New Formula of Stability Number of Wave Breaker Armour Units for Non-breaking Wave Effect Irregular Wave

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***Abstract*—It is common in the study of breakwater to evaluate variables that influence the stability number (Ns) and the breakwater armour units such as height of wave, wave period, wave angle direction, layer coefficient, and porosity. This research aims to obtain a new formula for the stability number of breakwater armour units ($H_s/\Delta D_n$ or Ns) for non-breaking wave effect irregular wave that can be applied for all types of breakwater armour units. It is based on a scaled physical model, especially undistorted model. The analysis of the wave and regression were conducted using zero up crossing data and least square method respectively. The New Stability Number (Ns) is a function of Porosity (P_o), Level of Damage (d), Number of Wave (N), Coefficient of Layer (C), Angle of Wave Approach (Cos Θ), and Surf Similarity (ξ_Z). The evaluation of the result has been made by comparing with existing formulas such as Hudson, Modified Hudson and Van der Meer. The result shows that the proposed stability number (Ns) is the smallest compared to the one obtained from the formulas of Hudson, Modified Hudson and Van der Meer, so it is the most reliable or optimum stability number.**

***Index Terms*—Armour units, breakwater, non-breaking wave, stability number.**

I. INTRODUCTION

Failure of a structure can be seen from many aspects such as design, construction and environment. In terms of design, the structure should be save and economic. In relation to breakwater structure, it is important to consider how reliable the formula is. For example the failure of breakwater at Sines Harbour in Atlantic beach, Portugal was caused by not considering long period or irregular waves, ignoring wave grouping, and not considering the influence of wave reflection [1]. When implementing Hudson's formula for the stability number of the breakwater layer units, it is required to multiply the height of wave with 1.06 of the existing wave in order to keep the stabilisation of structure [2].

Hudson's formula [3] was developed from Iribarren's formula. In analysing the stability of breakwater layer only some dominant variables are considered such as weight of breakwater, height of significant wave, mass density, relative mass density, slope angle and coefficient of stability (K_D). The value of the stability coefficient is very relative as this value covers variables of roughness of layer surface base including permeable or impermeable, the character of interlocking, form of material and method of random and arranged placement. These variables are not yet clearly interpreted, only some variables are considered such as variables of random and arranged placement. Besides that, if it is related with the value of stability number (Ns), then the magnitude of the stability number only depends on value of the damage coefficient (K_D) and angle of structure slope. From the said formula it can be seen that there are some variables that are still ignored such as damage level, wave period, number of waves, permeability and wave approach angle.

For non-breaking wave *(surging*), the stability number of breakwater layer units is proportional to the permeability, damage level, number of waves, structure slope angle, and number of Iribarren *(surf similarity).* This formula considers wave attack variables such as height of wave, number of waves, wave period, and wave defence variables such as structure slope angle and permeability [4]. The study of Van der Meer [5] shows that permeability will influence breakwater stability, based on the size of rock and filter layer including the core. The coefficient of permeability that is used here does not have physical meaning but it is included in the formula to make sure that the structure permeability has been considered. The result of the study shows that if the value of permeability is bigger than the stability of breakwater is bigger as well. The magnitude of permeability is about 0.1 to 0.6, and can increase the stability by around 35 %. There is no guidance to select exact permeability value.

Furthermore, the result of study shows that with big scale testing where the stability number is proportional to the upgrading stability factor, the factor of stability of Van der Meer that depends on permeability, level of damage, number of waves, and structure slope angle will be inversely proportional to the number of Iribarren [5]. This formula is combined with the formula of Van der Meer and is only used for rock material. From the proposed formula it can be seen that some variables are still ignored such as wave approach angle.

The magnitude of stability number (Ns), besides depending on the value of damage coefficient (K_D) and structure slope angle, it also depends on the wave approach angle [6]. This formula is modified from Hudson's formula, where the variable of wave approach angle has influences on the stability. The result of the study explains that if the wave approach angle is big, the damage sustained by the artificial breakwater is greater than angle of the natural rock breakwater.

