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Effects of pore pressure response around pile on horizontal subgrade reaction during liquefaction and lateral spreading in large shaking table tests

Effets de la réponse de la pression interstitielle autour d'un pieu sur la réaction horizontale du sol pendant la liquéfaction et l'écoulement latéral dans les essais par grande table vibrante

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ABSTRACT
Effects of pore water pressure response on the subgrade reaction of a pile during liquefaction and lateral spreading are investigated through large shaking table tests. In liquefied soils, the extension and compression stress states cyclically develop on both sides of the pile. The pore water pressure and earth pressure on the extension side decrease significantly, while keeping those on the compression side constant. As a result, the pile is pulled back by the soil where the reduction in pore water pressure occurs. In laterally spreading ground, a large pore water pressure reduction occurs only on the downstream side when the ground moves downstream, but on neither side when the ground moves upstream. Thus, the pile is pulled by the downstream soil only when the ground moves downstream. Such mechanisms of p-y relation in liquefied and laterally spreading soils are completely different from those occurring in dry sand.

RÉSUMÉ
Les effets de la réponse de la pression de l'eau interstitielle sur la réaction du sol d'un pieu pendant la liquéfaction et l'écoulement latéral ont été étudiés au moyen d'essais par grande table vibrante. Dans les sols liquéfiés, les états de contrainte de traction et de compression se produisent cycliquement des deux côtés du pieu. La pression de l'eau interstitielle et la poussée terrestre du côté de la traction diminuent considérablement, alors que celles du côté de la compression restent constantes. Il en résulte que le pieu est tiré en arrière par le sol où la diminution de la pression de l'eau interstitielle se produit. Dans le cas d'une terre qui s'écoule latéralement, il se produit une grande diminution de la pression de l'eau interstitielle en aval seulement, lorsque le sol se déplace en aval, mais qui ne se produit pas lorsque le sol se déplace en amont. Ainsi, le pieu est tiré par le sol en aval, seulement lorsque le sol se déplace en aval. De tels mécanismes de la relation p-y dans les sols liquéfiés et à écoulement latéral sont entièrement différents de ceux qui se produisent dans le sable sec.

1 INTRODUCTION

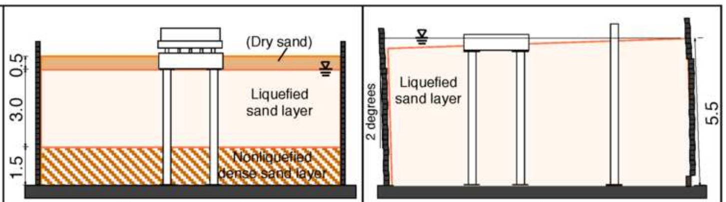
The field investigation after recent earthquakes indicated that ground movements induced by soil liquefaction and lateral spreading could have a significant effect on damage to pile foundations. To estimate p-y behavior, e.g., the kinematic effect from ground movement during liquefaction, defined as the relationship between subgrade reaction and relative displacement between soil and pile, has been studied using large shaking table tests and centrifuge model tests (Abdoun et al., 2003; Boulanger et al., 2003; Tokimatsu et al., 2001, 2004; Wilson et al., 2000). These studies have shown that the pore pressure response around a pile has a significant effect on p-y behavior; however, the response mechanism of pore pressure including its spatial variation around a pile and its relation to p-y behavior is still unknown.

The objective of this paper is to investigate the variation of pore water pressure around a pile on p-y behavior during liquefaction and lateral spreading, based on large shaking table tests in which many pore water pressure transducers and earth pressure transducers are installed on and around a pile.

