Subgrade reaction force of composite-type breakwater reinforced by embankment

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ABSTRACT

The subgrade reaction to a caisson reinforced by embankment was investigated by using centrifuge model tests. An embankment reduced the edge pressure on a caisson. The reaction force from a reinforcing embankment contributes to reducing the edge pressure. In addition, the model test results were compared with those of a simplified calculation model. The calculated subgrade reaction was found to be close to those in the model tests.

Keywords: breakwater; subgrade reaction; reinforcing embankment; centrifuge model test

1 INTRODUCTION

The tsunami caused by the 2011 Great East Japan Earthquake damaged many infrastructures, including port facilities. Caisson-type composite breakwaters, which are the most commonly used type in Japan, were also destroyed by the tsunami. To enforce the resistance of breakwaters, the method of piling up stones behind concrete caissons is considered to be effective. Model tests and numerical analyses conducted by Takahashi et al. (2015) showed that the embankment produced by stones reinforced the sliding resistance of caissons and bearing capacity of mounds. Takahashi et al. (2015) and Sato et al. (2017) also proposed an assessment method to evaluate the amount of reinforcement. However, the subgrade reaction force from a mound to a caisson reinforced by an embankment has not been studied, and the edge pressure at the corner of a caisson is also not clear. Large edge pressure might destroy the corner of a caisson and the stones of a mound, so it is important to understand the edge pressure.

In this study, model tests were conducted to examine the subgrade reaction at a caisson reinforced by an embankment. A model test is applicable to study the subgrade reaction because it is easier to model complicated granular material than perform numerical analyses. A centrifuge technique, which could reproduce prototype-scale stress and strain, was applied to the model tests. In addition, model test results were compared with those of a simplified calculation model for the design of breakwaters.

2 CENTRIFUGE MODEL TESTS

2.1 Test conditions

To measure a subgrade reaction force, a model caisson included load cells, dividing the base plate into three parts (see Figure 1). The load cell was a bidirectional indicator, which was able to measure a horizontal force as well as a vertical one. Acquiring horizontal forces on the bottom made it possible to understand the sharing ratio of the bottom friction and reaction force from a reinforcing embankment. Roughness with a width of 5 mm and a depth of 3 mm was adopted at 10-mm intervals to increase the friction between a caisson and mound, modelling the friction of real objects. The friction coefficient for a model caisson was approximately 0.65–0.85. Figure 2 shows the schematic view of a model. The bearing stratum and a mound were manufactured by fine silica sand and 6.0–15.5-mm crushed stones, respectively. The bearing stratum was sufficiently stiff because of its high density, and the deformation of the bearing stratum can be ignored. A mound was produced with soft tapping, and the relative density was 81–82%. The submerged unit weight was 9.8 kN/m^3. The surface of the mound was carefully levelled to avoid the concentration of the subgrade reaction on the bump. A membrane sheet coated with grease was put on the side walls of a specimen container. This is because the membrane sheet makes it possible to reduce the friction force between the rubble ground and side wall. A model caisson was put on the levelled mound, and stones were located behind the caisson. The type of stone used for

