STABILITY ANALYSIS FOR A RUBBLE-MOUND FOUNDATION THROUGH IRREGULAR WAVE TEST

by

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ABSTRACT

Irregular wave tests have been conducted to research into the stability characteristics of armor units for a rubble foundation of a composite breakwater.

A cover layer to protect the rubble foundation from erosion had two layers of tetrapods. Waves higher than $H_{1/10}$ (the average height of the highest 10% of all waves) caused damage to armor units at the point of critical stability. This suggested that wave height changes in the surf zone should be taken into consideration for design purpose.

1. INTRODUCTION

In Japan, composite breakwaters with superstructures resting directly on rubble foundations have been designed to be used even in areas of deep water. This is due to the fact that construction schedules of breakwaters can be shortened by adopting concrete caissons as a superstructure and damages during construction can be avoided. Many damages to breakwaters occur before completion of the construction.

These composite breakwaters are exposed to high design waves in areas of deep water and very large armor units are required to protect their rubble-mound foundations. Design wave heights sometimes exceed 10 meters in the southern districts of Japan e.g. Okinawa and Kogashima prefectures. Stones as foundations of composite breakwaters are unstable in such districts, especially in the surf zone. In such cases engineers have to use armor blocks like tetrapods to protect the foundations.

Stability analysis of vertical-faced superstructures such as concrete caissons have progressed remarkably. One example is Goda's (1974). To our knowledge some studies on rubble foundations have been reported but they are mostly based on regular wave test results.

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The results using stones based on regular wave tests by Brebner and Donnelly (1963) have been very useful design criteria. But caution should be paid in selecting the design wave heights because of the irregularity of waves, especially in deep water areas and against high design waves.

This paper deals with model tests on the stability of rubble foundations to irregular waves and two layers of tetrapods as an armor layer were used.

2. TEST EQUIPMENT AND TEST PROCEDURE

2-1. Test equipment

The tests on rubble-mound foundations were carried out in a wave tank, 49.0 m long, 1.0 m wide and 1.0 m deep as shown in Figure 1 at the Hydraulic Laboratory, Nippon Tetrapod Co., Ltd.

The wave generator consisted of a flap type paddle which was operated by a hydraulic piston enabling it to make random waves.

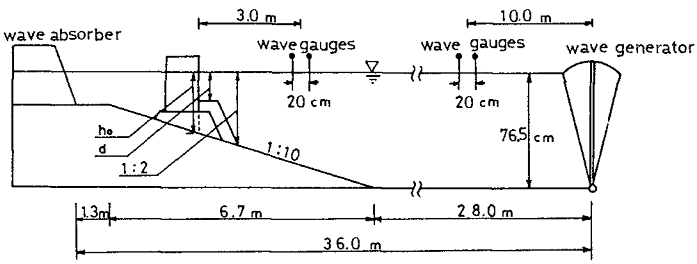

Figure 1 Wave tank and allocation of model

2-2. Test procedure

A simplified sketch of the allocation of model studies is also shown in Figure 1. The bottom slope was 1 in 10. Two pairs of wave gauges at a distance between them of 20 cm were set up at distances 10 m from the paddle of the wave machine and 3.0 m seaward from the model breakwater in order to separate incident and reflected wave heights using Goda's method (1976).

The test wave height was 10.8 cm at a point where the model breakwater was to be constructed. The wave periods were 1.3 sec and 1.8 sec in the model. These irregular waves of Bretschneider-Mitsuyasu spectrum presented by the following equation were simulated.

$$S(f)=0.257\, H_{1/3}^2 T_{1/3}(T_{1/3}f)^{-5}\exp(-1.03(T_{1/3}f)^{-4}) \text{---}(1)$$

where
$S(f)$; power spectrum density function
$H_{1/3}$; significant wave height
$T_{1/3}$; significant wave period
f ; frequency

Two layers of tetrapods as armor blocks were used. The range of model tetrapod weight was from 14.7 g to 190.0 g.

A section of the model breakwater is shown in figure 2.

