EFFECTS OF VERTICAL SEISMIC MOTION ON PERFORMANCE OF CAISSON TYPE QUAY WALLS

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SUMMARY

Many caisson type quay walls were damaged in Kobe Port during the 1995 Hyogoken Nambu earthquake. This earthquake was an inland earthquake and produced the great vertical seismic ground motion. The maximum displacement of the caisson walls was about 5m. Since the caisson walls were greatly damaged as mentioned above, the factors affected the damage to caisson walls were studied. The effects of the vertical seismic ground motion on the movement of the caisson walls were especially investigated. The effect of the horizontal seismic motion and liquefied ground flow in the backfill soil behind caisson walls were also investigated. Shaking table tests were carried out in order to discuss the influence of the vertical ground motion to the caisson walls. The results of tests suggested that not only the horizontal ground motion but also the vertical one significantly affected the increase of movement of the caisson walls.

INTRODUCTION

An inland earthquake usually produced large vertical seismic ground motion. The 1995 Hyogoken Nambu earthquake in Japan was an inland earthquake and caused serious damages to caisson type quay walls in Kobe Port. A lot of places in the port areas showed the traces of liquefaction. It was remarkable that the vertical ground motion of this earthquake was larger than that of the past earthquakes. So, it seemed that the strong vertical ground motion had great influence to performance of caisson walls. The vertical seismic motion acting on the caisson walls was, therefore, focused in this study. Shaking table tests by using the caisson model in a steel container were conducted in order to study the influence of the vertical acceleration.

The authors have conducted the shaking table tests to investigate the influence of the horizontal acceleration and the flow of liquefied backfill soil to the movement of the caisson walls. In these tests, it was clarified the flow of liquefied backfill soil was main cause of movement of the caisson walls [Nakagawa, et.al, 1997]. The inertia force of the horizontal acceleration was also moved the caisson walls and did not act, respectively, in comparison. Especially, when the inertia force of the horizontal acceleration and the flow of the liquefied backfill soil acted on the caisson walls toward the water pool as a sea model, the caisson walls moved greatly toward a sea model [Nakagawa, et.al, 1998].

In this paper, firstly, in order to investigate the influence of the vertical acceleration, the tests were carried out in a condition that the vertical acceleration acted on the caisson walls. Since the horizontal acceleration inputted

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the direction of parallel to the face line of caisson walls at that time, the inertia force of the horizontal acceleration did not act on caisson to move toward the water pool. Comparing these tests, it is investigated how the vertical acceleration influenced to the movement of the caisson walls. Second, the effect of the one wave of great vertical acceleration to the movement of the caisson walls was investigated. Finally, the influence of the phase difference between the vertical and horizontal accelerations to movement of the caisson walls was investigated.