According to the discussion of various formulas above, then besides variables of wave type, wave period, number of

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waves and wave approach angle, permeability is still considered partially by previous researchers. But variables of porosity and layer coefficient that interpret the character of interlocking are not yet considered by previous researchers [7].

The aim of this study is to obtain a formula for stability number of breakwater layer units caused by non-breaking wave. The objective of this study is to test the variables which influence the stability number (Ns) of the breakwater layer units, namely height of wave, wave period, structure slope angle, number of waves, level of damage, wave approach angle, coefficient of layer, and porosity.

II. Research Methodology

A. Research Implementation

Method used in this research is using hydraulic physical model in wave basin with Undistorted model, in which length scale used is 1: 65. As the result, the scale effect can be neglected because the Reynolds number analysis (R_n) = (3,32 × 10^4 - 5,75 × 10^4) is greater than Reynolds number (R_n) = 3 × 10^4 [8].

Tests have been done using different variables such as slope of 1:1 and 1:2; wave direction angle of 0^0, 15^0, and 30^0; number of wave (N) of 1000 and 2500; height of wave of 12 cm and 14 cm; and time period of 1.1 second and 1.4 second. Every selected parameter was tested three times. Required time for condition of non-breaking wave was 3,516 minutes. After fulfilling every selected variable, 144 pieces of data were collected.

B. Analysis of Laboratory Wave Data

The height of significant wave and wave period were calculated using zero up crossing method. At first, average elevation of water surface was decided according to the water surface fluctuation, where the water surface was defined as zero line. Then the curve of wave was traced from the beginning until the end.

The height of significant wave was H_{33} or average height of 1/3 of the highest value of wave data. Same method was used for period of wave.

C. Determination of Porosity (P_o) and Coefficient of Layer (C)

Porosity (P_o) is comparison between void volumes with total volume as written in following equation.

$$P_o = \frac{V_v}{V_{tot}} \quad (2.1)$$

where:

P_o = porosity
V_V = void volume
V_{tot} = total volume

This test was done for tetrapod, rectangular, and broken stone samples, each sample was in a dry condition. The coefficient of layer (C) was obtained using the following equation [9].

$$C = \frac{t}{n \times Dn} \quad (2.2)$$

TABLE I: Types of Important Variable

No.	Type of Variable	Notation	Formula	Unit
1	Height of significant wave	H_s	~	m
2	Wave period (zero up crossing)	T_z	~	second
3	Angle of structure slope	α	~	degree
4	Relative mass density	Δ	$\left(\frac{\rho s}{\rho w} - 1\right)$	~
5	Surf similarity	ξ_Z	$\xi_Z = \left(\frac{\tan\alpha}{\sqrt{Sz}}\right)$	~
6	Wave Steepness (H/L)	S_Z	$Sz = \frac{2\pi Hs}{gT_Z^2}$	~
7	Mass density of breakwater	ρ_s	~	kg/m^3
8	Mass density of water	ρ_w	~	kg/m^3
9	Nominal diameter	D_n	~	m
10	Weight of breakwater	W	~	kg
11	Porosity	P_o	~	percent
12	Level of damage	d	~	percent
13	Number of wave	N	~	~
14	Coefficient of layer	C	~	~
15	Angle of wave approach	θ	Cosθ	degree

where:

C = coefficient of layer
D_n = nominal diameter
t = thickness of layer
n = number of layer

D. Derivation of Formula of Stability Number

The method used in the analysis was Buckingham method (phi theorem). The result of the analysis of non-dimension values can be seen in Table I.

Variables that have influences on the stability are functional relationship between the stability number with surf similarity, porosity, level of damage, number of waves, coefficient of layer, and wave approach angle. Based on result of selection of variables that influence the analysis of stability is non-dimension variable.

