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FACTORS INFLUENCING DEFORMATION MODE OF PILES IN LIQUEFACTION-INDUCED LATERAL SPREADING TEST USING E-DEFENSE FACILITIES

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ABSTRACT

To investigate failure and deformation mode of piles during liquefaction-induced laterally spreading, a large shaking table test was conducted using E-Defense shaking table facilities. A 2x3 pile group having a footing and a superstructure was constructed near a quay wall in a liquefiable sand deposit that was prepared in a rigid box, 4.5 m in height, 16.0 m in length and 4.0 m in width. The test was conducted under two-dimensional shaking. Extensive soil liquefaction occurred in a few seconds after the start of shaking, causing seaward displacement of the quay wall, ground and piles. All piles yielded and buckled at their heads and also bent in the ground, which was probably induced by the inertial force and kinematic force in liquefied layer. Damage to piles was more significant on the landside of the pile group. This was probably due to the spatial variation of ground displacement and dilatancy of soil subjected to a large shear strain. Since the pile displacement is larger than the ground displacement in the test, the relative displacement with respect to the ground became larger in the landside pile than in the seaside pile. This created larger pore pressure reduction and made the soil around the landside pile stiffer than that around the seaside pile, inducing an increase in kinematic force on the landside pile.

Introduction

The 1995 Kobe earthquake induced geotechnical problems on various structures. In particular, many buildings supported on piles in laterally spreading areas settled and/or tilted without significant damage to their superstructures (BTL Committee 1998). It was also observed that failure and deformation modes of piles were different within a building located near the waterfront, probably due to spatial variation of lateral spreading (e.g. Oh-oka et al. 1996).

In order to clarify the kinematic effects on pile damage, many studies on seismic behavior of pile foundations in liquefied and laterally spreading ground have been conducted with physical model tests (e.g., Abdoun et al. 2003, Boulanger et al. 2003). It has been shown that the kinematic force or the horizontal subgrade reaction of a pile depends on its displacement relative to soil (p-y behavior) as well as on the pore water pressure response around the pile (e.g. Tokimatsu and Suzuki 2004, Wilson et al. 2000).

To investigate kinematic effects on pile damage during liquefaction-induced lateral spreading, a physical test on a soil-pile-structure model was conducted (MEXT and NIED 2006,

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Tabata et al. 2007) using E-Defense at the Hyogo Earthquake Engineering Research Center of the National Research Institute for Earth Science and Disaster Prevention (NIED). E-Defense was one of the largest shaking table facilities in the world, opened in 2005, commemorating the tenth anniversary of the 1995 Kobe earthquake. The objective of this study is to investigate factors influencing deformation and failure modes of a pile group during laterally spreading based on a shaking table test conducted at E-Defense.

Outline of Liquefaction-Induced Lateral Spreading Test

The E-Defense shaking table platform has a dimension of 15 m long and 20 m wide. It is supported on fourteen vertical hydraulic jacks and connected to five hydraulic jacks each in the two orthogonal horizontal directions. Fig. 1 and Photo 1 show a test model constructed in a rigid rectangular box, with a height of 5 m, a length of 16 m and a width of 4 m, placed on the large shaking table, in which a pile-supported building was placed on a saturated sand deposit near a quay wall facing waterfront.