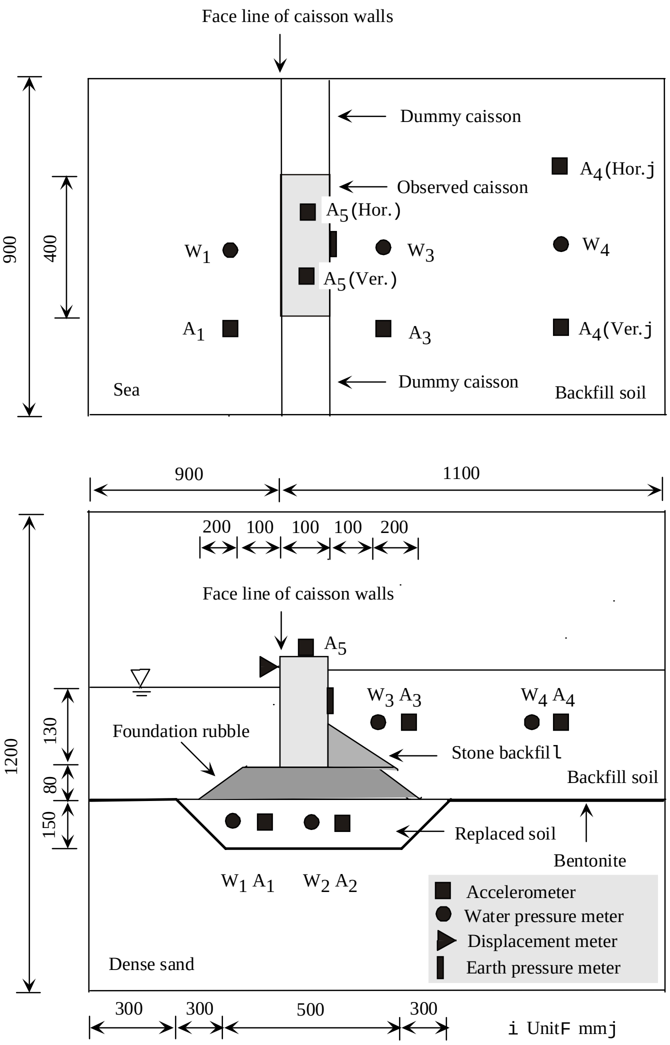

Figure 1: General view of test apparatus

TEST METHOD

The caisson type quay walls shown in Figure 1 were modelled as a scale of 1/50 -caisson walls in the Rokko Island of Kobe City. The caisson wall model was made in a steel container that was 2.0 m in length, 0.9 m in width and 1.9 m in depth on a shaking table. The backfill soil layer and replaced soil layer were made by No. 5 silica sand, and the foundation rubble was gravel. The caisson walls were made of concrete and their gravity was close to those of actual caisson walls. The dense sand layer was densified not to liquefy. The bentonite layer prevented penetration of water into the dense sand layer. The replaced soil layer and the backfill soil layer were saturated, and their relative densities were 0.31.

The inputted acceleration was sinusoidal wave and its frequency was fixed to 3 Hz. The shaking table can move only two directions of one horizontal and vertical directions. Changing the direction of a steel container was needed to shake the caisson model in parallel or perpendicular to the face line of the caisson walls. The open space in front of the caisson walls was filled up with water as a sea model.

Accelerometers were installed on the steel container in order to measure the inputted accelerations in the horizontal and vertical directions. Five accelerometers, which were waterproofed, were embedded in the model ground to measure the response accelerations in horizontal direction. Four water pressure meters were embedded in the model ground to measure the pore water pressure. Further, a laser displacement meter was set in the steel container to measure the displacement of the caisson wall. The limit of measurement of the laser displacement meter was 5 cm. When the movement of the caisson walls was more than 5 cm, the final displacement was measured by a ruler. The pins were put in the surface of backfill soil to measure the amount of the flow of backfill soil at the surface. The thickness of backfill soil was measured before and after shaking to measure the settlement of backfill soil.

INFLUENCE OF VERTICAL ACCELERATION TO CAISSON WALLS

Influence of Magnitude of Vertical Acceleration

In order to clarify the influence of vertical acceleration, the tests were conducted in a condition that a steel container was shaken in the direction of parallel to the face line of the caisson walls. The inertia force of the horizontal acceleration did not act on the caisson walls to move toward the water pool in a steel container in this case. It is considered that the movement of the caisson walls is related to the vertical acceleration and the flow of liquefied backfill soil.

The maximum excess pore water pressure ratios in backfill soil during shaking are shown in Figure 2. This figure indicates that the backfill soil completely liquefied in each case. Since the maximum excess pore water pressure ratio reached about 1.0 in this figure, liquefaction of the backfill soil did not depend on the magnitude of the inputted vertical and horizontal accelerations in these tests. Since the backfill soil was almost liquefied by the inputted horizontal acceleration, the backfill soil was liquefied any more by the inputted vertical acceleration. It could not clear that whether the vertical acceleration influenced to the degree of liquefaction in the backfill soil in these tests. The influence of the vertical acceleration to the liquefaction in backfill soil should be investigated in detail at another occasion.

