CHAPTER 132

THE RELATIONSHIP BETWEEN WAVE LENGTH AND WEIGHT OF ARMOUR BLOCKS

by

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ABSTRACT

Every coastal engineer realizes that the weight of armour blocks decided by Hudson's formula is safe enough for short steep waves, however, suffering damage from long period swells, even though the incidental wave height is the same. Several corrections have been made and submitted to ICCE as well as in other occasion. The authors try to explain analytically the influence of wave length on the design weight of armour blocks and justify by much of experiments in order to offer new formula and graphs for practical application.

INTRODUCTION

Armour blocks used as effective protection on seashore or structures, the wave energy absorbed due to its surface roughness, porosity and stability, when wave attacked. While an appropriate design of weight of armour unit, it is difficult to derive from theory because of many factors and conditions which conducted to

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select it. [1]. Generally, the most frequently used formla, today, modified by Hudson(1959) and given by

$$W = \frac{\rho_s \quad g \quad H^3}{K_d \left(\frac{\rho_s}{\rho} - 1 \right)^3 \cot \theta} \text{---------------------------------} (1)$$

Where: W = armour blocks design weight

ρ_s, ρ = mass density of blocks and sea water

K_d = stability number

θ = slope angle of riprap facing offshore.

H = wave height at the location of the breakwater without wave breaking.

Its popularity comes from the limited variable of parameters and convinient to use.

From the viewpoints of safety and economics, design of armour unit used as shore protection, selection of the type, arrangements and its weight are the main consideration factors. Some armour unit, developed with spescial characteristis on its shapes and arrangements, but the weight of armour unit depends on equation (1), though it's safe enough for short waves, the damage occured from long waves occassionally. Especially for the waves caused by Typhoon on the sea area around Taiwan during summer and fall every year.

In accordance with the expiriences abovementioned, the authors try to consider wave period as an important factor as design of appropriate weigut of armour unit. For wave energy is under various influences, such as wave height, wave length, etc, ie, $E = \rho\ (\rho, g, H^2, L)$. From the point, the authors developed fundamently the design equation for armour blocks involved the effect of wave period on stability, and justified by experiments for practical applications.

Some papers described armour blocks effected under irregular waves recent time, mostly based on Hudson's formula [8][10], However, Pilarczyk and Boer (1983), [7][11], developed series of stability formula, under random wave attacked, of which the parameters included wave period, number of waves, armour grading, spectrum shap, groupiness of waves and permeability of the core, etc. The abovementioned subjects were rubble mound but not armour unit, especially for artificial armour unit was lacking to make mention of. The authors have performed much expiriences on study and design of coastal and harbor engineering, [2,3,4,5,6,9,12] and realized that it is necessary to develop an application formula from the fundamentally studies.

ANALYSIS

If the weight of armoured block, on slope angle θ, is W, density ρ_s in air, then the vertical component force is $(1 - \frac{\rho}{\rho_s}) W \cos\theta$, therefore, the drag force (F_1) of aumour block against incoming waves express as follows, if μ as friction coefficient between block and mound. (Fig. 1)

$$F_1 = (1 - \frac{\rho}{\rho_s}) W (\mu\cos\theta - \sin\theta) \text{------------------} (2)$$

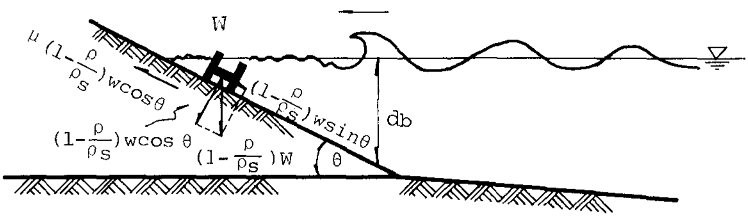

Fig. 1 Definition

The volume of armour block $V = \frac{W}{\rho_s g}$ is direct proportional to the cross sectional area of vertical direction of incoming waves, ie, proportional to $V^{2/3}$. if wave velocity v, then amour block attacked by wave force will be:

$$F_2 = C_D \rho v^2 \left(\frac{W}{\rho_s g}\right)^{2/3} \quad \text{------------------------------------(3)}$$