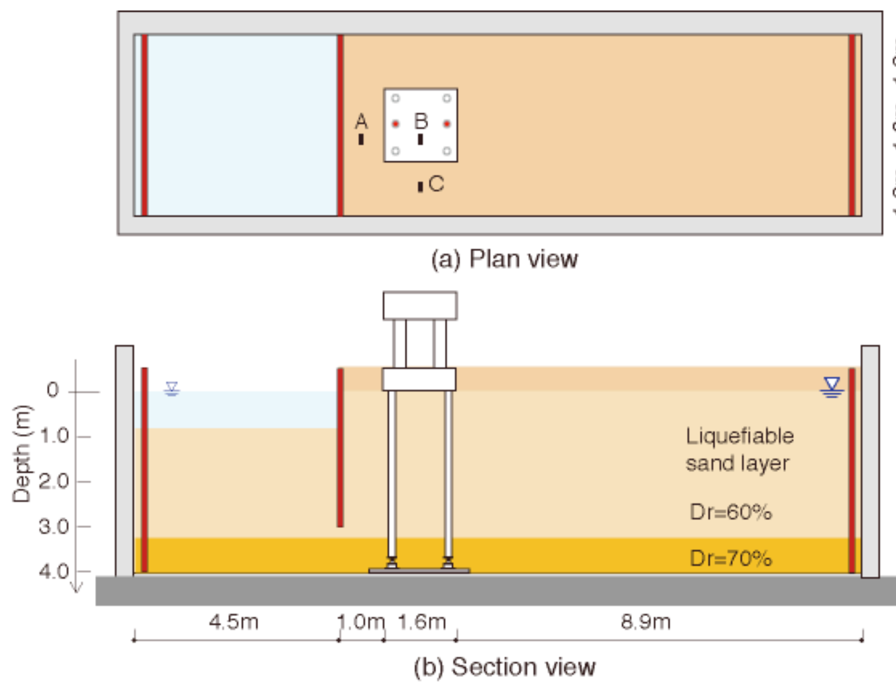


Figure 1. Soil-pile-structure model.

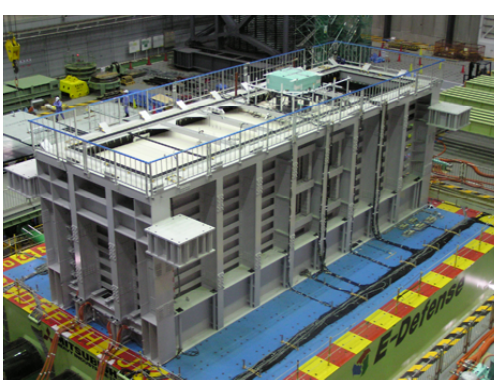


Photo 1. Rigid box on shaking table.

Photo 2. Sensors on piles.

Table 1 Numbers of installed sensors.

	Ground	Quay wall	Piles	Superstructure	Columns	Footing	Box	Total
Strain gauges	-	34	216	-	48	-	-	298
Accelerometer	122	12	22	12	-	12	24	204
Displacement transducer	11	6	-	7	-	4	-	28
Earth pressure transducer	-	13	104	-	-	16	-	133
Water pressure transducer	117	13	72	-	-	-	-	202
Load cell	-	-	18	-	-	-	-	18

Albany sand, imported from Australia, was used for preparing a sand deposit. The sand had a mean grain size D_{50} of 0.31 mm. After setting a pile group in the rigid box, the sand was air-pluviated and compacted to designated densities. The relative density was 70 % for an underlying dense sand layer with a thickness of 0.75 m and 60 % for an overlying sand layer. A quay wall penetrated the sand deposit with its tip located at the height of 1 m from the rigid box bottom, as shown in Fig. 1(b). The sand deposit behind the quay wall had a thickness of 4.5 m, while that in front of the quay wall had a thickness of 3.2 m. The groundwater table was 0.5 m below the landside ground surface.

A 3x2 steel pile group was placed behind the quay wall. Each pile had a diameter of 152.4 mm and a wall thickness of 2.0 mm. As shown in Fig. 1, the six steel piles were aligned with three paralleled to the quay wall in two rows, with a horizontal space of four-pile diameters or eight-pile diameters. The piles located close to the quay wall or far from the quay wall were, hereafter, called the seaside piles or the landside piles, respectively. The tips of the piles were jointed to the rigid box base with pins and their heads were fixed to a foundation of a weight of 10 tons with a superstructure of 12 tons supported by four steel columns.

