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HORIZONTAL LOAD DISTRIBUTION WITHIN PILE GROUP IN LIQUEFIED GROUND

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ABSTRACT

Distribution of horizontal load within a 3x3 pile group in liquefiable ground is studied based on a shaking table test conducted on a soil-pile-structure model constructed in a laminar box, 6.0 m high and 12.0 m long. The leading pile attracts larger shear force than does the trailing pile before pore pressure generation. The corner piles including those on the trailing side then attract larger shear force than does the inside piles during pore pressure generation, whereas such a difference in shear force within the pile group becomes negligibly small with cyclic ground softening after complete liquefaction. The difference in shear force before and after excess pore water pressure generation could be induced by the difference in subgrade reaction development mechanism between the two phases. The subgrade reaction before pore pressure generation is induced by an increase in normal stress on the compression side of a pile, with the largest normal stress in the leading pile, resulting in the largest shear force in the leading pile. The subgrade reaction during excess pore water pressure generation and after liquefaction is related to the pore water pressure reduction that is caused by soil dilation induced by its relative movement of pile. This could lead to the largest subgrade reaction of the corner piles.

Keywords: Pile group, Large shaking table test, Liquefaction, Horizontal load, Pore water pressure

INTRODUCTION

Recent earthquakes have indicated that soil liquefaction might have induced pile damage quite different from that observed in non-liquefied ground. Whereas the damage to pile foundations in non-liquefied ground mainly occurred near the pile head, that in liquefied ground occurred not only near the pile head but also at the bottom and/or the middle of the liquefied layer (e.g., Kansai Branch of Architecture Institute of Japan, 1996). This is because, while the inertial force form its superstructure mainly controls the damage to pile in the pile in non-liquefied ground, both the inertial force and kinematic force arising from large ground displacement play important roles in liquefied soil.

Pile damage may vary within a closely spaced pile group, as the stress zone induced by a pile overlap with those of adjacent piles. In non-liquefied ground, the leading piles tend to bear the largest loads and suffer the most significant damage within a pile group (e.g., Rollins et al., 1998 and Suzuki & Adachi, 2003). In constant, such pile group effects in liquefied ground is unknown. This is because studies on seismic behavior of a pile group in liquefied sand have been rarely made.

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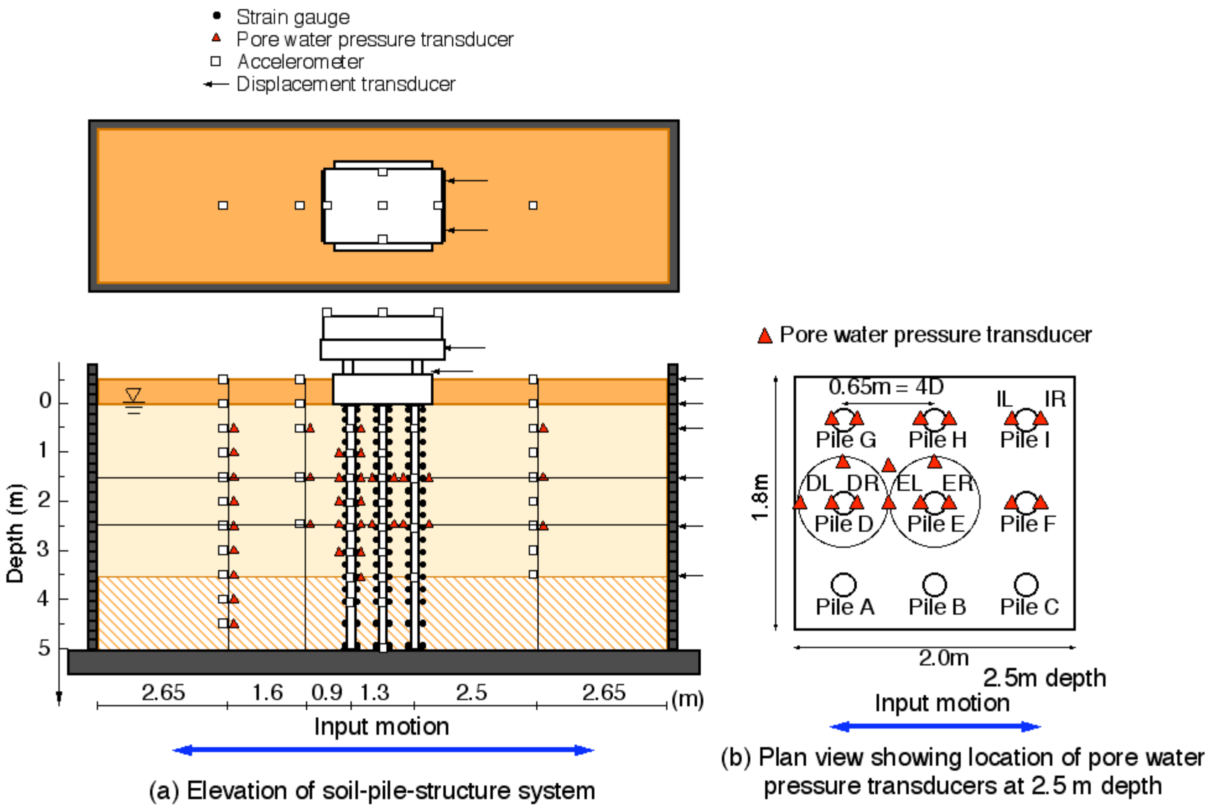

