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Shaking table tests on caisson-type quay wall with stabilized mound

Essais à table vibrante sur les murs de quai de type caisson avec butte stabilisée

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ABSTRACT: Caisson-type quay walls were one of the major types of quay walls in Japan. It was desired to increase the front-water depth of them, because vessels coming alongside them become larger and larger. The authors have been studying on a new construction method for the improvement. The method consisted of two steps. Step 1 was to solidify a part of rubble mound beneath a caisson and step 2 was to cut it to increase the front-water depth of the caisson. A series of shaking table tests were conducted to study the seismic behavior of caisson-type quay walls improved by the new method. This paper will introduce the test results and discuss the factors which affected the seismic behavior of the caisson-type quay walls with stabilized mound.

RÉSUMÉ : Les murs de quai de type caisson constituent l'un des types majeurs de murs de quai au Japon. On a désiré augmenter la profondeur frontale face à la mer car les navires venant acccoster le long des quais deviennent de plus en plus gros. Les auteurs ont étudié une nouvelle méthode de construction afin d'apporter des améliorations. Cette méthode est constituée de 2 étapes. La 1ère étape consiste à solidifier une partie de la butte de gravats sous le caisson et la 2ème étape à le découper afin d'augmenter la profondeur frontale du caisson. Une série d'essais à table vibrante a été menée afin d'étudier le comportement sismique des murs de quai de type caisson qui ont été améliorés grâce à cette nouvelle méthode. Cette étude présente les résultats des essais et analyse les facteurs qui affectent le comportement sismique des murs de quai de type caisson avec butte stabilisée.

KEYWORDS: caisson-type quay wall, front-water-depth enlargement, shaking table test

1. INTRODUCTION

In recent years, there has been increasing demand to reduce costs for public works in Japan. Correspondingly, great efforts have been directed toward using and upgrading existing infrastructures efficiently. In this context, the authors have been studying methods for enhancement and improvement of existing port facilities.

Because the caisson-type quay wall (see Figure 1) is one of the major types used in Japan (OCDI 2009), it is desirable that this type quay wall have more front-water depth to better accommodate the larger and larger vessels coming alongside. A method often employed for this improvement is to construct a new pier front onto the caisson quay wall as shown in Figure 2. It is impossible, however, to adopt this method for a caisson quay wall when there is not enough frontal space: thus, a new improvement method applicable to such situations is being developed. In the new method, a rubble mound beneath a caisson is solidified then cut to increase the front-water depth of the caisson as shown in Figure 3.

The authors conducted a series of shaking table tests to study the seismic behavior of caisson-type quay walls improved by the new method.

2. TEST METHOD

A model of a caisson quay wall was built in a sand box whose inside dimensions were 85cm in length, 35.4cm in width and 65cm in height. Figure 4 shows a schematic view of the model. The gravel layer at the bottom of the sand box was part of the box (for drainage). It was compacted sufficiently and it was assumed that the deformation of the gravel layer would not affect test results. A non-woven fabric was put on the surface of the gravel layer for sand prevention. The tests focused on the vibrational property and deformation mode of the quay walls with a stabilized mound; the model ground was dry for simplicity.

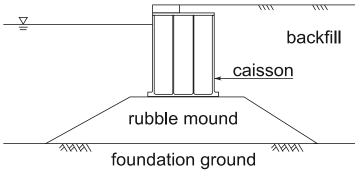


Figure 1. Typical cross-section of the caisson-type quay wall.

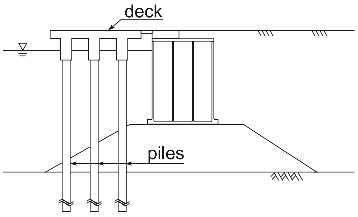


Figure 2. Construction of a new pier to enlarge the front-water depth of the caisson-type quay wall.

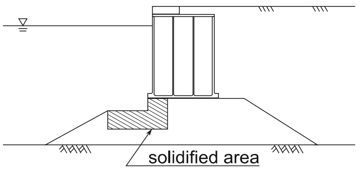


Figure 3. The new method to enlarge the front-water depth of the caisson-type quay wall without change in the face line of the quay wall.