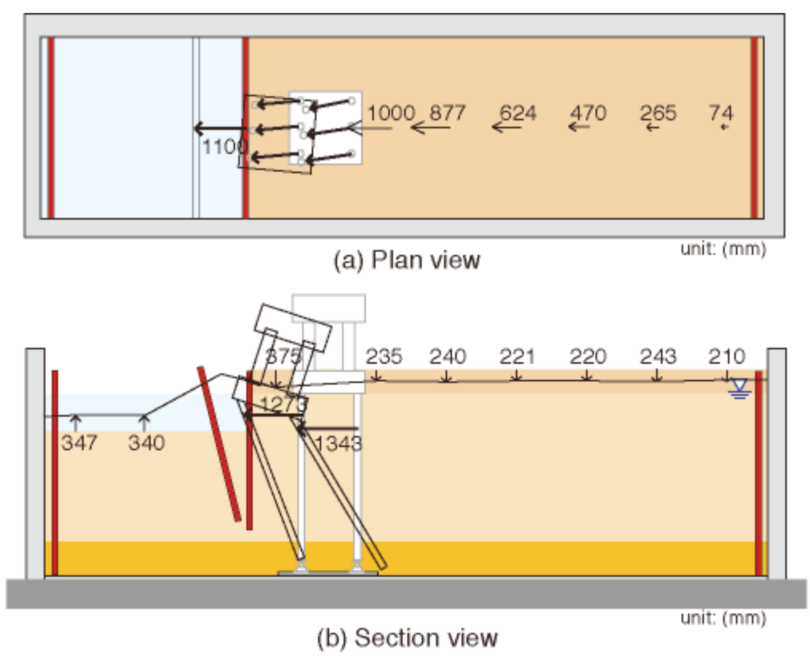


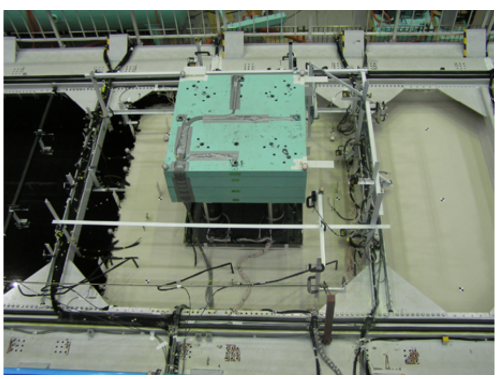
Figure 2. Residual deformation of test model (modified from Tabata et al. 2007).

Table 1 summarizes the number of sensors installed in the test model. Many strain gauges, accelerometers, earth pressure transducers, pore water pressure transducers, displacement transducers and load cells, about 900 sensors in total, were placed in the sand deposit as well as on the pile-structure system and the quay wall. To observe kinematic force on piles, many earth pressure transducers and pore water pressure transducers were placed on pile surface (Photo 2). In addition to sensors listed in Table 1, unique instruments including inclinometers and a digital video camera system were used for measuring motions of the ground and the structure. The inclinometers in which accelerometers were chained vertically provided ground displacement distributions with depth close to a pile group, at points A, B and C indicated in Fig. 1(a). The digital video camera system captured fluorescent spherical markers attached objects. Further detail of instruments and sensor layout is described elsewhere (MEXT and NIED 2006).

The shaking table test was conducted under two-dimensional loading with horizontal and vertical motions. A ground motion recorded at Takatori in the 1995 Kobe earthquake was used as an input motion. The NS and UD components were applied to the longer direction of the rigid box and the vertical direction, respectively. The maximum accelerations applied to the shaking table were adjusted to 6.0 m/s^2 in the horizontal direction and to 2.0 m/s^2 in the vertical direction (Fig. 3(n)(p)).

Residual Deformation of Test Model

Fig. 2 illustrates residual deformation of the ground surface, quay wall and pile-structure


(a) Before test

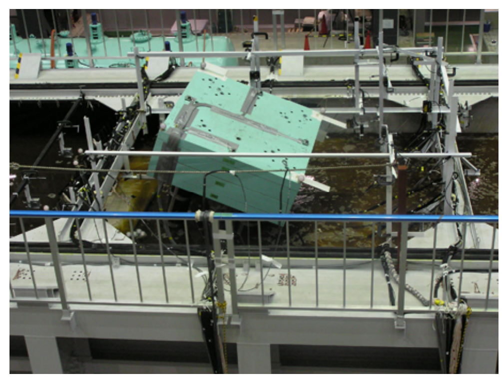

(b) After test

Photo 3. Superstructure before and after shaking event.


(a) Piles with residual seaward displacement


(b) Buckling at pile head

Photo 4. Damage to piles.

system. Photo 3 shows the deformation of the superstructure before and after the test. During the shaking event, the quay wall moved seaward about 1.2 m, inducing seaward movements and settlements of the ground behind. This caused horizontal deformation of the pile-structure with seaward displacement ranging from 1.1 to 1.4 m at the pile heads as well as the inclination of the superstructure and footing up to 20 degrees (Fig. 2). Photo 4 shows damage to piles after the test. All the piles yielded and buckled at their heads (Photo 4(b)). The piles also bent 1.5-2.0 m below their heads (Photo 4(a)). This trend was more significant in the landside piles than in the seaside piles.

