PORE WATER PRESSURE RESPONSE AROUND PILE AND ITS EFFECTS ON P-Y RELATION DURING LIQUEFACTION

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Abstract: The effect of pore water pressure response around a pile on p-y behavior during soil liquefaction is investigated based on shaking table tests with a laminar shear box 6.0 m high and 12.0 m long. Three soil-pile-structure models having liquefiable sand deposits prepared at different densities are tested with pore water pressure transducers densely instrumented around a pile. The pore water pressure around a pile in dense sand decreases considerably with increasing relative displacement between soil and pile. This causes an increase in subgrade reaction, making the p-y behavior stress hardening. A close examination indicates that the reduction in pore water pressure is greater on the extension side than on the compression side of the soil around the pile. This is because the pore water pressure on the extension side decreases due to the combined effects of extension stress and dilatancy characteristics of the soil induced by the shear stress developed around the pile, while that on the compression side does not decrease due to the adverse effects of compression stress and dilatancy characteristics. The pore water pressure around the pile in loose sand, in contrast, does not decrease despite a larger relative displacement, making the p-y behavior stress softening.

1. INTRODUCTION

The field investigation and subsequent analyses made after the 1995 Hyogoken-Nambu earthquake indicated that ground movements could have a significant effect on damage to pile foundations. Especially, in liquefied area where the ground moves largely, the effect cannot be neglected, as most of the pile damage was associated with large ground movement.

To estimate the kinematic effect from ground movement during liquefaction, p-y behavior, defined as the relationship of subgrade reaction with relative displacement between ground and pile, has been studied based on large shaking table tests and centrifuge model tests (Tokimatsu et al. (2002 & 2001) and Wilson et al. (2000)). These studies have shown that the pore pressure reduction around a pile has a significant effect on p-y behavior; however, the response mechanism of pore pressure reduction including its variation around a pile is unknown. Toward better understanding of the mechanism of p-y behavior and its effects on pile foundations, the distribution of pore pressure around a pile should be identified.

The object of this paper is to investigate the variation of pore water pressure reduction around a pile on p-y behavior during liquefaction. Large shaking table tests are conducted for this purpose with dense instrumentation of pore water pressure transducers around a pile, together with earth pressure gauges, strain gauges, displacement transducers, and accelerometers. The effects of pore water pressure reduction and its variation around a pile on p-y relation during soil liquefaction is then examined.

2. LARGE SHAKING TABLE TESTS

To investigate qualitatively the effect of pore water pressure on p-y relation, the results of large shaking table tests, conducted on soil-pile-structure systems using the shaking table facility at the National Research Institute for Earth Science and Disaster Prevention (NIED), are used. The dimensions of the shear box on the shaking table were 5.0 m high, 12.0 m wide and 3.5 m long.

Fig. 1 shows a soil-pile-structure system used for the tests. The soil profile consisted of a top dry sand layer 0.5 m thick, a liquefiable sand layer 3 m thick and an underlying dense gravelly layer about 1.5 m thick. The sand used was Kasumigaura Sand (e_{max} = 0.961, e_{min} = 0.570, D_{50} = 0.31 mm, F_c = 5.4 %). Table 1 summarizes test series. The soil densities estimated were loose for D1, medium for DL, and dense for DS. Test series D1 had a foundation of 16.7 kN without a superstructure. Test series DS and DL had a foundation of 20.6 kN with a superstructure of 139.3 kN, whose natural period was shorter or longer than that of the ground before liquefaction. All the structure models were supported by a 2x2 steel pile group that was fixed to the container base. The piles had a diameter of 31.85 cm with a 0.6 cm wall thickness.

The soil-pile-structure system was densely instrumented with accelerometers, displacement transducers, strain gauges, pore water pressure transducers, and earth pressure transducers, as shown in Fig. 1. The accelerations and pore water pressures on the piles and in the ground were measured at every 50 cm with depth and the bending strains of piles at every 10-25 cm. Particularly, many pore water pressure transducers and some earth pressure transducers were installed around a pile at 1.5 and 2.5 m depth, as shown in Fig. 2.

