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Experimental Studies on Dynamically Stable Breakwater under Irregular Wave Attacks

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Abstract

Dynamically stable breakwater is a breakwater in which the seaward slope is reshaped and reaches a stable condition under several wave attacks. The present study was conducted particularly to develop practical formulas for evaluating the stability of the seaward slope of breakwater with low berm crest height under irregular wave attack. Effects of the relative berm crest height, the wave steepness, and the initial seaward slope were assessed and indicated to affect significantly the relationship between stability number and both the relative horizontal eroded berm and relative toe width, and the relationship between relative horizontal eroded berm and relative vertical eroded berm respectively.

Key words : *Dynamically Stable breakwater, stability number, relative berm crest height, wave steepness, initial seaward slope.*

1. Introduction

Dynamically stable breakwater or berm breakwater is a type of S-shape (composite) seaward slope of breakwater, which uses the coarse materials, e.g., gravel and natural stone. This breakwater is formed as a consequence of reshaping its seaward slope by several wave attacks. As a conventional breakwater, this type is still popular because of its effectiveness in reducing wave run-up, increasing stability and increasing safety and economy[1)-3)].

Concerning the shape of seaward slope of breakwater, there were many studies has been performed previously. Priest et al. (1964), Moutzouris (1978), Kogami (1978), Naheer and Buslov (1983), Bruun (1985), and Aysen Ergin, et.al (1989) recommended that the S-shaped profile was superior in performance compared with statically stable breakwaters. However, few studies have been conducted on a low berm crest height (the height of berm emerge a little bit higher from the still water level, SWL) of dynamically stable breakwater. One is a study performed by Hall and Kao[4)]. This study was performed also on a dynamically stable breakwater with low berm crest height to examine the effect of the armor stones gradation and the amount of rounded stone. However, there were some parameters have not been considered yet, such as relative berm crest height, vertical eroded berm, steepness, initial seaward slope. To accommodate some parameters

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have not considered yet above, this study was presented.

2. Experimental setup and Procedure

A total of 110 series of tests were undertaken in a 0.8 m wide, 1.0 m deep, and 26 m long wave channel at the Laboratory of Water Supply and Management Engineering of Saga University, Japan (**Fig. 1**).

The waves correspond to periods of peak energy density (T_p), ranging from 0.8-1.6 s and significant wave heights (H_s) at the location of structure, from 6 to 12 cm. The duration of wave action performed per data set was 1 until 1.5 hours (the occurred waves were approximately around 3000), where during this time the seaward slope profiles have reached the equilibrium. Significant wave heights were calculated using Rayleigh distribution method[5], where the wave height distribution was defined by zero-up crossings method.

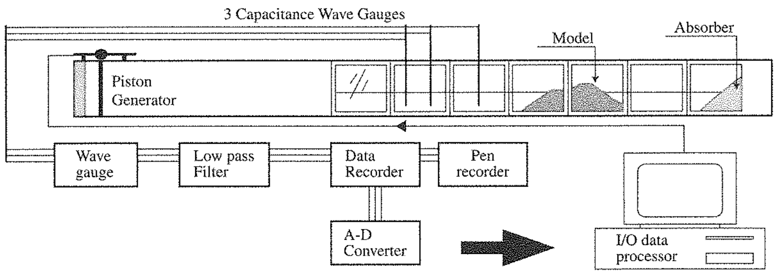

Fig.1 Experimental Setup

The breakwater model sections were installed about 20 m from the piston type of wave generator. The section model can be seen in **Fig. 2**. All tests were performed with irregular waves and used the JONSWAP spectra (γ=3.3)[6] to produce digital wave profiles for creating the irregular waves. Two stones diameters (D_{50}), which are larger by weight than 50% of the sample of crushed armor stones were used in this study.

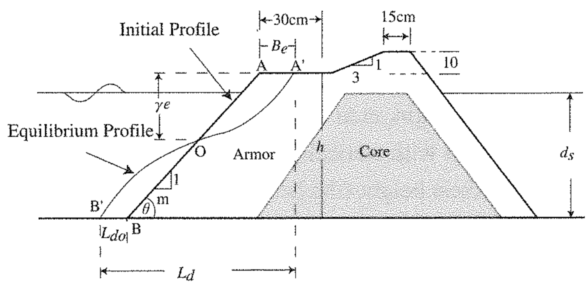

Fig. 2 Model section and parameter definitions

The D_{50}=1.50 cm was used in the shallower water depth (d_s=30 cm) and the D_{50}=2.24 cm was used in deeper water depth (d_s=40 cm). The core of structure of all model tests was D_{50}=1.2 cm where it does not have a significant effect on the results (Hall and Kao, 1990). The density of all stones (ρ_a) is 2.54 gf/cm^3. Basic data information completely can be seen in **Table 1**.