2 LARGE SHAKING TABLE TESTS

To investigate qualitatively the effect of pore water pressure on p-y behavior during liquefaction and lateral spreading, the results of large shaking tests conducted on soil-pile-structure systems using the shaking table facility at the National Research Institute for Earth Science and Disaster Prevention in Japan are used. Fig. 1 shows the shaking table tests used in this study in which pile-structure systems were constructed in either level

Model layout



Model ID	D1	DL	DS		C0
Soil density	Loose	Medium dense	Dense	Medium dense	
Super -structure	No	Yes		No	
Input base motion	RINKAI 1.5m/s²	RINKAI 2.0m/s²		Sine wave (2Hz) 2.0m/s²	

Figure 1. Model layout

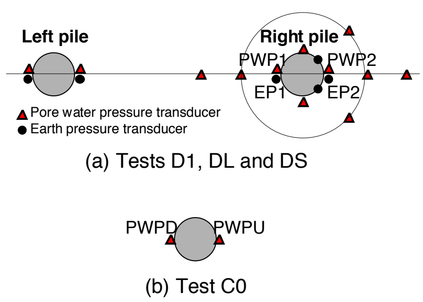


Figure 2. Plan view of transducers on and around piles at depth of 3 m

ground or inclined ground with a slope angle of 2 degrees. The dimensions of the laminated shear box on the shaking table were 5.0-5.5 m high, 12.0 m wide and 3.5 m long.

The soil profile for Tests D1, DL and DS consisted of three layers, including a top dry sand layer, a liquefiable sand layer and an underlying dense gravelly layer, while that for Test C0 consisted of only homogeneous liquefiable sand layer. The sand used was Kasumigaura Sand (e_{max} = 0.961, e_{min} = 0.570, D_{50} = 0.31 mm, F_c = 5.4 %). The soil densities estimated were loose for Test D1, medium for Test DL and Test C0, and dense for Test DS. All the piles used had a diameter of 318.5 mm with a 6.0 mm wall thickness, and were fixed to the container base. Tests D1, DL and DS included a 2x2 pile group of which heads were fixed to a foundation, while Test C0 included a single pile with a free rotational head. The foundation of Tests Dl and DS had a weight of 20.6 kN that carried a superstructure of 139.3 kN while that of Test D1 had a weight of 16.7 kN without a superstructure.

The soil-pile-structure systems were densely instrumented with accelerometers, displacement transducers, strain gauges, pore water pressure transducers, and earth pressure transducers. In particular, many pore pressure transducers and/or some earth pressure sensors were installed on and around a pile at a depth of 3 m, as shown in Fig. 2.

An artificial ground motion called Rinkai, produced as a design earthquake to be expected in the Southern Kanto district in Japan, was used as an input base acceleration to the shaking table for Tests D1, DL and DS, while a sine wave consisting of 20 cycles with a frequency of 2 Hz for Test C0. The maximum acceleration used for the tests was either 1.5 or 2.0 m/s^2.

3 EFFECT OF PORE WATER PRESSURE ON p-y BEHAVIOR IN LIQUEFIED LEVEL GROUND

To evaluate the effect of pore water pressure on p-y behavior, the displacements of the ground and pile were calculated from the double integration of accelerations and the subgrade reaction from the double differentiation of bending moment with depth. Fig. 3 shows the time histories of the displacements of soil and pile, the relative displacement of the two, the horizontal subgrade reaction and pore water pressure ratios at 3.0 m below the ground surface in Test DS with dense sand, together with that of the input motion. The pore water pressure ratios shown in the figure are those observed on both sides of the pile surface and that in the free field. The pore water pressure ratio increases to 1.0 in about 20 s, accompanied by an increase in relative displacement between soil and pile and the subgrade reaction. Of particular interest is the large reduction in pore pressure ratio on the pile surface (Fig. 3(f)(g)), when compared with that in the free field (Fig. 3(e)). In addition, the reduction in pore pressure appears to occur when both subgrade reaction (p) and the relative displacement (y) become large.

