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Model tests and analyses on the liquefaction-induced ground flow behind sea walls

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ABSTRACT: Shaking table tests and residual deformation analyses were carried out to demonstrate the mechanism of the liquefaction-induced ground flow behind sea walls. Two types of sea walls, caisson type quay wall and sheet pile type river revetment, which were damaged during the Hyogoken-nambu and Niigata earthquakes, were selected for the tests and analyses. The caisson type wall moved quickly and the sheet pile type wall tilted gradually after the occurrence of liquefaction in the tests. Analyzed displacements of the ground behind walls were roughly equal to the actual displacements

1 INTRODUCTION

Many quay walls moved towards sea and very large ground displacement occurred behind the walls due to liquefaction in and around Kobe City during the 1995 Hyogoken-nambu earthquake in Japan. For example, the average horizontal and vertical displacements of quay walls in Port Island were 2.7 m and 1.3 m, respectively. The ground behind the walls flow and brought severe damage to many structures, such as bridges, buildings and lifelines. The area to which flow expanded was almost 100 to 200 m behind the walls. About 30 years ago, revetments of Shinano River were also moved towards the river and the ground behind the revetments flowed towards the river in Niigata City during the 1964 Niigata earthquake. The maximum displacement of the ground near the river revetments was more than 8 m. And the maximum area to which flow expanded was more than 200 m. Several shaking table tests and simple analyses were carried out to demonstrate the mechanism of the ground flow behind the walls.

2 SHAKING TABLE TESTS

2.1 *Test method*

In the first stage of this study, several shaking table tests were carried out. Two types of sea walls, caisson type quay wall and sheet pile type river revetment, were selected for the tests. Figure 1 shows the model for the caisson type quay wall which simulates a quay wall in Kobe. The soil container used was 220 cm in length, 50 cm in depth and 45 cm in width as shown in Fig.1. Clean sand named Toyoura sand was used to construct the model ground. The relative density of liquefiable layer was adjusted as 40 %. Several piezometers, accelerographs and displacement transducers were installed. The model caisson was 11 cm in height and 5.7 cm in width.

On the contrary, a steel plate was used for the sheet pile type river revetment. Model ground for sheet pile type river revetment simulated the ground around Showa Bridge which was heavily damaged during the Niigata earthquake. Figure 2 shows the model for the sheet pile type river revetment and the ground. Thickness of the steel plate was 1.2 mm.

Several levels of shaking were applied to these models to know the effects of intensity of shaking on the ground flow.

