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LARGE SCALE SHAKE TABLE TEST ON LATERAL SPREADING OF LIQUEFIED SAND BEHIND A SHEET PILE WALL MODEL

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SUMMARY

Both caisson-type and sheet pile-type quay walls faced extensive damage during the 1995 earthquake in Kobe. Seaward displacement of the sheet pile quay walls due to lateral spreading of the liquefied backfill soil reached to several meters. As a result, neighboring pile foundations faced relatively large translations and inclinations. In order to realistically model liquefaction and lateral spreading of saturated sand deposits behind sheet piles and the consequent deformation and translation of neighboring pile foundations, the largest laminar box in the world (12m x 3.5m x 6m) was employed and a series of shake table tests were conducted at National Research Institute for Earth Science and Disaster Prevention in Japan (NIED). In these nearly full-scale tests, a group of four concrete piles were modeled behind steel sheet piles. Piles in the ground were extensively instrumented with strain gauges to measure distribution of moment during lateral spreading. This allowed computing the loading condition, as well as conducting damage and performance assessments. Other instrumentations including pore water pressure transducers and accelerometers were installed in various depths and locations. Displacements of the laminar box, top cap and top of the sheet pile were also measured by means of displacement transducers. The test results revealed that after a few cycles of loading and unloading, pore water pressure in saturated and relatively loose backfill increased and the consequent loss of effective stress resulted in lateral spread of the liquefied sand. The tendency towards minimal potential energy in the liquefied soil caused deformation in the sheet pile and resulted in bending moments and lateral deformation of the piles. It was also intended to model post liquefaction behavior of the liquefied sand as observed during real earthquakes, particularly during the 1964 Niigata earthquake. The delayed lateral displacement of the sheet pile started a few minutes after the end of the input shake. The clear evidence of pore water redistribution and second phase of lateral movement was observed. This paper reports the investigation on liquefaction and post liquefaction phenomena which occurred during the experiment, and presents the discussion on the experimental results.

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INTRODUCTION

Soil liquefaction brought severe damage to pile foundations of road bridges and buildings during 1964 Niigata earthquake in Japan. One of the most noteworthy phenomena during this earthquake was the collapse of Showa Bridge which was one of the connecting paths between the two sides of the river in the city (Photo 1). Some local citizens reported that they could pass the bridge safely during the earthquake and they were witnessed the collapse of the bridge after the ground motion was stopped (Photo 1). The extensive liquefaction of the soil behind the bridge abutments followed by the lateral spreading of the fluid-like mixture of sand and pressurized pore water caused seaward lateral displacements in the abutments and resulted in consecutive collapse of the bridge decks. The delayed lateral spreading of the liquefied sand behind this retaining structure was phenomenal.

Photo 1. Delayed collapse of Showa Bridge and the clear evidence of extensive liquefaction during the 1964 earthquake in Niigata – Japan

About three decades later and during the 1995 Kobe Earthquake, liquefaction and lateral spreading of the liquefied sand in Kobe port area caused extensive damage to port facilities. Seaward displacements of the sheet pile quay walls due to lateral spreading of the liquefied soil extended over several meters, and as a result, translation and inclination occurred to neighboring pile foundations.

Sheet pile quay walls have been widely used in metropolitan areas where many structures and bridges have been constructed using pile foundations. In order to mitigate the damage to these structures resulting from probable future earthquakes, it is therefore necessary to develop appropriate countermeasures. Consequently, it is important to understand the mechanisms regarding seismically induced ground deformation behind sheet pile quay walls and to evaluate their effects on neighboring pile foundations.

Recently, at National Research Institute for Earth Science and Disaster Prevention in Japan (NIED), a series of large scale shake table tests were conducted to study the seismic response of sheet pile wall system and the liquefaction and deformation characteristics of the saturated cohesionless backfill, as well as the response of the neighboring pile foundations. In these experiments, both the liquefaction and post liquefaction stages were modeled and studied. The largest laminar shear box in the world (12m x 3.5m x 6m) was employed in order to obtain nearly full-scale testing results to ascertain the mechanisms of lateral ground flow of the liquefied soil behind sheet pile quay walls and to evaluate the effects of the liquefied earth pressure acting on pile foundations both during the ground shaking and post liquefaction stage.

TEST PROCEDURE

Apparatus

A large-scale laminar box (6.0m x12.0m x 3.5m) which is the largest in the world to this date, and a large shake table (15m x 14.5m) in National Research Institute for Earth Science and Disaster Prevention (NIED) were used to perform the experiments. Photo 2 shows the shake table and the assembled laminar box. The laminar box consists of 29 laminar frames which are designed to slide to maximum one meter in horizontal direction. The height of each layer is about 20 cm and each layer can move independently regarding its upper and lower layers. A rubber membrane is placed to provide a waterproof space inside the box. External frames with horizontal rollers ensure safe and accurate movement of the layers, while the internal stoppers are used as limiting measures to stop excessive movement of the individual layers. Since the layers can be assembled one by one, the height of the box can be adjusted to the requirements of each experiment.

