An Experimental Study on External Forces on Pile Group from Flowing Liquefied Soil

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ABSTRACT:
The purpose of this study is to investigate the fundamental characteristics of the external forces on pile group from the flowing liquefied soil with shaking table tests under 30 G centrifuge condition, where a model of pile group was installed in flowing liquefied soil, were carried out. The pile group consists of 9 model piles. The following result was obtained from the experimental study. In the case when the model ground was not liquefied or partially liquefied, elastic force related with displacement of the ground is dominant, while in the case when the ground is perfectly liquefied, the viscous force related with the flow velocity of the ground is dominant. The viscous force is much larger than the elastic force.

KEYWORDS: liquefaction, liquefaction-induced large ground displacement, pile group, external force, experimental test

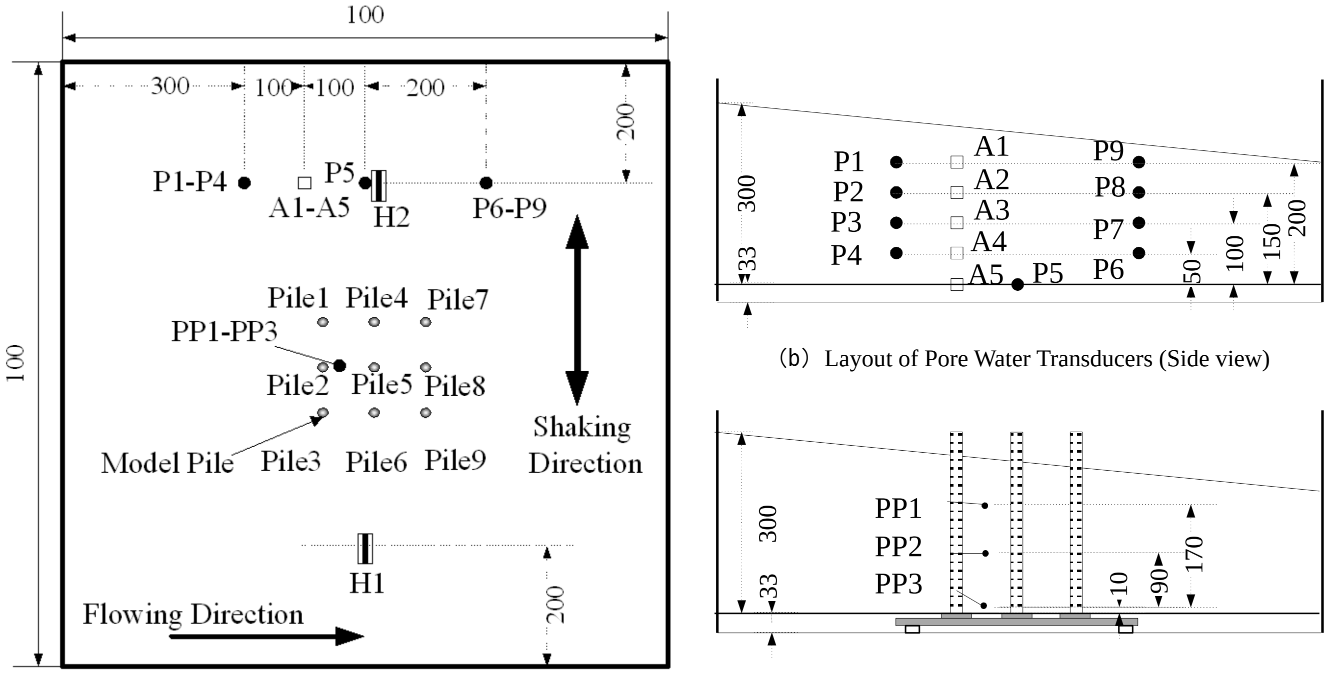
1. INTRODUCTION

During past earthquakes, such as 1964 Niigata earthquake, 1983 Nihonkai-chubu earthquake and 1995 Hyogoken-nanbu earthquake, liquefaction-induced large ground deformation caused severe damage on pile foundations of buildings and bridges. To develop countermeasures, it is necessary to understand behavior of pile group subjected to liquefaction-induced large ground displacement. Recent investigations mainly focus on the fundamental characteristics of the external force on single pile from liquefaction-induced large ground displacement, however, it is pointed out investigations on the pile group is necessary for the practical problems. The purpose of this study is to investigate the characteristics of the external forces on pile groups from liquefaction-induced large ground displacement. 30 G centrifugal shaking table tests with single pile and pile group (3 by 3) installed into a liquefiable sandy model ground were carried out.