The horizontal displacements of the caisson walls are shown in Figure 3. The larger the magnitude of the inputted horizontal acceleration was, the greater the horizontal displacement of the caisson walls was. Since the horizontal acceleration did not act on the caisson walls to move toward the water pool, the caisson walls seemed to be moved by the flow of liquefied backfill soil. Therefore, it is considered that the difference in the horizontal displacement of the caisson walls is related to the flow of liquefied backfill soil. Also, there is a difference in the displacement of the caisson walls by the magnitude of the inputted vertical acceleration. So, the caisson walls were moved by the inertia force of the vertical acceleration and by the flow of the liquefied backfill soil.

In order to clarify the influences of the inertia force of the vertical motion and the flow of backfill soil to movement of the caisson walls, the time history of the earth pressure of the backfill soil acting on the caisson walls and the vertical acceleration were investigated. The time histories of them are shown in Figure 4. It was found from this figure that the wave forms of the earth pressure, the inputted acceleration and the displacement of the caisson walls were similar each other. When the value of the inputted horizontal and vertical accelerations increased, the value of the earth pressure also increased in this figure. Therefore, when the liquefied backfill soil pushed the caisson walls toward the water pool, the inputted vertical acceleration acted on the caisson walls in the upper direction. This means that, the inertia force of the vertical acceleration acted on the caisson walls to

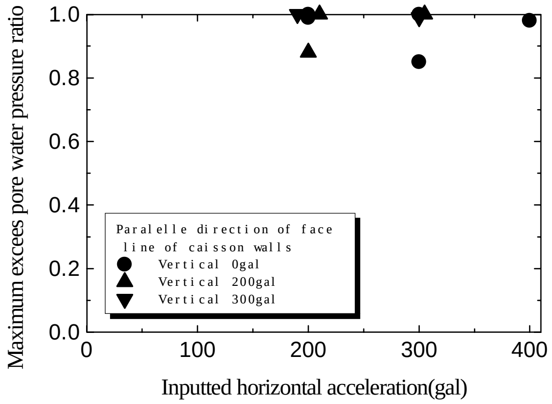

Figure 2: Maximum excess pore water pressure ratio of backfill soil

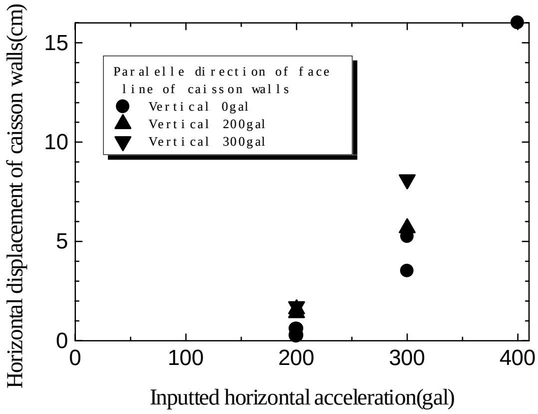

Figure 3: Horizontal displacement of caisson walls

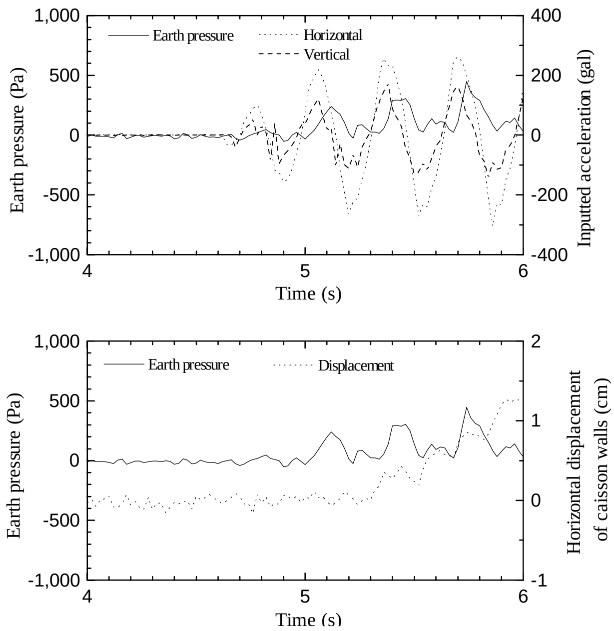

Figure 4: Time histories of earth pressure, inputted accelerations and displacement of caisson walls