In these tests, an artificial ground motion called Rinkai, produced as an earthquake in Southern Kanto district in Japan was used as an

Table 1 Test series

Series ID	Superstructure	Soil density
D1	No	Loose
DL	Yes ($T_b > T_g$)	Medium
DS	Yes ($T_b < T_g$)	Dense

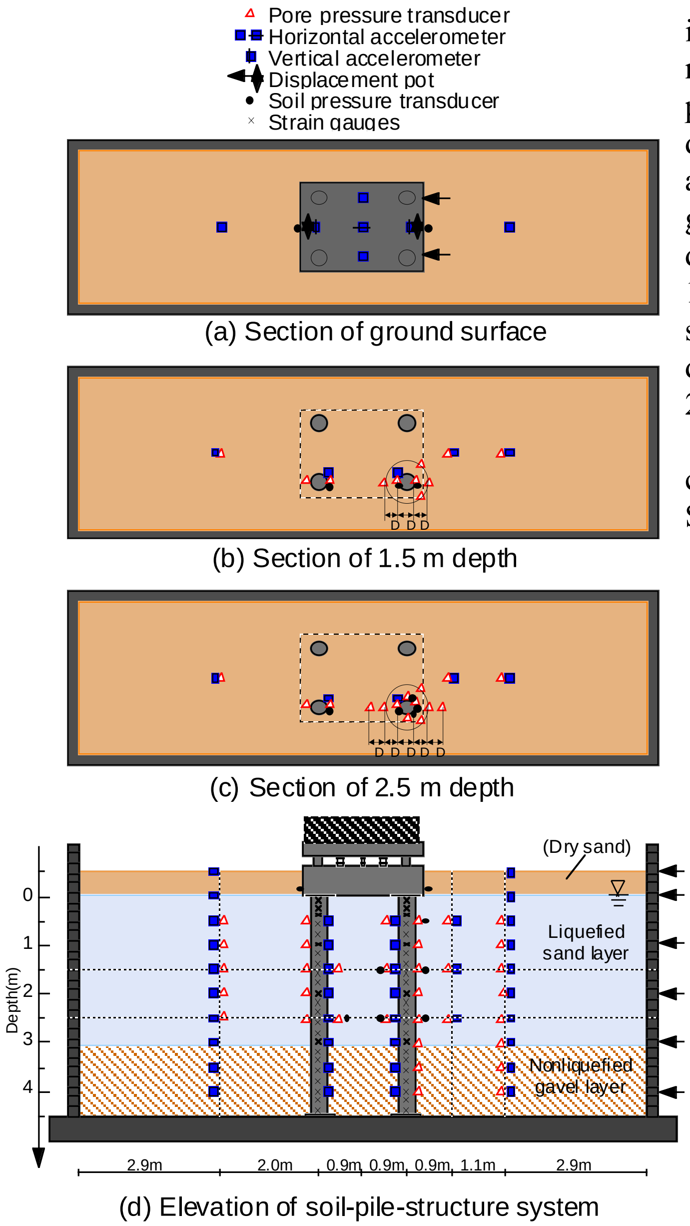

Fig. 1 Model layout

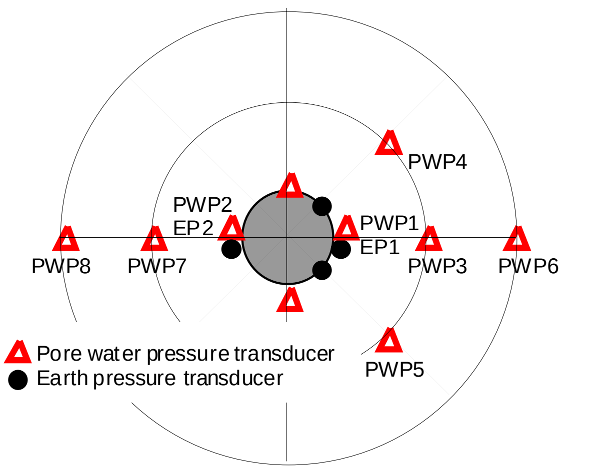

Fig. 2 Instrument on and around pile

input base acceleration to the shaking table, with a maximum acceleration of either 1.5 or 2.0 m/s^2. The test results evaluated in this study are those of series D1 with a peak input acceleration of 1.5 m/s^2, and series DL and DS with 2.0 m/s^2.