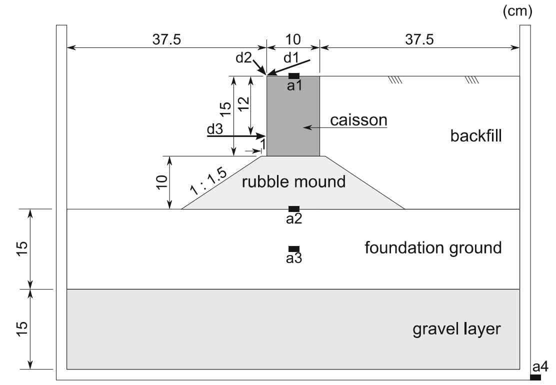
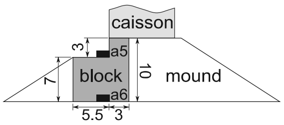
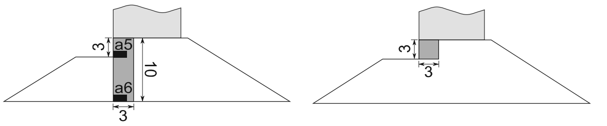


Figure 4. Schematic view of the model ground.



Type 1 Type2



Type 3 Type 4

Figure 5. The blocks used in the tests to simulate solidified area in the rubble mound.

First, foundation ground was made by the air pluviation method with Souma sand #6 (ρ_s = 2.649g/cm^3, ρ_{dmax} = 1.544g/cm^3, ρ_{dmin} = 1.169g/cm^3, D_{60} = 0.161mm). Relative density of the foundation ground was about 60%. A rubble mound was built on the foundation ground by gravel #7 (single-sized crushed stone S-5, JIS A 5001) whose particle size was from 2.5 to 5mm. The gravel was placed into a mound by hand, and was not compacted. Density of the rubble mound was about 1.5g/cm^3. The solidified area in the mound was modeled as a block made of cement paste, and put in the rubble mound. The surface of the rubble mound was covered by gauze to prevent sand particles from dropping into voids within the rubble mound. Then a caisson was located on the mound. The caisson was a wood box in which sand was filled to adjust its weight. Density of the caisson was 0.98g/cm^3. Finally, backfill was prepared in the same way as the foundation ground.

In the series of tests, blocks having the four shapes, shown in Figure 5, were used. Moreover, the model of the quay wall before improvement, a model without any blocks as shown in Figure 4, was tested.

Accelerometers were placed at points a1-a6 shown in Figures 4 and 5. Acceleration of the shaking table was measured at a4 in Figure 4. Displacement of the caisson was measured at d1-d3. The caisson was divided into three parts in the direction of the face line of the quay wall. The face line is perpendicular to the plane of this page in Figure 4. The measurement was conducted at the center of the caisson to eliminate the effect of friction between the caisson and side walls of the sand box. The blocks, which were the models of solidified area, were divided into three parts in the same manner.

The input wave was a sine wave with a frequency of 10Hz and a wavenumber of 50. Direction of the shaking was perpendicular to the face line of the quay wall. The model was tested by the input wave with 100Gal maximum acceleration, and the residual deformation of the model was recorded by digital camera. Next, the amplitude of the input wave was increased to 200Gal maximum acceleration, and the model was tested again. In this manner, the model was tested with the input waves whose maximum acceleration was 100, 200, 300, 500, and 800Gal. Several tests were aborted at 500Gal, because deformation of the models was too large to continue the test procedure.

The objective of the tests was to evaluate the variation of vibrational properties and deformation mode caused by the different shapes of the solidified area. The similarity rule for the model was not considered. The tendency of the vibration and deformation of the models was compared relatively, and derivation of the factor which affected the behavior of the quay wall from the comparison was attempted.