decrease the weight of the caisson walls. Therefore, it seems to be reason why the displacement of the caisson walls in case of horizontal and vertical shaking was larger than that in case of only the horizontal shaking. It is clarified that the vertical seismic motion greatly influenced the movement of the caisson walls through these tests.

Next, in order to investigate the influence of the vertical acceleration to movement of caisson walls remarkably, only one wave of the vertical acceleration was inputted to the model when the horizontal acceleration was inputted for 5 seconds. The inputted horizontal acceleration was 250 gal and its frequency was fixed to 3 Hz in this case.

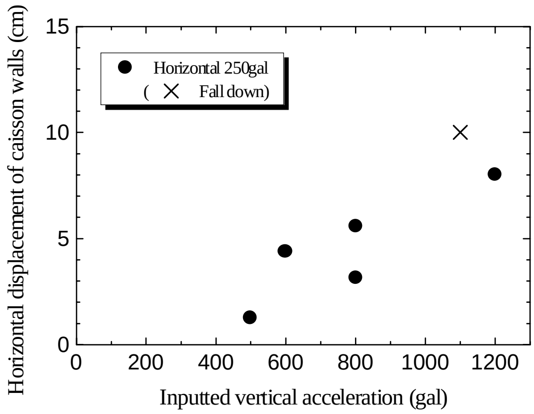

Figure 5: Relationship between inputted vertical acceleration and displacement of caisson walls

Figure 5 shows the relationship between the inputted vertical acceleration and the horizontal displacement of the caisson walls. The displacement of the caisson walls moved about 5 cm in case of 600 gal of the vertical acceleration. This value of the displacement was equal to the case of the 300 gal only horizontal acceleration in Figure 3. It is found that the caisson walls can move largely when the large vertical acceleration was inputted at only one wave.

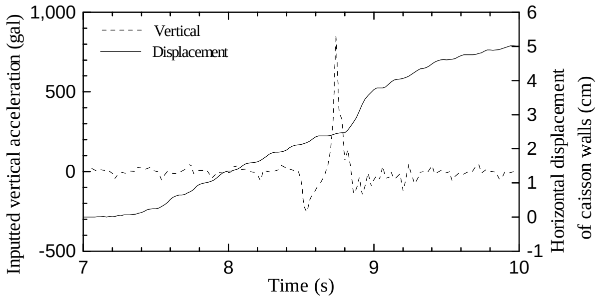

Figure 6: Time histories of inputted vertical acceleration and displacement of caisson walls

Figure 6 shows the time histories of the inputted vertical acceleration and the displacement of the caisson walls. It is found that the caisson walls were gradually moved by the flow of liquefied backfill soil. The flow was occurred by the inputted horizontal acceleration before the vertical acceleration was inputted. The caisson walls were suddenly moved about 1 cm when the one wave of 800 gal acceleration was vertically inputted. This phenomenon is explained as follows. The plus of the vertical acceleration means movement of the steel container downward in Figure 6. When the inertia force by the vertical acceleration acts on the caisson walls, the weight of the caisson walls becomes lighter than the actual weight of caisson walls. Since the flow of the liquefied backfill soil pushes the lighter caisson walls, the displacement of the caisson walls was larger at that time.