To estimate further the effect of pore water pressure on p-y behavior during liquefaction, Fig. 4 shows the relationships of relative displacement with subgrade reaction and average pore water pressure ratio at 3.0 m below the ground surface in Tests D1, DL and DS, for a time segment from 20–50 s, during which the ground liquefied. The pore water pressure ratio is the average of the two values observed on both sides of the pile surface. In dense sand (Fig. 4(c)), the p-y behavior shows stress hardening with an inverted S-shape in which the subgrade reaction increases sharply with increasing relative displacement. This is probably caused by the dilation of dense sand induced by shear deformation around the pile, since the average pore water pressure ratio decreases significantly with increasing relative displacement as shown in Fig. 3(f)(g) and Fig. 4(f). In loose (Fig. 4(a)) to medium (Fig. 4(b)) sand, by contrast, the p-y behavior shows stress softening in which the subgrade reaction does not seem to show any increase beyond a certain critical limit. This is probably due to compressive or lesser dilative nature of loose

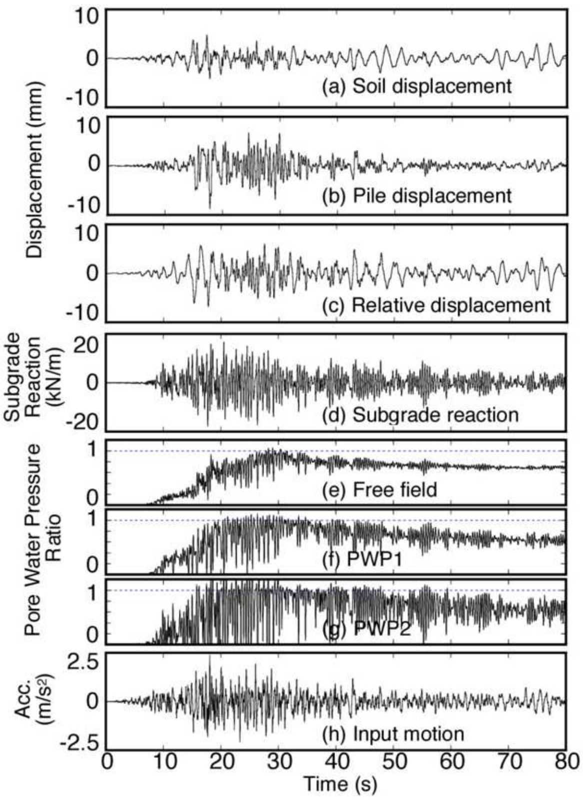


Figure 3. Time histories in Test DS

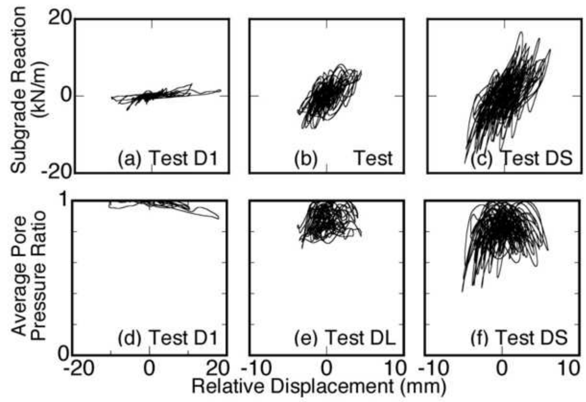


Figure 4. Relations of relative displacement with subgrade reaction and pore water pressure ratio in Tests D1, DL and DS

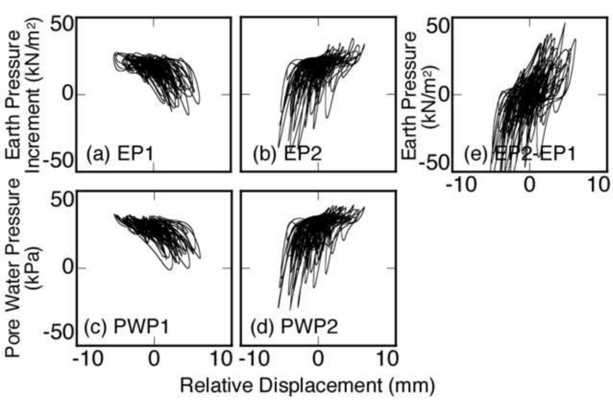


Figure 5. Relations of relative displacement with earth pressure and pore water pressure measured on pile in Test DS

to medium sand since the reduction in pore water pressure ratio in loose (Fig. 4(d)) to medium (Fig. 4(e)) sand is significantly smaller than that in dense sand (Fig. 4(f)).

