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Shaking table tests for hydrodynamic pressure acting on double cylindrical caisson type breakwater in deep sea

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ABSTRACT: Shaking table tests were conducted to examine characteristics of hydrodynamic pressure acting on a double cylindrical caisson which is developed for a breakwater in deep sea. The caisson is composed of a permeable outer cylinder, whose upper part has many openings, and an impermeable inner cylinder. The experiments were conducted under single caisson condition and under multiple caissons condition with different opening sizes in each condition. The test's results showed that the resultant force of hydrodynamic pressure on the multiple caissons without openings was nearly equal to the value from Westergaard's formula for the wall whose width was the same as the diameter of the outer cylinder. On the other hand, the resultant force of hydrodynamic pressure on the model with openings decreased with increase of the opening ratio.

1 INTRODUCTION

As offshore and waterfront development is advanced in recent years, many large structures have been constructed in deep sea area for port and airport facilities. Among these structures, breakwaters are constructed on deeper seabed ground. Therefore it becomes necessary to develop design technique of deep sea breakwaters. A composite type of breakwater, that consists of a rubble mound and concrete caissons, is constructed in several cases in Japan. To reduce the cost of the rubble mound of deep sea breakwater, it has an advantage to develop a large size caisson. The double cylindrical caisson discussed in this study is one of them. The caisson shown Figure 1 is composed of a permeable outer cylinder whose upper part has many openings and an impermeable inner cylinder. Wave that permeates through the outer cylinder is dissipated in the wave chamber that is formed in between outer and inner cylinders.

Generally a main design force for a breakwater is wave force. The hydrodynamic pressure during earthquake is an additional major external force for design of the deep sea breakwater. In the current design standard of port and harbour facilities, the hydrodynamic pressure is given by the Westergaard's formula for a vertical wall, and is given by Zangar's formula for an inclined wall. But characteristics of hydrodynamic pressure on a cylindrical caisson with openings have not been studied in the past, and consequentially there is no description about this pressure in the current design standard. The shaking table tests were conducted to make clear the characteristics of hydrodynamic pressure on the double cylindrical caisson.

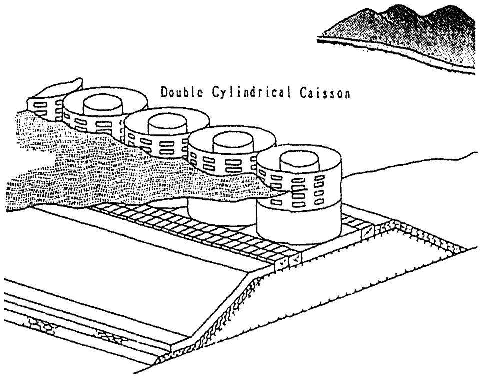


Figure 1. Outline of double cylindrical caisson type breakwater

2 MODEL TESTS

2.1 Model

Model caissons for the shaking table tests were made of acrylic boards. We used a instrumented model and two dummy models as shown in Figure 2. The size of the models was 50cm in height and 50cm in diameter. The diameter of the inner cylinder is 30cm.

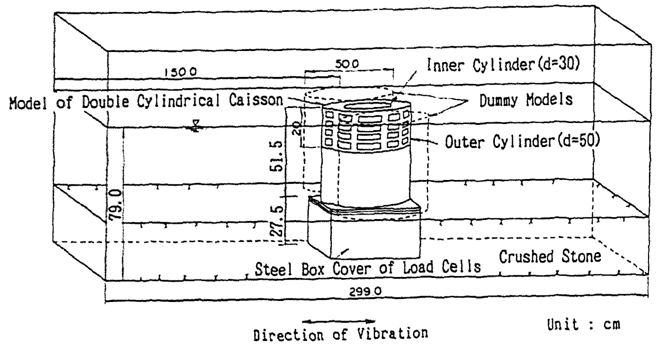
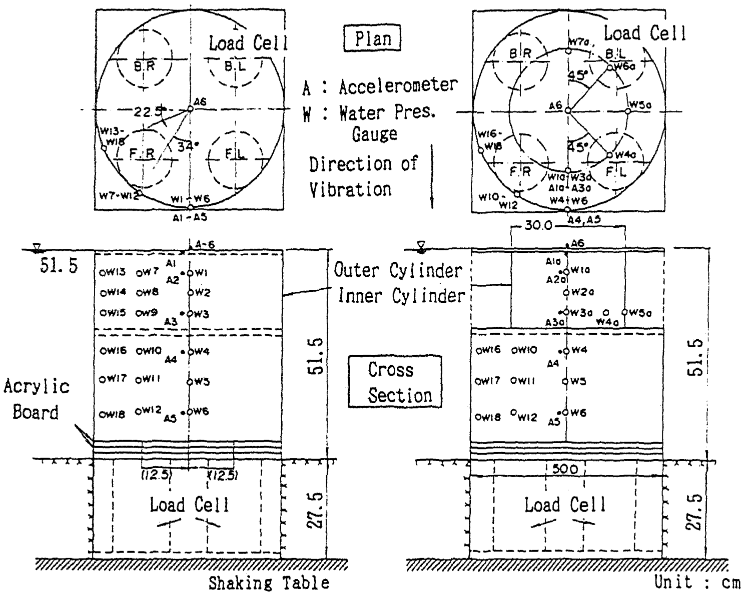