2. CENTRIFUGE SHAKING TABLE TEST

2.1. Setup and Procedures for the Experiment

The experiment was conducted under centrifugal acceleration of 30g, by using a rigid soil box with a length of 100cm, a height of 37.5cm and a width of 100cm. Figure 1 shows a schematic drawing for the model of ground, foundation piles, and locations of accelerometers and pore water transducers. In all of cases, the model grounds with a thickness of 25cm were liquefied. The gradient of the ground surface is 10% and the surface of ground water is located at 25cm high from the bottom of the center of soil box. Two laser displacement transducers were also installed on the surface of the model to trace the time history of surface movement of the model. Model piles (Case1; single pile model, Case2; pile groups 3 by 3 which consists of with center-to center pile spacing of 2.5D in terms of pile center (D: diameter of model pile) are installed in liquefied soil. Table 1 shows the conditions of two cases of the tests.



(a) Layout of Model Piles and Instruments (Top view)

(b) Layout of Pore Water Transducers (Side view)

(c) Layout of Model Piles and Instruments (Side view)

Figure 1 Model Ground Layout (Unit: mm)

Table 1 Experimental Conditions

caseNo.	Pile Spacing		Relative Density	Amplitude
	-	cm	%	gal
case1	Single Pile		41	453
case2	2.5D	5.0	39	442

Stainless steel pipes with a diameter of 20mm and a wall thickness of 0.5mm were used as the pile model. The bending moments of the pile along the depth during the ground flow were estimated from the strain gages, placed on the inner wall of the pipes. All the piles were rigidly fixed to the bottom of the soil box and free at the top. The similitude for deformation between model piles and prototype piles was not taken into consideration because the experiments were focused only on the characteristics of the external forces from flowing liquefied soil flow.

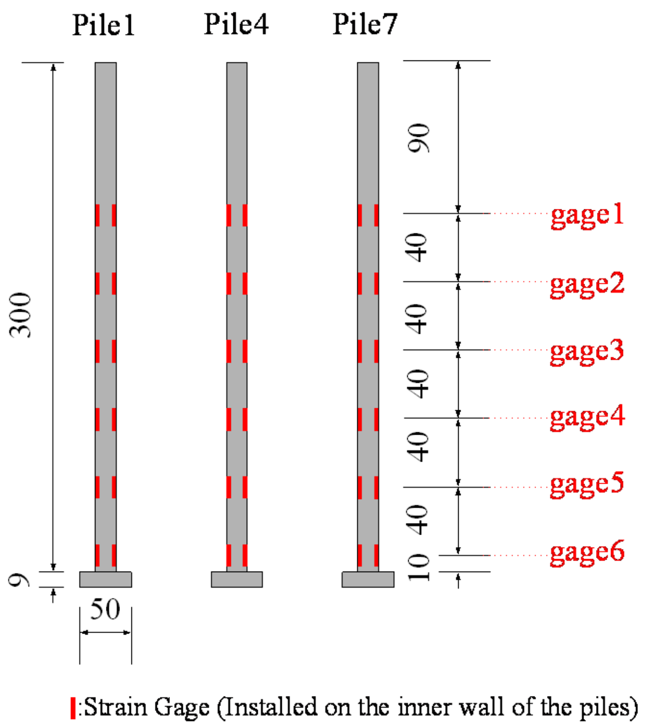


Figure 2 Model Piles and Measuring Point (Unit: mm)