The pore pressure changes on both sides of the pile surface shown in Fig. 3(f)(g) are different from each other in phase and value. To examine the effects of different pore pressure reduction on both sides of the pile on the p-y behavior, Fig. 5(a)-(d) show the relationships between relative displacement and earth pressure increments and pore water pressures measured on both sides of the pile (EP1, EP2, PWP1, and PWP2 in Fig. 2) in dense sand (Test DS). The positive displacement in Fig. 5 indicates that the pile pushes the soil on the right side, and the negative value on the left side. If the pile pushes the soil on the right (i.e., positive relative displacement develops), the earth pressure on the back/left side (Fig. 5(a)) decreases significantly, while that on the front/right side (Fig. 5(b)) maintains almost constant at 30 kN/m^2. If the pile pushes the soil on the left (i.e., negative relative displacement develops), the stress states on both sides are reversed, i.e., the earth pressure on the back/right side (Fig. 5(b)) decreases significantly, while that on the front/left side (Fig. 5(a)) maintains almost constant. In any case, the earth pressures on both sides do not increase at any time, which appears to contradict with the trend shown in Fig. 4(c) in which the subgrade reaction increases with increasing relative displacement.

Fig. 5(e) shows the relation of the relative displacement with the total earth pressure acting on the pile, $P_{total}=P_{EP2}-P_{EP1}$, given by the difference between the two earth pressure increments, P_{EP1} and P_{EP2}. The total earth pressure in Fig. 5(e) cannot directly correspond to the subgrade reaction shown in Fig. 4(c); however, a good agreement in trend between the two exists, indicating that the earth pressures observed with small sensors are reasonable to characterize the stress acting on both sides of the pile. It is, therefore, interesting to note that the increase in total earth pressure acting on the pile is not induced by the increase in earth pressure on the front side but induced by the reduction in earth pressure on the reverse side. The unexpected contribution of earth pressure on the reverse side is induced by the pore water pressure reduction on the same side (Fig. 5(c)(d)) as it decreases largely in accordance with the earth pressure reduction on the same side (Fig. 5(a)(b)).

Fig. 6 shows a schematic figure indicating how the earth pressure acts on a pile during soil liquefaction. With increasing relative displacement between pile and soil on the right, the compression stress state (compression and shear) develops on the right side with the extension stress state (extension and shear) on the left side. On the extension/left side, the reduction in pore water pressure becomes pronounced probably due to the combined effects of extension stress and dilatancy characteristics of the sand induced by the shear stress. On the compression/right side, in contrast, the reduction in pore water pressure becomes small probably because the compression stress that increases pore water pressure, tends to cancel the reduction in pore water pressure due to dilation induced by the shear stress. This results in the pore pressure and earth pressure reduction only on the reverse side. As a result, the pile is pulled back by the soil where the earth pressure reduces significantly.