This paper discusses factors influencing deformation modes of the seaside and landside piles based on the observed data for the middle piles in each row, highlighted in Fig. 1(a). This is because the sensors on the middle piles were densely placed.

Factors Influencing Deformation Modes of Piles

Time Histories of Major Values

Fig. 3 shows time histories of displacements of the footing and ground surface, bending strains at three depths of 0.15, 1.5, 3.0 m of the seaside and landside piles, excess pore water pressure at the seaside and landside of the pile group, accelerations of superstructure and shaking table. The positive values in the figures stand for the landward displacement or acceleration and clockwise moment, while the negative values stand for the opposites. The footing displacement

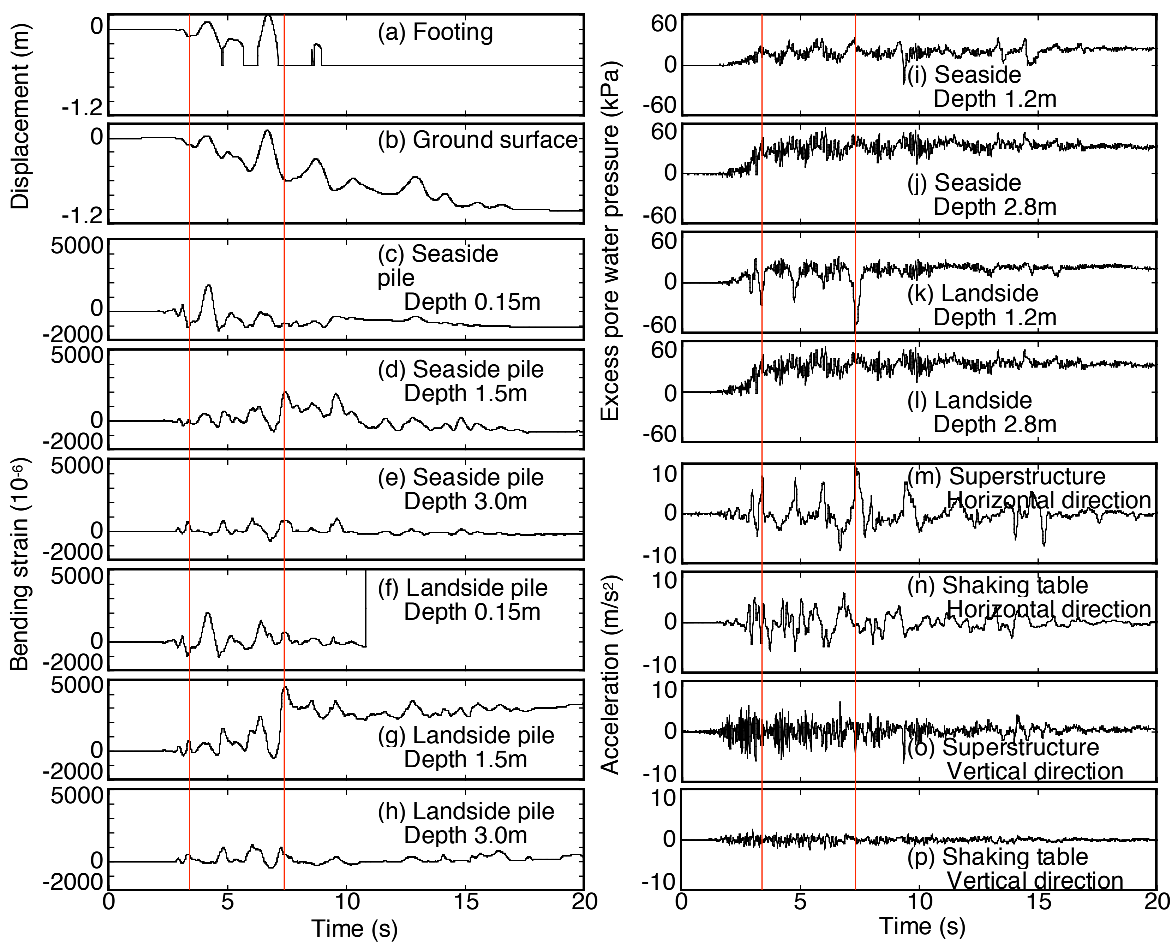


Figure 3. Time histories of displacements, bending strains, pore water pressures and accelerations.

and bending strain at the seaside pile head are ranged out after 5-10 s in Fig. 3(a)(f).