Material

Clean sand from Kasumigaura area in Ibaraki prefecture in Japan was sampled and used in this experiment. Index tests were performed on this sample, and Figure 1 shows the grain size distribution and physical properties of the material.

Photo 2 Large-scale laminar container fixed on the shake table in NIED

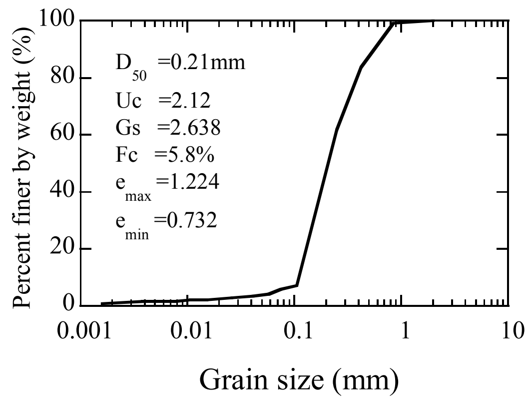


Figure 1 Grain size distribution curve and physical properties of Kasumigaura sand

Sample Preparation Method

Four reinforced concrete piles were installed in the center of the laminar box by pin connection to the base. Diameter of the piles was 15 cm and their length was 4.5 m (L/D=1/30). Center to center space between the piles was 0.9 m and a steel top cap provided a rigid connection on top of the piles. A sheet pile was installed in the east side of the piles with 30 cm space from the laminar box wall. This sheet pile was used to provide lateral soil pressure on the liquefied soil to keep it moving toward the pool side. The box was partially filled with water, and dry sand was pluviated in the water (Figure 2). As the hydraulic sediment was filled in the box, the water level was also increased. Based on the past experience, it was proved that this method gives a uniform and relatively loose saturated sample (Dr= 40 ~ 50%). In the next step, the main sheet pile installed, and the filling procedure continued until the soil level in east and west side of the sheet pile reached to 4.0 and 3.2 m, respectively. The water level at this stage was 4 m from the base. Then, in the east side, a layer of unsaturated soil was placed to raise the ground level to 4.5 m. Soil, piles and sheet piles were heavily instrumented with pore water pressure and displacement transducers, as well as accelerometers and strain gauges. Two directional bender elements were also installed in the box to measure shear wave velocity of the sample. Instruments were fixed on a thin net and installed in the box, before sand pluviation. Total number of 256 channels was used for data acquisition of outputs of the instruments. Then, heavy plates were mounted and fixed on top cap until its weight reached to about 10 tons, as a model for a massive super structure (Figure 3).