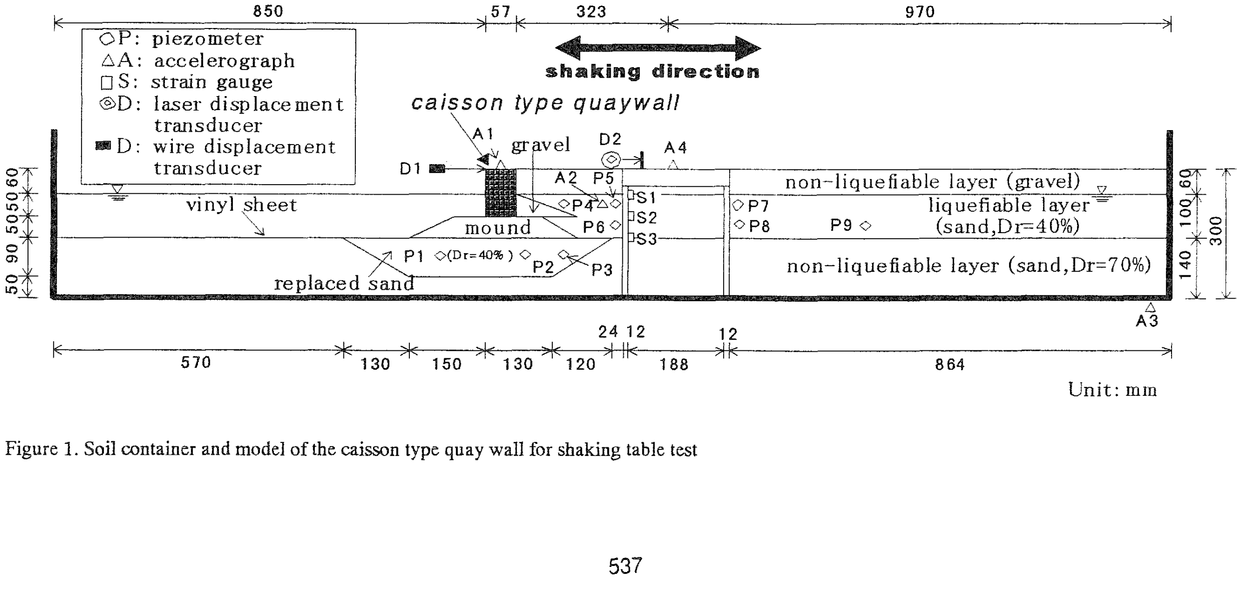


Figure 1. Soil container and model of the caisson type quay wall for shaking table test

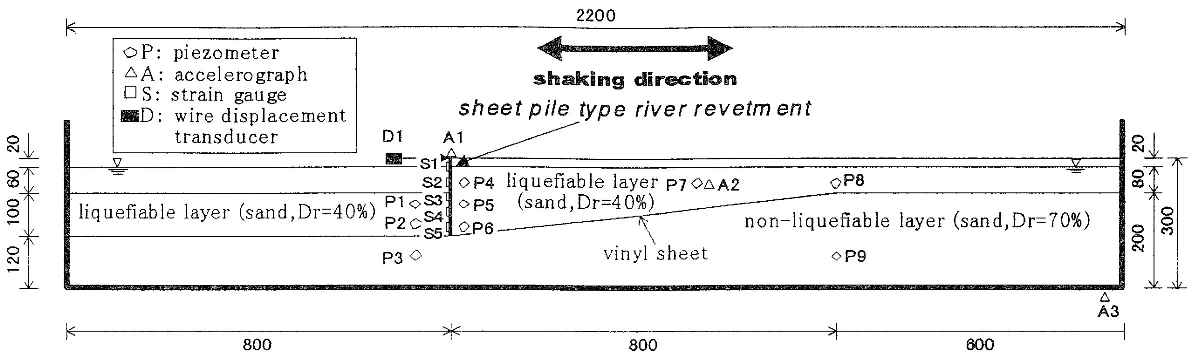


Figure 2. Soil container and model of the sheet pile type river revetment for shaking table test

2.2 *Movement of the walls*

Figures 3 and 4 show time histories of the displacements of the sea walls for the caisson type quay wall and the sheet pile type river revetment, respectively. As shown in Fig.3, the caisson type wall moved quickly after the occurrence of liquefaction. On the contrary, the sheet pile type wall tilted gradually after the occurrence of liquefaction. Final displacement of the walls increased with the intensity of shaking in both cases.

2.3 *Relationships between the movement of sea walls and pore water pressure*

Figure 5 shows the detailed time histories of displacement of caisson (D1), pore water pressure ratio in the ground behind the caisson (P6) and acceleration of shaking table (A3). As shown in the figure, negative pore pressure occurred when the caisson type wall moved toward the sea. On the contrary, as shown in Fig.6, negative pore pressure did not occurred when the sheet pile type wall moved towards the sea. This means the caisson type quay wall moves due to not only the liquefaction-increased earth pressure but also inertia force because the weight of the caisson is heavy, though the sheet pile type wall moves due to the increased earth pressure only. And it seems that these different mechanism of displacement for each wall caused different time histories of displacement as shown in Figs.5 and 6.

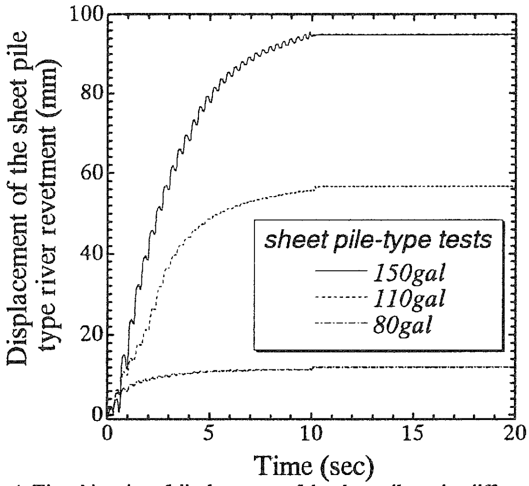


Figure 4. Time histories of displacement of the sheet pile under different intensity of shaking