The pore water pressure rises up to the initial effective stress at about 3 s after the start of shaking, leading to liquefaction of the soil (Fig. 3(i)-(l)). The pore water pressure after reaching the initial effective stress changes with cyclic loading, the trend of which is significant at a depth of 1.2 m in the landside soil of the pile group (Fig. 3(k)). The acceleration of the superstructure is amplified with respect to the input acceleration (Fig. 3(m)-(p)). The displacements of the footing and ground surface increase with time (Fig. 3(a)(b)). The bending strain increases at the pile heads as well as at depths of 1.5 and 3.0 m (Fig. 3(c)-(h)). It is interesting to note that the bending strain at a depth of 1.5 m is significant larger in the landside pile than in the seaside pile (Fig. 3(d)(g)).

Factors Influencing Deformation Modes of Piles

To investigate factors influencing pile deformation, Fig. 4 shows relations of the inertial force with the earth pressure acting on the footing and the ground surface displacement. The inertial force is computed by accelerations of the superstructure and footing. The earth pressure acting on the footing is estimated using outputs from the earth pressure sensors attached on the footing surface. The inertial force and ground displacement increase seaward almost at the same time (Fig. 4(b)). With increasing inertial force, the earth pressure also becomes large (Fig. 4(a)) but acts against the inertial force.

Fig. 5 shows bending strain distributions with depth for the seaside and landside piles at about 3 s and 7 s, with symbols of circles (3 s) and triangles (7 s) in Figs. 4 and 6. At these instants both the inertial force and ground displacement increase seaward. The bending strain of both the piles at 3 s becomes large at their heads (Fig. 5(a)) due to the seaward inertial force (Fig. 4), inducing yielding of the pile heads. It is interesting to note that the bending strain shows different distributions between the seaside and landside piles. Namely, a depth at which the bending strain takes the peak other than the pile head is shallower in the landside pile than in the seaside pile. This suggests that the shear force at the pile head of the landside pile is reduced more at shallow depths, while that of the seaside pile is transmitted to much deeper depths. At 7

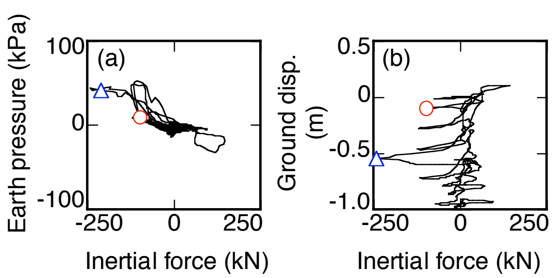


Figure 4. Relations of inertial force with earth pressure and ground displacement.

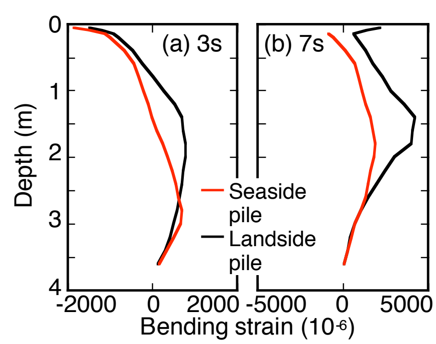


Figure 5. Distributions of bending strains.

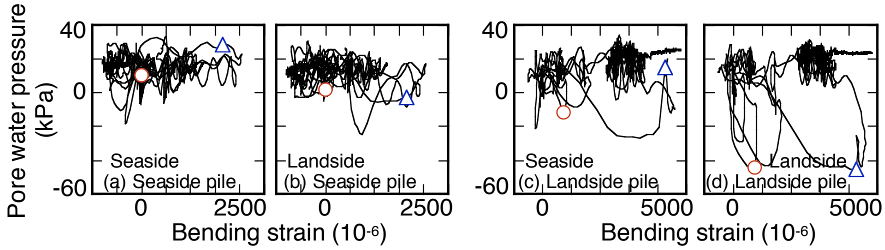


Figure 6. Relations of bending strains and pore water pressures.

s, the bending strain of the landside pile becomes large at a depth of 1.5-2.0 m. A similar trend can be found in the seaside pile (Fig. 5(b)). The magnitude of bending strain in the seaside pile is, however, much smaller than that in the landside pile.

