Calculation and hydraulic model experiments for the stable weight of rubble-mound considering the overflow and seepage flow

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ABSTRACT

When The Tohoku-Pacific Ocean Earthquake occurred on the March 11th, 2011, harbor facilities such as breakwaters and tide embankments suffered serious damages from the Tsunami. The following three mechanisms are considered to be related to the collapse of the breakwater: 1) scouring of the mound due to overflow, 2) the horizontal force originated from the difference of water level between the sea side and the harbor side on the breakwater, and 3) reduction of bearing power of the mound induced by seepage flow. However, the mechanism of the instability of the rubble-mound by overflow and seepage flow induced by tsunami is not fully clarified. In this study, the formula to calculate the stable weight of rubble-mound was proposed in consideration of the overflow and seepage flow, and hydraulic model experiments were conducted on Kamaishi Bay breakwaters as the subject in order to confirm the effectiveness of the proposed formula. Using the results, the stability of the breakwater was evaluated from the geotechnical engineering point of view.

Keywords: breakwater, overflow, seepage flow, rubble-mound, stable weight, tsunami

1 INTRODUCTION

The Tohoku-Pacific Ocean Earthquake gave serious damages to many breakwaters in Tohoku region. The major cause of failure is the tsunami wave force. However, a new type of failure is confirmed: caused by scouring of the harbor side mound by overflow and seepage flow. In fact, the cause of failure of 9 among the 22 destroyed breakwaters was scouring of the mound.

For a long time, Hudson’s equation or Isbash’s equation have been used to estimate the stability of armor units of rubble mound breakwater against tsunamis. The both methods, however, are empirical formula. A. Matsumoto and S. Takahashi pointed out the issue of the Hudson’s equation. In Hudson’s theory, the seepage flow was not considered and the same thing can be said about Isbash’s equation. Therefore, we think they do not correspond to the new type of failure.

Since the Tsunami in Tohoku, a number of researches on overflow and seepage flow have carried out. Nevertheless, the mechanism of the instability of the breakwater on rubble-mound by overflow and seepage flow induced by tsunami is not fully clarified.

In this study, we propose the formula to calculate the stable weight of rubble-mound in consideration of the overflow and seepage flow. Hydraulic model experiments were conducted on Kamaishi Bay breakwaters as a subject in order to confirm the effectiveness of the proposed formula.

2 FORMULA FOR STABLE WEIGHT OF MOUND

2.1 Proposing the formula

As mentioned above, Hudson’s and Isbash’s equation do not include a term of seepage flow. Sakakiyama improved Hudson’ equation in 1989. However, Sakakiyama’s equation did not include the seepage flow term, either. We refer to the derivation of Hudson’s and Sakakiyama’s equation and reconstruct it with the seepage flow term.

Our aim is to calculate accurate stable weight by one formula. Here, we define stable weight as the
minimum rubble weight at a time of the maximum conceivable tsunami.

Figs. 1 and 2 show the relationship between the wave force \( F_w \) and the resistance force \( F_b \) acting to one rubble.

\[
F_w = \frac{1}{2} \gamma_w C_D A u |u| + \gamma_w C_M V \frac{\partial u}{\partial t} \quad (1)
\]

\( C_D \) : resistance coefficient, \( C_D \) : resistance coefficient, \( C_M \) : inertia force coefficient, \( \frac{\partial u}{\partial t} \) : acceleration of fluid around rubble \([\text{m/s}^2]\), \( A \) : projected area of rubble \([\text{m}^2]\), \( V \) : volume of rubble \([\text{m}^3]\), \( g \) : acceleration of gravity \([\text{m/s}^2]\), \( \gamma_w \) : unit volume weight of the fluid \([\text{kN/m}^3]\).

On the other hand, the seepage force \( F_L \) is expressed by the following equation.

\[
F_L = \gamma_w V (1 + e) i \quad (2)
\]

Therefore, the resistance force \( F_b \) is given by the following equation.

\[
F_b = f \gamma_w V (1 + e) i - W' \sin \theta \quad (3)
\]

\( f \) : frictional coefficient, \( W' \) : submerge weight of rubble \([\text{kN}]\), \( e \) : void ratio, \( i \) : hydraulic gradient, \( \theta \) : gradient of mound \([\text{rad}]\).

Since the stability limit of the rubble is given at the moment when the wave force and resistance force are balanced, the equation (1) and (3) are substituted for equation \( F_w = F_b \). Then, using the following definitions:

\[
W' = \gamma_w V (G_s - 1) \quad G_s = \gamma_s / \gamma_w, \]

we rearrange equations from (1) to (3) regarding configuration characteristics \( A \) and \( V, \gamma_s \) is unit weight of rubble \([\text{kN/m}^3]\).

\[
\frac{V}{A} = \frac{1}{2} C_p \theta |u| \quad (4)
\]

In addition, the next equations are established by using configuration coefficients.

\[
k_v = k_d q^3, \quad A = k_d q^2 \quad (5)
\]

\( k_v \) : volume coefficient, \( k_d \) : area coefficient, \( q \) : represented rubble length \([\text{m}]\).