3. TEST RESULTS

3.1 Time History of Observed Value

To evaluate the effect of pore water pressure on p-y relation, the displacements of the ground and pile are calculated from the double integration of accelerations and the subgrade reaction from the double differentiation of bending moment with depth. Figs. 3, 4 and 5 show the time histories of the displacements of soil and pile, the relative displacement of the two, the horizontal subgrade reaction and pore water pressure ratio at 2.5 m depth in series DS, DL and D1, together with that of the input motion. The pore water pressure ratio is the average of the four values observed on the surfaces of the pile. The pore water pressure ratio increases to 1.0 in about 20 s, accompanied by an increase in relative displacement between soil and pile.

In dense sand (DS, Fig. 3), the subgrade reaction becomes large at about 20 s, at which the variation of pore water pressure ratio with time is pronounced. Both the subgrade reaction and the variation of pore water pressure ratio with time in

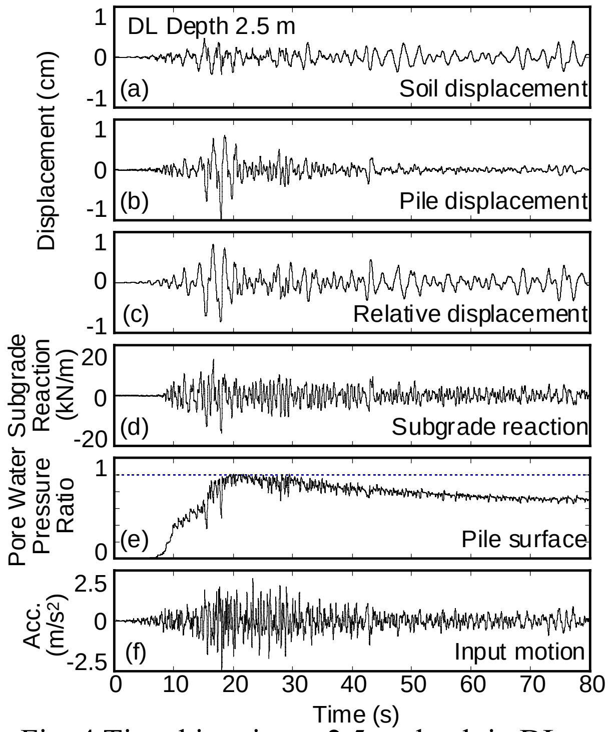

Fig. 4 Time histories at 2.5 m depth in DL

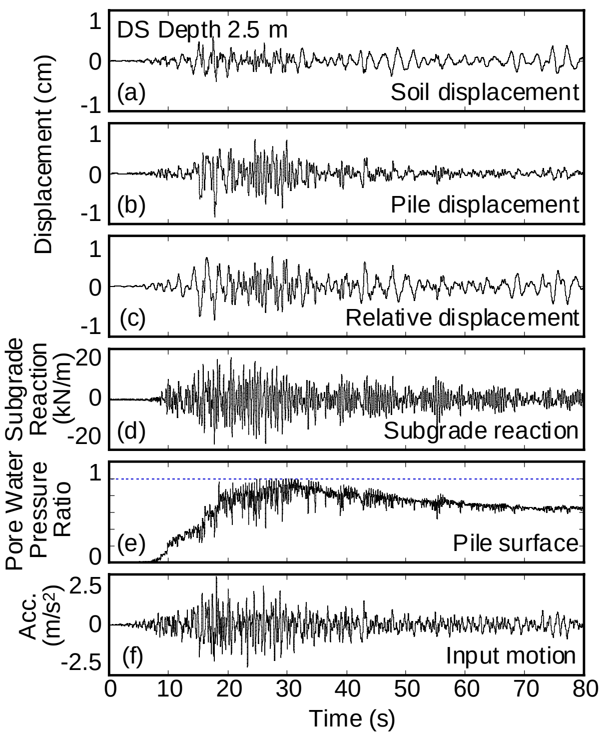

Fig. 3 Time histories at 2.5 m depth in DS

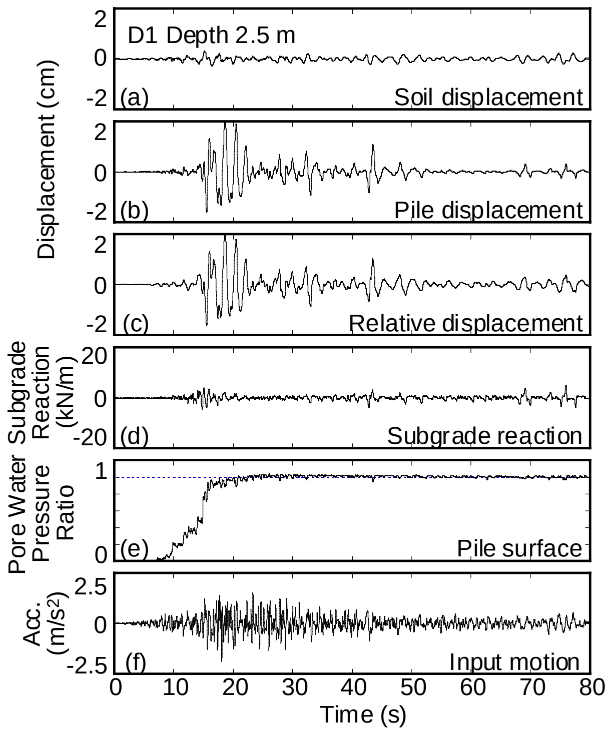

Fig. 5 Time histories at 2.5 m depth in D1

medium dense (DL, Fig. 4) to loose sand (D1, Fig. 5) are less than those in the dense sand (DS). In particular, the pore water pressure does not occur in the loose sand (D1) despite the largest relative displacement among the three tests, yielding a very small subgrade reaction.

3.2 Effect of Pore Water Pressure on p-y Relation