Fig. 7(a)(b) shows the lowest pore pressure ratio observed during liquefaction (20-30s) with distance from the pile in the three tests having different soil densities. The upper figure corresponds to the state in which the pile moves right with respect to soil, and the lower figure to the state in which the pile moves left. Note that the pore pressure reduction occurs mainly on the reverse side of the pile. This is because the extension stress develops on the reverse side of the pile. The closer the distance from the pile and the denser the soil, the larger becomes the pore water pressure reduction on the extension side. It is interesting to note that the pore water pressure reduction is more significant in soil outside the pile group than inside the pile group. This is probably because, while the compression and extension stresses from left and right piles are cancelled out in

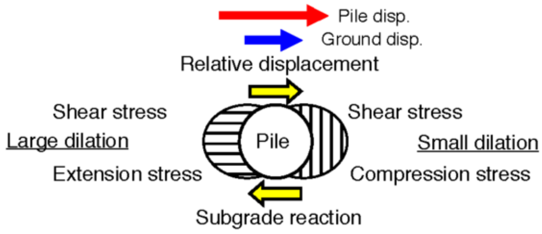


Figure 6. Stress states around pile in liquefied level ground

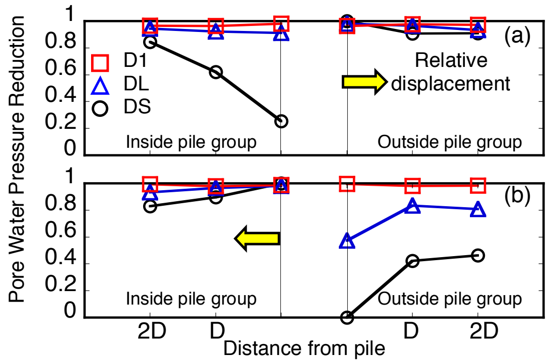


Figure 7. Distribution of pore water reduction in three tests with different soil density

the soil inside the pile group, such cancellation cannot occur in the soil outside the pile group.

4 EFFECT OF PORE WATER PRESSURE ON p-y BEHAVIOR IN LATERALLY SPREADING GROUND

To estimate the mechanism of subgrade reaction development during lateral ground spreading, Fig. 8 shows 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 3.0 m below the ground surface in Test C0, together with that of the input motion. The relative displacement cyclically occurs in both downstream and upstream directions, but with increasing residual component on the downstream side particularly after 2 s when the ground starts to move downstream. At the beginning of shaking, the subgrade reaction occurs whenever the relative displacement takes place either in the downstream or upstream direction; however, the subgrade reaction occurs only downstream (positive values in Fig. 8(d)) after 4 s when the soil completely liquefies. It is interesting to note that the pore pressure reduction occurs only on the downstream side (Fig. 8(f)), suggesting its strong effects on the development of subgrade reaction.

To confirm the effects of pore pressure variation around the pile, Fig. 9 shows the relation of relative displacement with subgrade reaction or the pore water pressures observed on both sides of the pile. As expected, with increasing downstream residual relative displacement, the downstream pore water pressure decreases, contributing to the development of subgrade reaction on the downstream direction; however, the upstream pore pressure maintains almost constant and does not seem to contribute to the development of subgrade reaction on the upstream direction. This suggests that the pore water pressure distribution around a pile has a significant effect on subgrade reaction in lateral spreading ground as well.

Fig. 10 shows a schematic figure indicating how the earth pressure acts on pile during lateral spreading. When the ground and pile move downstream, the extension stress state develops on the downstream side with the compression stress state on the upstream side as shown in Fig. 10(a). This induces a large pore water pressure reduction on the downstream/front side of the pile. As a result, the pile is pulled by the downstream soil. In contrast, when the ground and pile move upstream, neither the extension nor compression stress state develops on both sides of the pile as shown in Fig. 10(b), as it is considered to be unloading with decreasing relative displacement. This might have kept the pore pressure ratio almost constant on both sides, yielding a very small subgrade reaction.

5 CONCLUSIONS

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

(1) In the liquefied level ground, the extension and compression stress states cyclically develop on both sides of the pile. The pore water pressure and earth pressure on the extension side decrease with increasing relative displacement, while those on the compression side maintain almost constant. The combined effects of extension and shear stresses probably induce large dilation, accelerating the pore pressure reduction on the extension side. In contrast, the opposite effects of compression and shear stresses yield small dilation, keeping the pore pressure constant on the compression side.

