acceleration, i.e., 300 Gal in this study. As can be seen in Fig. 19, both 300 Gal and 500 Gal induced similar soil displacements. Since the configuration of the sloping ground became horizontal after the shaking (Fig. 7), acceleration greater than 300 Gal had no remarkable effect on the lateral soil displacement.
- The frequency of input motion had an inverse effect on the lateral soil deformation (Fig. 20). As frequency in-
creased, the lateral soil displacement decreased.

- According to Fig. 21, the direction of input motion had a substantial impact on the lateral soil deformation as the motion transverse to the slope produced larger soil movement than the input motion parallel to the slope. By applying shaking in the perpendicular direction to the lateral flow, it seems that the effect of input inertial force would no longer have any interference with the static gravity-induced driving force, hence the lateral soil flow could move to a further extent.

- Time history of input motion in Fig. 19 clearly indicates that the lateral soil displacement occurred during the shaking and diminished as it stopped.

The first two findings are consistent with the Newmark’s rigid block analogy (Newmark, 1965) in which the seismic slope movement has a direct relation with the amplitude and an inverse relation with the frequency of input motion. In this regard, it should be noted here that the liquefaction-induced lateral spreading, in this study, occurred during the shaking which is consistent with the Newmark’s theory and discussion on the post-shaking lateral spreading is out of scope. Similar findings to this section were reported by Toyota et al. (2004) using shaking table tests on sloping ground.

**Effect of Ground Characteristics**

Furthermore, the effect of ground features such as den-
Density and slope inclination was investigated, and the results are given in Figs. 22 and 23. Three different soil relative densities were considered in this study: 18%, 30%, and 60%, among which the first two densities are classified as loose sand, while the last one as medium dense ground. Dense sand is not included in this comparison, because liquefaction-induced large ground displacement could not be developed. In addition, two different slope inclinations were examined including 3° and 5°. The results illustrate that both parameters considerably affect the soil displacement as follows:

- Density of soil was found to be important as the loose soil deformed more significantly than the medium dense ground. However, this observation is valid as far as soil liquefies and laterally moves.
- Inclination of the ground surface had direct correlation with the lateral soil deformation.

**Effect of Top Non-liquefying Soil Layer**

The effect of top non-liquefying soil layer overlaying the liquefiable soil on the lateral soil displacement was examined, and the results are presented in Fig. 24. The results illustrate that the existence of the top non-liquefiable soil layer remarkably reduced the surface soil displacement, and as the thickness of non-liquefying layer increased, lateral soil displacement decreased.

Finally, the effects of above mentioned parameters on the residual soil displacement at surface are summarized in Figs. 25 to 28. These figures provide a clear understanding of the mechanism of liquefied soil flow in the sloping ground configuration, revealing the significance of the discussed parameters. In addition, it should be noted that the observations in this study are consistent with the results reported by Toyota et al. (2004) on flow dy-
Fig. 25. Effect of amplitude and frequency of input motion on maximum soil displacement

Fig. 26. Effect of density and slope of ground on maximum soil displacement

Fig. 27. Effect of direction of input motion and top non-liquefied soil on maximum soil displacement at surface

Fig. 28. Effect of top non-liquefied soil on maximum soil displacement at surface in large pile group experiment—Dr = 40%, 300 Gal, 10 Hz (Y)

LATERAL FORCE OF LIQUEFIED SOIL ON PILES

The lateral force of liquefied soil exerted on piles was back-calculated from the bending moment records. Since the main focus of this study was on the kinematic aspect of this lateral force, the monotonic component of the lateral force was obtained as follows for further investigations. The back-calculated lateral force ($P_{\text{Record}}$) was separated into the monotonic ($P_{\text{Monotonic}}$) and the cyclic ($P_{\text{Cyclic}}$) components using a smoothing method (adjacent averaging), and the monotonic component was employed for the discussions. Hence, the values of lateral force, either maximum or total, presented in this paper correspond to the monotonic component only. An instance of this procedure is illustrated in Fig. 29.

In the next step, the maximum monotonic lateral forces along each pile were plotted including the profiles from experiments on both large and small pile groups (Fig. 30). This figure comprises the data from different pile rows: front in upstream, middle, and rear in downstream. As can be seen, no specific vertical distribution was consistently observed in all the experiments. However, considering a uniform vertical distribution for the monotonic lateral force appears to be a proper suggestion, though more data from large scale experiments are needed to confirm this finding. A similar conclusion was also reported by Dobry et al. (2003) and Elgamal et al. (2006). While, the JRA design code (Japan Road Association, 2002) recommends that the lateral force is proportional to total stress, increasing with depth.