Table 1 Stone gradation, berm crest height and water depth characteristics

D_{50} (cm)	h (cm)	ds (cm)	h/ds	Remarks
1.5	35	30	1.17	Armor
2.24	45	40	1.13	
2.24	42.5	40	1.06	
1.9	42.5	40	1.06	Hall & Kao (1990)

3. Parameters Studied

According to the aim of this study 3 dependent dimensionless parameters have been considered, that is, B_e/D_{50}, Y_e/D_{50}, and $L_d/(D_{50}.m)$. In which B_e is the horizontal eroded berm, which is measured from initial point (point A) to the equilibrium eroded point (A'), Y_e is the vertical eroded berm, which is measured from point A to point O as an intersection point between initial profile and equilibrium profile, and L_d is the toe width, which is a summation value of L_{d0}, $h*cot\,\theta$, and B_e. Based on the description of **Fig. 2**, each of those three dimensionless parameters were considered depends primarily upon the values of some independent variables as shown in the equation (1).

$$\frac{B_e}{D_{50}},\ \frac{Y_e}{D_{50}}\ and\ \frac{L_d}{D_{50}\cdot m}=f\left\{N_s,\ h/_{d_s},\ s,\ \cot\theta\right\} \qquad (1)$$

where the parameters definition are explained in the **Table 2**.

Stability number that is denoted by N_s is a coefficient introduced by Van der Meer[7] which was derived from the general formula for stability of quarry-stone armor unit of Robert Y. Hudson[8]. This formula is very useful for obtaining the functional relation of the dynamically or statically breakwater and to characterize the relative severity of the irregular wave attack. The formula is de-

Table 2 Nomenclatures

A, B, C, D	coefficients of regression ;
B_e	width of horizontal eroded berm (cm) ;
d_s	water depth at toe breakwater (cm) ;
D_{50}	diameter of stone, that is larger by weight, than 50% of the sample (cm) ;
h	berm crest height (cm) ;
g	gravity acceleration (cm/s^2) ;
H_s	significant wave height (cm) ;
L_p	Airy wavelength obtained using d_s and T_p (cm) ;
L_d	toe width (cm) ;
L_{d0}	width of deposited stones from the initial toe width (cm) ;
m	$cot\ \theta$
N_s	stability number ;
s	wave steepness (H_s/L_p) ;
T_p	period of peak enegy density of incident wave spectrum (sec) ;
θ	slope angle
$tan\ \theta$	initial slope
Y_e	height of vertical eroded berm (cm) ;
ρ_a	density of stones (gf/cm^3) ;
ρ_w	density of water (gf/cm^3).

scribed as follows,

$$N_s = \frac{H_s}{\left(\rho_a/\rho_w - 1\right) D_{50}} \tag{2}$$

In order to know the effect of crest height and water depth, a dimensionless parameter of relative berm crest height or h/d_s was made. Three conditions of this parameter were arranged in this study, that is 1.06, 1.13, and 1.17 (see **Table 1**).

Wave steepness is one of the important parameters, which affects the stability of breakwaters. This parameter can conveniently be used for describing the wave breaking phenomena.

According to Van deer Meer[9], wave steepness should be between 0.005 and 0.06, where for wave steepness is greater than 0.06, indicates the unstable wave, and break because of their steepness. The present study only conducted the tests on range of wave steepness between 0.03 and 0.05. The data represents wave steepness values less than 0.03 cannot be collected because of the limited capability of the piston generator.

For an irregular wave, wave steepness is generally defined as :

$$s = \frac{H_s}{L_p} \tag{3}$$

where, L_p is obtained using peak time period (T_p). For the transitional water condition which meets with the range of $0.04 < d_s/L_p < 0.5$ the equation of L_p is defined as :

$$L_p = \frac{gT_p^2}{2\pi} \tanh\left(\frac{2\pi d_s}{L_p}\right) \tag{4}$$

Initial slope ($tan\,\theta$) is a parameter, which also considered effect the stability of breakwater. The steeper slope is indicated contributes larger erosion on the slope than the more gradual slope due to severe wave attacks. In order to identify its effect to the present model, especially the effects to the relationship between the relative of horizontal eroded berm, B_e/D_{50} and stability number, N_s, thus three initial seaward slopes namely 1 : 1.25, 1 : 1.50, and 1 : 1.70 were arranged.