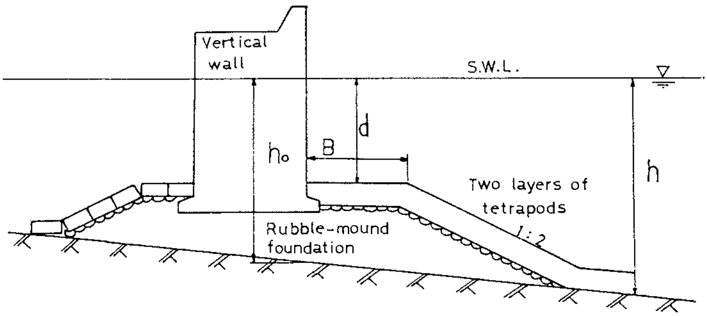

Figure 2 Sketch of cross section of model breakwater

where
h; water depth at the toe of breakwater
h_o; water depth at the structure site
d; depth at the crest of rubble-mound foundation
B; berm width of rubble-mound

B was fixed constant 15.0 cm. d values were 9.0 cm, 13.0 cm and 16.0 cm below the still water level in the cases where h_o=-28.0 cm and 9.0 cm, 11.0 cm and 14.0 cm were the d values in the case where h_o=-23.0 cm.

Wave duration time was 30 minutes in each case in the model.

3. TEST RESULT AND DISCUSSION

The conditions were classified. Three categories were decided on:

(1) Stable condition where the number of armor units which moved was zero and the number of rocking blocks was less than three.
(2) Unstable condition where more than two unis were moved by wave forces while more than four rocking units were discernable.
(3) Critical condition which is an intermediate state between the stable and unstable conditions.

The stability test results are shown in Figure 3 and 4. These figures show the relation between d/h and weights of tetrapods used. In these two figures black represents unstable, white is stable and black and white is the critical state respectively.

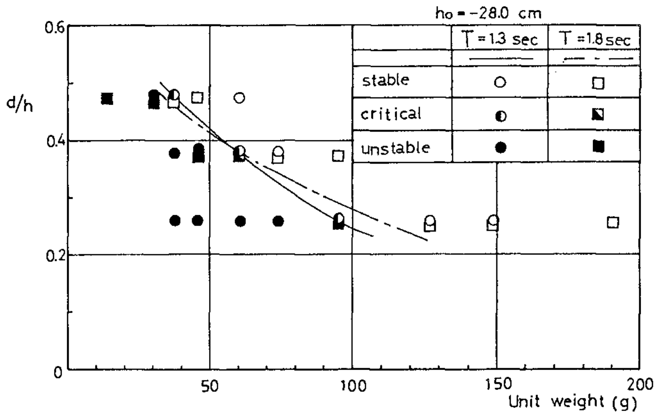

Figure 3 Test results (h_o=-28.0 cm)

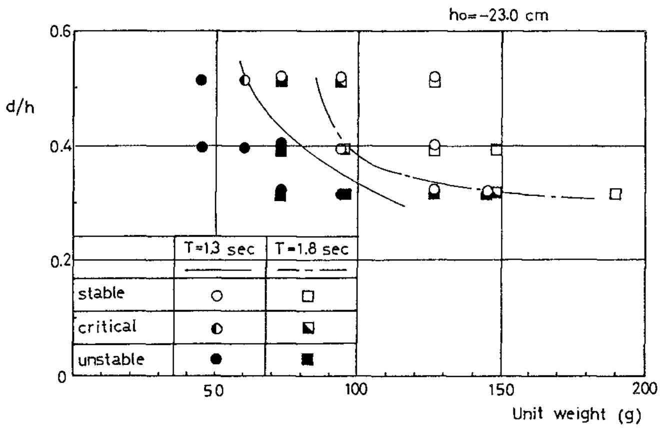

Figure 4 Test results (h_o=-23.0 cm)

Lines show the critical relation between d/h and the unit weight. As shown in Figure 3 and 4 the critical weights increase rapidly as d/h decreases indicating that d is smaller, the critical weight is required to be heavier if h is constant. In addition, it can also be seen that the critical weight is influenced by the wave period, especially in the case where h_o=-28.0 cm, the effects of the wave period are not so apparent. However as the water depth at the breakwater (h_o) increases, it becomes less apparent that the critical weight increases as the wave period increases.

Observation during the tests

In order to investigate how armor units had been damaged by a certain wave in the wave train, the wave action in front of the vertical wall and the movement of tetrapods were filmed by means of a video camera with a rotary shutter. The speed of the shutter was 1/60 seconds.