Figure 2. Model of double cylindrical caisson



(a)without opening (b)with openings

Figure 3. Locations of instruments

Many openings were made around the outer cylinder evenly at upper 20cm of the model. The opening ratio, which is defined as the ratio of the total area of openings to the area of that part, was varied with 0,10,25 and 100%. The opening ratio of 0% means that there are no openings on the outer cylinder and the opening ratio of 100% means that there is no outer cylinder at that part. These models with evenly distributed openings around the cylinder were called as a permeable type. Additionally, the model that had a permeable half circle in front of the cylinder and an impermeable half circle in the rear side was made and called as a wave dissipating type. Therefore we used four permeable type models (opening ratio: 0, 10, 25, 100%) and three wave dissipating type models (opening ratio: 10, 25, 100%).

2.2 Instrumentation

The hydrodynamic pressures were measured by water pressure gauges that were placed on the surface of the model. Distribution and resultant force of the hydrodynamic pressure on the model without openings were calculated based on these measurements. However in the case with openings, it is impossible to measure the hydrodynamic pressure on opening. Therefore the resultant force of the hydrodynamic pressure was measured by four load cells that were placed underneath the model.

Figure 3(a) shows locations of instruments in the case without opening. The water pressure gauges were deployed in six rows and in three columns on a quarter area of the outer cylinder. These gauges were located at 0, 34 and 67.5 degrees from the direction of vibration. Figure 3(b) shows locations of instruments on the model with openings. Seven water pressure gauges were used to measure distribution of the hydrodynamic pressure on the inner cylinder. Positions of the water pressure gauges were placed on the lower part of the outer cylinder were the same to those of the case without opening.

2.3 Test conditions

The following cases of model tests were performed;

(1) In case without opening
  a) Single caisson condition
  b) Multiple caissons condition
  c) Spaced multiple caissons condition
    (Spacing between models: 0.5, 4.0cm)
(2) In case with openings
  a) Single caisson condition
    (opening ratio: 10, 25, 100%)
  b) Multiple caissons condition
    (opening ratio: 10, 25, 100%)

A container(3 x 1.5 x 1.2 m) was placed on the shaking table in the model tests. The tests of single caisson condition mean that only the instrumented model was placed in the container, while the tests of multiple caissons condition mean that two dummy models were placed in contact with the instrumented model. The tests of the spaced multiple caissons condition were only conducted using model without opening. In those cases, the dummy models were equally spaced from the instrumented model, and then relations between the characteristic of hydrodynamic pressure and the spacing were examined.

The location of the models is shown Figure 2. The load cells set in a steel box was placed under instrumented model. Crushed stones were poured around the steel box so that the level of the bottom of the model was the same to that of the surface of the crushed stone.

Besides the tests described above, the model tests in which the models were directly fixed on the bottom of the container were conducted to remove the effects of the load cells and the crushed stones.

Input motion used for the experiments was 10 cycles of sinusoidal wave form with 5Hz. Maximum accelerations of the input motion were 50, 100 and 200Gal.

Table 1 shows the summary of the test conditions mentioned above.

Table 1. Summary of tests

Set up of models	Single caisson condition Multiple caisson condition Spaced multiple caisson condition (Spacing between models: 0.5,4.0cm)
Opening ratio	0 , 10 , 25 , 100 %
Type of caisson	Permeable , Wave dissipating
Measuring item	Hydrodynamic pres. , Acceleration
Input motion	Sinusoidal motion (5Hz, 10waves)
Max. acceleration	50 , 100 , 200 Gal

3 RESULT OF MODEL TEST

3.1 Distributions of hydrodynamic pressure

Distributions of the hydrodynamic pressure on the model, which was fixed on the bottom of the container, are described here. The model was shaken as a rigid body so that the mean value of accelerations measured at each accelerometer was used here as the response acceleration of the model. A ratio of this response acceleration to the gravity acceleration was named as the seismic intensity (called as k). Since the relation between the hydrodynamic pressure (p) and k was nearly liner, we used a mean value of p/k for the following discussion.