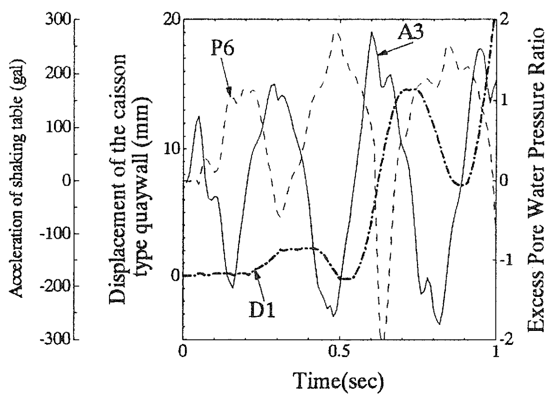


Figure 5. Detailed time histories of pore water pressure and the displacement of the caisson

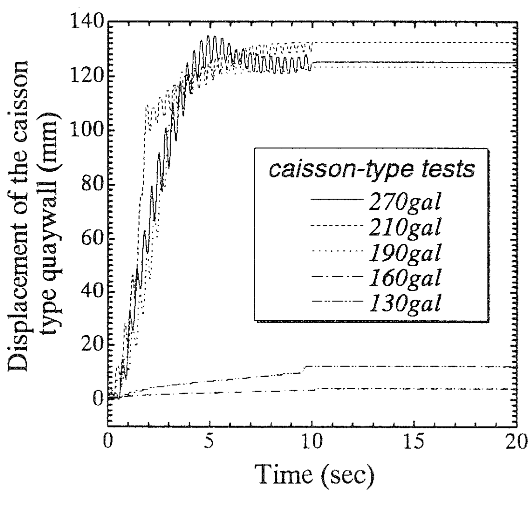


Figure 3. Time histories of displacement of the caisson under different intensity of shaking

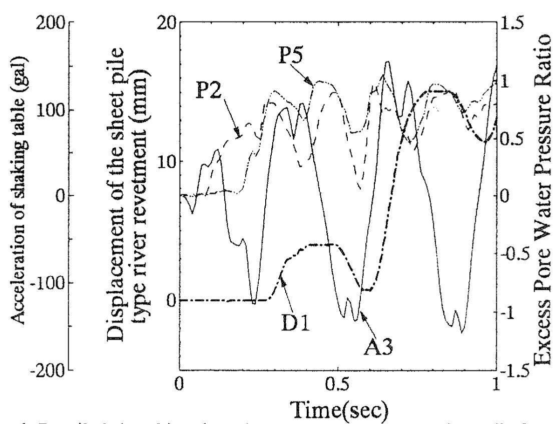


Figure 6. Detailed time histories of pore water pressure and the displacement of the sheet pile

3 SIMPLE ANALYSES FOR THE LIQUEFACTION-INDUCED GROUND FLOW

3.1 *Analytical method*

In the second stage of this study, residual deformation analysis method which was developed by the authors (Yasuda et al. 1999) was applied to the same models to demonstrate the adaptability of the method. In this procedure, the authors assumed that residual deformation would occur in liquefied ground due to the reduction of shear modulus. Figure 7 shows the flow chart of the analytical method. The finite element method was applied twice as follows :

1. In the first step, the deformation of the ground is calculated by the finite element method using the shear modulus before earthquake.
2. The finite element method is applied again by using the decreased shear modulus due to liquefaction.
3. The difference in the deformations measured by the twc analyses is supposed to equal the residual ground deformation.

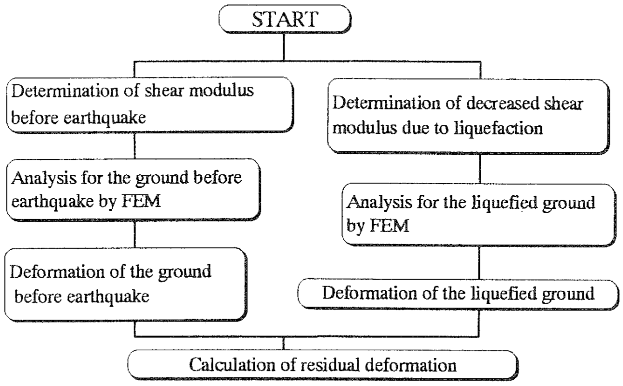


Figure 7. Flow chart of the simplified analysis

3.2 *Determination of input soil data*

Reduction of shear modulus due to liquefaction was evaluated based on cyclic shear tests on Toyoura sand and Masa which was taken in Kobe. Reduction of shear modulus thus evaluated for liquefied Toyoura sand and Masa were about 1/500 and 1/300, respectively (Yasuda et al. 1998). Analyses were carried out also under several different values of reduction of shear modulus.