In term of mathematics, functional relationship between Ns with variables of P_o, d, N, C and Cot α, Cos θ, ξ_z , can be stated as follows:

$$Ns = f(P_o, d, N, C, \text{Cot}\ \alpha, \text{Cos}\ \theta, \xi_z) \quad (2.3)$$

1) Formulation non-linear regression equation model

To get non-linear regression equation model, the least square method is used, with the help of MathLab program version 6.50 [10]. This analysis is used to know the relation or the influence between free variable and non free variable, where free variable is (P_o, d, N, C, Cot α, Cot θ, Δ, ξ_z) , and non-free variable is Ns or Hs/Δ.Dn. If non-free variable is Y and free variable is $X = [X_1\ X_2\ \ldots\ X_k]$ it means the relation form is non-linear and can be written as follow:

$$Y = f(X, \beta) + \varepsilon \quad (2.4)$$

With $\beta = \beta_1, \beta_2, \ldots, \beta_p$ and ε are assumed in normal distribution with mean (0) and variation σ^2 or ε ~ N(0, σ^2). If the observed data (n) in form of:

$$Y_u, X_{1u}, X_{2u}, \ldots, X_{ku}. \quad (2.5)$$

For u = 1, 2, ..., n we can write the model into it's alternative form:

$$Y_n = f(X_{1u}, X_2u, \ldots, X_{ku,}\ \beta_1, \beta_2, \ldots, \beta_p) + \varepsilon_u \quad (2.6)$$

With ε_u are residual to u, u = 1, 2, …, n. This can be summarized into:

$$Y_n = f(X_u, \beta) + \varepsilon_u \quad (2.7)$$

The Sum square residual for non-linear model defined as:

$$S(\beta) = \sum_{u=1}^{n} \left(Y_u - f(X, \beta)\right)^2 \quad (2.8)$$

Because (Y) and (X) represent observed variabel hence it is fixed and its sum square represent the function of β. *A least square estimate* for β symbolized with $\hat{\beta}$ value which β minimum the S(β).

To find the least square estimate ($\hat{\beta}$) we have to diferentiate the equation (2.8) relatively to β . This will result in (n) normal equation which have to solved to get $\hat{\beta}$. This normal equation have the form of :

$$\sum\left(Y - f(X, \beta)\right)^2 \left[\frac{\partial f(X, \beta)}{\partial \beta_i}\right] = 0 \quad (2.9)$$

with i = 1, 2, ..., p whereas the scale inside the parenthesis is derivative of f (X, β) toward all β changed with $\hat{\beta}$ which have the same subscript.

The method which is used to estimate the parameter β is a Taylor's series method. For example, a model which formulated (postulated) take the form of model (3). For example $\beta_{10}, \beta_{20}, \ldots, \beta_{p0}$ are initial values for $\beta = \beta_1, \beta_2, \ldots, \beta_p$ in this case we specified randomly and picked a value between 0 and 1.

These initial values will be expected being updated in the iteration process. In this case, decomposition of

Taylor's series method for f(X_u, β) around point $\beta_0 = \beta_{10}, \beta_{20}, \ldots, \beta_{p0}$ and limited until second derivative.

Iterative process was done until it obtained a convergent value. On every step of iteration prosedures, S value (β) was counted to see if there is a decrease on its value and stop if the solution reach its stability. If the iteration process does not reach a stabil value, the sum square will continue to rise indefinitely (divergent condition).

2) Goodness of fit test

a) Determination coefficient (R2)

Determination Coefficient has the character that if the points of scatter diagram were located closer to regression line, the price of determination coefficient (R2) is closer to price 1 (one). In the contrary, if points located farther from the regression line, it is closer to 0 value (zero).

b) (F) and (t) statistic test

(F) statistic test was intended to evaluate if all independent variable or free variable which was included in the model have the together influence toward dependent variable or non-free variable. Whereas, (t) statistic test was intended to know each independent which give contribution toward regression model.

III. Analysis and Discussion

A. Height and Period of Wave

Based on the result of the tests, 144 pieces of data for non-breaking wave type were obtained. The magnitude of significant height and period of wave used in this research were based on zero upcrossing method.

The calculation of height of wave, period of wave, and damage for non-breaking wave can be seen in Table II.