(1) without opening

Figure 4 shows horizontal distributions of the hydrodynamic pressure on the model at 33cm below the water level. Though the hydrodynamic pressure becomes small with increase of the angle from the direction of vibration in the single caisson condition,

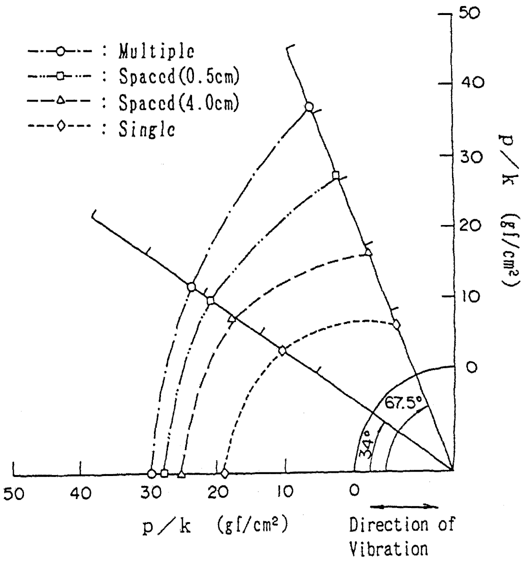


Figure 4. Circular distributions of hydrodynamic pressure (33cm depth)

that pressure becomes large in the multiple caissons condition. The hydrodynamic pressures measured in the spaced multiple caissons condition are between them. These facts suggest that a little spacing between models decreases the hydrodynamic pressure that concentrates near the contact points of cylinders in the multiple caissons condition.

Figure 5 shows vertical distributions of the resultant force of the hydrodynamic pressure on the model, that were approximately calculated using the horizontal distributions at each level. Distributions obtained from a FEM program, the Goto&Toki's formula and the Westergaard's formula are also shown in this figure. This FEM program is able to analyze three dimensional water-structure interaction during vibration, and the Goto&Toki's formula gives the hydrodynamic pressure on a single cylinder. The distribution of the Westergaard's formula that is obtained for the wall whose width is the same as the diameter of the outer cylinder agrees with the distribution in the case of the multiple caissons condition. Therefore it is considered that the resultant force of the hydrodynamic pressure on the multiple caissons can be obtained by the Westergaard's formula.

Since the results of FEM were in good agreement with those of the model tests as shown in Figure 5, relations between the resultant force and spacing between models were investigated using an analytical method of the FEM program. Figure 6 shows the results. The vertical axis shows the ratio of the resultant force of the spaced multiple caissons condition to that of the multiple caissons condition. The resultant force ratio of the spaced multiple caissons condition with 4.0cm spacing, which is equal to 8% of the water depth, is about 0.7. As described earlier, this result suggests that the hydrodynamic pressure is strongly decreased with a small increase of spacing between caissons.