Fig. 1 Model layout

The objective of this paper is to investigate seismic behavior of a pile group and to estimate horizontal load distribution within the pile group based on a large shaking table test conducted on a 3x3 pile group in a liquefiable sand deposit. In the large shaking table test, many pore water pressure transducers were installed on and/or around piles in addition to many strain gauges on piles. This gives information on stress states in soil around the piles and its effects on p-y behavior as well as pile stresses within the pile group.

LARGE SHAKING TABLE TEST

To investigate horizontal load distribution within a pile group in liquefied ground, a large shaking table test was conducted on a liquefiable soil-pile-structure system using the shaking table facility at the National Research Institute for Earth Science and Disaster Prevention in Japan. Fig. 1 shows the soil-pile-structure system on the shaking table used in the test. The soil-pile-structure system was constructed in a laminar shear box with dimensions of 5.6 m x 12.0 m x 3.5 m on the shaking table.

A soil profile prepared in the laminar shear box consisted of three layers including a top dry/ unsaturated sand layer 0.5 m thick, a liquefiable saturated sand layer 3.5 m thick and an underlying non-liquefiable dense sand layer about 1.5 m thick. The water table was located at 0.5 m below the ground surface. The sand used was Kasumigaura Sand (e_{max} = 0.961, e_{min} = 0.570, D_{50} = 0.31 mm, F_c = 5.4 %). After forming the bottom non-liquefiable dense layer by compaction, the laminar shear box was filled with water to a certain level. Wet sand was pluviated into the water to prepare the liquefiable sand deposit below the water table, while dry sand was air-pluviated to form the top layer above the water table.

A pile group consisted of 3x3 steel piles 5m long. Each pile had a diameter of 165.2 mm with a 3.7 mm wall thickness and thus a flexural rigidity of 1.26 MNm^2. The piles were set up with a horizontal space of four-pile diameters center to center (Fig. 1(b)) and are hereby called Piles A to I. The tips of piles were fixed to the base of the laminar shear box and their heads were fixed to a steel foundation of 16.7 kN. The foundation carried a steel superstructure of 176 kN.

The soil-pile-structure system was densely instrumented with accelerometers, displacement transducers, strain gauges and pore pressure transducers, as shown in Fig. 1(a). To investigate pile stresses in liquefied ground, many strain gauges were placed on piles. In addition to strain gauges, many pore water pressure transducers were densely installed on piles at 2.5 m depth below the pile head (Fig. 1(b)), to estimate stress states in liquefied soil around the piles. Prior to the shaking table test, both geophysical test and mechanical cone penetration test were conducted to characterize the soil profile. The geophysical test showed that a P-wave velocity is 1,500 m/s, which indicated that the liquefiable sand layer was under nearly saturated conditions with a S-wave velocity is 120 m/s.