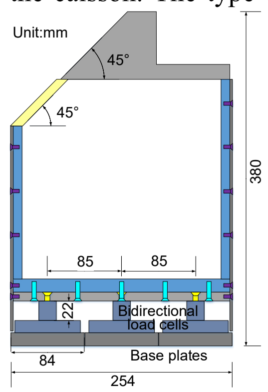

Fig. 1. Schematic view of model caisson

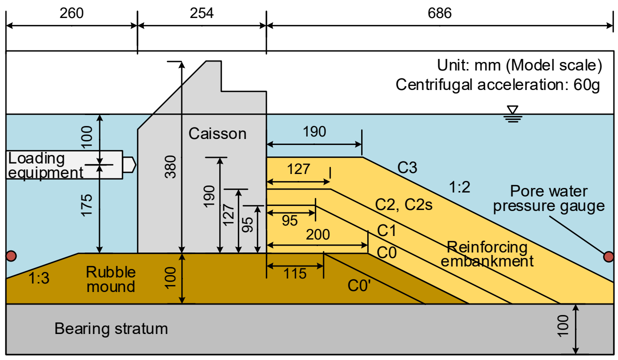

Fig. 2. Schematic view of breakwater model

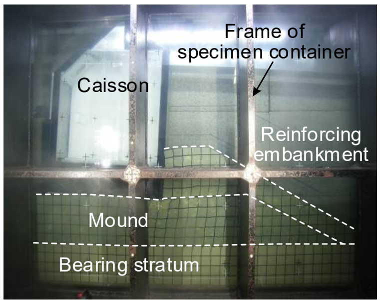

Fig. 3. Captured picture under loading

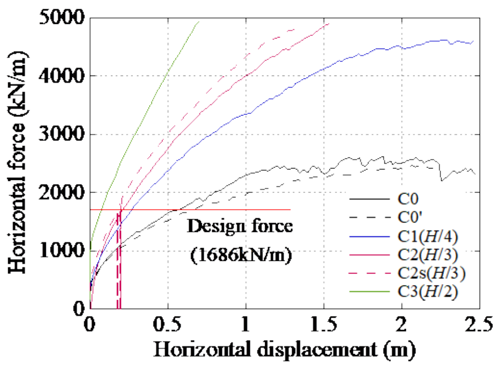

Fig. 4. Horizontal force and displacement of caisson

Table. 1. All test cases

Case	Mound width	Embankment height	Loading
C0	200mm	–	Monotonic
C0’	115mm	–	Monotonic
C1	200mm	95mm (*H*/4)	Monotonic
C2	200mm	127mm (*H*/3)	Monotonic
C2s	200mm	127mm (*H*/3)	Cyclic
C3	200mm	190mm (*H*/2)	Monotonic

#*H* is the height of caisson

the reinforcing embankment was the same as that of the mound. The way the embankment was produced corresponded to that of the mound.

Table 1 lists all test cases. These cases included different volumes of the reinforcing embankment. The width of the embankment top was equal to the height in each case. In Case C2s, where the shape of the embankment was the same as that of Case C2, the horizontal force was released once and added back when it reached the design wave force. The act of unloading and reloading was repeated three times. This case was carried out to investigate the effect of cyclic loading. Case C0’ had a narrow embankment. The tests were conducted using the centrifuge machine PARI Mark II-R, owned by the Port and Airport Research Institute (Kitazume and Miyajima, 1995). Centrifugal acceleration makes it possible to reproduce prototype-scale stress conditions in the model ground. The subgrade reaction depends on the deformation properties of a mound, and it is important to reproduce the prototype-scale stress and strain. A caisson was horizontally loaded under the centrifugal acceleration of 60*g*, and the horizontal force and subgrade reaction were measured during loading. The loading apparatus included a rod that moved at a constant speed and received reaction from the side wall of a specimen container. The capacities of load and displacement were 7000 N and 45 mm, respectively. When the load or displacement approached the limit values, loading was stopped. It was difficult to add uplift and vertical wave forces synchronously with a horizontal force. Accordingly, the forces were deducted from the weight of a caisson in advance. In addition, the centre of gravity was adequately shifted.

2.2 Horizontal force and displacement

Figure 3 shows a picture of Case C1. The horizontal displacement of the caisson was 40 mm at this point, corresponding to approximately 2.4 m in the prototype scale. This displacement was so large that the breakwater was damaged. The grid marking on the membrane sheet revealed the strain of a mound. Localization of strain, such as a sliding surface, did not occur, and a shear band with a width can be observed. This is because the particle sizes of stones are relatively large against soil such as sand and clay, and localization of strain is difficult. In other test cases, similar behaviour could be observed.

The relation between a horizontal force and displacement is shown in Figure 4 at prototype scale. The figure shows a large displacement at the peak and non-softening after the peak. These properties are natural for rubble ground. In Case C0, which did not have a reinforcing embankment, the horizontal displacement was approximately 1.0 m at the peak. It was approximately 17% against the mound height, and the strain level at the peak was large, compared with soil such as sand. Locating a reinforcing embankment made the peak value larger. To compare the effect of the volume of a reinforcing embankment, a large embankment demonstrated large stiffness and strength of the ground. Piling stones up is effective as reinforcement, and the effect is controlled by the volume of the embankment. In Case C2s, including the process of unloading and loading, the relation was shifted upward in the figure. The cyclic loading might