From this observation, as shown in Figure 5, armor unit suffered an up-lift force and rose up just after a large wave hit the site.

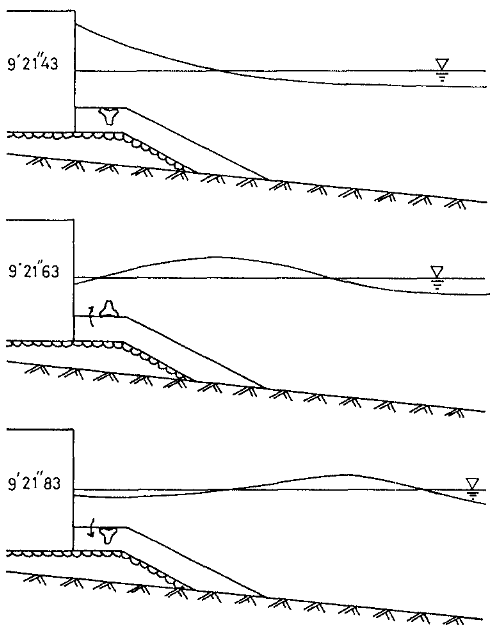

Figure 5 (a) Movement of tetrapod resulting from wave action

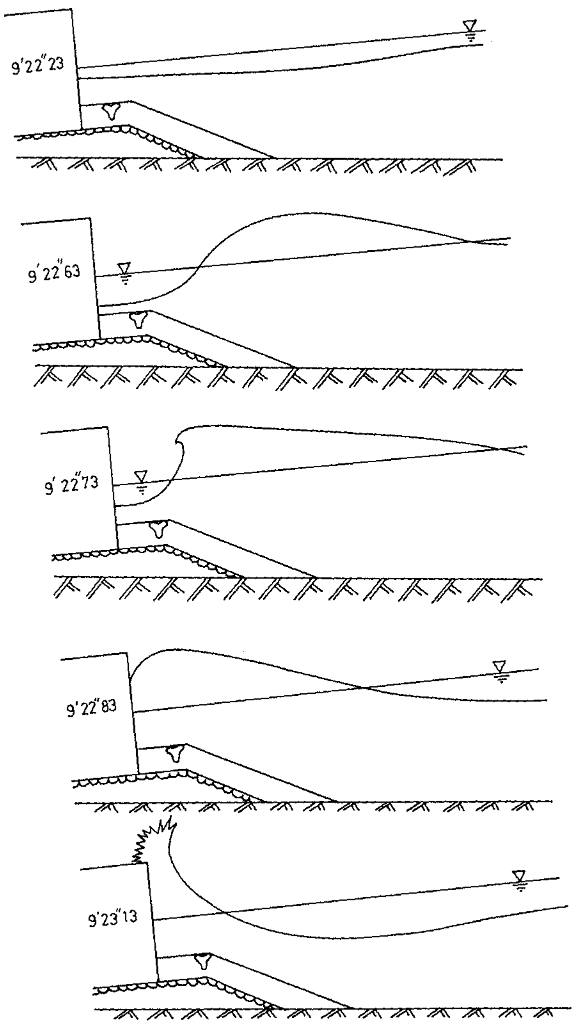

Figure 5 (b) Movement of tetrapod resulting from wave action

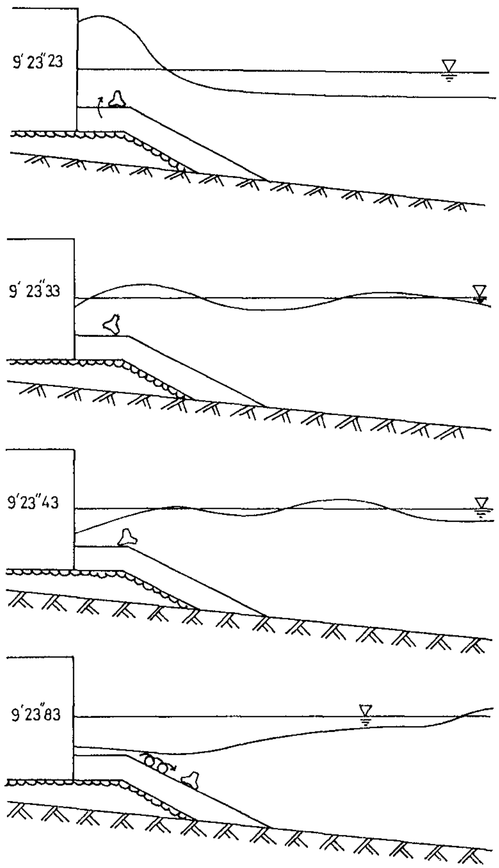

Figure 5 (c) Movement of tetrapod resulting from wave action

Subsequent run-down washed the units seaward. It could be seen that waves breaking on the mound were influenced by the previous run-down. It can be assumed that the magnitude of the lift force was influenced by the previous run-down meeting an incoming wave resulting in damage of the units. Damage in rubble foundations was observed to depend on how much of the top of the foundation was exposed above the water, especially when the troughs of waves near Hmax hit vertical faced structures.

Figure 6 shows an example of a surface elevation measured at a station at a distance of one wave length away from the site whereas Figure 7 shows a record of the waves without the breakwater measured at the point where the model breakwater was to be set up.

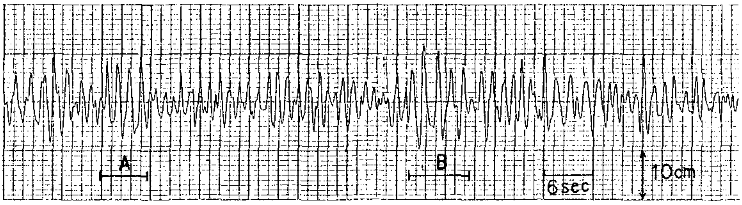

Figure 6 An example of a wave record at a distance of one wave length from the breakwater