In the shaking table test, an artificial ground motion called Rinkai having a maximum acceleration scaled to 2.0 m/s^2 was used as an input motion.

VARIATION OF HORIZONTAL LOAD WITHIN PILE GROUP

To investigate seismic behavior of the pile group before and after pore water pressure generation, the displacements of soil and pile and the relative values of the two are calculated by double integration of their observed accelerations with time. Shear force and subgrade reaction of a pile are calculated by differentiation or double differentiation of bending moment calculated from observed strain gauge data.

Figs. 2 and 3 show time histories of: accelerations of the superstructure, foundation, ground surface and shaking table; bending moments and shear forces at the heads of Piles D, E and I; and excess pore water pressures on both sides of the three piles and in free field. Pile D was located in the left side center in the 3x3 pile group, pile E in the center and Pile I in the right side corner, as shown Fig. 1(b).

Fig. 3(g) shows that the soil liquefies in 20 s after the start of shaking, at which all the excess pore water pressures reach the initial effective stresses, e.g., about 20 kPa at 1.5 m depth and 30 kPa at 2.5 m depth. The pore water pressures fluctuate significantly during their generation. It is interesting to note that such pore water pressure fluctuation is more significant on the outside of the pile group (on the left side of pile D or on the right side of pile I (Fig. 3(a)(f))) than on the inside the pile group (Fig. 3(b)-(e)). The pore water pressure fluctuation, however, becomes insignificant with cyclic degradation after complete liquefaction.

The shear forces and bending moments in three piles increase with increasing acceleration of the superstructure but decrease with decreasing superstructure acceleration after excess pore water pressure generation. A comparison among the shear forces at the three pile heads shows that the shear force is the smallest at Pile E located at the center of the pile group among others.

To investigate difference in pile stress within the pile group in liquefiable ground, Fig. 4 shows relations between inertial force and shear force in Piles D, E and I. Plates (a)-(c) of Fig. 4 correspond to the relations before pore water pressure generation (0-6s), plates (d)-(f) to those during excess pore water pressure building up and in the early phase of soil liquefaction with significant pore water pressure fluctuation (10-30s) and plates (g)-(i) to those in the later phase of soil liquefaction with small pore water pressure fluctuation (50-60s).

When the inertial force increases on the right (positive) side before pore water pressure generation (Fig. 4(a)), the shear force on the right side of the pile increases (Pile I, Fig. 4(c)). Conversely, when the inertial force increases on the left (negative) side, the shear force on the left side increases (Pile D, Fig. 4(a)). This indicates that the shear force is larger in the leading pile than in the trailing piles, the trend of which is similar to that in dry sand (e.g., Rollins et al., 1998 and Suzuki & Adachi, 2003). During the early phase of soil liquefaction with significant fluctuation (Fig. 4(d)-(f)), regardless of the direction of the inertial force, the shear force is the largest on the outside corner pile (pile I, Fig. 4(f)) and the smallest on the inside center pile (Pile E, Fig. 4(e)). This is completely different from the trend before pore water pressure generation. In the later phase of soil liquefaction with small pore water pressure fluctuation, the shear force is almost the same within the pile group (Fig. 4(g)-(i)), which is different from the trend in the early phase of soil liquefaction with significant