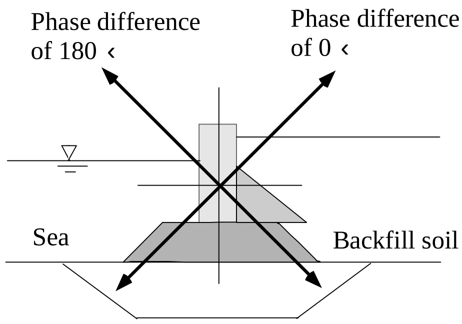

Figure 7: Composite directions of inputted vertical and horizontal motions

Influence of Phase Difference between Vertical and Horizontal Acceleration

The effects of phase difference between the inputted horizontal and vertical accelerations on the movement of the caisson walls were studied. Shaking table tests were carried out in two cases in Figure 7. One was that when the inertia force of the vertical acceleration acted on the caisson walls, the horizontal acceleration acted toward the water pool. The other was that when the vertical acceleration acted on the caisson walls, the inertia force of the horizontal acceleration act toward the backfill soil. The difference in the amount of the horizontal displacement of the caisson walls was investigated in both cases.

Firstly, the tests were carried out to investigate the influence of the phase difference on the movement of the caisson walls remarkably. In this test, backfill soil behind caisson walls was densified, and not saturated. The backfill soil, therefore, did not liquefy in this case. So, the displacement of the caisson walls was not affected by the flow of liquefied backfill soil in this case but only by the inertia force. The horizontal acceleration was inputted in the perpendicular direction to the face line of caisson walls in this case.

The results of these tests are shown in Figure 8. This figure indicates the relationship between the phase difference and the displacement of the caisson walls. In this figure, the displacement of the caisson walls at the phase difference of 180° was larger than that at no phase difference. So, it suggests that the phase difference influenced the displacement of the caisson walls.

Next, in order to investigate the influence of the liquefied ground flow, the tests were carried out in the case that backfill soil were saturated and were liquefiable. Figure 9 shows the maximum excess pore water pressure ratio in the backfill soil. The maximum excess pore water pressure ratios were close to 1.0 in each case. Backfill soil completely liquefied in these tests.

Figure 10 shows the relationship between the phase difference and the displacement of the caisson walls. Although Figure 8 indicated only the influence of phase difference to the movement of the caisson walls, the displacement of the caisson walls was influenced by both the flow and the phase difference in Figure 10. The displacement of the caisson walls in the phase difference of 180° was larger than the that of the caisson walls in the no phase difference. In these tests, it is found that the phase difference well influenced on the displacement of the caisson walls. Comparing Figure 10 with Figure 8, the displacement of the caisson walls became larger on the whole in Figure10. The difference in the displacements between Figure 10 and Figure 8 was influenced by the liquefied ground flow.

In case of the phase difference of 180°, when the vertical acceleration was inputted in the upper direction to the caisson walls, the inertia force worked on the caisson walls to decrease the weight of the caisson walls than the actual weight. The horizontal acceleration was also inputted in the direction of moving the caisson walls toward the water pool. Conversely, in the case of phase difference of 0°, when the vertical acceleration was inputted in the upper direction

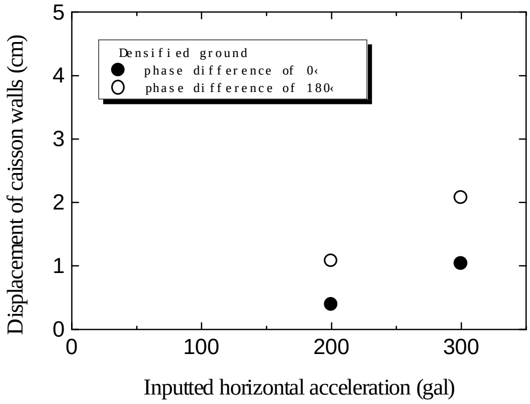

Figure 8: Relationship between phase difference and displacement of caisson walls at densified ground