Reduction of shear modulus of non-liquefied layer which is upper covered the liquefied layer was assumed as 1/10 of the reduction rate of the liquefied soil.

3.3 *Analyzed results*

Figure 8 shows analyzed results for the caisson type quay wall .As shown in these results, the quay wall and the ground behind the wall moved toward the sea and settled. Figure 9 shows distributions of ground displacements behind the wall. Measured displacements of the ground during the Hyogoken-nambu earthquakes is also shown in the figure. By comparing analyzed results and the actual, it can be said that the horizontal displacements analyzed based on the test results were roughly equal to the actual displacements.

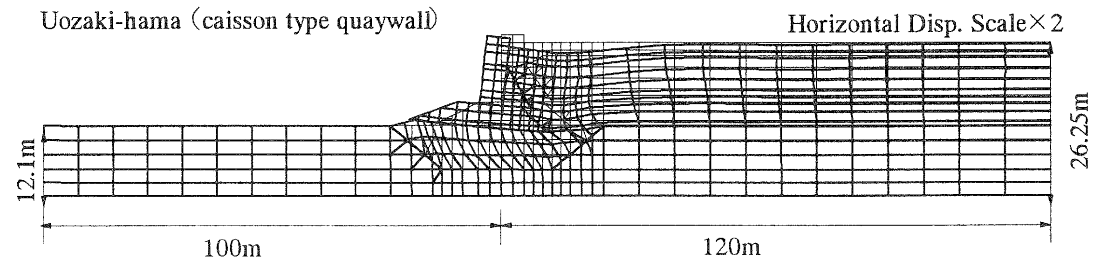
Figure 10 shows analyzed results for the sheet pile type river revetment. As shown in these results, the sheet pile and the ground behind the sheet pile moved toward the sea.

Figure 11 compares distributions of ground displacements behind the wall in different rate of reduction of shear modulus. Measured displacements of the ground during the Niigata earthquake is also shown in the figure. By comparing analyzed results and the actual displacement, it can be said that the horizontal displacements analyzed based on the test results on Toyoura sand were slightly smaller than the actual displacements.

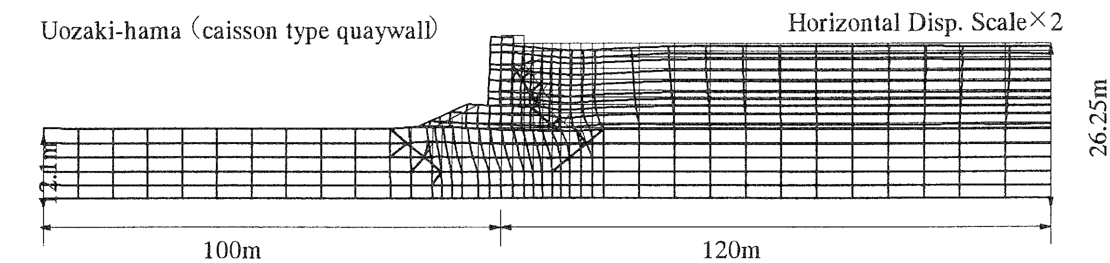
4 CONCLUSIONS

Several shaking table tests and residual deformation analyses were carried out to demonstrate the mechanism of the liquefaction-induced ground flow behind two types of sea walls, and the following conclusions were derived:

1. The caisson type wall moved quickly and the sheet pile type wall tilted gradually after the occurrence of liquefaction in the tests.