To estimate the effect of pore water pressure on p-y behavior, Fig. 6 shows the relationships of relative displacement between pile and soil with subgrade reaction or pore water pressure ratio at a depth of 2.5 m in series DS, for three time segments, i.e., 0-20 s, 20-50 s and 50-80 s. The subgrade reaction increases sharply with increasing relative displacement and the p-y behavior shows an inverted S-shape, probably due to the dilatancy effects of dense sand. This is well illustrated in Fig. 6(e) in which the pore water pressure in the dense sand decreases with increasing relative displacement between pile and soil.

To examine the mechanism of the large subgrade reaction observed in series DS, Fig. 7 shows the relationships between relative displacement and earth pressure increments measured with EP1 and EP2 on the surfaces of the pile (Fig. 2). The earth pressure increment at EP1 is shown in (a)-(c), and that at EP2 is shown in (d)-(f). The total earth pressure acting on the pile, given by the difference between the two, is shown in (g)-(i). The total earth pressure obtained by the earth pressure gauges is almost consistent with the value of subgrade reaction (Fig. 4) if it is divided by the pile diameter. As expected, according to Fig. 7 (a) and (d), when the earth pressure on one side increases, that on the other side decreases. This creates the compression stress state on one side and extension stress state on the other side of the pile. It is interesting to note that the change in earth pressure is larger on the extension side than on the compression side particularly in the period of 20-50 s.