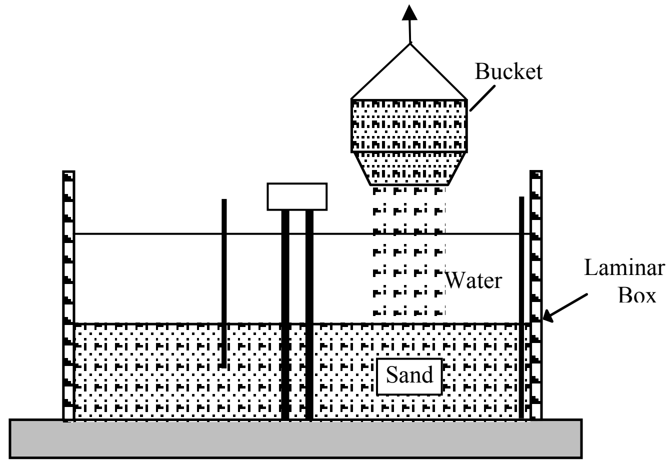


Figure 2 Sample preparation method

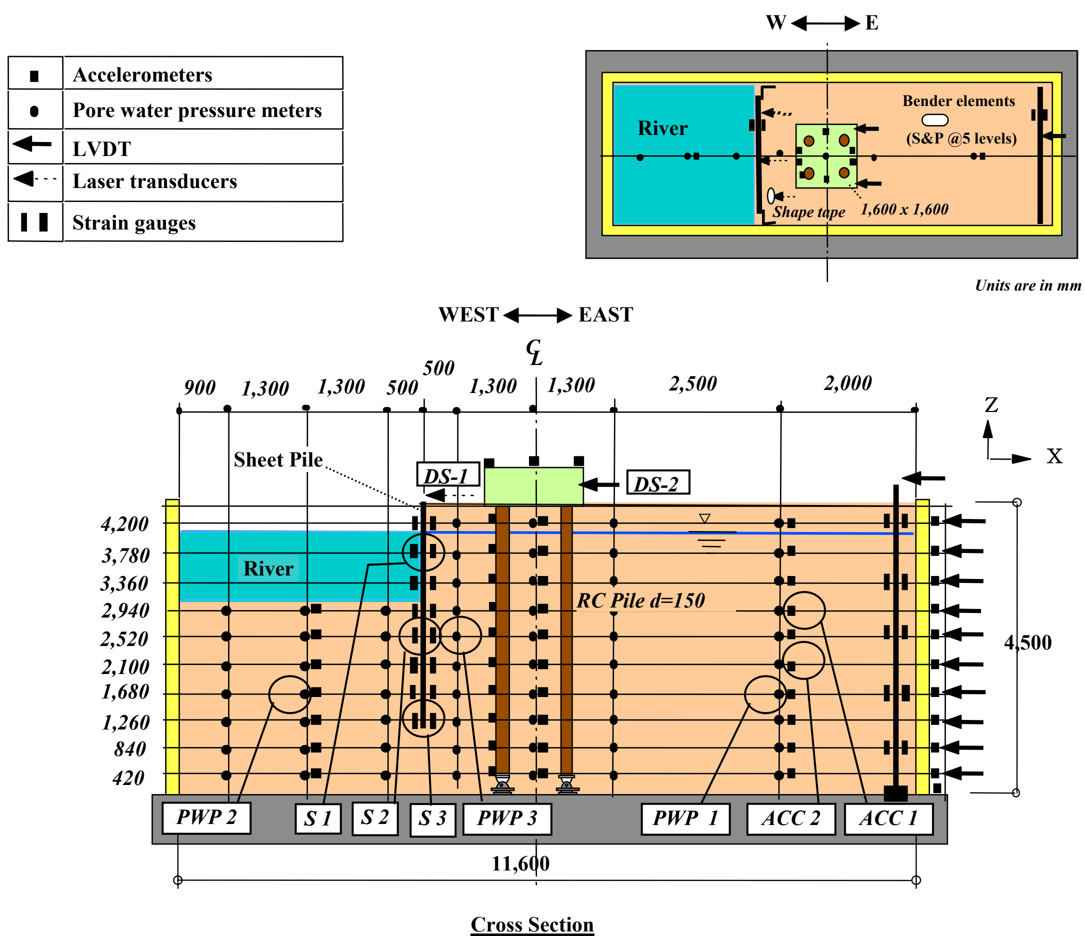


Figure 3. Schematic illustration of the shake table test model

Input motion

Five cycles of sinusoidal wave with maximum acceleration of about 450 gal and frequency of 4 Hz was used as input motion. Figure 4 shows the time history of the input shake. It was planned to apply a relatively swift and strong motion to help the saturated soil liquefy after two or three cycles of loading and monitor the lateral spreading phenomenon during and after shaking.

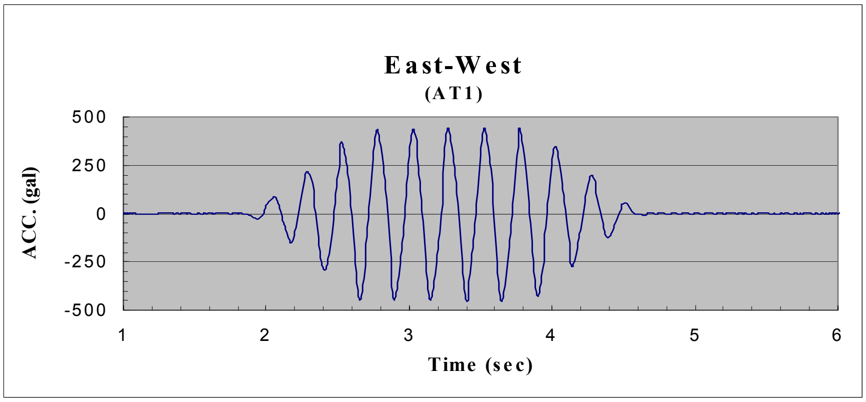


Figure 4 Measured input motion time history on shake table

TEST RESULTS

Data of the test results were recorded through 256 channels during the shaking. The measurement continued for about 10 min. after the shake, as well. Since the main purpose of this paper is to study the liquefaction and post liquefaction behavior of the model ground, only the related outputs are discussed in this part, and the rest of the data will be published in a different paper.