Also, represented rubble length \( q \) is expressed as the following equation (6) by using rubble weight \( W \) \([\text{N/each}]\).

\[
W = \gamma_s V = \gamma_s k_v q^3 \quad \therefore \quad q = \left( \frac{W}{\gamma_s k_v} \right)^{\frac{1}{3}} \quad (6)
\]

Rearranging equations (4) and (6), we obtain the following one.

\[
\frac{V}{A} = \frac{k_v}{k_d} q^3 = k_v \left( \frac{W}{\gamma_s k_v} \right)^{\frac{1}{3}} \quad (7)
\]

Then, this equation is cubed and deformed to the following form.

\[
W = \frac{k_v^3 \gamma_s C_p r^6}{8 k_v^2 g \left[ f \gamma_w V (1 + e) i - W' \sin \theta \right]} \quad (8)
\]

Now, based on the Nakamura’s and Sawaraki’s assumption, in this study, we regard that tsunami is in a steady state because tsunamis are very long waves. Therefore, the inertia term can be ignored. We use this equation (8) as the proposed formula in this study.
2.2 Use of the proposed formula

We computed the stable weight of the Kamaishi bay breakwater by the proposed formula (8). You can see the cross section of Kamaishi Bay breakwater in Fig. 3. Table 1 shows the input constants. Fig. 3 shows the result of the comparison of two methods: proposed formula and Isbash equation. We set the Isbash coefficient as 0.86.

Table 1. Input constants.

| Symbol | Unit weight | Frictional coefficient | Gradient of the mound |
|--------|-------------|------------------------|-----------------------|
| $C_D$  | kN/m²       | $f_r$                  | $\theta$              |
| Unit   |             |                        |                       |
| Value  | 0.1         | 22.54                  | 0.7002                | 0.4637               |

Fig. 4. The relation the overflow water depth and the stable weight at the Kamaishi bay breakwater.

Maximum overflow water depth in Kamaishi Bay breakwater at the time of the Tohoku-Pacific Ocean Earthquake was 7.2m. The result calculated by proposed formula was 1.64 times deeper than calculated by Isbash’s equation. Therefore, we point out the possibility of over-evaluation about the stability of rubble-mound by the Isbash’s equation when overflow water depth increases as shown in Fig.4.

3 HAYDRAULIC MODEL EXPERIMENT FOR KAMAISHI BAY BREAKWATER

Fig. 5 shows the schematic of experimental devices. The model is the Kamaishi bay breakwater, and the reduced scale is 1/100. Water pressure gauge is used to calculate the hydraulic gradient in the mound. Fluid velocity gauge or wave gauge are used to calculate the overflow water velocity.

Table 2 shows the test condition of this experiment. To simulate the tsunami, we caused the water level difference between the front and the back of the breakwater by ring flow.

Table 2. Test conditions.

| Model | Kamaishi bay breakwater (1/100) |
|-------|---------------------------------|
| Caisson | Height 195mm ×Breadth 185mm ×Depth 190mm (19.5m×18.5m×19.0m) |
| Size | 2.03g/cm³ |
| Saturated density | 1.86g/cm³ |
| Rubble-mound | Case 1 | Case 2 |
| Particle size | 2mm-4.75mm (0.2m-0.475m) | 2mm-19mm (0.2m-1.9m) |
| Saturated density | 1.81g/cm³ |
| Water level difference | 0mm, 40mm, 80mm, 120mm, (0m, 4.0m, 8.0m, 12.0m, 14.5m, 18.5m, 21.0m) |
| Water level at harbor side | 25mm (2.5m) |

※Real scale showed in ( )

Figs. 6 and 7 show the state of model breakwater in the experiments. In Case 1, we can see only the seepage failure. In Case 2, the scouring of the mound due to the overflow and seepage flow is confirmed. Table 3 shows the result of the experiments.
In Case 1, seepage failure has occurred when the water level difference becomes 145mm. Because the equation (8) is assumed to overflow, it is not used. In Case 2, seepage and overflow failure has occurred when the water level difference becomes 185mm. Fig. 8 shows the result of using equation (8) in Case 2.

The average weight of rubble (0.024[N/each]) and equation (8) compute the beginning of failure at 130mm. However, the breakwater actually collapsed when the overflow water depth was 350mm. This is because the failure began at 130mm, and the resistance force reached its limit at 350mm.

| Case | 1     | 2     |
|------|-------|-------|
| Weight of rubble [N/each] | 0.002-0.005 | 0.004-0.027 |
| Water level deference at the time of failure [mm] | 145 | 185 |
| Overflow water depth at the time of failure [mm] | 0 | 350 |
| Cause of failure | Seepage flow | Overflow and seepage flow |

In Fig. 9 we can also see the safety factor at the time of each failure in Case 1 and 2.

In case 1, it is confirmed that seepage failure in the experiment occurred at the part where the safety factor is lowest.
In case 2, although the reduction of safety factor at the overall inner surface of the rubble-mound is confirmed, the safety factor was not reduced at one part. This is because, in this area, seepage failure occurred before the overflow so that we could not compute the safety factor in the way we attempted to use.

4 CONCLUSIONS

Conclusions are given below. Using the results, the stability of the breakwater was evaluated from the viewpoint of the geotechnical engineering. Some problems, however, are also revealed.

1) We propose the formula for calculating the stable weight of rubble-mound considering the overflow and seepage flow at tsunami.
2) We propose the possibility of over-evaluation about the stability of rubble-mound by the existent formula, because it does not include the complex factors. For example, stable weight determined by the proposed formula in Kamaishi bay breakwater at the time of the overflow water depth of 7.2m was 1.64 times deeper than calculated by Ishash’s equation.
3) We conducted the hydraulic model experiments with Kamaishi bay breakwater as a subject, and estimated its stability using the proposed formula. As a result, In Case 1 (grain size from 2mm to 4.75mm), failure was caused only by seepage flow. In Case 2 (grain size from 2mm to 9mm), failure was caused by both the overflow and seepage flow at the time of overflow water depth of 350mm (3.5m in real scale). There is the estrangement of the result between the experiment and the calculation. This is because of the difficulty to calculate the hydraulic gradient at the failure point. Moreover, failure occurs as a result of move of many rubble. We can only predict the level of water that causes move of one rubble by this proposed formula. We think this problem will be solved by considering damage ratio or analyzing the all rubble. This will be our future challenges.

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