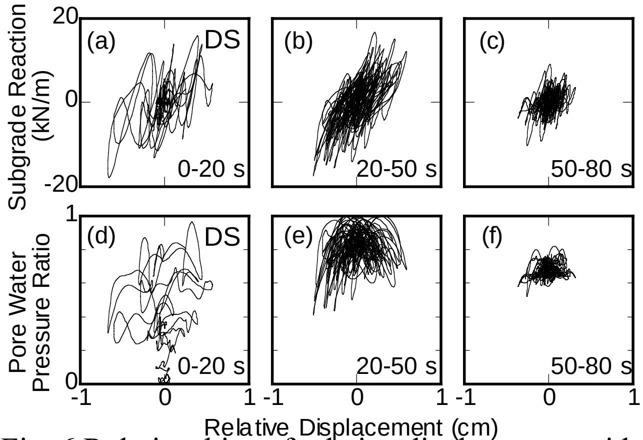

Fig. 6 Relationships of relative displacement with subgrade reaction or pore pressure ration in DS

It seems that the above deference in earth pressures on the extension and compression sides is due to the response of pore water pressure around a pile. Fig. 8 shows the relationships between the relative displacement and pore water pressure ratios measured at the both sides of the pile surface. The pore water pressure on the extension side reduces considerably, while that on the compression side is almost unchanged or increases slightly. The trend is related to the variation of earth pressure shown in Fig. 7, suggesting that the large stress increment on the extension side could have occurred due to the large reduction in pore water pressure and the small stress increment on the compression side due to the small change in pore water pressure.

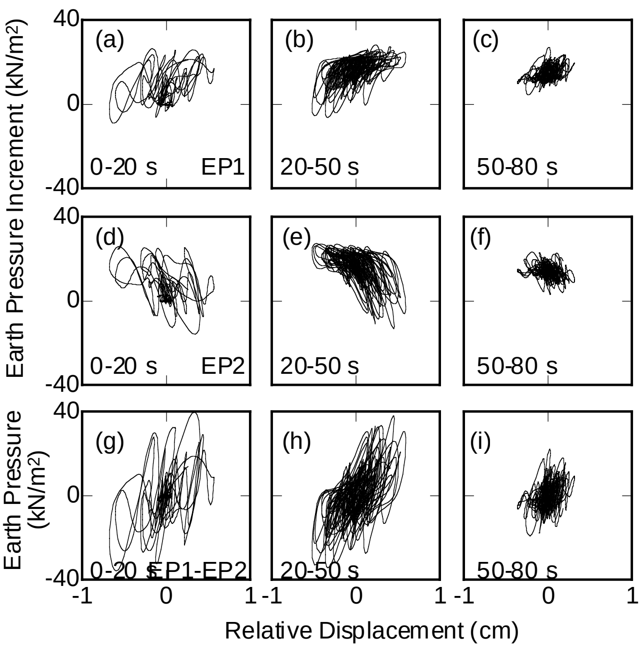

Fig. 7 Relationships between relative displacement and earth pressure in DS

The differences in pore water pressure and earth pressure responses between compression and extension sides of a pile are probably caused by the difference in stress state as schematically shown in Fig. 9 (Narita et al. (2003)). With increasing relative displacement between soil and pile, not only extension and compression stresses but also shear stress develops on the front and rear sides of the pile. Noting that both extension and shear stresses can reduce pore water pressure, the reduction in pore water pressure on the extension side becomes pronounced due to the combined effects of extension stress and dilatancy characteristics of the sand induced by the shear stress. In contrast, the reduction in pore water pressure on the compression side becomes small probably because the compression stress that increases pore water pressure, tends to reduce the reduction in pore water pressure due to dilatancy of the soil induced by the shear stress.

Fig. 10 shows the relationships between relative displacement and pore water pressure ratio at distances equal to and twice the pile diameter from the pile at 2.5 m depth, after liquefaction (20-50 s). The closer the distance from the pile, the larger becomes the pore water pressure reduction for the extension stress (positive displacement in plates (a) and (b), and negative displacement in plates (c)-(f)). In addition, the reduction in pore water pressure at PWP8 is smaller than that at PWP6, in spite of the same distance from the pile of the two sensors. This is probably because the compression and extension stress from the left and right piles are canceled out in the soil inside the pile group (Figs. 1(c) and 2) where PWP8 is located. In contrast, the stress from the pile cannot be cancelled out in the soil outside the pile group where PWP6 is located. A similar trend can be seen in the pore water pressure response observed at the pile surface, as shown in Fig. 8, in which the reduction in pore water pressure measured at PWP1 in the soil outside the pile group is significantly larger than that at PWP2 inside the pile group.