Acceleration

Figure 5 shows the time history of the response accelerations observed at mid height of the model ground which are marked as Acc 1 and Acc 2 in Figure 3. The comparison of these acceleration time histories (as well as the records measured in other points, which are not shown here) with input acceleration as shown in Figure 4 indicates that soil liquefaction occurred after 2 or 3 cycles and then, vibrations did not transfer to upper layers due to soil liquefaction.

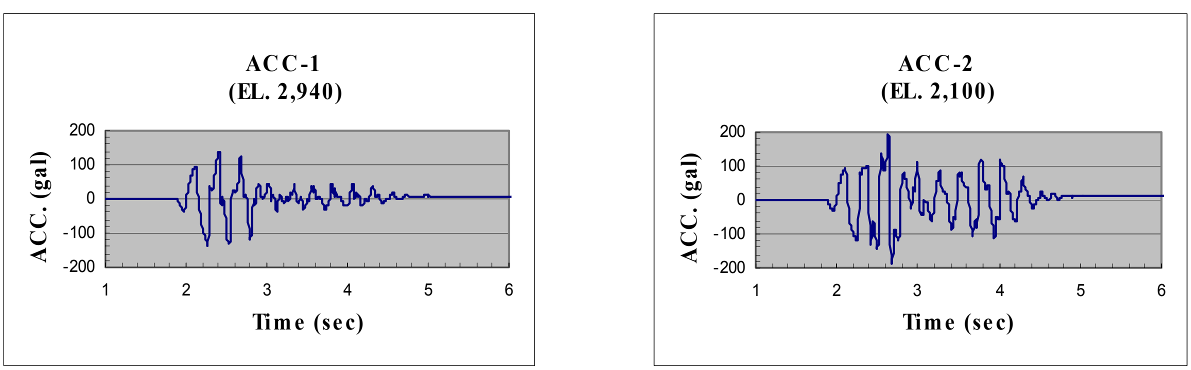


Figure 5 Acceleration time history at points Acc-1 and Acc-2 (Figure 3)

Pore water Pressure

Test results revealed that after a few pulses of shaking, pore water pressure in saturated and relatively loose backfill increased. Figure 6 shows examples of pore water pressure time history in center of back fill and river bed (marked as PWP 1 and 2 in Figure 3, respectively). Pore water pressure reached to its maximum value after about 2 cycles of loading and unloading. Measurements were continued after shaking, in order to trace the dissipation time history, as well. Figure 7 represents pore water pressure ratio, which is the ratio of the pore water pressure to initial effective stress at each point. The ratio reached to unity in initial stage of the cyclic loading that indicates the state in which the effective shear stress was reduced to about zero.

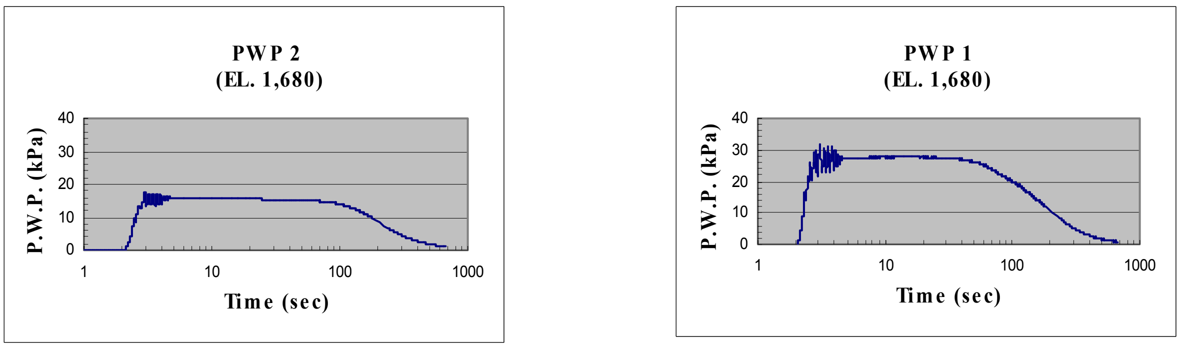


Figure 6 Pore water pressure generation and dissipation time history at points PWP 1 and 2 (Figure 3)