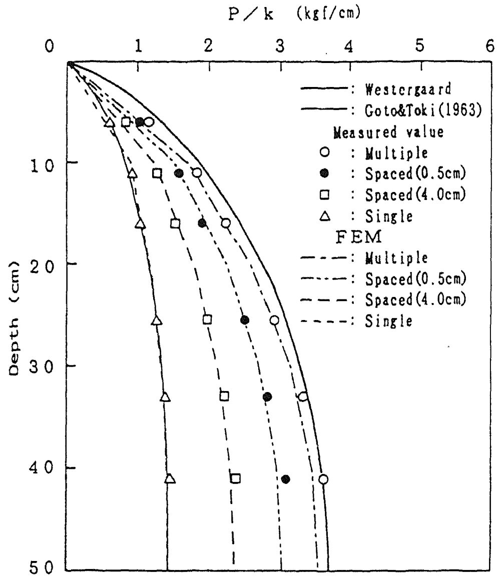


Figure 5. Vertical distributions of hydrodynamic pressure

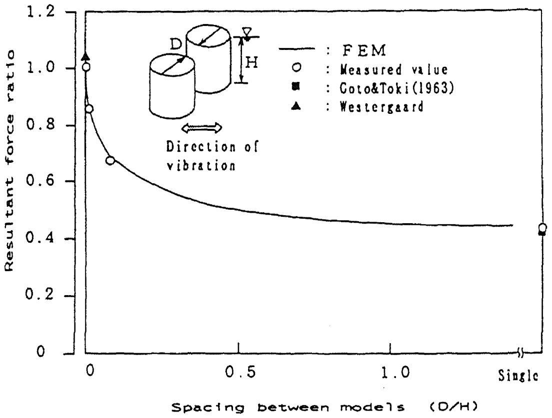


Figure 6. Resultant force ratio with spacing between models

(2) with openings

Figure 7 shows vertical distributions of hydrodynamic pressure in the multiple caissons condition with openings. The values above 20.0cm depth were measured by the water pressure gauges on the inner cylinder. Though the hydrodynamic pressures measured at W1a-W3a of the inner cylinder increase with increase of the opening ratio, the pressures at W4-W6 of the outer cylinder decrease. In particular, the values at W4 considerably decrease. The hydrodynamic pressure on the upper part of the outer cylinder is decreased with increase of permeability. According to this effect, it seems that the hydrodynamic pressure on the lower part of the outer cylinder was decreased. On the other hand, the hydrodynamic pressure on the inner cylinder increases with increase of the permeability. In the case of the wave dissipating type, though the differences between the hydrodynamic pressures of each opening ratio are small as compare with those of the permeable type, similar characteristics of the hydrodynamic pressure on the cylinder were obtained.

Figure 8 shows the comparison of the distributions of hydrodynamic pressure between the permeable type and the wave dissipating type. Though the hydrodynamic pressure in the wave dissipating type is larger than that in the permeable type as expected, the differences at W4-W6 are very

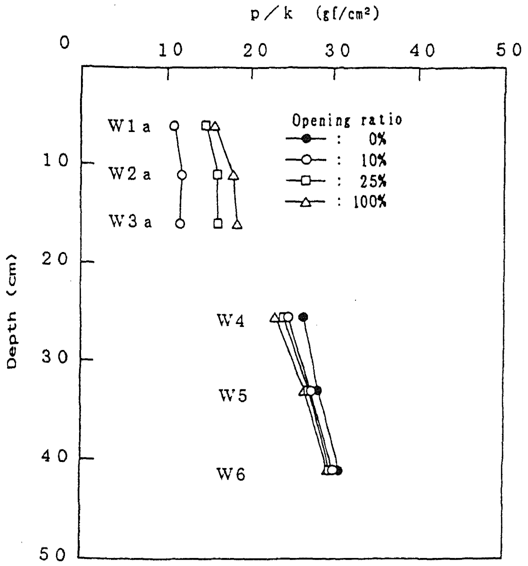


Figure 7. Vertical distributions of hydrodynamic pressure (multiple caissons condition with openings)

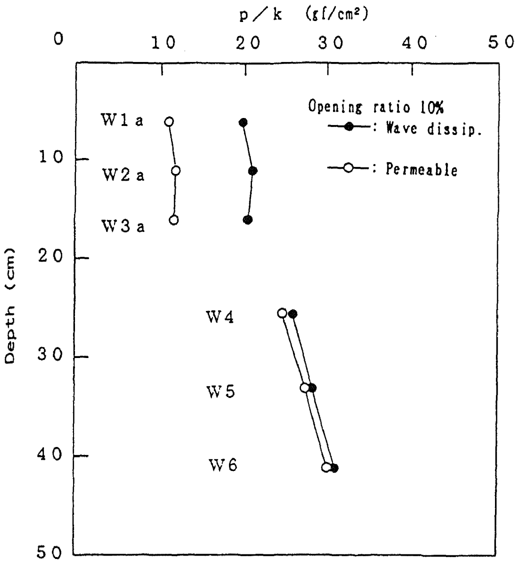


Figure 8. Hydrodynamic pressure of permeable and wave dissipating type(10% opening)

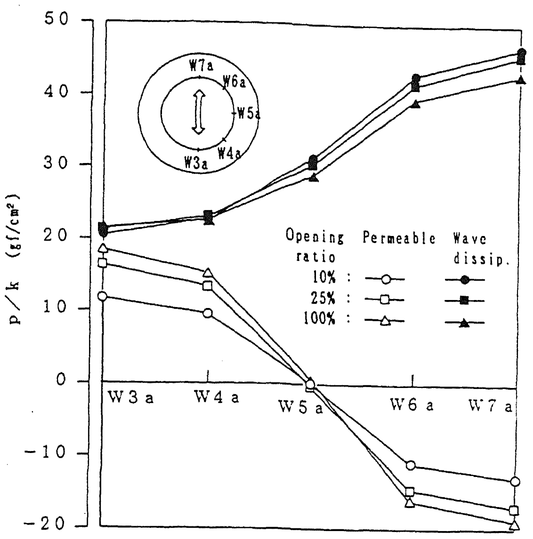


Figure 9. Horizontal distributions of hydrodynamic pressure on inner cylinder

small. These characteristics in the multiple caissons condition as described above were observed similarly in the single caisson condition.