The values of significant wave height (H_s) and periods of peak energy density (T_p) are respectively obtained using Rayleigh distribution and spectrum analysis by employing the FFT

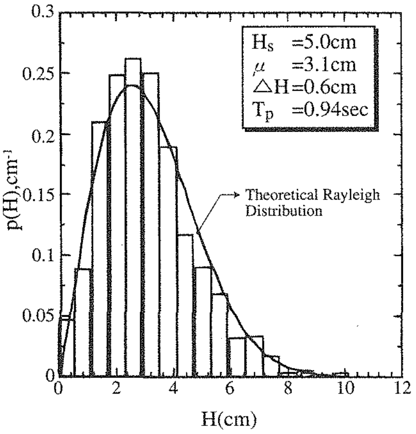

Fig. 3. A sample of theoretical and experimental wave height distribution

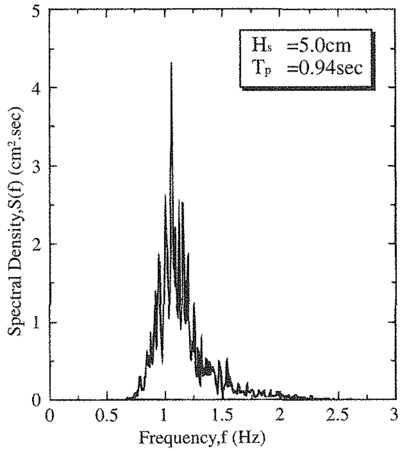

Fig. 4. A Sample of Wave Spectrum

(Fast Fourier Transform). Result samples from those two methods are presented in **Fig. 3** and **Fig. 4**.

4. Results and Discussions

4.1 Effect of relative berm crest height

Fig. 5 shows the relative horizontal eroded berm, B_e/D_{50} as a function of stability number. Some of Hall and Kao's [4] data, which have similar characteristics with the present study data, (h/d_s=1.06 and $tan\ \theta$=1 : 1.25, see Table 1) is also plotted in this figure as comparison data. It is seen that there is a good agreement position between the present data and Hall and Kao's data, where both are lied in a similar line of h/d_s=1.06.

Fig. 5 also provides the information that h/d_s effects significantly the relationship, where B_e/D_{50} increases with decreasing h/d_s. This phenomenon can probably be explained in physical way, that when the berm crest height (h) is decreasingly lower above water depth (d_s) or h/d_s is smaller, the incoming waves to the berm will be bigger overtopped, then finally results the bigger eroded as well.

Fig. 6 shows the relationship between the relative vertical eroded berm, Y_e/D_{50} and the relative horizontal eroded berm, B_e/D_{50}.

Relative horizontal eroded berm was determined as a function of the relative vertical eroded berm because during the analysis it was found that this relationship has a better correlation comparing with the relationship between B_e/D_{50} and N_s. With this relationship it is clearly shown the value of h/d_s differs distinctly from each other, as h/d_s increases, Y_e/D_{50} also increases. Moreover, this figure also provides information where the relationship meets the following requirements :

- For B_e/D_{50}<5, the function is almost linear.
- For B_e/D_{50}>5, the value of Y_e/D_{50} on a certain value of h/d_s seems to be constant. This case is may be happened due to the erosion on the vertical direction (Y_e) has stopped or Y_e has reach the equilibrium condition, although B_e and L_d are still accruing.

Fig. 7 shows the relationship between $L_d/(D_{50,m})$ and N_s. It can be seen that h/d_s also affects

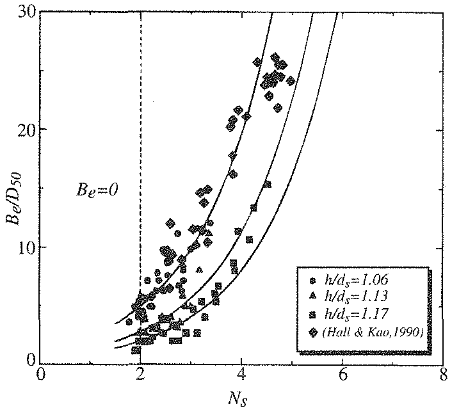

Fig. 5 Effect of h/d_s on B_e/D_{50} and N_s relationship

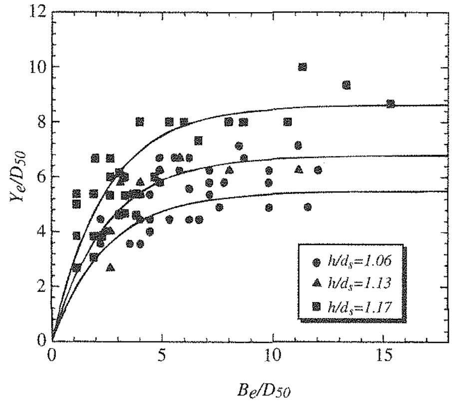

Fig. 6 Effect of h/d_s on Y_e/D_{50} and B_e/D_{50} relationship

this relationship where $L_d/(D_{50}.m)$ increases with decreasing h/d_s.