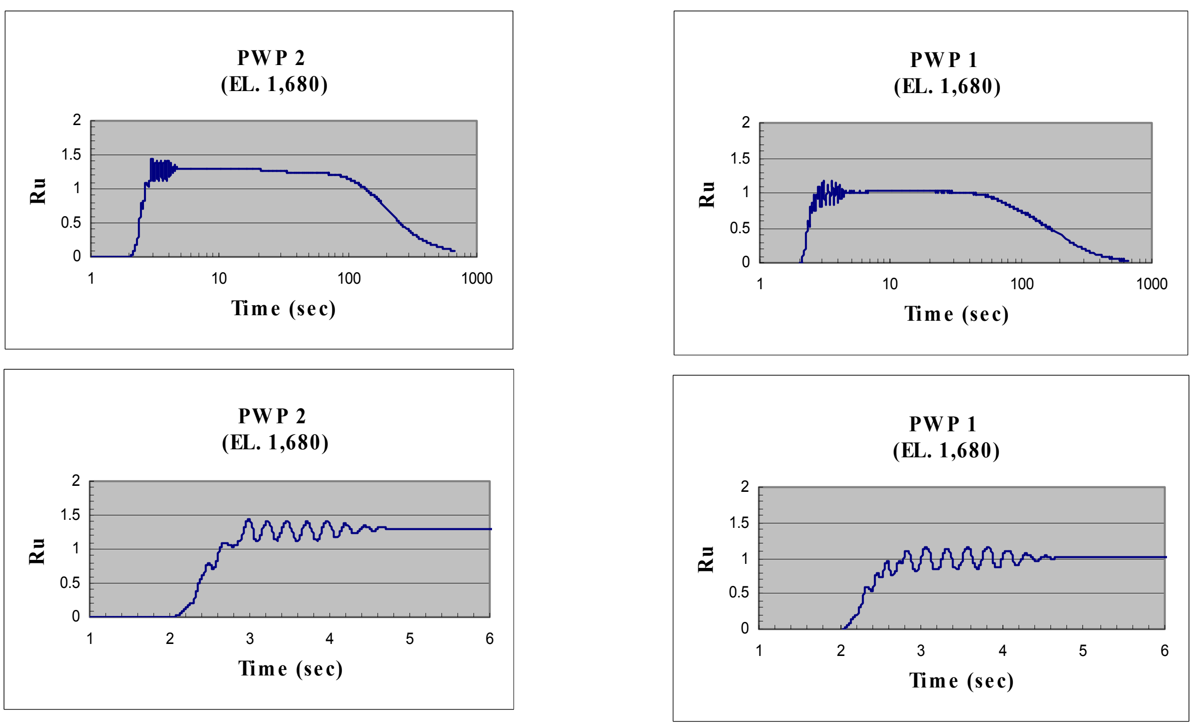
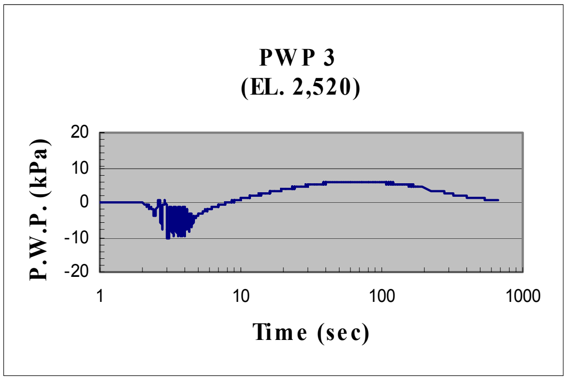


Figure 7 Pore water pressure ratio time history at points PWP 1 and 2 (Figure 3)

Figure 8 shows the pore water pressure time history of the point behind the sheet pile (marked as PWP 3 in Figure 3). These results indicate that during and immediately after the shake, the displacement and deformation of the sheet pile and backfill soil caused negative pore water pressure generation. After the end of the shake, and during the drainage stage, pore water pressure re-distribution occurred and the negative pore water pressure was regained. The negative pressure shifted to positive side smoothly and the peak was obtained nearly at the same time that pore water dissipation started in other zones (Figures 6 and 7). At about 100 seconds after the start of the shake, pore water pressure at this point seems to drain very similar to the point shown in Figures 6 and 7.



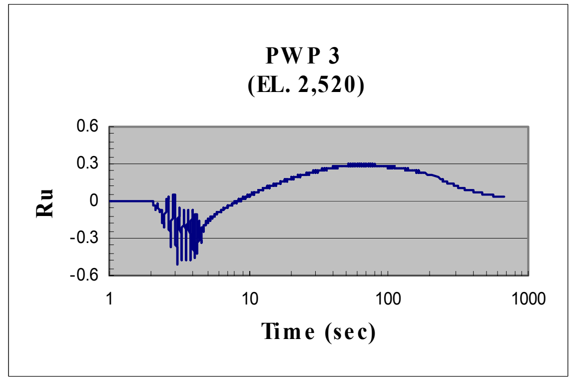


Figure 8 Time history of pore water pressure and pore water pressure ratio behind the sheet pile (point PWP 3 as shown in Figure 3)

Displacements

Soil deformation was measured on laminar box, on top cap of the pile group and on top of the sheet pile. As shown in Figure 9, the lateral displacement of the sheet pile was cyclically accumulated during the shaking. The total displacement at the end of the shaking (about t=4.5 s) was about 28 mm. The figure indicates that at t=30 s, the lateral displacement increased only about 2 mm, and from this time, a rapid change in rate of lateral displacement was observed. The flow continued until t=180 s and the maximum displacement reached to about 100 mm at top of the sheet pile. The delayed accumulation of displacements was observed during the shake test.