Figure 9 shows horizontal distributions of the hydrodynamic pressure on the inner cylinder in the case of the permeable type and of the wave dissipating type. In the case of the permeable type, values at W4a and W6a, and at W3a and W7a are symmetrical about the value at W5a, respectively. Absolute values of each water pressure gauge increase with increase of the opening ratio. In the case of the wave dissipating type, however, signs of the hydrodynamic pressures are the same at each point and the absolute values of them increase as increase of the direction angle. Also the hydrodynamic pressures measured at W5a, W6a and W7a increase with decrease of the opening ratio. In the single caisson condition, though the hydrodynamic pressure was smaller than that in the multiple caissons condition, the same results mentioned above were also obtained.

3.2 Relation between resultant force and opening ratio

Besides the hydrodynamic pressure, measured values of load cells contained inertial forces of the model, load cells and water inside the model. Therefore the model was shaken without water and with water in the experiments. The resultant force of the hydrodynamic pressure was then obtained by removing the measured value without water and inertial force of water inside the model from measured value with water. At this time, the inertial force of the water inside the wave chamber was not removed in the case without opening to compare with the results in the case with openings.

Figure 10 shows relations of the resultant forces of the hydrodynamic pressure and the opening ratio. The vertical axis shows the ratio of resultant force in the case with openings to that in the case

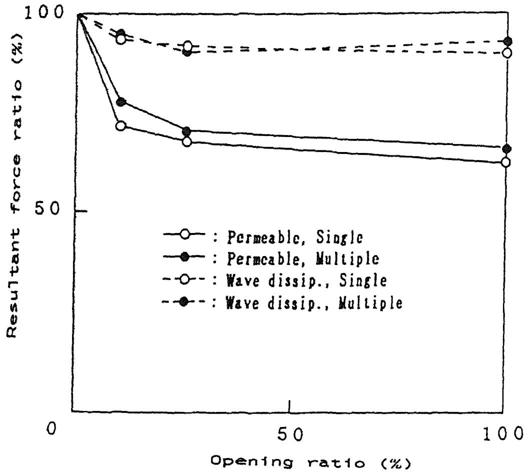


Figure 10. Relation between resultant force ratio and opening ratio

without opening. The ratio of resultant force with 10% opening is 72%, and that with 100% opening is 62% in the case of the permeable type of single caisson condition. As similar to these results, the ratio of resultant force with 10% opening is 78%, and that with 100% opening is 66% in the case of the permeable type of multiple caissons condition. Thus the openings on the outer cylinder are able to decrease the hydrodynamic pressure even though the opening ratio is very small. On the other hand, the ratio of resultant force in the case of the wave dissipating type shows little decrease with increase of the opening ratio.

4 CONCLUSION

Shaking table tests were conducted to examine characteristics of the hydrodynamic pressure acting on the double cylindrical caisson. The following conclusions were obtained.

1. The resultant force of hydrodynamic pressure on the multiple caissons condition was nearly equal to the value of the Westergaard's formula for the wall whose width is the same as the diameter of the cylinder.
2. The hydrodynamic pressure on the multiple caissons concentrates near the contact points of cylinders. This pressure concentration is relaxed by a little spacing between them.
3. In the case of the permeable type, the hydrodynamic pressure on the lower part of the outer cylinder decreases with increase of the opening ratio. In particular, the pressure near the openings considerably decreases. In contrast with this, the hydrodynamic pressure on the inner cylinder increases with increase of the opening ratio. These characteristics were also observed in the case of the wave dissipating type.
4. In the case of the wave dissipating type, the sign of the hydrodynamic pressures around the inner cylinder is same and the absolute values of those increase with increase of the angle from the direction of vibration.
5. The resultant force of hydrodynamic pressure on the model considerably decreases with increase of the opening ratio in the permeable type. In the wave dissipating type, however, the ratio of resultant force on the model to that on the model without opening is above 0.9.

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