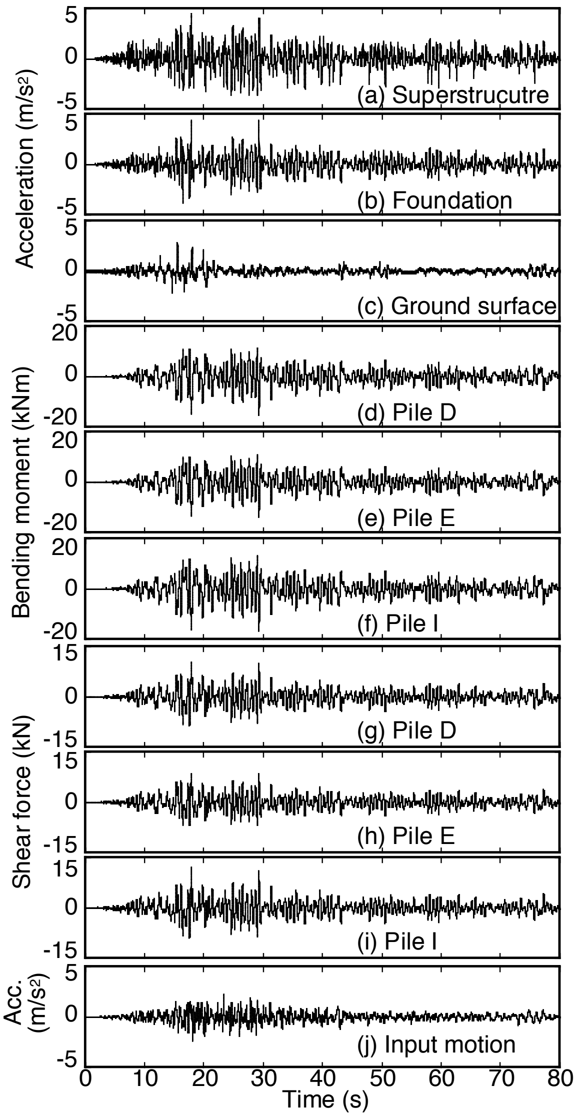

Fig. 2 Time histories of accelerations, moments and shear force

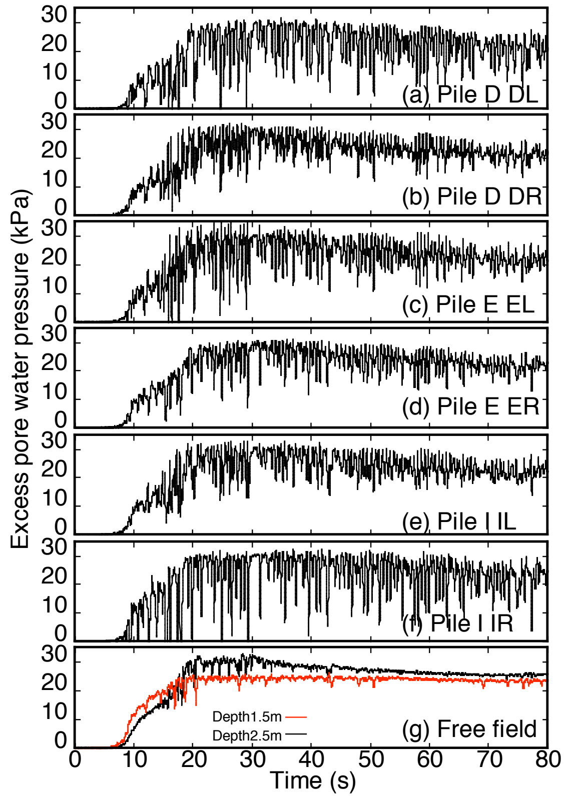

Fig. 3 Time histories of excess pore water pressures

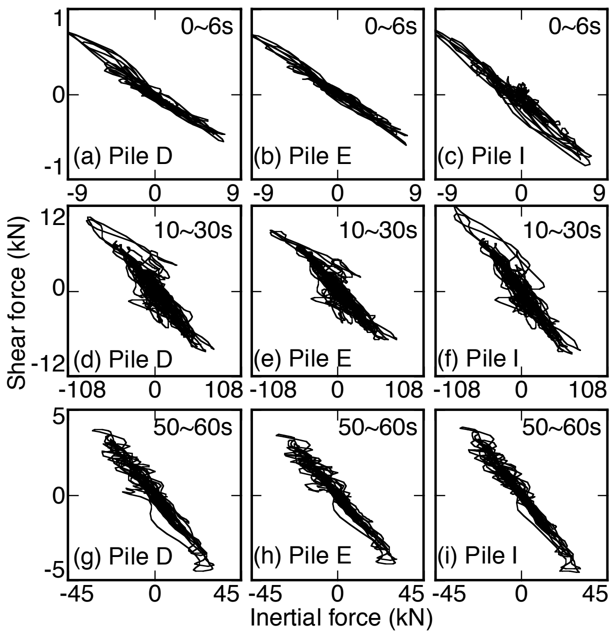

Fig. 4 Relations of inertial force and shear force

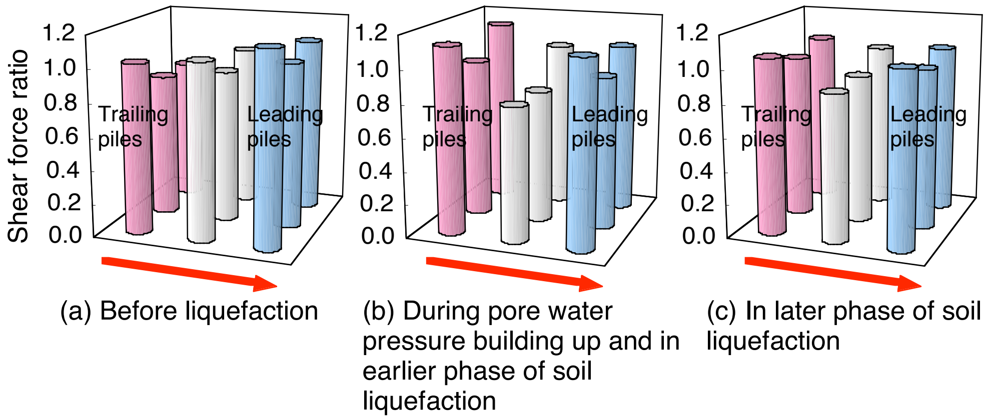

Fig. 5 Distributions of shear force within pile group

pore water pressure fluctuation. This suggests that the shear force distribution within the pile group could change considerably throughout the process of soil liquefaction.

To confirm the above tendency, Fig. 5 shows the distributions of shear force ratio of each pile in the 3x3 piles for periods of 0-6s, 10-30 and 50-60s. The shear force ratio is the ratio of the shear force in each pile to the total shear force of the pile group divided by nine, with the leading pile on the right. The shear force ratio distribution with the leading pile on the left was reversed and added. The figure confirms that the shear force ratio is larger in the leading piles before pore water pressure generation (Fig. 5(a)) but larger in the corner piles during excess pore water pressure generation with significant fluctuation (Fig. 5(b)). In addition, the difference in shear force ratios among piles becomes small with cyclic degradation of soil after liquefaction (Fig. 5(c)).