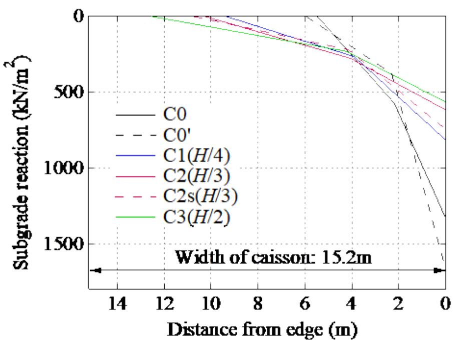

Fig. 5. Distribution of subgrade reaction

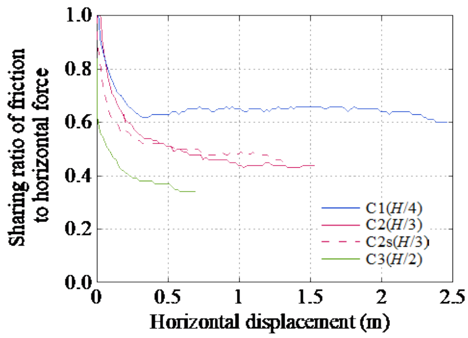

Fig. 6. Sharing ratio of friction to horizontal force

increase the stiffness and strength of the ground. Case C0’ with a narrow top of the slope showed a smaller ultimate load than Case C0. The bearing capacity would be small in Case C0’, because it has a small mound.

2.3 Subgrade reaction force

The subgrade reaction was measured by the load cells attached on the bottom of a model caisson. However, a detailed distribution could not be obtained, because the number of load cells was only three, so that this study assumes trapezoidal or triangular distributions for the subgrade reaction in each load cell. Additionally, an inclination of a caisson subjected to horizontal loading generated a vertical force from a loading rod. This force reached, at most, 20% against the submerged weight of a caisson, and it could not be ignored. The subgrade reaction discussed was corrected considering this vertical force. The ratios of the edge pressure and interaction width were calculated by comparing subgrade reaction forces both taking and not taking the vertical force into account. The measured subgrade reaction was multiplied by these ratios as correction coefficients.

Figure 5 shows the distributions of the subgrade reaction. These are the distributions when a caisson was loaded by the design wave force. In every case, the subgrade reaction force was concentrated on the edge, and the edge pressure in cases C0 and C0’, without a reinforcing embankment, were especially large. The figure shows that piling up stones dissipated the subgrade reaction and reduced the edge pressure. These effects were largely increased by enlarging the reinforcing embankment. For example, the edge pressure in Case C2, where the height of the embankment was 1/3 that of a caisson, was 46% of that in Case C0. There were mainly two reasons why the edge pressure was reduced. First, a friction force between a caisson and reinforcing embankment acted on the caisson upward and decreased the subgrade reaction force on the bottom. Second, a reaction force from an embankment to a caisson reduced the eccentricity and inclination of a caisson. The edge pressure in Case C2s, subjected to cyclic loading, was slightly larger than that of Case C2. Although the reason was not clear, it is possible that cyclic loading might slightly increase the eccentricity and inclination of a caisson. However, even in Case C2s, the edge pressure was much smaller than that in Case C0, and the reinforcing embankment was effective. Case C0’, with a narrow top of the slope, had larger edge pressure than Case C0. The angles of inclination of the caisson were 1.0° and 1.4° in Cases C0 and C0’, respectively, when a caisson was loaded by the design wave force. The large inclination in Case C0’ was caused by the narrow top of the slope, and it increased the edge pressure.

2.4 Reaction force from embankment

The load cell installed in the bottom of the caisson was a bidirectional indicator, and it was able to measure bottom friction as well as subgrade reaction. Another load cell measured a horizontal force from a loading rod. Figure 6 shows the sharing ratio of a friction force to a horizontal force. In the first stage of loading, the horizontal force was mostly supported by the friction force. The sharing ratio decreased and reached a steady state by displacing the caisson. The sharing ratio at the steady state was found to be approximately 0.4–0.6. The friction can be affected by the friction coefficient and deformation property of a mound, and the reaction force from a reinforcing embankment can be affected by the deformation property of an embankment.