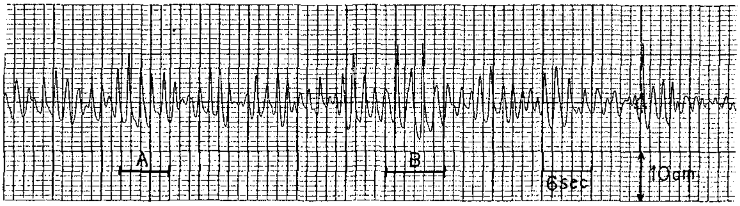

Figure 7 An example of a wave record at the breakwater

A few tetrapods moved due to waves in sections A and B (Figure 6 and 7).

Waves except those in sections A and B caused no movement to armor units. The damage of the armor units by waves in B section was greater than that in A. The maximum wave in this train appeared in section B and several large waves occured successively. These subsequent waves including the maximum wave struck the breakwater damaging the armor units. The consequtive wave heights including sections A and B are shown in Figure 8. The significant wave height and the one-tenth maximum wave height are illustrated in the same figure.

From the investigation using the video film, in critical cases, the movement of tetrapods was caused by those wave groups in sections A and B. Waves exceeding the one-tenth maximum wave height damaged the armor layer. Waves included in B section caused damage more sever than that in A section. Although the only maximum wave can damage, a group of waves exceeding the critical wave height (Hc) is more destructive.

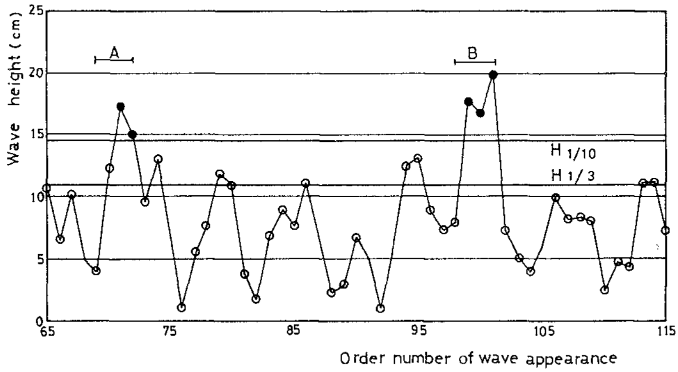

Figure 8 An example of wave group

Stability Number

Stability Number is presented by the following equation.