TABLE II: Calculation of Height of Wave, Period of Wave, and Damage

No	Testing Material	Height of Wave			Period of Wave			Damage			Sensor Nb.
		H_{max}	H_{min}	H_{ave}	T_{max}	T_{min}	T_{ave}	d_{max}	d_{min}	d_{ave}	
1	Tetrapod	0.1306	0.0765	0.1036	1.757	1.11	1.4333	7.41	0.21	3.81	8
2	Rectangular	0.1059	0.0701	0.088	1.647	1.13	1.3883	4.88	0.42	2.65	9
3	Rock	0.1481	0.0783	0.1132	1.703	1.12	1.4117	6.84	0.61	3.73	10

B. Porosity and Coefficient of Layer of Testing Material

Based on testing of porosity for each testing material, i.e. broken rock, rectangular, and tetrapod, values of 45.764 percent for broken rock, 48.114 percent for rectangular, and 62.888 percent for tetrapod were obtained.

The coefficient of layer for broken rock is (C) = 1.01163 with weight (W) = 0.170 kg, mass density (ρS) = 2508.82 kg/m ^{3}; nominal diameter (Dn) = 0.041m, thickness of layer (t) = 0.083 m (two layers).

The coefficient of layer for rectangular is (C) = 1.02674 with weight (W) = 0.234 kg, mass density (ρS) = 2500 kg/m ^{3}; nominal diameter (Dn) = 0.0955 m, thickness of layer (t) = 0.1018 m (two layers).

The coefficient of layer for tetrapod is (C) = 1.31652 with weight (W) = 0.067 kg, mass density (ρS) = 2208.02 kg/m ^{3}; nominal diameter (Dn) = 0.03143m, thickness of layer (t) = 0.0828 m (two layers).

C. Result of Analysis of Model Formulation

1) Model formulation of stability number

The functional relationship between Ns with variables (Po, d, N, C , Cot α , Cos θ , ξz) is already stated in Equation (2.3):

$$Ns = f\,(P_o, d, N, C, \text{Cot}\ \alpha, \text{Cos}\ \theta, \xi_z) \quad \textbf{(3.1)}$$

The analysis of smallest power method regression was done using the packet program of MathLab version 7.

Based on the analysis above, it is determined that a model of non-linear regression equation for non-breaking wave condition is as follows:

$$\text{Ns} = 0{,}0874 \times P_o^{-4{,}1580} \times \text{d}^{0{,}0486} \times \text{N}^{-0{,}0278} \times \text{C}^{7{,}3935}(\cos\theta)^{0{,}5385} \times \xi_z^{-0{,}4640} \quad \textbf{(3.2)}$$

where:

Ns = number of stability
ξ_z = surf similarity
d = level of damage
P_o = porosity
C = coefficient of layer
N = number of wave
θ = angle of wave approach

The new formula is applied on two types of armour units i.e. natural rock (broken stone) and tetrapod. While the results from applying the new formula are as follow.

For new formula of armour units of natural rock (broken rock) with structure slope angle of (α) = 1 : 1 (cot 1), 1 : 1.5 (cot 1.5), 1 : 2.5 (cot 2.5) and 1:3 (cot 3), the stability numbers obtained were Ns = 1.107, Ns = 1.3362, Ns = 1.6935 and Ns = 1.843. For Hudson formula of armour units with the same structure and slope, the stability numbers obtained were Ns = 1.3572, Ns = 1.5536, Ns = 1.842, and Ns = 1.9574. For modified Hudson formula of armour units with the same structure and slope, the stability numbers obtained were Ns = 1.3572, Ns = 1.5536, Ns = 1.842 and Ns = 1.9574. Van der Meer formula of armour units with the same structure and slope, the numbers of stability were obtained as Ns = 1.123, Ns = 1.3207, Ns = 1.6201 and Ns = 1.7427.