Total Lateral Force

The total lateral force in each individual pile was calculated by integrating the lateral soil force along the pile using Eq. (1). As a result, the time history of total lateral force for each pile, $Q_i(t)$, was obtained. This procedure was carried out for all piles in each row, giving the total lateral force in each row, $Q_{\text{row}}(t)$ (Eq. (2)). Finally, by...
Fig. 29. Decomposition process for lateral force of liquefied soil

Fig. 30. Profiles of maximum monotonic component of lateral force exerted by liquefied soil

summing the time histories of all rows in the group, the time history of the total lateral force in the pile group, \( Q_{\text{total}}(t) \), was derived (Eq. (3)). The average lateral force per pile, \( Q_{\text{average}} \), was then obtained by dividing the maximum total lateral force of the group by the number of piles in the group (Eq. (4)).

\[
Q(t) = \int_{z=0}^{H} P_1 dz = \left( \frac{dM}{dz} \right)_{\text{at bottom}} \tag{1}
\]

\[
Q_{\text{row}}(t) = \sum_{i=0}^{n} Q_i(t) \tag{2}
\]

\[
Q_{\text{total}}(t) = \sum_{j=0}^{N} Q_{\text{row}}(t) \tag{3}
\]

\[
Q_{\text{average}} = \frac{Q_{\text{max}}\text{total}}{n \times N} \tag{4}
\]

where

\( P_1 \): Lateral force of liquefied soil back calculated from strain gauges records (N/cm)

\( H \): Height of pile (cm)

\( z \): Soil depth below the ground surface (cm)

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

\( n \): Number of piles in a row

\( N \): Number of pile rows in group

The time histories of the monotonic component of the total lateral force for each pile row and whole pile group are depicted in Fig. 31 for the case of 6 \( \times \) 6 pile group. As is shown, the total lateral force reached its pronounced peak during the early stage of shaking, and this parameter will be further discussed in the following section.

**Distribution of Maximum Lateral Force in Pile Groups**

The distribution of maximum total lateral force for the pile groups was carefully studied, and the results are displayed in Fig. 32 for both large (6 \( \times \) 6 and 11 \( \times \) 11) and small (3 \( \times \) 3) pile groups. These distributions demonstrate that in the sloping ground model, both front-row (in upstream) and rear-row piles (in downstream) sustain larger lateral forces in the group than middle row piles (inside pile group). The reason is that the piles in the front row (upstream) were directly pushed by the significant soil flow, hence demonstrated a substantial lateral forces; while, the middle-row piles were protected by the upstream piles from the effect of soil flow (shadow effect), carrying smaller lateral forces. However, remarkable lateral force in the rear-row piles, which appeared to be protected by other piles, was interesting and consistent with the past researches (e.g., McVay et al., 1998; Kimura et al., 2002; Rollins et al., 2005, among others). This ob-
Group pile liquefaction flow

![Fig. 31. Time histories of total lateral force of pile group (6 × 6) and each pile row in large pile group (6 × 6)—data include instrumented piles](image1)

![Fig. 32. Distribution of maximum total lateral force in large and small pile groups—data include instrumented piles from large group and all piles in small group tests](image2)

![Fig. 33. Photo and magnified schematic illustration of surface ground deformation around pile group](image3)

Ground surface on the downstream side of the pile group was caused by the lateral expansion because the soil was free to flow laterally in this zone. Moreover, the resulted elevation differences around the rear-row piles in the downstream can be somewhat responsible for the large lateral force too. This finding was further confirmed using pore water pressure records, and an instance of the records in Fig. 34 reveals the stress condition in upstream and downstream sides. As can be seen, profound drops in the excess pore water pressure time history in the downstream side of the pile group clearly indicates extension stress state, signifying that the rear-row piles were pulled by the liquefied soil in this zone. In this regard, displacement contour plot in Fig. 15 (plan view) is also able to reveal this finding to some extent. Further detailed discussion on this issue can be found in Motamed et al. (2008) in which PWP records and vane shear test results were employed to evaluate the stress state around pile groups in sloping ground models. A similar finding was reported by Tokimatsu and Suzuki (2004) on cyclic behavior of piles in liquefying ground.

On the basis of above findings, a new mitigation strategy for existing pile groups embedded in the sloping ground configuration can be proposed. By installation of additional non-structural pile rows in front and behind a pile group, the newly added pile rows can sustain a large portion of the liquefaction-induced lateral forces during a strong earthquake and protect the middle row piles.
Parametric Study on Total Lateral Force in Pile Group

In this section, the effect of several parameters such as amplitude, frequency and direction of input motion; density and slope inclination of ground; thickness of top non-liquefying layer; and pile numbers on the maximum total lateral force are discussed.

For comparison, recommended values of the maximum total lateral force of liquefied soil by the JRA 2002 design code (Japan Road Association, 2002) are presented in this section. The JRA 2002 recommends 30\% of the total overburden pressure (total stress) to be multiplied by the outermost width of the pile group to obtain the lateral force per unit depth exerted by the flow of liquefied soil. Moreover, passive pressure of the dry soil layer is added to above mentioned value if a top non-liquefiable soil layer exists. For design purposes, it is assumed this total lateral force is equally distributed among piles in the group.