(2) The increase in horizontal subgrade reaction in the liquefied level ground is caused by the reduction in earth pressure on the extension side. This means that, if the pile displacement exceeds the soil displacement, the pile may be pulled back by the soil where reduction in pore pressure occurs. The higher the soil density, the larger the reduction in pore pressure and earth pressure on the extension side.

(3) The pore pressure reduction on the extension side is more remarkable in the soil outside the pile group than inside the pile group, probably because the compression and extension stresses are cancelled out in the soil inside the pile group.

(4) When the ground moves downstream in the laterally spreading ground, the extension stress state accompanied by large dilation develops on the downstream side, with the compression stress state on the upstream side. When the ground moves upstream, on the contrary, the stress states developed on both sides of the pile are considered to be unloading accompanied by small dilation due to accumulated downstream ground movement. Thus, the reduction in pore water pressure and earth pressure only occur on the downstream side when the ground moves downstream. As a result, the pile is pulled by the downstream soil only when the ground moves downstream.

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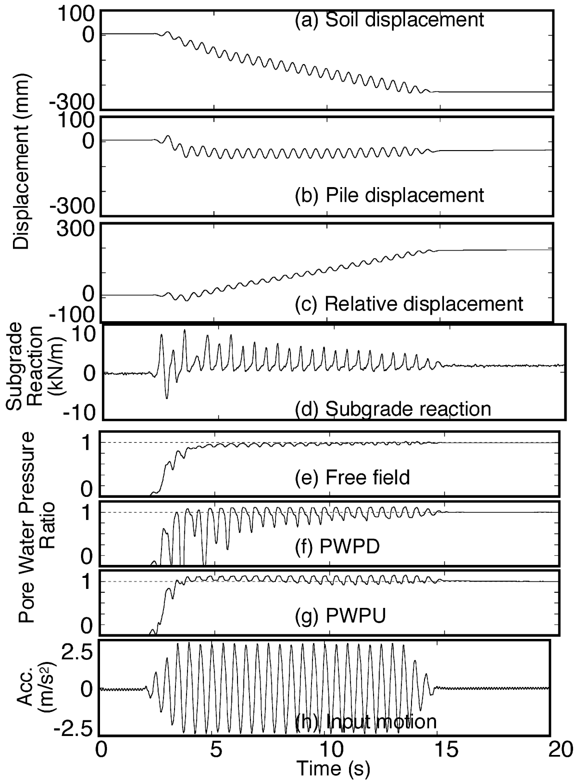

Figure 8. Time histories in Test C0

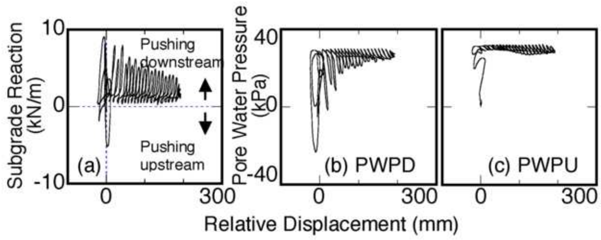

Figure 9. Relations of relative displacement with subgrade reaction and pore water pressure ration in Test C0

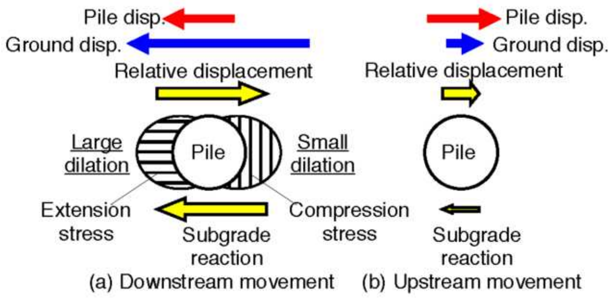

Figure 10. Stress states around pile in laterally spreading ground

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