4.2 Effect of wave steepness

To evaluate the effect of wave steepness to the relationship, the values of wave steepness were collected on the constant conditions of relative berm crest height and initial slope that is h/d_s =1.06 and $tan\ \theta$= 1 : 1.25.

Fig. 8 shows the example seaward profile of breakwater due to the effect of wave steepness. Based on this figure, it can be seen that the bigger horizontal eroded occurred on the bigger effect of wave steepness. Interesting result is also shown that even though wave steepness is different between one and another, the end point of vertical eroded berm. Then it can be concluded that the wave steepness has no significant influence on the increment of vertical eroded berm.

Fig. 9 shows the relationship between the relative horizontal eroded berm, B_e/D_{50} and stability number, N_s under the effect of wave steepness in a constant h/d_s and $tan\ \theta$. It can be seen that, although the divergence between one and others of steepness effect seem rather small, the effect of wave steepness to the relationship still can be distinguished.

Furthermore, the value of B_e/D_{50} increases with decreasing wave steepness. Thus, it can be

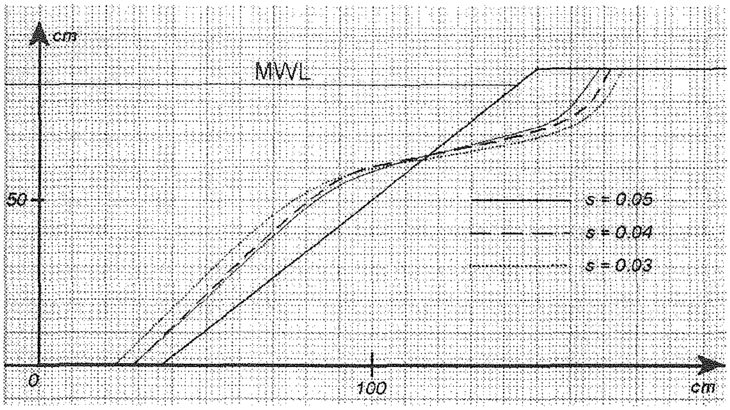

Fig. 8 Example of seaward profile of breakwater

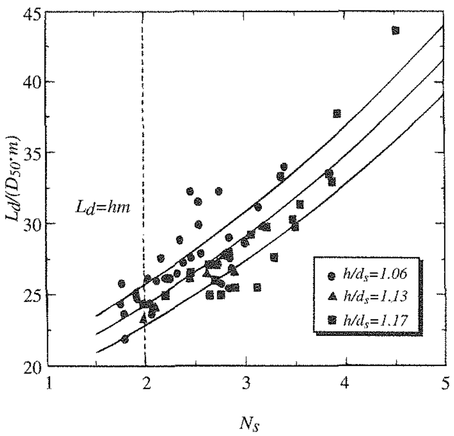

Fig.7 Effect of h/d_s on $L_d/(D_{50}.m)$ and N_s relationship

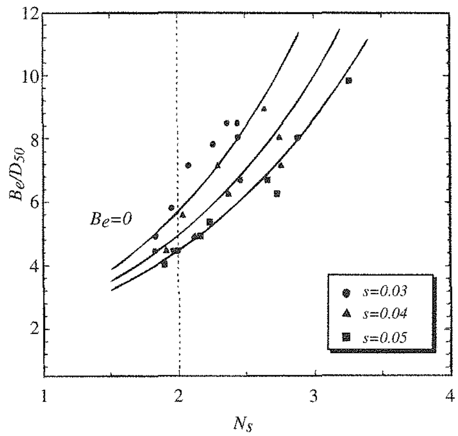

Fig. 9 Effect of s on B_e/D_{50} and N_s relationship

said that in this case, the waves of long period were more effectively causes the erosion than short period waves.

During the analysis, the effect of steepness has been observed for the relationships between Y_e/D_{50} and B_e/D_{50}, and $L_d/(D_{50}.m)$ and N_s, however, there were not any significant effects founded. Thus, the graphic relationships are not necessary to be shown here.

