AN EXPERIMENTAL STUDY ON THE PIER DAMAGED BY 1995 HYOGOKEN-NANBU EARTHQUAKE

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SUMMARY

The open-type pier with vertical piles in Kobe port had serious damages during 1995 Hyogoken-Nanbu Earthquake. From the investigation carried out after the earthquake, large displacement of the pier was observed and buckling failure of the piles were found at the pile heads and portions buried in the ground. To investigate the damage mechanism of the piers, experimental studies have been carried out using large underwater shaking table tests. The retaining wall behind the pier was subjected to lateral forces more than expected in its design due to liquefaction of the fill, and result in the damages on the foundation piles. In this paper, the methods and the results of the shaking table tests are explained.

INTRODUCTION

Hyogoken-Nanbu Earthquake 1995 damaged of the facilities at Kobe port and almost paralyzed their function. The open-type pier with vertical piles in Kobe port had serious damages during the earthquake although it had been considered to have earthquake-proof because it was lighter than gravity-type quay wall. The analysis of damaged mechanism has been investigated, based on the investigation after the earthquake, which including effective stress analysis. Three causes of failure maybe identified for the pier from the series of these analysis. First, the seismic inertia force on the deck. Second, liquefaction of the reclaimed soil behind the retaining wall and alluvium sand layer under the pier, an excessive large displacement between the deck and top of the retaining wall. Third, displacement in the dike will directly push the piles seaward. Due to lateral forces more than expected in its design caused as mentioned earlier, Buckling of the pile heads and portions buried in the ground and 1.5m residual displacement toward the sea. To investigate the mechanism of the piers precisely, we made an experimental studies using large underwater shaking table. In this paper, the methods and the results of the shaking table tests are explained.

DAMAGED CONDITIONS OF THE PIER

Fig.-1 shows typical cross-section and damaged conditions of the open-type pier with vertical piles which was object of these studies. The pier consists of piles in the three row(ie. Seaward pile, central pile and landward pile) and deck work of reinforced concrete. The open-type pier and retaining wall which is in back of this pier is combined by the approach bridge of reinforced concrete. The lateral force is subjected to the open-type pier through this RC bridge. The backfill soil behind this retaining wall is reclaimed with loose sand of which SPT N-value is about 10.

From the results of the investigation carried out after the earthquakes, buckling failure of the piles were found and large displacement of the pier was observed. In the Fig.-1 ● represent the locations of buckling failure of the piles. As for pile heads, buckling appears in the seaward pile and central pile, but doesn't appear in landward

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pile. A crack was found at the pile cap of landward pile. As for in the ground, buckling was located close to the boundary between the layers of alluvial sand and pleistocence gravel. The lateral residual displacement was about 1.5m seaward.

OUTLINE OF THE SHAKING TABLE TEST

We used a shaking table with a water depth of 2m to model the behavior of the pier, which is constructed in the water, under earthquake more faithfully. The cross-section of the test model is shown in Fig.-2. This test model is a scale of 1 to 15 in longitudinal directions. The similitude in 1G field for soil-structure-fluid system was adopted for this shaking table tests. And the scaling factors were shown in Table-1.The similitude law was proposed by Dr. Iai[1)].

Soma-sand was used in substitution for reclaimed soil behind the retaining wall, which was scattered into water. The shear wave of the reclaimed soil meet similarity law. Crushed stone #6 was used in substitution for stone backfill behind the retaining wall and #4 was for rubble dike. The location where four type transducer(gauge) were installed is shown in Fig.-2. Displacement transducer (represented as→)measured horizontal displacement and settlement of the pier and retaining wall. At intervals of 20cm, stain gauges(represented as■) were installed at front and back of piles measured bending moment. Pore pressure transducers(represented as□) and accelerometer(represented as●) were installed at three rows: reclaimed soil behind the retaining wall, right under the retaining wall, and below the rubble dike. They measured excess pore water pressure and response acceleration.

Flexural rigidity of the model piles was intended to meet similarity law and mass of the model deck was also intended to meet it. Model piles and deck were firmly jointed. In order to verify this model eigen value analysis between the actual object and this model was made. An analytical model is shown in Fig.-3. Natural vibration of the prototype was 0.28Hz,and that of the model converted into actual scale was 0.29Hz. It was concluded that this model practically meets similarity law.