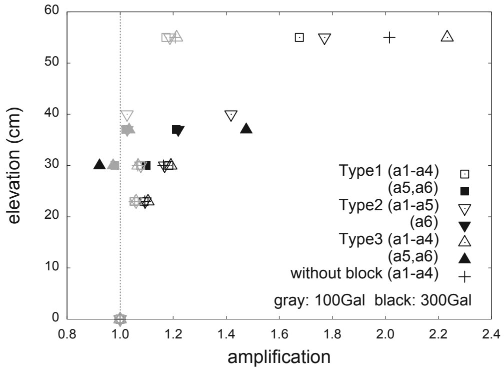


Figure 6. Amplification of acceleration seaward.

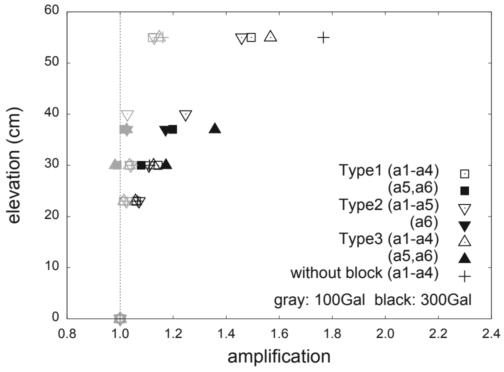


Figure 7. Amplification of acceleration landward.

3. VIBRATIONAL PROPERTY OF QUAY WALL

The vibrational property of the quay wall would be different before and after the improvement. Figures 6 and 7 compare the maximum acceleration amplitude between the models with differently shaped blocks. Figures 6 and 7 also show the amplitude observed in the test of the model without any blocks. Gray marks in the figures show the results observed with the input waves whose maximum acceleration was 100Gal, while black marks show the results with 300Gal. The maximum acceleration amplitudes in figures were calculated as follows: find the maximum acceleration in each cycle of sine waves, calculate the average of the maximum acceleration for the whole of input waves (50 cycles), and divide the average value by the average of the maximum acceleration of a4 (the acceleration of the shaking table, elevation = 0cm). The acceleration time histories were stable for all tests with 100 and 300Gal acceleration, and the maximum acceleration for each cycle remained largely unaltered during the shaking. The calculation was made for each direction; Figure 6 shows the amplitude of acceleration seaward (from the right-hand side to the left in Figure 4) and Figure 7 shows that landward (from left to right in Figure 4). In the case of the tests in which the maximum acceleration of the input wave was larger than 500Gal, large deformation was induced and the accelerometers tilted; the data were not processed because the accuracy of the measurement of acceleration would be less.

For the test results with 100Gal (gray marks in figures), it could be said that the amplification was small and that there was no large difference among the tests. The amplitude of seaward acceleration was slightly larger than that landward.

In the case of the test with 300Gal (black marks in figures), the amplification tendency differed among the test cases. In the case of quay walls with Type 1 and Type 2 blocks, the acceleration amplitudes at the crown of the caisson were smaller than in the test without blocks both seaward and landward; the stability of the caisson was improved by the blocks. In the case of Type 3 blocks, the amplitude seaward was larger than in the test without blocks at the crown of the caisson, while the amplitude landward was smaller. It was remarkable that the amplitude at the head of the Type 3 block (a5) was much larger in both directions.

Figures 8 and 9 show the phase delay of the acceleration observed in the tests. The phase delay was calculated in the same way as acceleration amplitude. Figure 8 and 9 show that there was no large delay in the case of the tests with 100Gal. Large delay was detected in the landward acceleration observed in the tests with 300Gal acceleration as shown in Figure 9. In the tests with Type 1 and Type 2 blocks, the delay was the same as in the test without any blocks. On the other hand, delay of acceleration landward in the case of the test with Type 3 blocks was much larger than in the case without blocks.

One of the causes of the large acceleration amplitude and delay observed in the test with Type 3 blocks could be the instability of the blocks because the shape was vertically long.

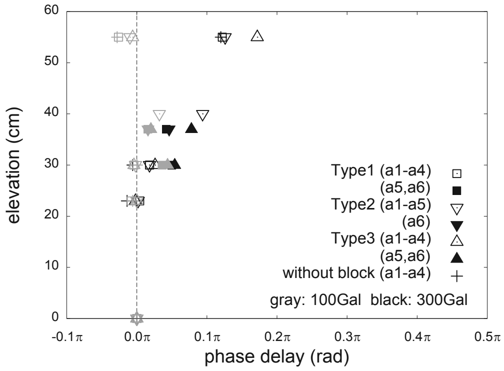


Figure 8. Phase delay of acceleration seaward.