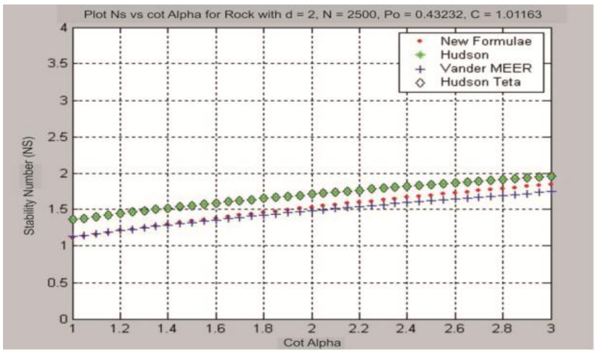

Fig. 1. Comparison of values of (Ns) for natural rock (broken rock) armour units.

According to the data above, it can be concluded that for structure slope angle less than (cot 1.25), the new formula is more reliable compared to the formula of Van der Meer; but with structure slope angle more than (cot 1.25), the formula of Van der Meer is more reliable than the new formula. However, the new formula is more reliable compared to the formulas of Hudson and Modified Hudson. The stability number of the formulas of Hudson and Modified Hudson have the same value when the wave approach angle is zero. The comparison of results of values of (Ns) for armour units of natural rock with zero wave approach angle can be seen in Fig. 1.

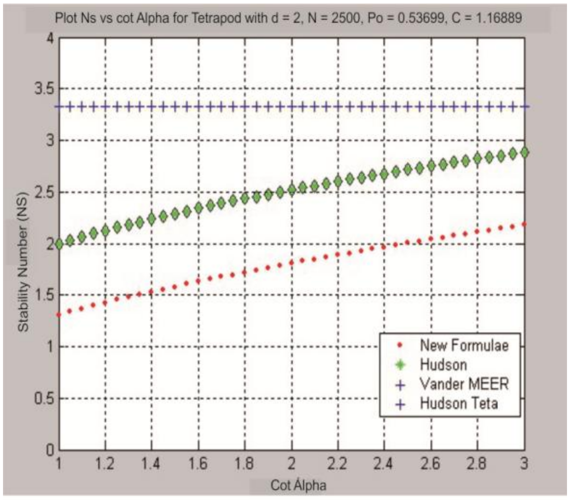

Fig. 2. Comparison of values of (Ns) for tetrapod armour units.

For the new formula with tetrapod armour units and structure slope angle of (α) = 1 : 1 (cot 1), 1 : 1.5 (cot 1.5), 1 : 2.5 (cot 2.5) and 1:3 (cot 3), the stability numbers obtained were Ns = 1.3079, Ns = 1.5787, Ns = 2.0009, and Ns = 2.1776. For Hudson's formula of armour units with the same structure and slope, the stability numbers obtained were Ns = 2, Ns = 2.2894, Ns = 2.7144 and Ns = 2.8845. For the modified Hudson formula of armour units with the same structure and slope, the stability numbers obtained were Ns = 2, Ns = 2.2894, Ns = 2.7144, and Ns = 2.8845. For the formula of Van der Meer with the same structure and slope, the stability numbers obtained were Ns = 3.329, Ns = 3.329, Ns = 3.329, and Ns = 3.329.

It can be concluded that for the new formula with structure slope of (cot 1.25) is more reliable if it is compared with the formulas of Van der Meer, Hudson and Modified Hudson. The stability number of the formulas of Hudson and Modified Hudson have the same value as the wave approach angle is zero. The comparison of the results of the values of (Ns) for armour units of tetrapod with zero wave approach angle can be seen in Fig. 2.

2) Test of Statistic

a) Validation of model

The validation of the model for non-breaking wave has obtained a residual average (difference between observation points with points of the model) of average = 0.00056, minimum = 0.0004, and maximum = 0.3445. This difference can be seen in Fig. 3.