$$N_s = \frac{\gamma^{1/3} H}{W^{1/3}\,(S_r - 1)} \qquad \text{--------} \qquad (2)$$

where

Ns ; Stability Number
γ ; specific gravity of armor unit
W ; average weight of armor unit
Sr ; specific gravity of armor unit relative to water
H ; wave height

The relationships between d/h and Ns calculated by equation (2) using significant wave heights measured in the tests are shown in Figure 9 and 10.
Figure 9 shows the results in the case where h_o=-28.0 cm and Figure 10 is the results where h_o=-23.0 cm. In order to compare the test results with those obtained by Brebner and Donnelly(1963), their values of Ns are included using dashed lines in Figure 9 and 10. As it is not possible to compare directly with the results of Brebner and Donnelly(1963), their values of Ns were roughly revised using Kd values of quarry stones and tetrapods. Solid and dotted lines show the results of the cases where T=1.3 sec and T=1.8 sec respectively.

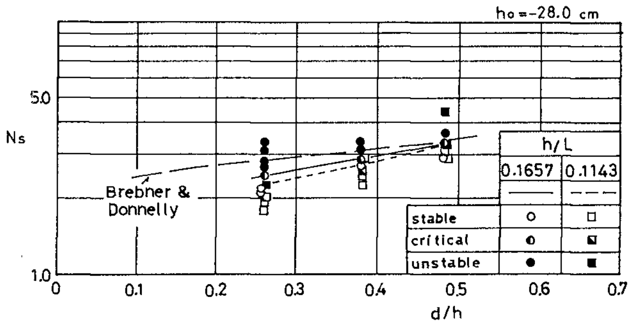

Figure 9 Stability Number as d/h ($H_{1/3}$ as H)

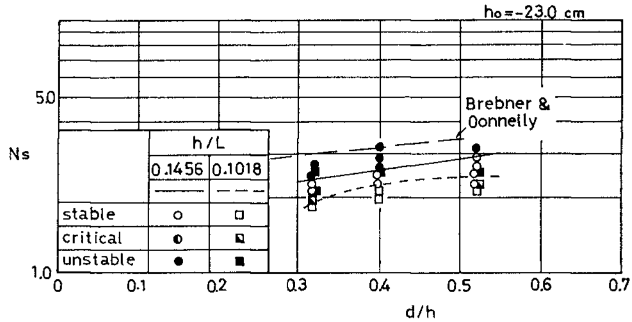

Figure 10 Stability Number as d/h ($H_{1/3}$ as H)

Stability Numbers show a tendency to increase as d/h increases. The rate of increase become smaller in the case where h_o=-23.0 cm.

Where h_o=-23.0 cm, if the wave period was 1.3 sec, the Stability Number is slightly smaller than that where T=1.8 sec. Hence the Stability Number seemed to be affected by the wave period.

The revised Stability number of Brebner and Donnelly(1963) dashed lines) is greater than that found in these test results which were obtained by substituting $H_{1/3}$ measured into equation(2).

Figure 11 and 12 show the Stability Number which was calculated using $H_{1/10}$ measured at the point of a site without a breakwater. In these figures the revised Ns found by Brebner and Donnelly(1963) is also included(by dashed lines). As shown in these figures, Their revised Ns has almost the same value as our results.

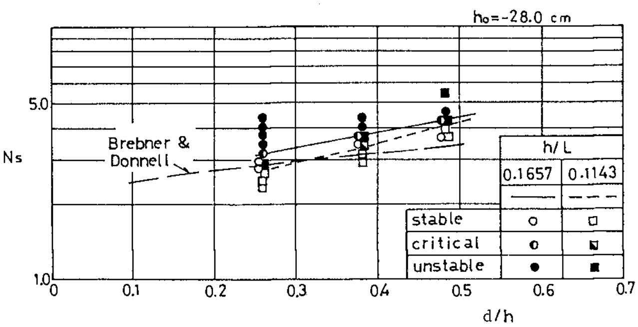

Figure 11 Stability Number as d/h ($H_{1/10}$ as H)

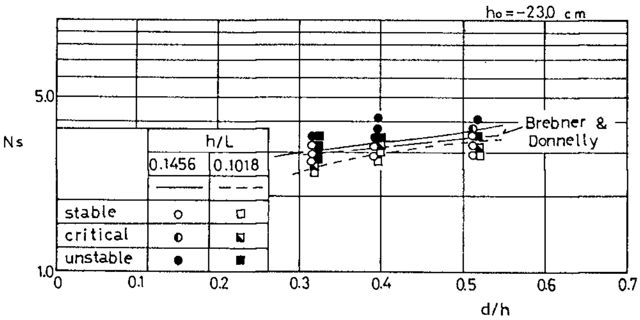

Figure 12 Stability Number as d/h ($H_{1/10}$ as H)

As mentioned above, if $H_{1/3}$ is used in the estimation of a critical unit weight using the revised Ns when the weight calculated is lighter than the required weight.