Displacement accumulation on top cap, sheet pile and the backfill were become very small after the shaking. However, lateral displacement of the sheet pile and the backfill soil continued and gradually open cracks appeared in the back fill soil and as time passed, an extensive network of tension cracks appeared in the back fill soil indicating large lateral displacement and settlement of the backfill soil (Photo 3). Consequently, as shown in Figure 10, displacement time history on top of the pile cap followed the lateral soil deformation and displacements exhibited similar post liquefaction behavior. The residual displacement at time 180 s increased to about double value compared to the end of the shake (about t=4.5 s).

Photo 3 Extension of cracks behind the sheet pile after the end of shaking

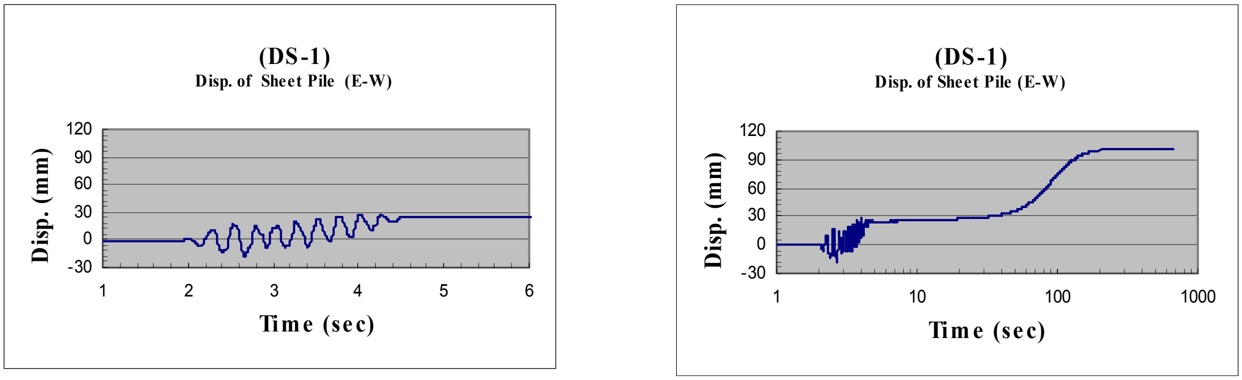


Figure 9 Displacement time history on top of the sheet pile

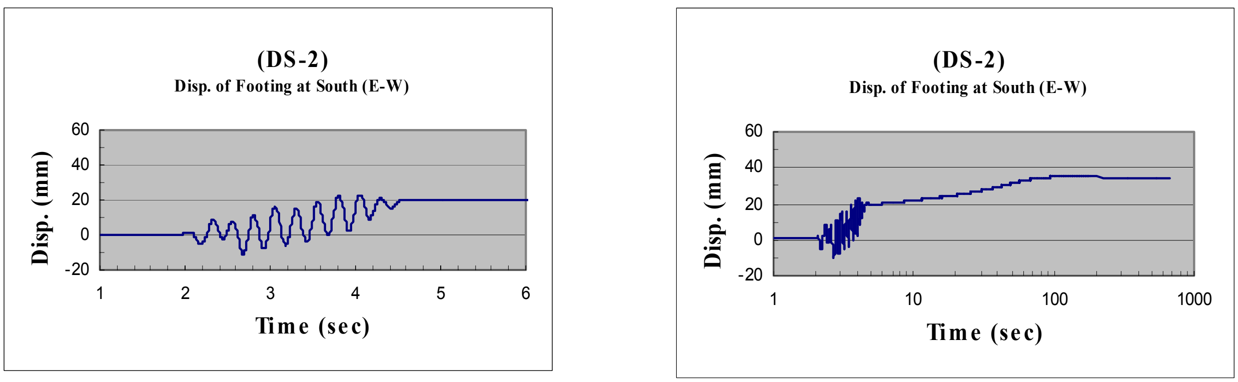


Figure 10 Displacement time history on top of the sheet pile

A six meter long ShapeTape, a Measurand product based in Canada, were used in this experiment. ShapeTape is a fiber optic based bend and twist sensor, that knows where it is continuously along its length, providing accurate position and orientation information, even when in partial or variable contact with an object. The position of the tape is shown in Figure 3. Since it was the first attempt in this kind, the results were extensively studied. Figure 11 compares soil displacement on top of the shape tape and the reference measurement by a conventional laser transducer. Although two measurements show slightly different results, ShapeTape measurements demonstrated relatively acceptable trend. The application of ShapeTape in large scale shake table tests is still under progress and the results will be published later.