3) Test of goodness of fit model

b) Coefficient of determination (R2)

The coefficient of determination means that if points of distribution of the diagram are located closed to the regression line then the value of determination coefficient (R2) is almost 1 (one). Otherwise, if those points are away from the regression line then the value is almost 0 (zero). Based on the calculation for non-breaking wave, the determination coefficient (R2) is 0.954. This result shows that the model of wave regression is good, because the value of the determination coefficient (R2) is almost 1 (one).

c) Test of statistic (F)

Test of statistic (F) means to evaluate wether all independent variables which are involved in the model have same influences as the dependent variables. The number of

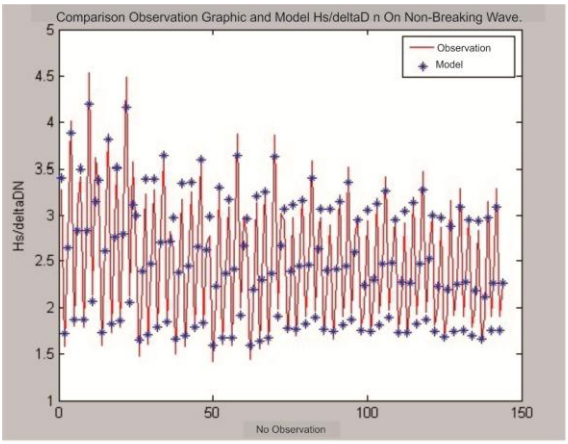

Fig. 3. Comparison between observation and model.

Variables was n = 144 and the number of variable k = 6 for non-breaking wave. The result of the analysis for non-breaking wave yields Fcal = 280.771 bigger than Ftable = 1.77. This result shows that all independent variables have the same influences as the dependent variables for non-breaking wave.

d) Test of statistic (t)

The test of statistic (t) is a test to find out how each independent variable contributes to the regression model. The result of analysis for non-breaking wave has yielded porosity (Po) = 0.103, level of damage (d) = 4.028, number of wave (N) = -344.785, coefficient of layer (C) = 2.827, angle of wave approach (Cos θ) = -0.159, angle of structure slope (Cot α) = -0.857, iribarren number (ξ_Z) = -4.998. From this data if compared with ttable = 1.96, it shows that for non breaking wave the variables which contribute the least are porosity and angle of wave approach.

IV. Conclusions

The formula of the stability number of the layer units of breakwater for non-breaking wave is Ns = 0,0874 $\times P_o^{-4,1580} \times d^{0,0486} \times N^{-0,0278} \times C^{7,3935} (\cos\theta)^{0,5385} \times \xi_Z^{-0,4640}$.

Where, Ns = number of stability, P = porosity, d = level of damage, N = number of wave, C = coefficient of layer, cos θ = angle of wave approach, cot α = angle of structure slope, ξ_z = tan α $/(H_s/L_o)^{1/2}$, $L_o = gT_z^2/2\pi$, H_s = height of signicant wave, L_o = length of wave, T_z = period of wave.

b. The value of the coeficient determination for non-breaking wave (R^2) is 0.954. It shows that the regression model for non-breaking wave is good, because the value of the coefficient of determination (R^2) is almost 1 (one). The result of analysis for non-breaking wave yields Fcal = 280.771 bigger then F_{table} = 1.77. This result shows that all independent variables have the same influence as the dependent variables. Otherwise the test of statistic (t), for non-breaking wave yields porosity (P_o) = 0.103, level of damage (d) = 4.028, number of wave (N) = -344.785, coefficient of layer (C) = 2.827, angle of wave approach (Cos θ) = -0.159, angle of structure slope (Cot α) = -0.857, iribarren number (ξ_Z) = -4.998. From this data, if it is compared with t_{table} = 1.96, porosity and angle of wave approach are less to give contribution to non breaking wave.

The results of the evaluation of the new formula compared to the formulas of Hudson, Van der Meer and modified Hudson for types of armour units i.e. broken rock (natural rock) and tetrapod shows that the stability number (Ns) of the new formula is the lowest stability number. This means that the new formula is more reliable than Hudson's formula, Van der Meer's formula and modified Hudson's formula when the angle of the structure slope is between (1:1) (cot 1) and 1:3 (cot 3).

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