The results of the parametric study are presented in Figs. 35 and 36 for large (6×6 and 11×11) and small (3×3) pile group tests, respectively; and the following points are made:

- The existence of a top non-liquefiable layer significantly increased the total lateral force because of consequential passive earth pressure. This finding is in strong agreement with the observations from past earthquakes (Hamada and O’Rourke, 1992, among others). This observation was valid for both large (Fig. 35) and small pile groups (Fig. 36(a)). According to Fig. 36(a), as the thickness of top non-liquefying layer increased (from 5 cm to 10 cm), the lateral force was also intensi-
Figure 35 illustrates that the total lateral force increased with the number of piles in the group even if the entire width of the pile group remains constant.

As the input frequencies decreased (10 ⇒ 5 ⇒ 3 Hz), the total lateral force increased (Fig. 36(a)).

Two different relative densities of sand: 18% and 30% were employed to evaluate the effect of soil density. However, the results were almost identical (Fig. 36(b)). This is because both relative densities are categorized as loose sand. As mentioned in the section related to soil displacement (Figs. 22 and 26), the soil lateral displacement was also similar in these two experiments.

Results demonstrate that as the amplitude of input acceleration decreased, the total lateral force also decreased (Fig. 36(b)).

The input motion was mainly applied in the direction parallel to the slope of ground in the small pile group tests. However, in order to evaluate the effect of the direction of input motion, the model was shaken once in the direction transverse to the slope of ground. The results indicate that parallel shaking produced larger lateral force rather than transverse shaking (Fig. 36(b)). A phase study was then performed between the input inertial force and the total lateral force in the pile group (Fig. 37), and it is apparently understood that they are both in-phase, intensify the lateral force in the pile group.

Two different configurations of the sloping ground inclination, i.e., 5% and 3%, were used to evaluate the effect of ground slope inclination. The outcome reveals that as the slope inclination decreased, the total lateral force also decreased (Fig. 36(b)).

Although the JRA 2002 design code underestimated the maximum lateral force, by considering a safety factor (~1.5) this design code can provide a reasonable preliminary evaluation for the maximum lateral force. A quantitative comparison illustrated in Fig. 38 reveals that by increasing the maximum lateral force by 47%, the JRA 2002 estimation would be in strong agreement with the test results. This increase in the maximum lateral force shown in Fig. 38 (linear fit) is also consistent with the test results on pile groups behind sheet pile quay wall (Motamed and Towhata, 2010) as depicted in the figure.

Despite to JRA 2002, which uniformly distributes the force among piles in the group regardless of the position of pile in the group, experimental data of this study clearly reveals that the contribution of each pile row in the total lateral force is significantly affected by its position in the group.

### Soil-Pile Interaction

In order to investigate the soil-pile interaction, several experiments were conducted with different pile spacings: 5D, 2.81D, and 2.5D. In addition, two experiments were 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 spacings, and the results are illustrated in Fig. 39. As is shown in this figure, the average total lateral force per pile decreased as the pile spacing became smaller. This behavior, which is called the group effect, exhibits the extent of soil-pile interaction and its relation with the pile spac-
ing. This observation was also consistent for the two layer soil configuration in which a top non-liquefiable layer overlaid the liquefiable layer. The data in Fig. 39 are mainly from the large pile group tests; however, three data from small-group experiments are included for which the force is slightly greater than the large group data. This discrepancy is because the large group tests were shaken in the transverse direction to the ground slope, while the small group models were shaken parallel to the slope.

CONCLUSIONS

This paper presented the results of 1-g shaking table model tests on large and small pile groups subjected to lateral flow of liquefied subsoil. The following main conclusions are drawn:

1. The reliability and accuracy of instrumental tools (inclinometers and shapetape) to measure lateral soil displacement was confirmed through direct comparison with the direct observation of the colored sand and small tags.

2. The distribution of displacement and velocity of liquefied soil in the model (soil motion) illustrated larger magnitude in both upstream and downstream sides of the pile group, while smaller values were observed inside the pile group.

3. The profiles of bending moment in piles manifested the intensifying effect of top non-liquefiable layer as bending moment was drastically increased by the passive earth pressure due to the surface dry layer.

4. Amplitude, frequency, and direction of the input motion have significant effect on the magnitude of lateral soil displacement. Moreover, density and inclination of ground slope noticeably affect the lateral displacement of liquefied soil.

5. The maximum lateral force that the liquefied soil flow exerts on a pile is uniformly distributed along the pile depth.

6. The distribution of the maximum total lateral force in the pile groups indicated that both front (in upstream) and rear (in downstream) row piles received greater lateral forces than middle row piles. This behavior is attributed to the distribution of liquefied soil motion (displacement and velocity) in the sloping ground model. On this basis, retrofitting strategy, it is proposed to install additional pile rows in front and behind an existing pile foundation.

7. The JRA 2002 design code is able to provide a preliminary estimation of the total lateral force if a reasonable factor of safety is considered.

Topics for further studies can be the effect of pile diameter; configuration of pile groups; bottom connection of piles; and pile material properties. In addition, limitations of small scale 1-g testing should be considered. Therefore, further experimental program in centrifuge, large shaking table and field tests should be carried out to enhance the findings.

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GROUP PILE LIQUEFACTION FLOW