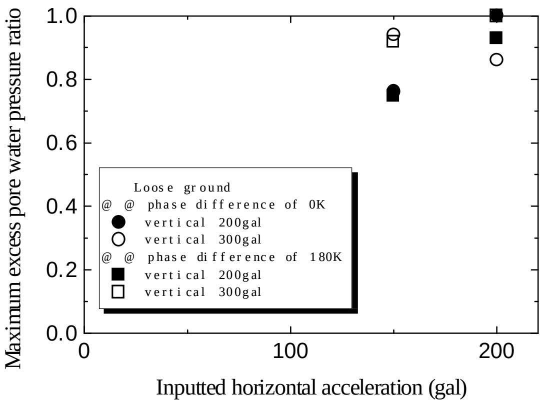

Figure 9: Maximum excess pore water pressure ratio of the backfill soil

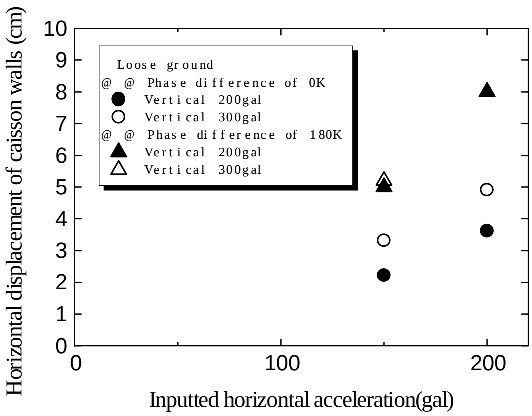

Figure 10: Relationship between phase difference and displacement of the caisson walls at loose ground

to the caisson walls, the inertia force worked on the caisson walls to increase the weight of the caisson walls than the actual weight. The horizontal acceleration was also inputted in the direction of moving the caisson walls toward backfill soil. So, the horizontal displacement of the caisson walls was smaller than that in the phase difference of 180°. It is conceivable that the vertical acceleration especially influenced to the horizontal displacement of the caisson walls, when the inertia force of the vertical acceleration acted on the caisson walls to decrease the weight of caisson walls than the actual weight.

CONCLUSIONS

In this paper, the effects of the vertical acceleration to the movement of the caisson walls were investigated through shaking table tests. Firstly, the tests, which the vertical acceleration inputted the caisson walls model with the horizontal acceleration, were conducted. As the inertia force of the horizontal acceleration did not act on caisson to move toward the water pool in this case, it was investigated how the vertical acceleration influenced to the caisson walls. Second, one wave of great vertical acceleration was inputted to the caisson walls with the horizontal acceleration. The effect of one wave of great vertical acceleration to the movement of the caisson walls was investigated. Finally, the influence of the phase difference between the vertical and horizontal accelerations to the movement of the caisson walls was investigated. The conclusions can be drawn from these studies are as follows.

(1) In case that the vertical acceleration was not inputted and only the horizontal acceleration was inputted the caisson walls model, the caisson walls moved by the liquefied ground flow of backfill soil. Test results were indicated that the flow of liquefied backfill soil was one of the important factors influenced to the movement of caisson walls.

(2) The tests were conducted in case that the vertical acceleration was inputted to caisson walls with the horizontal acceleration. These test results were indicated that the caisson walls moved by the inertia force of the vertical acceleration and by the flow. Especially, when the inertia force of the vertical acceleration acted on the caisson walls in upper direction, the flow of liquefied backfill soil pushed the caisson walls toward the sea at that time, the caisson walls moved largely.

(3) One wave of the great vertical acceleration was inputted to caisson walls with the horizontal acceleration. The caisson walls moved greatly by the great vertical acceleration. So, it was clarified that the great vertical motion could move largely the caisson walls when the great inertia force acted on caisson walls in upper direction. Since an inland earthquake sometimes produces the great vertical seismic motion, it is suggested that the caisson walls may move greatly by the great vertical acceleration in an inland earthquake.

(4) Effects of the phase difference between the horizontal and vertical acceleration on the movement of the caisson walls were investigated. When the inertia force of the horizontal acceleration acted on the caisson walls toward the sea and the inertia force of the vertical acceleration acted on caisson walls in upper direction, the caisson walls moved largely toward the sea. It is conceivable that the phase difference influenced greatly to the movement of the caisson walls.

REFERENCES

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