Three dimensional shaking was applied using the surface motion recorded at a depth of 32m by the vertical seismic array at Port Island. The input motion was applied in accordance with the direction of the pier.

RESULT OF THE EXPERIMENT

The time history of the excess pore water pressure, response acceleration, and displacement

The time history of acceleration, excess pore water pressure, and displacement are shown in Fig.-4. In the history of excess pore water pressure, the solid line represents the vertical effective overburden pressure. W2,W3,W4 in this figure, which indicate time history of excess pore water pressure of reclaimed soil, began to be added around 9seconds. At 12seconds the excess pore water pressure reached 90% of the vertical effective overburden pressure. This result confirms that full liquefaction of whole area in the reclaimed soil is performed then. Response acceleration AH5,AH6,AH7 reduce its maximum acceleration as it approaches the ground level and long period component get more dominant.

Relation with the residual bending moments and the buckling failure

In Fig.-5, ○ represent the experimental results of the residual bending moments, which were converted into the actual scale. ● represent the locations of buckling failure found by the investigation after the earthquake. From the result of experiment, maximum bending moments are observed at both pile heads and portions buried in the ground. The correspondence between the point of maximum bending moments and the points of the buckling failure was in good agreement. These observation brings our presumption that an excessively large displacement at the top of the retaining wall was occurred, the excessive lateral force distribute to the pier through the bridge the deck will be pushed seaward, and generated buckling failure.

Consideration for the damage mechanism from the experimental studies

Compared with the time history of horizontal displacement of the retaining wall D6 and one of the excess pore water pressure in the backfill soil behind the retaining wall W3, both of them are in good agreement. The excess pore water pressure in backfill soil had increased and this increase certainly affected the retaining wall deformation. As the result, the retaining wall displaced toward sea. Since the time history of the horizontal displacement of the pier D2 was very similar to one of the retaining wall D6, it was assumed that both the pier and the retaining wall were same motion during the earthquake. The damage mechanism of the pier which can be drawn from this shaking table test is as follows. The retaining wall behind the pier was subjected to lateral forces more than expected in its design due to liquefaction of the fill, and the large lateral displacement occurred. This caused the excessive lateral force distribute to the pier, and resulted in the damages on the foundation piles.

CONCLUTION

To investigate the damage mechanism of the pier, experimental studies have been carried out using large underwater shaking table tests. From these studies we can get conclusions as follows. The retaining wall behind the pier was subjected to lateral forces more than expected in its design due to liquefaction of the fill, and the large lateral displacement occurred. This caused the excessive lateral force distributed to the pier, and resulted in the damages on the foundation piles.

In order to clarify damage mechanism more precisely, we will carry out experimental and analytical studies including effective stress analysis. These are to evaluate the effects of various conditions, liquefaction of the fill, existence of the approach bridge, and the behavior of the dike, etc.

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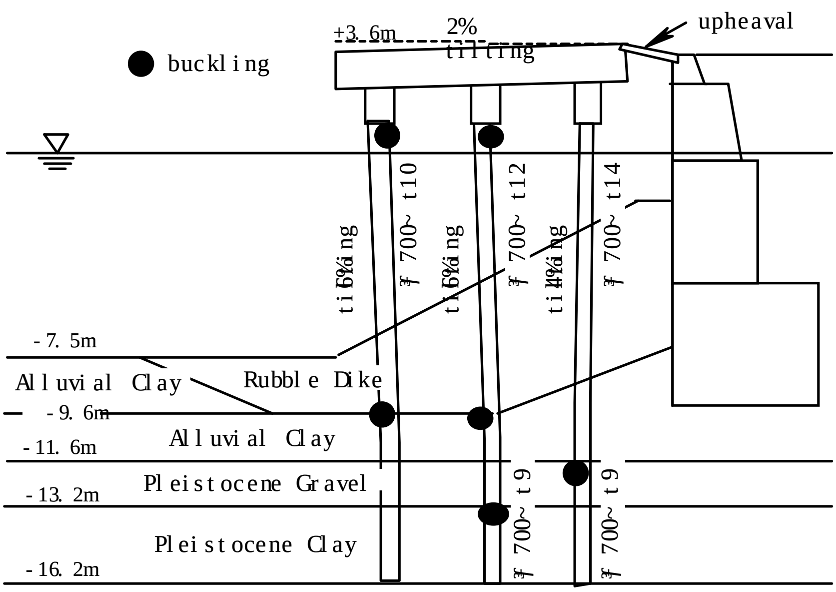
Fig.-1 Damage of pier