3.3 Effect of Soil Density on p-y Relation

To investigate the effect of soil density on p-y relation, Figs. 11 and 12 compare the relationships of relative displacement with subgrade reaction or the pore water pressure ratio at the pile surface at 2.5 m depth in series D1 and DL having soil densities looser than that in DS. The reduction in pore water pressure is found to be smaller than that in DS, suppressing the increase in subgrade reaction. Especially, the pore pressure in D1 does not show any reduction despite its large relative displacement, yielding a very small subgrade reaction.

Figs. 13 and 14 show the relations between relative displacement and pore water pressure around the pile at 2.5 m depth in DL and D1. The pore water pressure around the pile in DL reduces slightly on the extension side, while keeping almost the same value on the compression side. The larger the distance from the pile, the smaller

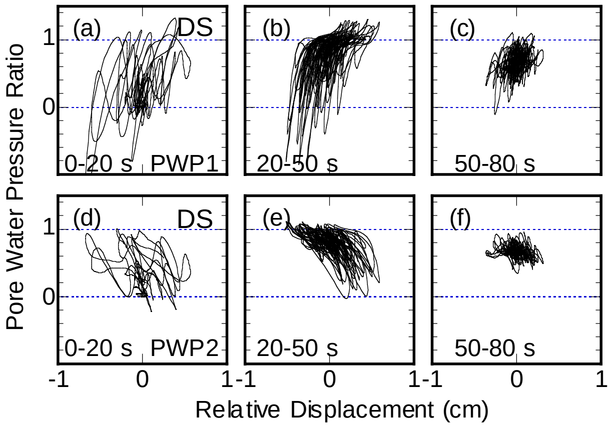

Fig. 8 Relationship between relative displacement and pore pressure ratio in DS

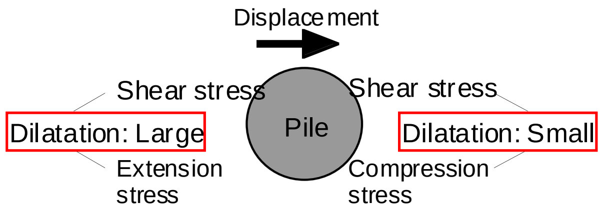

Fig. 9 Stress states around pile

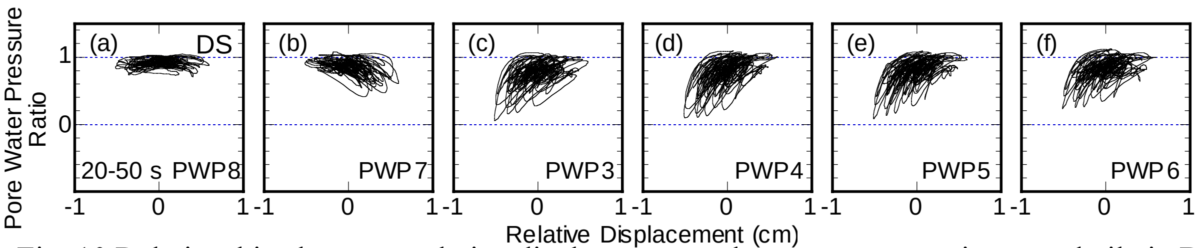

Fig. 10 Relationships between relative displacement and pore pressure ratio around pile in DS

becomes the pore pressure reduction on the extension side (Fig. 13). This trend is similar to that observed in DS. The pore water pressures around the pile in D1, in contrast, do not show any sign of reduction at any place (Fig. 14).

The above findings confirm that the soil density around the pile affects the p-y behavior during liquefaction. Namely, with increasing relative displacement, the dilative nature in dense sand reduces the pore water pressure around the pile particularly on the extension side, making the liquefied sand solid and increasing the subgrade reaction. Conversely, the contractive nature in loose sand does not induce any reduction in pore water pressure at any place around the pile, keeping the liquefied sand liquid and yielding a very small subgrade reaction.