To estimate the difference in bending strain between the seaside and landside piles, Fig. 6 shows relations between the bending strain at a depth of 1.5 m and the pore water pressure at a depth of 1.2 m either on the seaside of the seaside pile or the landside of the landside pile. The pore water pressure on the landside pile decreases, with increasing bending strains (Fig. 6(c)(d)). The pore water pressure reduction is more significant on the landside of the landside pile. Such a trend is unclear in the case of the seaside pile (Fig. 6(a)(b)). This relates to the trends observed in the time histories shown in Fig. 3(i)-(l), in which the pore water pressure on the landside of the pile group decreases with cyclic loading, and suggests that the dilatancy characteristics of the soil is more significant on the landside of the pile group than in the seaside.

To further investigate the difference between the seaside and landside piles, Figs. 7 and 8 show distributions of the ground and pile displacements, earth pressures and pore water pressures on the seaside and landside of the piles. The ground displacement presented in Figs. 7 and 8(a) corresponds to the average of the observed ones at points A and B shown in Fig. 1(a) and that in Figs. 7 and 8(b) corresponds to the one at point B. The pile displacement is computed by the integration of bending strains in pile with depth (Figs. 7 and 8(a)(b)). The earth pressure and pore water pressure are either those on the seaside of the seaside pile or those on the landside of the landside pile (Figs. 7 and 8(c)-(f)). The positive earth pressure indicates compression pressure on each side. Thin lines in Figs. 7 and 8(c)(d) stand for the difference between two earth pressures observed on both sides of each pile, hereby called total earth pressure. The positive total earth pressure indicates that the soil pushes the pile landward, and the negative one indicates that the soil pushes the pile seaward.

At 3 s, the pore water pressure at a depth of about 1.5 m on the landside of the landside

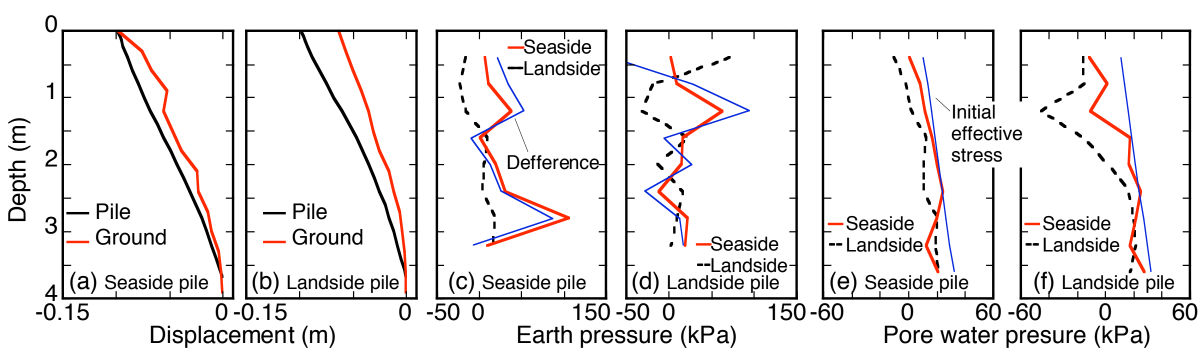


Figure 7. Distributions of displacement, earth pressure and pore water pressure at 3 s.