The ratio rapidly decreased and stayed at the low state when a reinforcing embankment was enlarged. This indicated that a large embankment could produce a large reaction force. Takahashi et al. (2015) showed, using finite-element analyses, that the sharing ratio was 0.4–0.65 when the height of the reinforcing embankment was 1/4–1/2 that of the caisson. The sharing ratio measured in the model test was consistent with that in the analyses. Thus, the reaction force from a reinforcing embankment partially supported the horizontal force, and it contributes to reducing the edge pressure.

3 SIMPLIFIED CALCULATION MODEL

The simplified calculation model is proposed for a general breakwater without a reinforcing embankment in the Japanese design standard for port facilities. This shows that the subgrade reaction force can be obtained

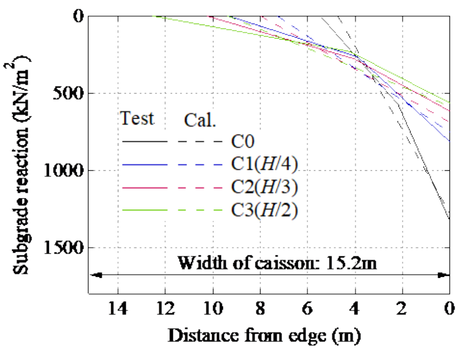

Fig. 7. Distribution of subgrade reaction calculated

by the equilibrium equation of the moments of a wave force, gravity, and the subgrade reaction. The distribution shape of the subgrade reaction is assumed to be trapezoidal (low eccentricity) or triangular (high eccentricity). Figure 7 shows the subgrade reaction calculated by this method. This figure includes the test results. As shown in the figure, the calculated subgrade reaction was close to that in the model test.

To consider the subgrade reaction of a caisson with a reinforcing embankment, the reaction force from the embankment should be taken into consideration. Takahashi et al. (2015) and Sato et al. (2017) examined the reaction force and proposed the calculation method. In this method, a horizontal force is supported by a friction at the bottom of a caisson and the reaction force from a reinforcing embankment. Friction between a caisson and embankment is determined by assuming a friction angle of 15°. The reaction and friction forces, P_H and P_V, are obtained in the following equations.

$$P_H = (1-r)H, \quad P_V = \tan 15° \cdot P_H \tag{1}$$

Here, r is the sharing ratio and H is the horizontal force. Using the equilibrium equation in the vertical direction, the subgrade reaction, V, is obtained in the following equation.

$$V = W - P_V \tag{2}$$

Here, W is the caisson weight. Substituting these equations into the equilibrium equation of the moments, an action point of subgrade, x_v, reaction can be obtained as follows.

$$x_v = \frac{Wx_w + P_H x_p - Hx_h}{V} = \frac{Wx_w + \{(1-r)x_p - x_h\}H}{W - \tan 15° \cdot (1-r)H} \tag{3}$$

Here, x_w is the gravity centre of the caisson, x_p is the action point of the reaction force from the embankment, and x_h is the action point of the wave force. The parameters of W, H, x_w, x_p, and x_h are known, and the above equation is a function of the sharing ratio of r. When x_v is determined, the edge pressure, p, can be obtained by the following equations, assuming the shape of the reaction distribution is triangular.

$$\frac{1}{2} p \cdot 3x_v = V \tag{4}$$

$$p = \frac{2}{3x_v}\{W - \tan 15° \cdot (1-r)H\} \tag{5}$$

Figure 7 shows the calculation results, assuming the sharing ratio is r = 0.5. The calculated subgrade reaction was found to be close to those in the model tests. Thus, the subgrade reaction could be simulated, even by a simplified calculation model. In addition, it was found that even a small embankment could contribute the reduction of the edge pressure.

4 CONCLUSION

In this study, the subgrade reaction to a caisson reinforced by embankment was investigated by using centrifuge model tests. In the model tests, the subgrade reaction was measured by the load cells installed in the bottom of a caisson. As a result, a reinforcing embankment dissipated the subgrade reaction and reduced the edge pressure on a caisson. This is because of the friction and reaction forces from a reinforcing embankment to a caisson. The larger the embankment became, the smaller the edge pressure was. The reaction force from a reinforcing embankment was found to support the horizontal force partially, and it contributes to reducing the edge pressure. In addition, the model test results were compared with those of a simplified calculation model. The calculated subgrade reaction was found to be close to those in the model tests. In further research, the results should be generalised, examining the subgrade reaction under various conditions.

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