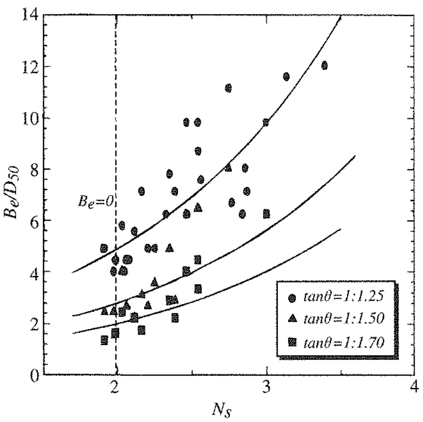

Fig. 10 Effect of $tan\,\theta$ on B_e/D_{50} and N_s relationship

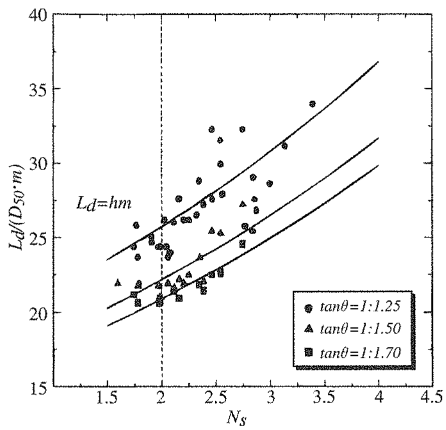

Fig. 11 Effect of initial slope on L_d/D_{50} and N_s relationship

4.3 Effect of initial seaward slope

The initial seaward slope after some analysis, in fact only significantly affects the relationship between B_e/D_{50} and N_s, *and* $L_d/(D_{50}.m)$ and N_s. **Figs. 10** and **11** show their relationships. In **Fig. 9** can be clearly seen that steeper slope contributes larger erosion, where B_e/D_{50} increases by increasing initial seaward slope. The same condition is occurred on the toe width, where L_d in $L_d/(D_{50}.m)$ will be longer by increasing the initial seaward slope.

4.4 Relationship Formulas

Based on analysis above, a regression analysis using minimization techniques in order to determine the relationship between the dependent and independent parameters was undertaken. Eqs. 5, 6, and 7 are the relationship equations found from the regression analysis.

$$\frac{B_e}{D_{50}} = A \cdot e^{B \cdot N_s} \tag{5}$$

where,

$$A = 22.21 \left(\frac{h}{d_s} \right)^2 - 56.08 \cdot \frac{h}{d_s} + 2.41 (m)^2 - 8.71\, m + 44.05$$

$$B = 100 s^2 - 14\, s + 1.10$$

$$\frac{L_d}{D_{50}} = mC \cdot e^{0.179 \cdot N_s} \tag{6}$$

where,

$$C = 12.22\,m^2 - 43.61\,m - 97.40\left(\frac{h}{d_s}\right)^2 + 199.03\frac{h}{d_s} - 30.11$$

$$\frac{Y_e}{D_{50}} = D \cdot \left[1 - Exp\left(-0.4 \cdot \frac{B_e}{D_{50}}\right)\right] \tag{7}$$

where,

$$D = \left[240.26 \cdot \left(\frac{h}{d_s}\right)^2 - 507.60 \cdot \frac{h}{d_s} + 273.60\right]$$

5. Conclusion

The results of the present study are subjected to the following limitations with regard to the conditions of wave features and structure model : The generated waves should be non-breaking irregular waves at the toe of breakwater. The formulas introduced in this paper are valid for $1.2 \geq h/d_s \geq 1.0$, and $0.05 < s < 0.03$, and $2 < N_s < 5$. Although the results of this study may be applicable for breakwaters of 1 : 1.70 slopes and steeper, the conclusions need to be experimentally justified for slopes other than 1 : 1.25, 1 : 1.50, and 1 : 1.70 as used in this study. With the above limitations, the conclusions of the study may be summarized that, the practical design formulas have been improved for the seaward slope stability of dynamically stable breakwater under irregular wave attack. The relative berm crest height (h/d_s), steepness (s) and initial seaward slope ($\tan\theta$) are important parameters should be considered especially to design a stable profile of the seaward slope of low berm crest height dynamically stable breakwater under irregular wave attack.

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不規則波が作用する離岸堤の動的平衡断面に関する研究

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摘　　要

石積みの離岸堤に波が作用したとき，堤体は動的に平衡な断面にリフォームされる．本研究は，小段付き離岸堤に不規則波が作用したとき，平衡断面形状変化を実験的に調べた．その結果，水平侵食長さ，鉛直侵食深さ及び底面移動長さが堤体の初期前面勾配，波形勾配をパラメーターとして安定係数の関数として表すことができた．