2.2. Comparison of Time History

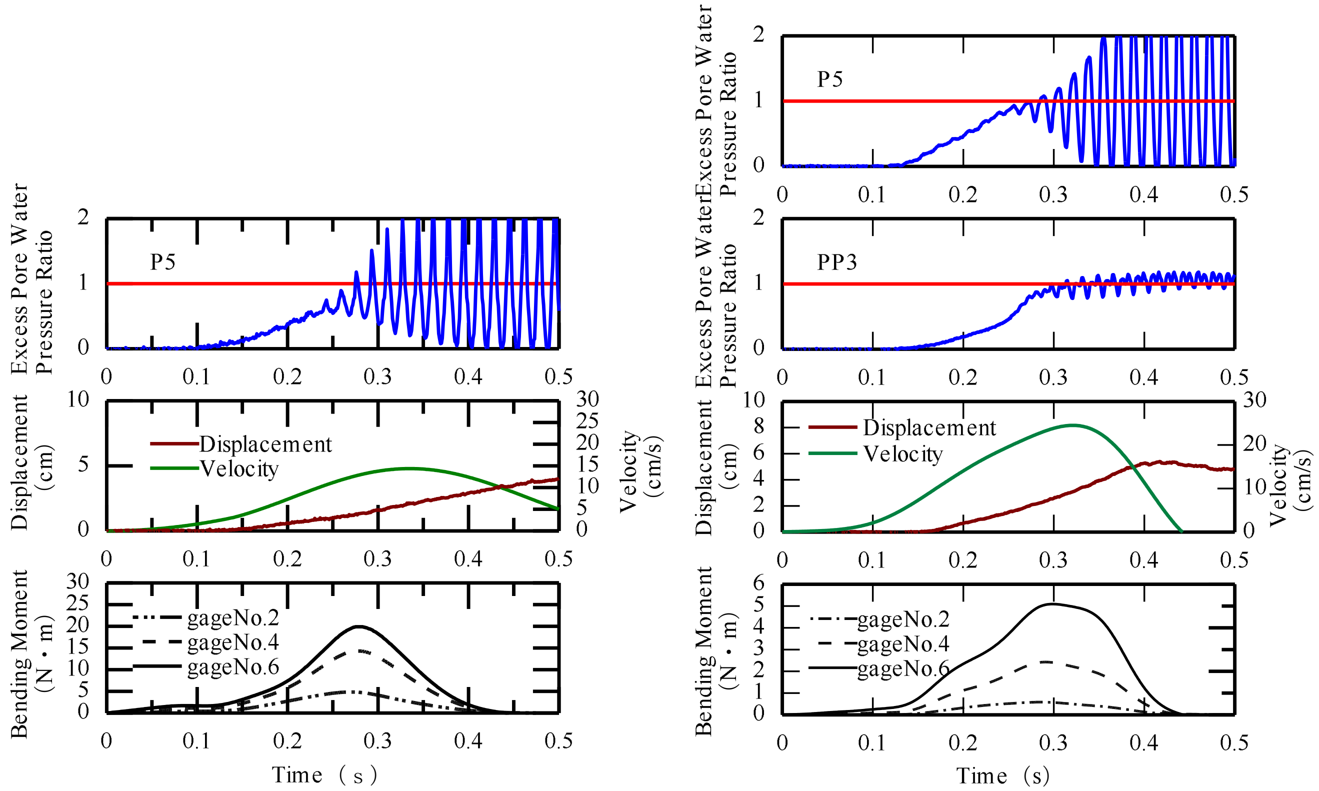
Figure3 shows the time histories of the excess pore water pressure ratio, displacements and velocities of the ground surface (H2; see Figure1) and bending moments of piles (case2; it shows one of Pile1 in the front corner of pile group) at some gages (gageNo.2, 4, 6; see Figure 2). The ground velocity was calculated by a differentiation of the measured ground displacement time histories. From the results shown in Figure 3, followings can be obtained.