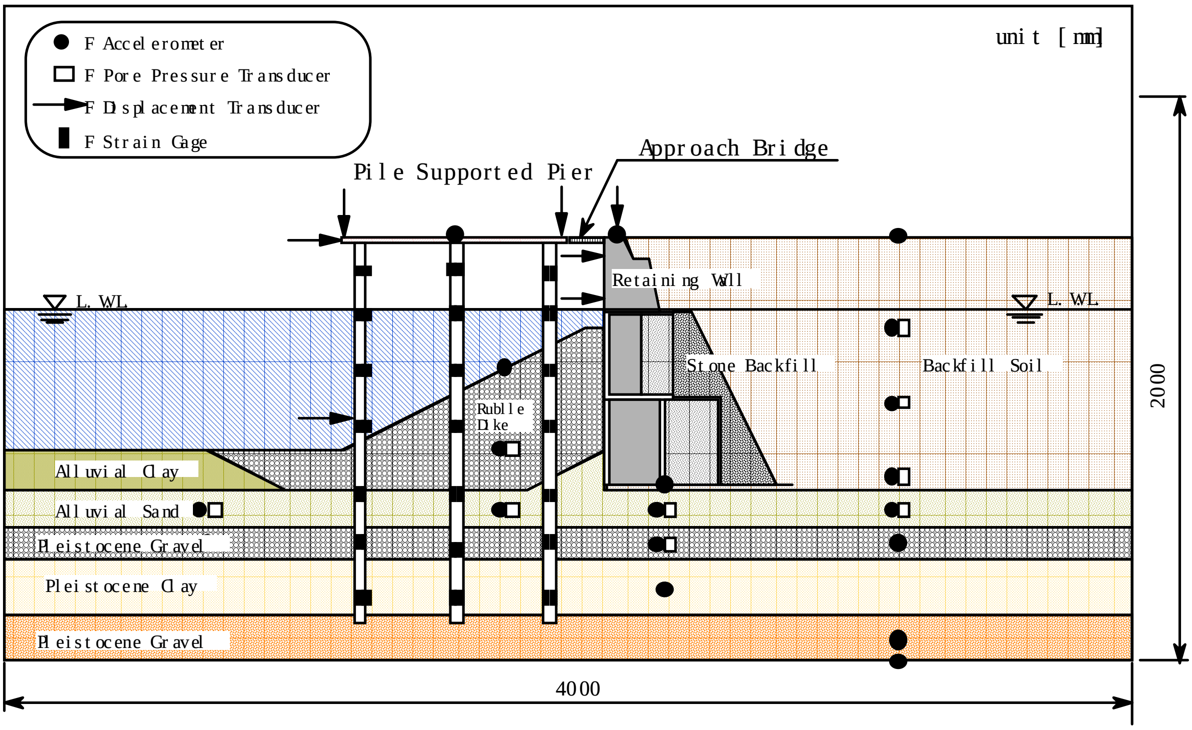


Fig.-2 Cross-section of a model pier for shaking table tests

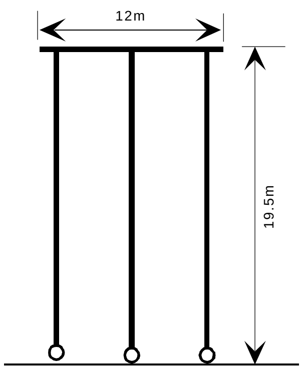


Table-3. Analytical model

Table-3. Scaling factors for 1G shaking tests.