(a) G/G_0=1/100(liquefiable layer),G/G_0=1/10(upper layer from G.W.L.),G/G_0=1/100(replaced sand)



(b) G/G_0=1/300(liquefiable layer),G/G_0=1/30(upper layer from G.W.L.),G/G_0=1/30(replaced sand)

Figure 8. Deformation of the ground behind the caisson under two rates of reduction of shear modulus

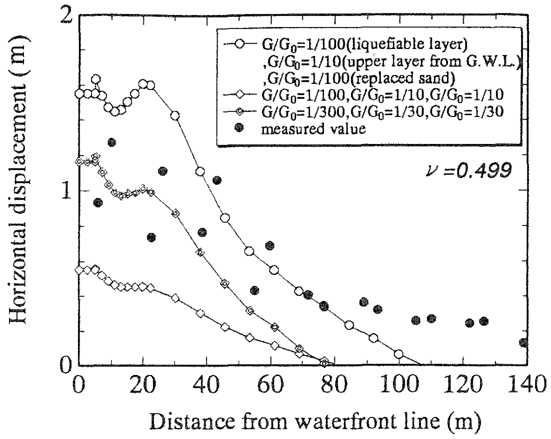


Figure 9. Displacements of the ground behind the caisson under different rates of reduction of shear modulus

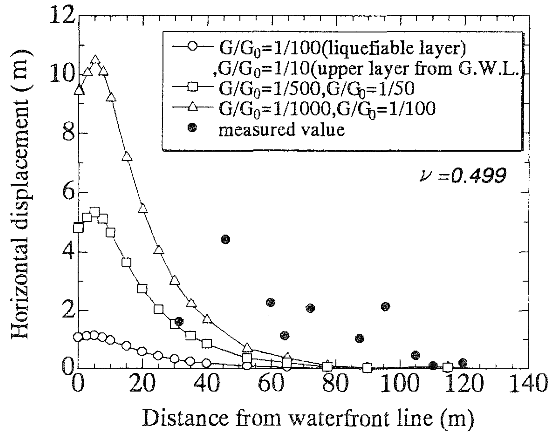
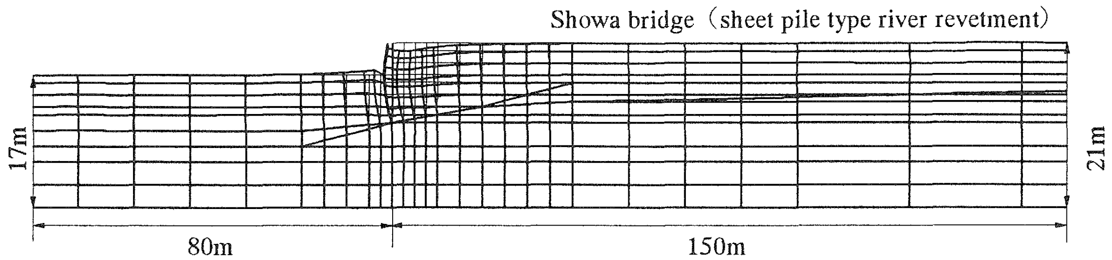
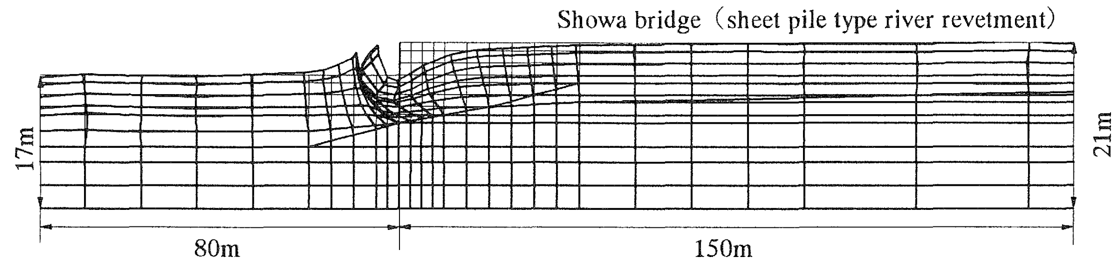


Figure 11. Displacements of the ground behind the sheet pile under different rate of reduction of shear modulus



(a) G/G_0=1/100(liquefiable layer),G/G_0=1/10(upper layer from G.W.L.)



(b) G/G_0=1/500(liquefiable layer),G/G_0=1/50(upper layer from G.W.L.)

Figure 10. Analyzed deformation of the model for the sheet pile type quay wall and the ground

2. A simplified analytical method by considering the reduction of shear modulus due to liquefaction could simulate the displacements of the ground behind walls.

ACKNOWLEDGEMENTS

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