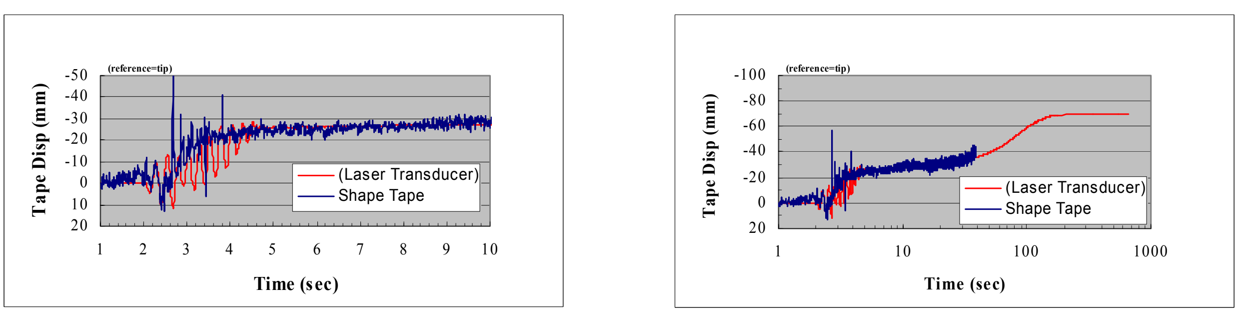


Figure 11 Displacement time history of shape tape and laser transducer on Top of the tape

Bending Strains

Strain gauges were attached on both sheet pile and pile foundations to measure the bending strain time history during and after the shaking. Figure 12 shows bending strain time history on points S1 near top and S2 on middle of the sheet pile, as marked in Figure 3. The figures indicate that the sign of bending moment changed after the end of the shake, and the time of these turning points coincides to what we observed in Figures 8 and 9 for pore water pressure ratio time history behind the sheet pile and displacement time history on top of the sheet pile, respectively.

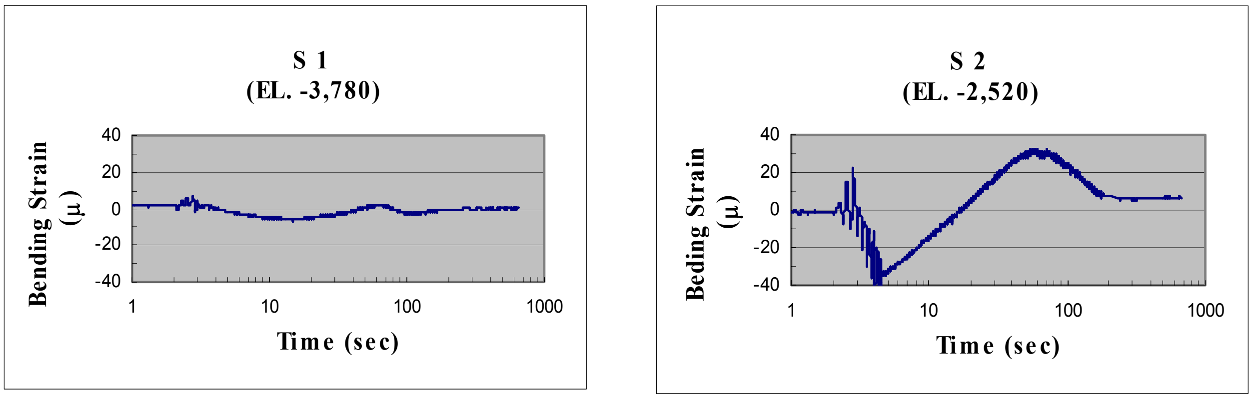


Figure 12 Bending strain time history measured on sheet pile

Bending strains measured on four different heights of the south western pile foundation is presented in Figure 13. The results confirm that bending moment distribution of the piles underwent two clearly visible stages. The first stage was bending moment distribution during the shaking period, in which inertia force was applied on the piles in a cyclic manner. The second stage or post liquefaction phase started immediately after the end of the shake and bending moment re-distribution was progressed in the piles. This is simply because of the redistribution of effective soil pressure in different depths of the model ground.