1) Both of the displacements on the ground surface increased constantly during the shake event. On the other hand, bending moments at the bottom of the pile increased greatly until the excess pore water ratio reached 1.0 and decreased afterwards. This results implies that the ground displacement might be a controlling factor on the external force on the pile before the excess pore pressure ratio reached 1.0, but after the ratio reached 1.0 the ground displacement was not only one factor to govern the deformation of the pile.
2) As shown in Figure.3, the velocity at the surface reached to their maximum values after excess pore water pressure ratio reached 1.0. On the contrary, the bending moment at the bottom of the piles (gage 6) continued to increase even after the velocities reached its maximum value. This result means that the ground velocity could not regard as the governing factor for the formation of external forces on the pile before the

excess pore pressure ratio reached 1.0.

3) After the excess pore water pressure ratio reached nearly 1.0, the ground velocity began decreasing, and the bending moment at the bottom of the pile started slightly decreasing with a little time delay as well. It is considered that the external force was governed by the ground velocity acted on the model piles after the excess pore water pressure ratio reached 1.0. However, other factors besides the ground velocity could be also involved to produce the external forces on the pile since the bending moment and the velocity reached to their maximum values with time differences.

Basing on the experimental findings described as above, it can be inferred that the influence of ground displacement and velocity on the external force had accordingly changed during the excess pressure ratio is increasing to 1.0 in both case (single pile and pile group).



(a) Case1 (single pile)

(b) Case2 (Pile1;in the corner of pile group)

Figure 3 Time Histories of Excess Pore Water Pressure Ratio, Ground Displacement, Ground Flow Velocity and Bending Moment of Piles

2.3. Estimation of Forces on Single Pile and Pile Group

There are two kinds of the external forces acting on the piles: One is the force resulting from the ground displacement and another is the force resulting from the ground velocity. In this section, the characteristics of external forces will be quantitatively examined by the measured bending moments, and secondarily effects of ground displacement and velocity on the force were estimated.

Figure 4 shows the distribution of bending moment of piles of pile groups (Pile1; in front along with the soil flow direction, Pile5; in middle of the soil flow direction and Pile7; in rear along with the soil flow direction) along the depth. From this figure, the distribution of the moment could be approximated by cubic polynomial. Therefore, it was assumed that the force from liquefied soil had a linear distribution. Figure 5 shows the calculate model of external force. The coefficients a and b representing the force distributions were determined from the measured bending moments of the piles by the least mean square method.

As mentioned previously, two kinds of external forces are acting on the piles during pore water pressure ratio is increasing from 0.0 to 1.0. One is the force resulting from ground displacement (so-called elastic force) and the other from ground velocities (so-called viscous force). In order to estimate these two kinds of forces, the Voigt model was adopted as shown in Figure 6.

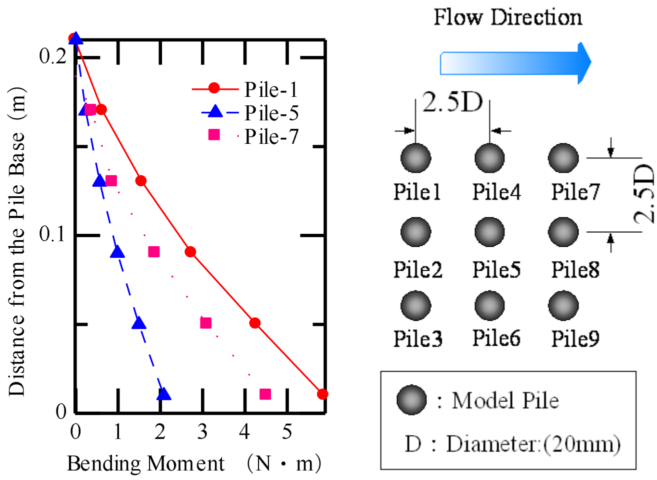


Figure 4 Distribution of Bending Moment along the Pile (case2)