To compare the response of pore water pressure around the pile in the tests, the reduction in pore water pressure with distance from the pile is presented in Fig. 15. The value of pore water pressure ratio is the average of those of the lowest peaks in the period range of 20-30 s. The arrow shows the direction of pile displacement. The compression stress develops in the soil on the front

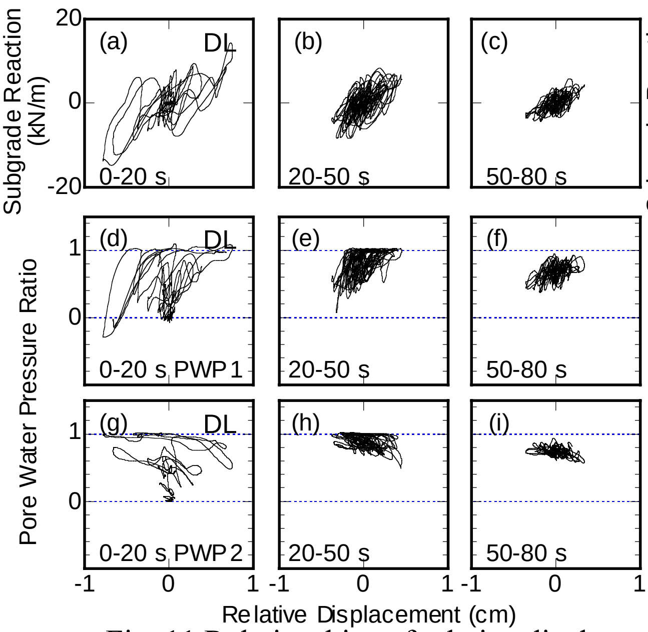

Fig. 11 Relationships of relative displacement with subgrade reaction or pore pressure ratio in DL

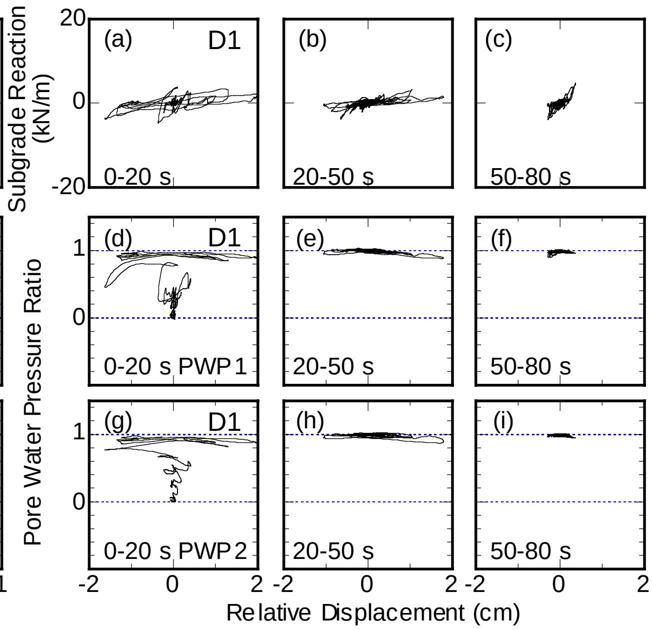

Fig. 12 Relationships of relative displacement with subgrade reaction or pore pressure ratio in D1

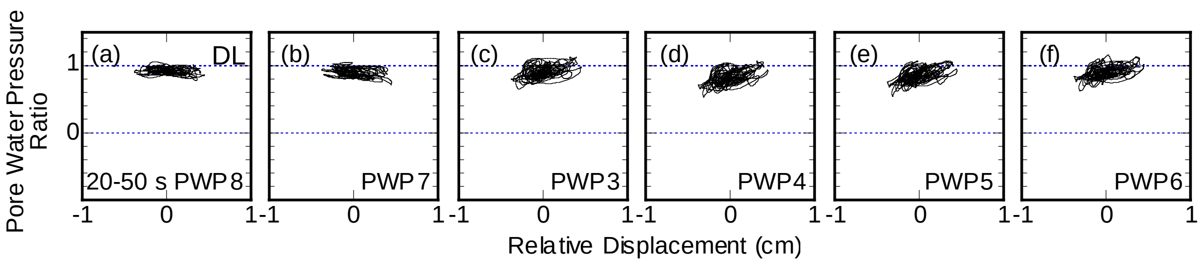

Fig. 13 Relationships between relative displacement and pore pressure ratio around pile in DL