Quantity	Scaling factor	Scaling factors for 1/15 model
Length	ƒ É	15.0
Density	1	1.0
Time	ƒ É$^{0.75}$	7.6
Displacement	ƒ É$^{1.50}$	58.1
Acceleration	1	1.0
Flexural Rigidity	ƒ É$^{4.50}$	196070.0

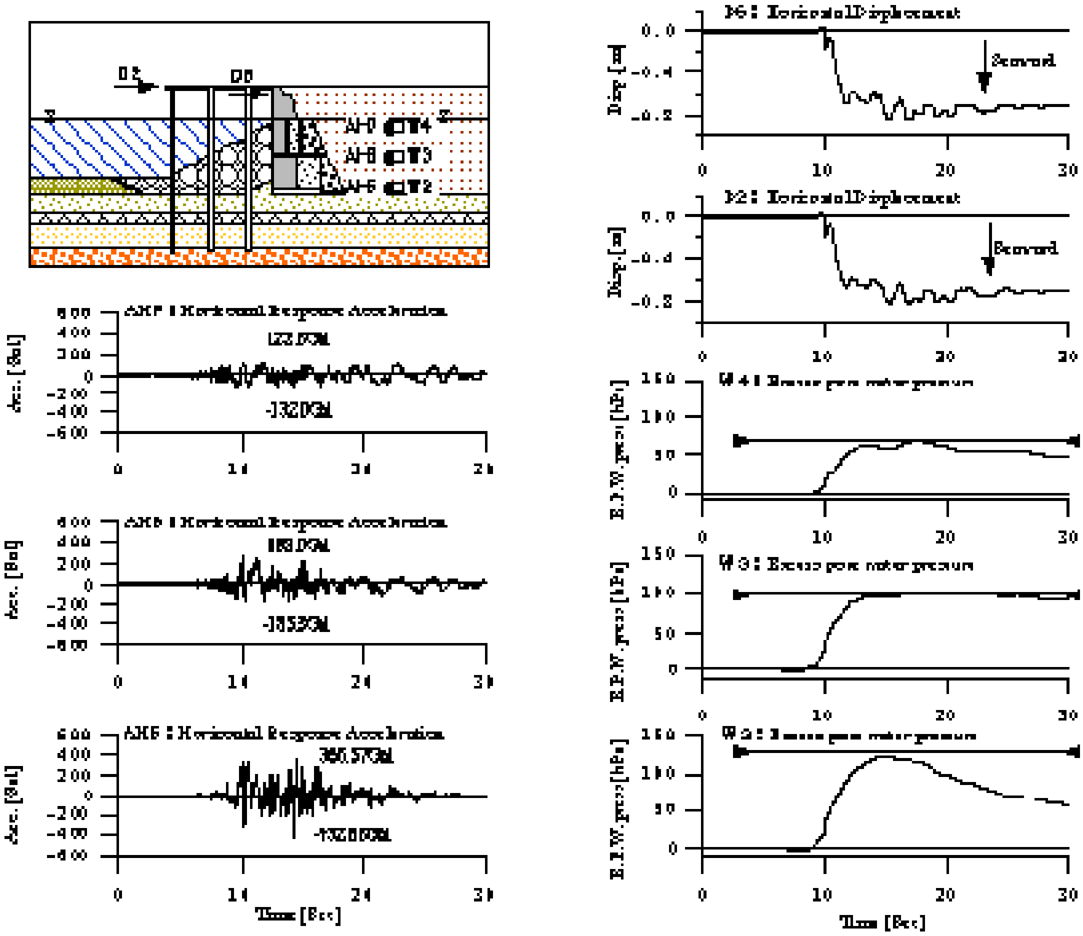


Fig.-4 Time histories of acceleration, excess pore water pressure and displacement

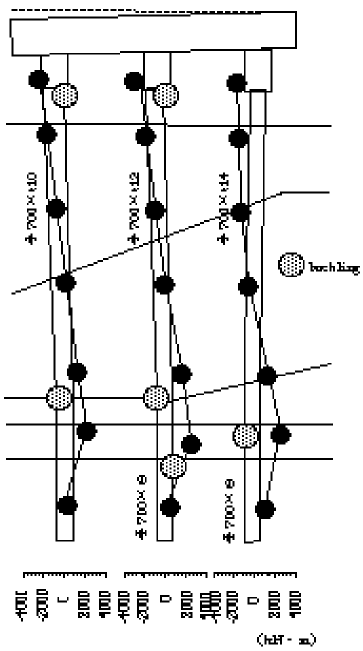


Fig.-5 Distribution of bending moment after exciting motion