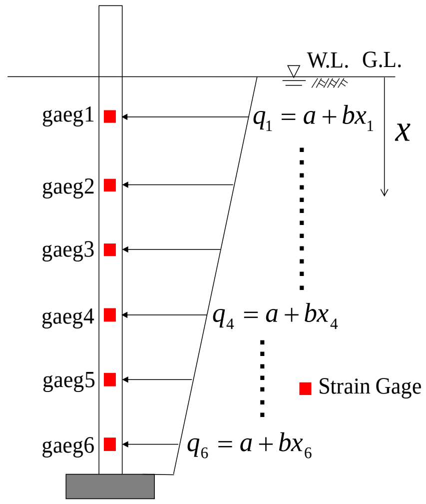


Figure 5 Evaluate Model of External Force

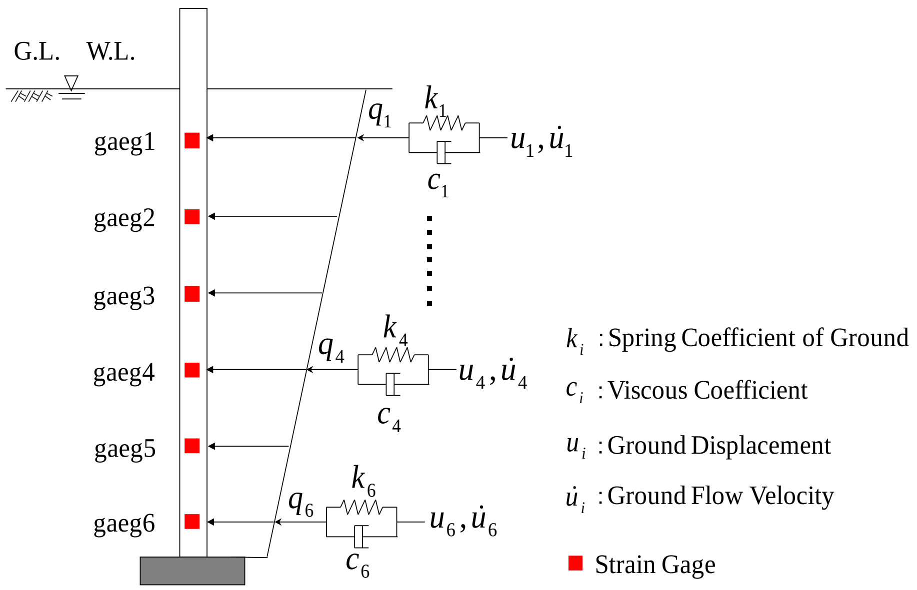


Figure 6 Voigt Model for Estimation of External Force

The elastic force is induced by the relative displacements between the pile and the ground, and the viscous force is induced by the relative velocities. In this experiments, the displacement and velocity of the model pile was enough small to negligible than those of ground. Therefore the force on the pile at the depth i was defined as Equation (2.1) in proportion with displacement and velocity of ground.