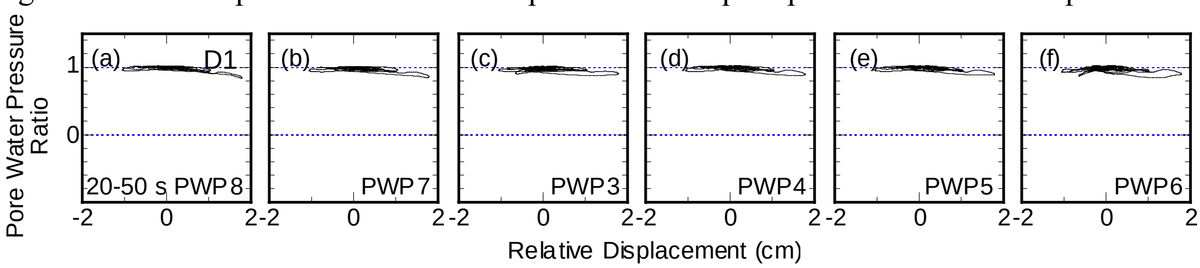

Fig. 14 Relationships between relative displacement and pore pressure ration around pile in D1

side, while the extension stress on the rear side. The denser the soil, the more pronounced the pore pressure reduction on the extension side. It seems that the reduction in pore water pressure on the extension side depends on the direction of displacement. Namely, the pore water pressure reduction is more significant in soil outside (Fig. 15(b)) than inside (Fig. 15(a)) the pile group. This is probably because the compression and extension stresses from the left and right piles are canceled out in the soil inside the pile group. In contrast, the extension stress from the pile cannot be cancelled in the soil outside the pile group.

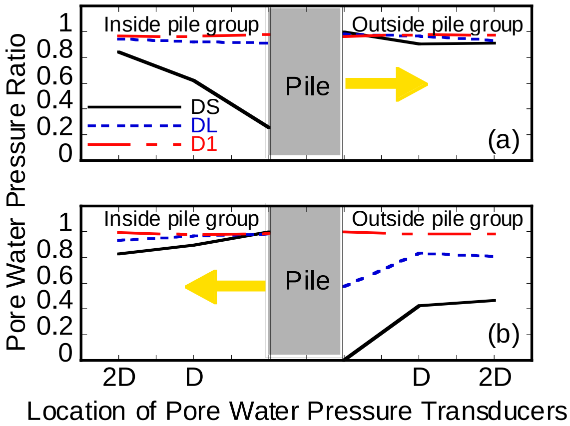

Fig. 15 Reduction in pore pressure around pile in DS, DL and D1

4. CONCLUSION

The effect of pore water pressure response on the subgrade reaction of a pile during liquefaction was investigated based on the large shaking table tests. The test results and discussions lead to the following conclusions:

(1) The pore water pressure around a pile in dense sand decreases considerably with increasing relative displacement between soil and pile. This causes an increase in subgrade reaction, making the p-y behavior stress hardening. The pore water pressure around the pile in loose sand, in contrast, does not decrease despite a larger relative displacement, making p-y behavior stress softening.

(2) The reduction in pore water pressure is greater on the extension side than on the compression side of the soil around the pile. This is because the pore water pressure on the extension side decreases due to the combined effects of extension stress and dilatancy of the soil induced by the shear stress, while that on the compression side does not decrease due to the adverse effects of compression stress and dilatancy of the soil.

(3) The reduction in pore water pressure on the extension side is more remarkable in the soil outside the pile group than inside the pile group. This is probably because the compression and extension stresses from the left and right piles are canceled out in the soil inside the pile group. In contrast, the extension stress from the pile cannot be cancelled in the soil outside the pile group.

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