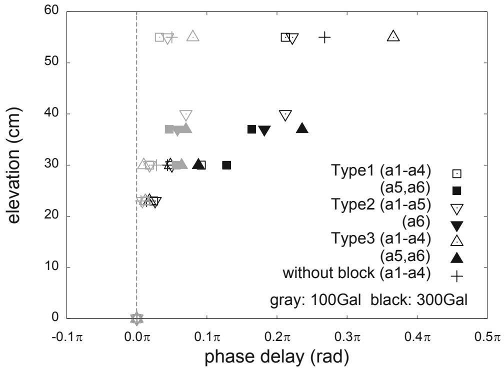


Figure 9. Phase delay of acceleration landward.

4. DISPLACEMENT OF QUAY WALL

The trace of the top-left corner of the caisson in Figure 4 was calculated from displacement measured by d1-d3 for each case. Figure 10 shows the trace observed during the final step of shaking. The maximum acceleration of the input wave for the final shaking was deferent among the tests as mentioned before. Tilt angle of the caissons was also calculated from the data of displacement meter; Figure 11 shows the tilt angle observed during the final step.

Figure 12 shows the deformation of the quay wall models observed after the tests. A few millimeters of settlement of the foundation ground were observed in all cases. Sand dropped into clearance gap between the rubble mound and the sand box; the boundary between the mound and the backfill ground was not clear. Figure 12 shows the boundary in outline.

In the case of the model without blocks, the caisson moved seaward with forward inclining as shown in Figures 11 and 12; the large deformation observed with the input wave whose maximum acceleration was 500Gal and the test was aborted (see Figure 12). The caisson in the test with Type 4 blocks showed similar behavior as in the test without blocks. Thus the improved quay wall with Type 4 blocks was comparable in seismic resistance to the quay wall before improvement in spite of the front-water-depth enlargement. Figure 11 shows the tilting of the caisson with Type 4 blocks smaller than the caisson without blocks. The caisson with Type 4 blocks was displaced with small rotation as shown in Figure 12. It could be said that even small blocks like Type 4 had a certain degree of effect on caisson stability.

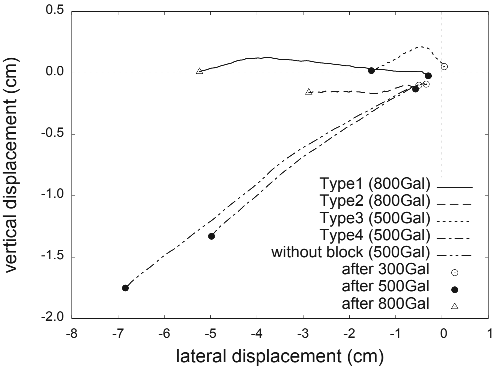


Figure 10. Trace of the top-left corner of the caisson.

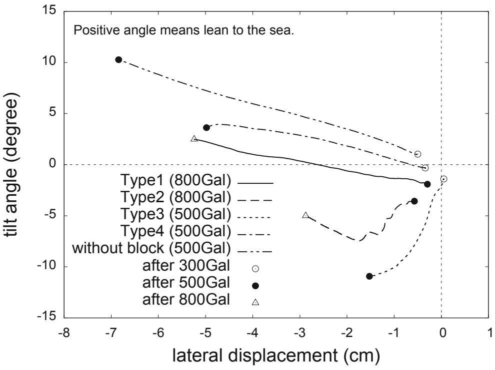
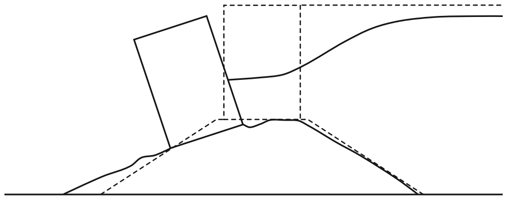
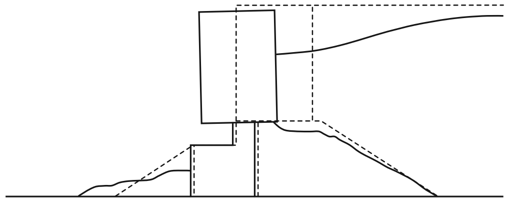