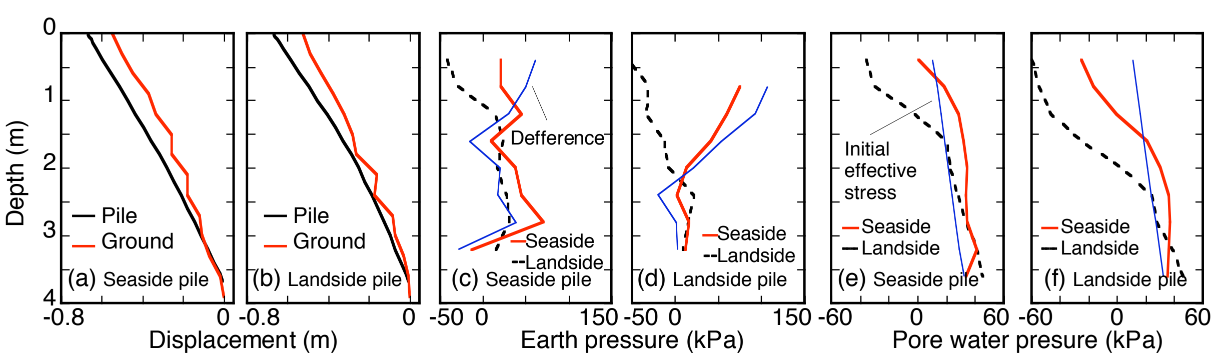


Figure 8. Distributions of displacement, earth pressure and pore water pressure at 7 s.

pile decreases (Fig. 7(f)). At this instant, the earth pressure at the same depth on the seaside of the landside pile increases accompanied by a decrease in earth pressure on the landside of the same pile (Fig. 7(d)), indicating that the compression stress state develops on the seaside with the extension stress state on the landside. As a result, the total earth pressure increases landward. This confirms that the earth pressure is related to the pore water pressure changes, as mentioned in the previous study (Tokimatsu and Suzuki 2004). Namely, the total earth pressure is induced by the combined effects of the pore water pressure reduction and of the soil dilation caused by the shear stress. Reduction in pore water pressure and earth pressure of the seaside pile, in contrast, is insignificant (Fig. 7(c)(e)).

The abovementioned trends in earth pressure correspond to the bending strain distributions, in which the bending strain at a depth of about 1.5 m of the landside pile is significantly larger than that of the seaside pile (Fig. 5(a)). The difference in earth pressure and pore water pressure between the landside and seaside piles is probably due to spatial variation of ground displacement and dilatancy of soil subjected to large shear strain. As shown in Fig. 7(a)(b), the ground displacement becomes larger with decreasing distance to the quay wall. Since the pile displacement is larger than the ground displacement (Fig. 7(a)(b)), the relative displacement with respect to the ground of the landside pile becomes larger than that of the seaside pile. This could have created larger pore pressure reduction, thereby making the soil around the landside pile stiffer than that around the seaside pile.

At 7 s, the pore water pressure decreases on both the landside and seaside piles (Fig. 8(e)(f)). As a result, the total earth pressure acting landward on the seaside pile as well as the landside pile increases (Fig. 8(c)(d)). This is probably because, with increasing seaward movement, the relative displacements of both seaside and landside piles with the ground could have become large, making the soil around both piles stiff. Due to the yielding at the heads and an increase in kinematic force in liquefied layer, the bending strains of both the seaside and landside piles become large at a depth of about 1.5-2.0 m. This corresponds to the observation of pile damage after excavation.

Conclusions

To investigate failure and deformation mode of piles during liquefaction-induced laterally spreading, a physical model test on a soil-pile-structure system with a quay wall was conducted using the large shaking table at E-Defense, NIED. The test results and discussions have led to the following:

Extensive soil liquefaction occurred in a few seconds after the start of shaking, causing laterally spreading. The quay wall had a residual deformation of 1.2 m, inducing seaward movements and settlements of the ground behind. The piles moved seaward with a landward inclination of the superstructure. All piles buckled at their heads and also bent at 1.5-2.0 m below their heads. This trend was more significant in the landside piles than in the seaside piles.

At the initial stage, piles yields at their heads due to the seaward inertial force. The bending strain of the landside pile becomes larger than that of the seaside pile, with their peak values occurring in the ground (at depths of about 1.5-3.0 m) as well as at the pile head. This is probably due to the spatial variation of ground displacement and dilatancy of soil subjected to a large shear strain. Since the pile displacement is larger than the ground displacement that becomes larger with decreasing distance to the quay wall, the relative displacement with respect to the ground becomes larger in the landside pile than in the seaside pile. This creates larger pore pressure reduction and thus makes the soil around the landside pile stiffer than that around the seaside pile, inducing a larger kinematic force on the landside pile.

With increasing seaward movement, the relative displacement with the ground becomes large for both the seaside and landside piles. This makes the soil around the seaside and landside piles stiff, inducing an increase in kinematic force on both piles. Due to the yielding at the heads and the increase in kinematic force, the bending strain of both the seaside and landside piles becomes large in the ground.

Acknowledgments

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