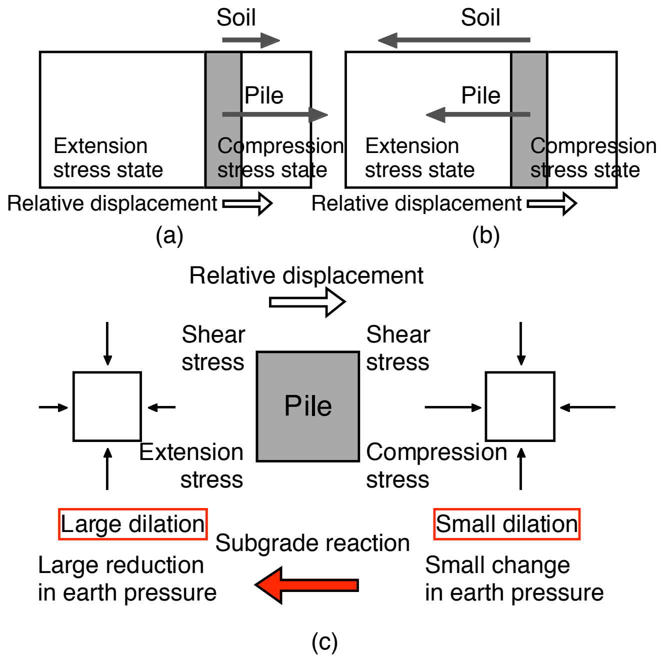

Fig. 6 Stress states in soil around pile

The difference in shear force ratio within the pile group described above might have been induced by the difference in subgrade reaction development between non-liquefied and liquefied grounds. Tokimatsu and Suzuki (2004) have shown that the subgrade reaction development in liquefied ground was completely different from that in non-liquefied ground, as shown in Fig. 6. With increasing relative displacement between a pile and ground, extension stress state occurs on one side of the pile with the compression stress state on the other side, accompanied by an increase in shear stress on both sides as shown in Fig 6(a)(b). The pore water pressure reduction on the extension side becomes pronounced due to the combined effects of decrease in normal stress and soil dilation induced by the shear stress, while that on the compression side becomes small due to the adverse effects of increase in normal stress and soil dilation induced by the shear stress (Fig. 6(c)). The subgrade reaction in liquefied ground is thus induced not only by the increase in normal stress on the compression side but also by a decrease in stress on the extension.

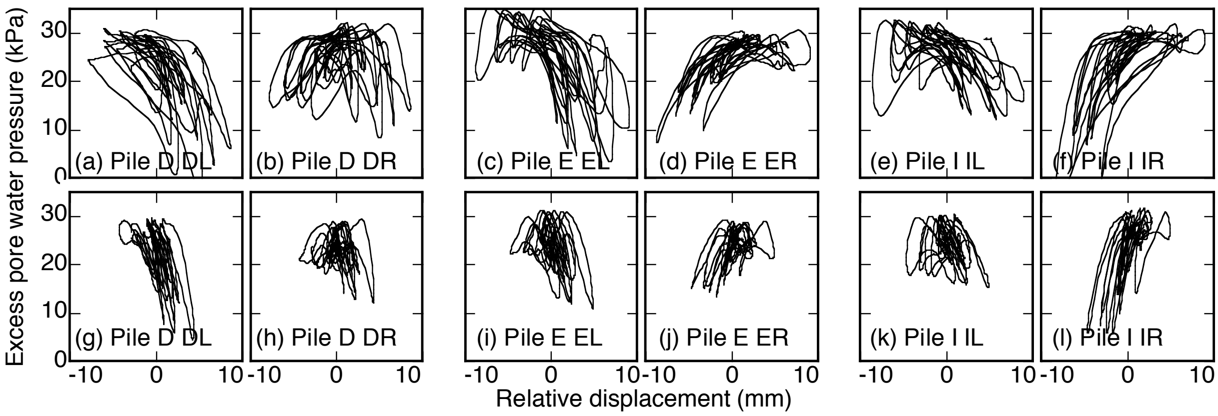

Fig. 7 Relations of excess pore water pressure and relative displacement between soil and pile