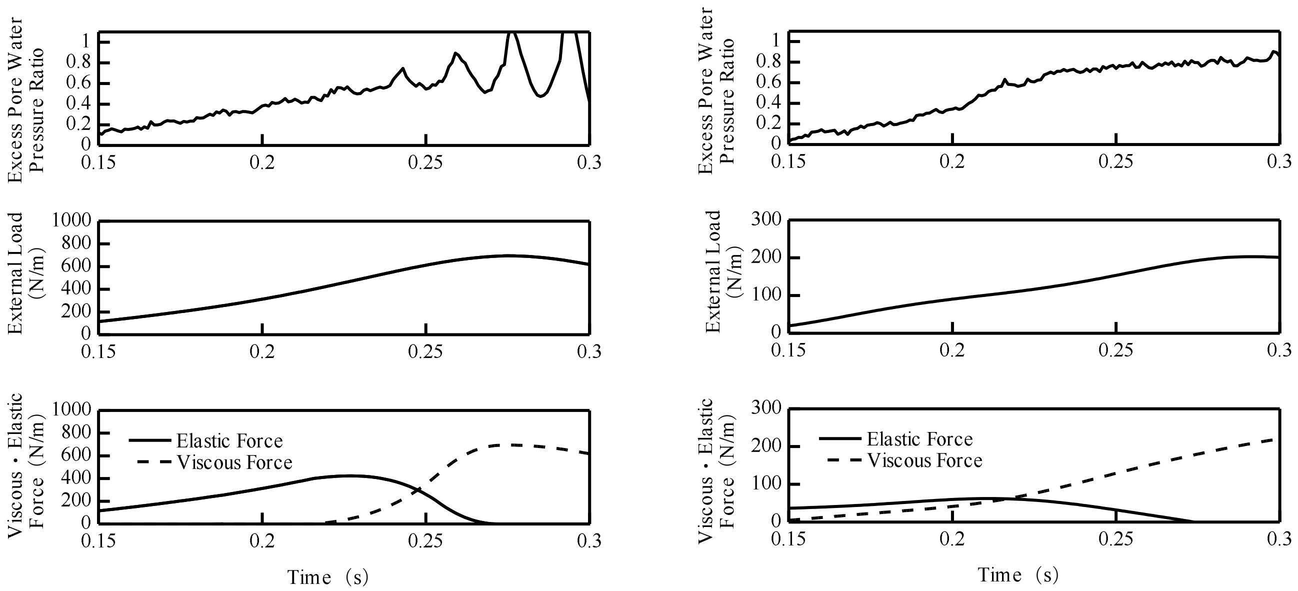
The spring coefficient and viscous coefficient are identified at each time from the estimated forces on the piles, velocities and displacements of the ground at the same depth. The coefficients k_i and c_i in Equation (2.1) can be estimated from the data of external forces on the pile, the displacements and the velocities of the ground in this range by the least mean square method. Consequently the time history of elastic force can be obtained. At each time step as moving the range (Time range for estimation; 0.02s) for the estimation sequentially, the time history of elastic force and viscous force can be obtained.

$$q_i = k_i u_i + c_i \dot{u}_i \tag{2.1}$$

Where k_i is the spring coefficient of ground and c_i is the viscous coefficient. u_i and $\dot{u}_i$ are the ground displacement and velocity at the depth i.

The time histories of the ground displacements and velocities on the surface (H2, see Figure1) is used for the identification of elastic and viscous forces. Figure 3 (a) and (b) show the time history of displacement and velocity in each case.

The results of the estimation of case 1 and 2 are shown in the Figure 7. The time histories of excess pore water pressure ratio, which were measured at nearly same locations, where the external forces were calculated, and external forces are plotted in the same figure. The elastic forces plotted as solid line and the viscous forces plotted as dotted line in Figure7.



(a) Single Pile (at gage 4)

(b) Pile1 in Pile Group (at gage4)

Figure 7 Time Histories of the results of Identification

In Figures 7 (a), results of single pile, the elastic force is larger than the viscous forces before 0.25 sec, but after that moment, the viscous forces reversely exceeded the elastic force. Similarly, in Figure 7 (b), results of pile of pile group, the elastic force exceeded the viscous forces before 0.22 sec, but after that moment, the viscous forces reversely is larger than exceeded the elastic forces. This indicates that the elastic force resulting from ground displacement acted on the piles before liquefaction, or partially liquefied after excess pore water pressure ratio reached 1.0.

Compare between the magnitude of elastic forces and viscous forces acted on piles, viscous force is larger than elastic force. And when bending moment of piles shows maximum value and the excess pore water pressure ratio reached 1.0, viscous forces are acted. In addition, it was found when soil is liquefied completely, viscous forces are dominant.

3. CONCLUTION

The characteristic of the external force acted on single pile and pile group from flowing liquefied soil was cleared based on a series of experiments 30g centrifuge as gravity. From the experimental result, the follows are obtained.

1) While in the case when the model ground is not liquefied or partially liquefied, elastic force depending displacement of the ground is dominant.
2) While in the case when the model ground is perfectly liquefied, the viscous force related with the flow velocity of the ground is dominant.
3) The viscous force is much larger than the elastic force.

These results are confirmed in single pile and pile group.

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