CONCLUDING REMARKS

A series of large scale shake table tests were conducted to study the seismic response of sheet pile wall system and the liquefaction and deformation characteristics of the saturated cohesionless backfill, as well as the response of the neighboring pile foundations. The test results revealed that after a few pulses of shake, pore water pressure in saturated and relatively loose backfill increased and the consequent loss of effective stress resulted in lateral spread of the liquefied sand. The tendency towards minimal potential energy in the liquefied soil caused deformation in the sheet pile and resulted in bending moments and lateral deformation of piles. Post-liquefaction behavior of the liquefied sand was quite remarkable. The delayed lateral displacement of the liquefied soil started a few minutes after the end of the input shake. The negative pore water pressure behind the sheet pile re-distributed and increased smoothly to gain positive values. This means that effective stress in soil behind the sheet pile started to decrease and when shear stress ratio reached to a certain value, second phase of displacement was occurred. Obviously, this

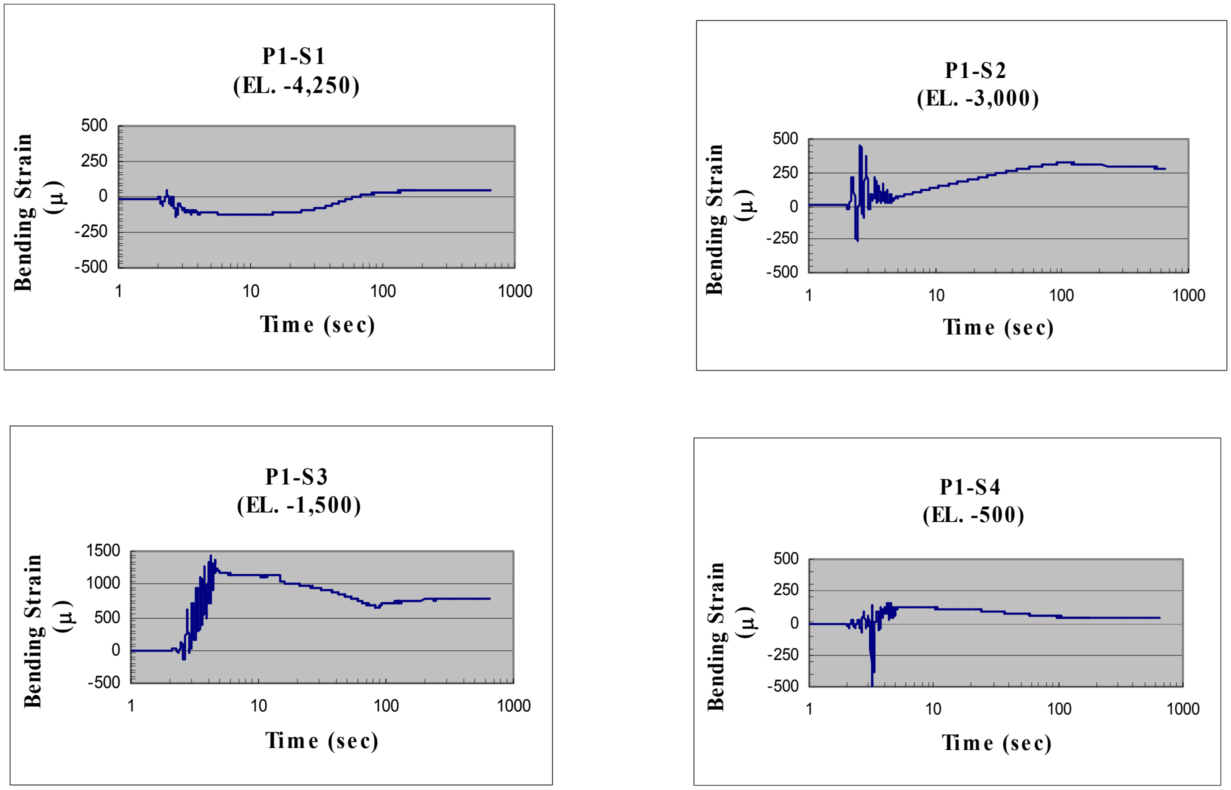


Figure 13 Bending strain time history measured on south western pile foundation

trend of effective stress change is equal to change in lateral soil pressure on sheet pile and pile foundations, which resulted in bending moment re-distribution of these embedded elements after the shake stopped. This process was continued until excess pore water pressure was fully drained and reached about zero .The test results clearly showed the significance of the post-liquefaction behavior of the liquefied backfill sand. It seems that the scale effects are quite remarkable in experimental study on liquefaction behavior, since such results were rarely observed and reported from small scale tests.

It is important to note that this study is an on-going research process and more data analysis, shake table tests, centrifuge tests and numerical analysis are being conducted and the results will be published later.

REFERENCES

Air Photographs of the Niigata City Immediately after the Earthquake in 1964. Published by Japanese Geotechnical Society, 1999.

ACHNOWLEDGEMENT

The photo of Showa Bridge shown in Photo 1 of this paper is downloaded from: http://www.ce.uiuc.edu/sstl/education/liquefaction/SHOWA.html. The writers acknowledge the written permission to use this photo.