When the results obtained though regular wave tests are applied to evaluate a required weight of armor units, it seems that the one-tenth maximum wave height as a design wave height is appropriate.

There are no formulae for estimation of weights of armor units, like tetrapods, which protect the rubble-mound at present. Engineers have estimated the stable weight of the armor units as foundations referring to the results of Brebner and Donnelly(1963). However they have to select the design wave height with caution.

Critical weight

From the test results, the critical weight seemed to be a function as d/H where H is a representative wave height, e.g. $H_{1/3}$ and $H_{1/10}$, measured at a point on the site without a breakwater. The relationship between $Wc/w_o H_{1/3}{}^3$ (w_o: unit weight of water) and $d/H_{1/3}$ are shown in Figure 13 and 14.
Figure 13 shows the results of two cases where h_o=-28.0 cm and h_o=-23 cm at the fixed period of T=1.3 sec. Figure 14 shows similar results where the wave period was 1.8 sec.

From each figure, the boundaries of each case between stable and unstable results can be separated using one straight line, independent of the water depth at the site (h_o), on semilogarithmic graph paper.

Critical relationships are obtained as following equation in each case where T=1.3 sec and T=1.8 sec as a result of the lines drawn.

$$W/w_o H_{1/3}{}^3 = 0.284 \times 4.58^{-(d/H_{1/3})} \quad \text{(at T=1.3 sec)-----(3)}$$

$$W/w_o H_{1/3}{}^3 = 0.695 \times 6.55^{-(d/H_{1/3})} \quad \text{(at T=1.8 sec)-----(4)}$$

These two equations show the effect of the wave period.

Engineers have problems in making decisions about what wave height to use ($H_{1/3}$, $H_{1/10}$, Hmax) as design wave heights.

As mentioned before, the armor units were damaged by waves of heights exceeding the one-tenth maximum wave height under critical conditions. In addition, if the depth at the breakwater and the gradient of sea bottom change, the ratio $H_{1/10}$ to $H_{1/3}$ also changes. Then critical conditions would be presented more directly by $H_{1/10}$ than the significant wave height.

The relationship between $W/w_o H_{1/10}{}^3$ and $d/H_{1/10}$ is shown in Figure 15 and 16.

The empirical equations of the critical relationship are obtained as follows.

$$W/w_o H_{1/10}{}^3 = 0.125 \times 6.72^{-(d/H_{1/10})} \quad \text{(at T=1.3 sec)-----(5)}$$

$$W/w_o H_{1/10}{}^3 = 0.187 \times 7.56^{-(d/H_{1/10})} \quad \text{(at T=1.8 sec)-----(6)}$$

These results seem to have an application in estimation of the critical unit weight as suggested by Inagaki et al (1971). When these equations are applied, attention should be paid to the effects of the wave period because the wave with longer period are more destructive than those of shorter periods.

However, these equations were obtained through tests under conditions of a constant wave height, two values of wave period and a constant gradient sea bottom. The effects of these are not yet apparent. Some additional test will be tried.

The test wave height was not so longer in the model, therefore there still remains the problem of the scale effect.