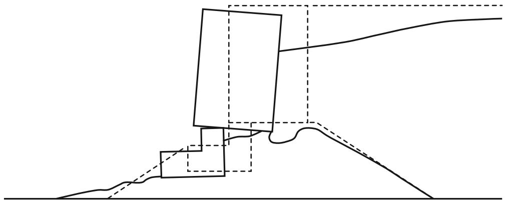
Figure 11. Relationship between tilt angle and lateral displacement of the caisson.



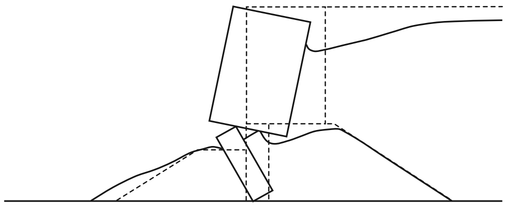
without blocks (500Gal)



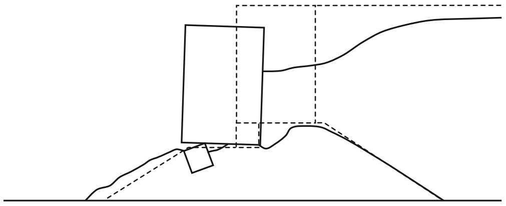
Type 1 (800Gal)



Type 2 (800Gal)



Type 3 (500Gal)



Type 4 (500Gal)

Figure 12. Deformation of the quay wall models after the tests.

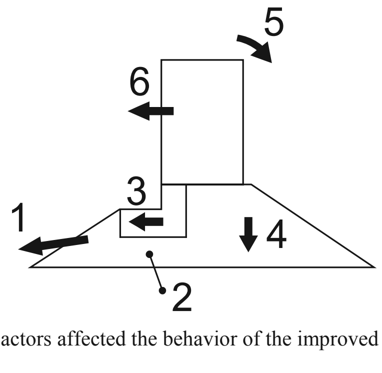


Figure 13. Factors affected the behavior of the improved quay walls.

The caisson with Type 1 blocks had small backward inclining after 500Gal shaking as shown in Figure 11, and was displaced seaward over the block by 800Gal shaking (see Figure 10). After the tests, the tilt angle of the caisson returned to about zero degree. The caisson with Type 2 blocks had backward inclining after 500Gal, the same as the caisson with Type 1 blocks; however, during 800Gal shaking, the blocks moved seaward together with the caisson and the backward inclination of the caisson remained (see Figure 12).

In the case of the model with Type 3 blocks, the blocks leaned seaward, and the caisson had significantly large backward inclining after 500Gal shaking. One of the causes of this result could be the lack of stability of the blocks. The inherent stability of the blocks would be an important factor of the new improvement method.

Based on the final deformation shown in Figure 12 and the results of measurement mentioned above (especially from the observed displacement), it could be said that six factors affected the behavior of the improved quay wall: (1) collapse of foreside slope rubble mound, (2) dimensions of solidified area and ground condition beneath solidified area, (3) displacement of solidified area, (4) settlement of rubble mound and differential settlement between solidified area and rubble mound, (5) leaning of caisson, and (6) displacement of caisson. The numbers correspond to those indicated in Figure 13. These factors correlated strongly with each other, making it was difficult to clarify which was the dominant factor on the behavior of quay walls.

5. CONCLUSION

A series of shaking table tests were conducted to study the seismic behavior of caisson-type quay walls improved by the new method. It was derived from the results of the model tests that six factors affected the behavior of the caisson-type quay walls improved by the new method. Further study will be continued to evaluate the effect of each factor, and the design methodology of the new-type quay walls will be discussed base on the results.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

The Overseas Coastal Area Development Insitute of Japan. 2009. *Technical standards and commentaries for port and harbour facilities in Japan*. OCDI, Tokyo.