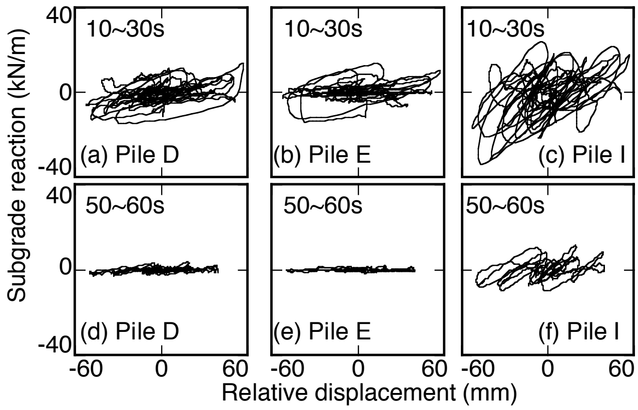

Fig. 8 Relations of subgrade reaction and relative displacement

To estimate pore water pressure changes in soil around piles, Fig. 7 compares the relations of excess pore water pressure with relative displacement between soil and pile at 2.5m depth for two periods of 10-30s and 50-60s, the shear force distributions of which are different from each other. When the piles push the soil on the right side (i.e., positive relative displacement develops) in 10-30s, the pore water pressures on the back/left side of all the three piles decrease significantly (Fig. 7(a)(c)(e)), while those on the front/right side of Piles D and E (Fig. 7(b)(d)) decrease slightly on Piles D and E and maintain almost constant on Pile I (Fig. 7(f)). When the pile pushes the soil on the left (i.e., negative relative displacement develops), the trends are reversed, i.e., the pore water pressure on the back/right side of the three piles decrease significantly (Fig. 7(b)(d)(f)), while those on the front/left side decrease slightly on Piles E and I (Fig. 7(c)(e)) and maintain almost constant on Pile D (Fig. 7(a)). In addition, such pore water pressure decrease is more significant on the outside pile (Fig. 7(a)(f)) than on the inside pile, leading to a larger difference in pore water pressure change between both sides of the outside pile. This is because the extension stress induced by one pile and the compression stress induced by the adjacent pile may cancel out within the pile group. Such pore water pressure decrease near the outside pile, however, gets small with cyclic degradation after complete liquefaction (Fig. 7(g)-(l)).

Fig. 8 shows relations of subgrade reaction with relative displacement between pile and soil in 10-30s and 50-60s. The subgrade reaction in Pile I is the largest among others (Fig. 8(c)). This indicates that the difference in subgrade reaction within the pile group might have been induced by the difference in pore water pressure change between both sides of the piles. As a result, the subgrade reaction and shear force are larger in the corner piles but smaller in the inside pile, as shown in Fig. 9(b). This is different from the trend in non-liquefied ground, in which the subgrade reaction and shear force are the largest in the leading piles (Fig. 9(a)). Such uneven distribution of subgrade reaction during pore pressure generation, however, becomes obscure with cyclic degradation of soil after complete liquefaction (Figs. 7(g)-(h) and 8(d)-(f)). Then, the difference in shear force within the pile group becomes insignificant (Fig. 5(c)).

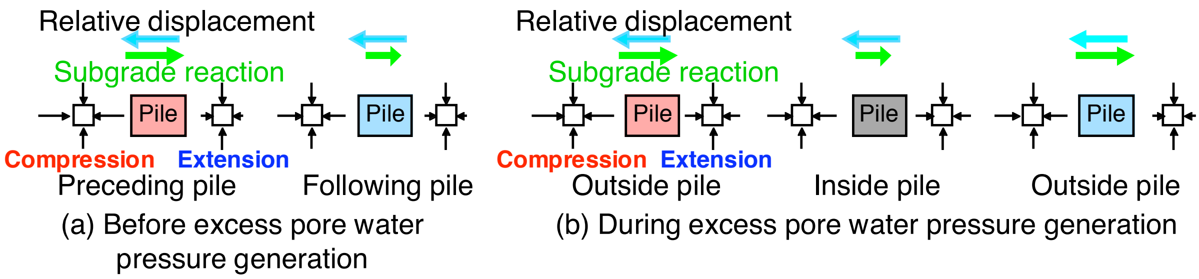

Fig. 9 Stress states in soil within pile group

CONCLUSIONS

The distribution of horizontal load within a 3x3 pile group in liquefiable ground has been investigated through the large shaking table test conducted on a soil-pile-structure system. The test results and discussions have led to the followings:

1) Pile stresses before excess pore water pressure generation become larger in the leading piles than in the trailing piles, whereas those during excess pore water pressure generation and immediately after liquefaction become larger in the outside corner piles than in the inside center piles. The difference in pile stresses within the pile group becomes insignificant in the later phase of soil liquefaction.

2) The difference in pile stresses within a pile group is probably induced by difference in the mechanism of subgrade reaction development before and after excess pore water pressure generation. The subgrade reaction before excess pore water pressure generation is induced by an increase in normal stress on the compression side of a pile, with decreasing normal stress on the compression sides of the following piles. This leads to smaller subgrade reaction of the trailing piles. The subgrade reaction during excess pore water pressure generation is, in contrast, induced by difference in pore water pressure changes between compression and extension sides of a pile. Such compression and extension stresses induced by the adjacent two piles might cancel out with each other in soil inside the pile group. This leads to smaller subgrade reaction of the inside piles. Such uneven distribution of pile stress before and immediately after soil liquefaction becomes obscure probably due to cyclic softening of soil after complete liquefaction.

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