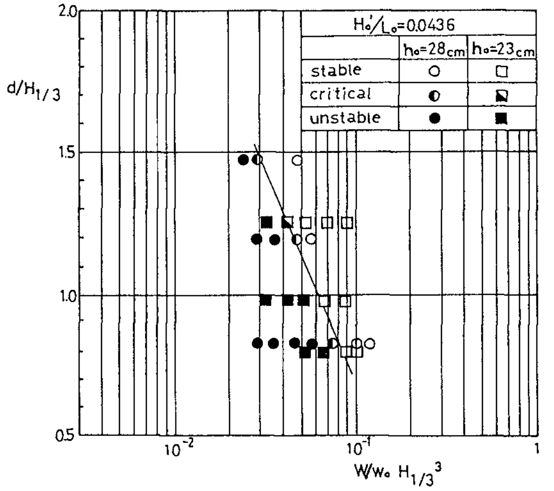

Figure 13 Critical weight as $d/H_{1/3}$ (T=1.3 sec)

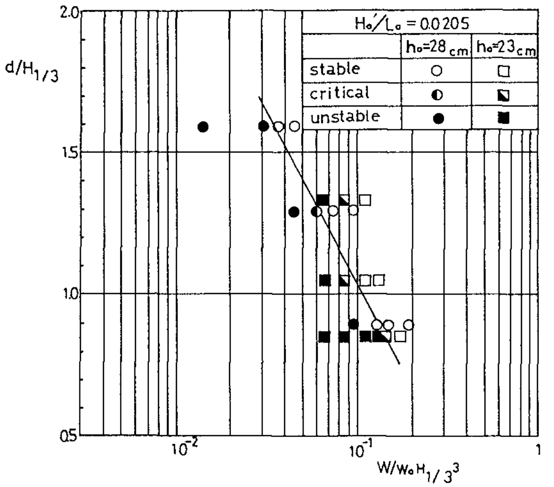

Figure 14 Critical weight as $d/H_{1/3}$ (T=1.8 sec)

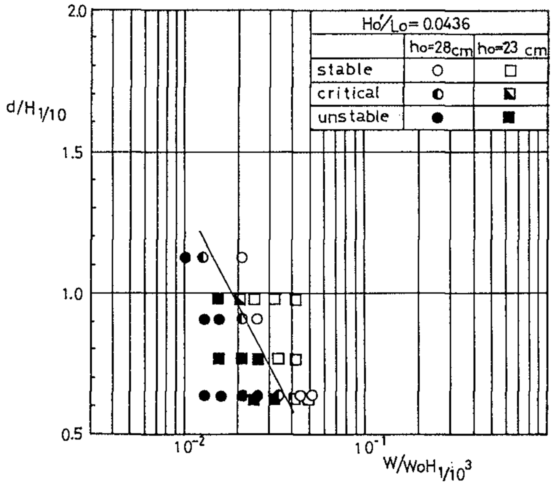

Figure 15 Critical weight as $d/H_{1/10}$ (T=1.3 sec)

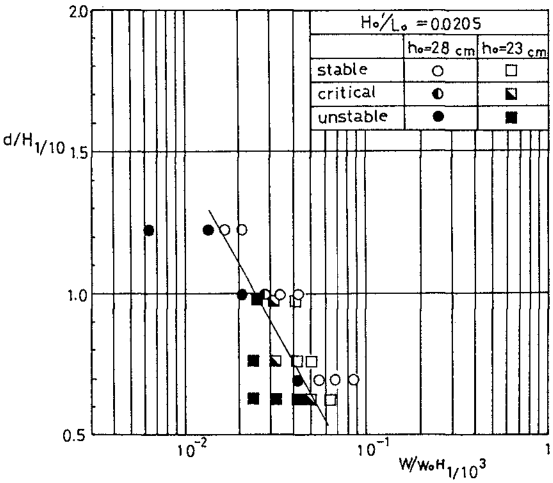

Figure 16 Critical weight as $d/H_{1/10}$ (T=1.8 sec)

Design wave heights are often greater than 7 m and 8 m in the southern area of Japan and the depths of foundations are around -10 m in many cases and as concrete armor units are used to protect such foundations. Figure 13 to 16 could be utilized when faced with this situation.

4. CONCLUSIONS

The conclusions obtained by the tests are summarized as follows.

1. The waves with longer periods were more destructive than shorter waves when h_o was small.
2. Under critical conditions, the tetrapods as a protection of the rubble-mound received damage by waves of height exceeding $H_{1\ 10}$.
3. The stability of the armor unit was affected by the wave group.
4. Critical weight was a function of d/H (H: representative wave height) and increased as the wave period became longer in our range of d/H. It is recommended to use $H_{1/10}$ for design, especially in the surf zone.

5. REFERENCES

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