Irribarren derived from velocity of long wave, under the stability conditions of armour block, $F_1 \geq F_2$. ie,

$$\left(1 - \frac{\rho}{\rho_s}\right) W \left(\mu\cos\theta - \sin\theta\right) = \frac{1}{2} C_D \rho g H \left(\frac{W}{\rho_s g}\right)^{2/3} \text{----(4)}$$

Irribarren's formula

$$W = \frac{K' \mu^3 \rho_s g H^3}{\left(\frac{\rho_s}{\rho} - 1\right)^3 \left(\mu\cos\theta - \sin\theta\right)^3} \quad \text{--------------(5)}$$

Where, $K' = C_D^3/8\mu^3$, C_D = drag coefficient.

In the case of a definite cross section, μ, ρ_s, ρ, and θ may be regarded as constant but C_D will be different according to the shape of block and velocity.

Let

$$C = \frac{1/8 \ \rho_s g}{\left(\frac{\rho_s}{\rho} - 1\right)^3 \left(\mu\cos\theta - \sin\theta\right)} \quad \text{--------------------------(6)}$$

Consequently

$$W = C \, C_D^3 \, H^3 \quad \text{--(7)}$$

H is to be replaced by H' under water level

$$H' = \frac{\pi H^2}{L_o \left(\sinh \frac{2\pi d}{L} \right)^2} = \frac{2\pi H^2}{L \sinh \left(\frac{4\pi d}{L} \right)} \quad \text{------------------(8)}$$

Substitute (8) to (7)

$$W = C\, C_D^3\, H^6 \frac{(2\pi/L)^3}{\sinh^3 (4\pi d/L)} \quad \text{------------------------------(9)}$$

A non-dimensional expression is worked out as follows

$$\frac{W}{\rho_s\, g\, C_2\, C_D^3\, H^3} = \frac{(H/L)^3}{\sinh^3 (4\pi d/L)} \quad \text{------------------------(10)}$$

Where

$$C_2 = \left[\frac{\pi}{(\frac{\rho_s}{\rho} - 1)(\mu \cos\theta - \sin\theta)} \right]^3 \quad \text{--------------------(11)}$$

This will be a new formula if the coefficients μ and C_D are selected properly which authors will be measured by experiments.

EXPERIMENT INVESTIGATION

In order to verify under the conditions of the armour blocks attacked by incoming waves, equation (10) and (11) in which friction coefficient μ and drag coefficient C_D included.

The values of μ and C_D which is obtained by a series of experiments.

Test on friction coefficient, it measured friction between block and mound under water, due to the block considered as submerged condition when wave attacked. The test layout as Fig.2, the value

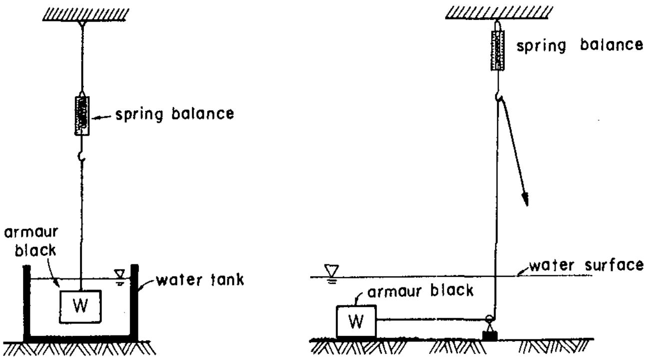

Fig. 2 Test of Friction Coefficient

of μ was obtained in average value of repeated experiments, as table 1.

Table-1 Friction Coefficient

Types	Wa (grf)	Ww (grf)	f (grf)	μ
HOLTRIPOD	74.9	42.5	61.67	1.4511
HEXA-HOLLOW TRI-LEG	46.1	30.1	50.00	1.6667
	67.4	45.0	75.00	1.6667
	84.9	57.5	83.75	1.4565
	110.9	72.5	103.57	1.4286
	137.6	79.1	119.45	1.5101

Another test on drag coefficient C_D, due to C_D related to reynoulds number of flow, authors tried to express volume of block as 2/3 order of characteristic length, using falling velocity experiment to find out the falling velocity, the instrument as Fig.3

and Photo-1, tested blocks namely Holtripod and Hexa-Hollow Tri-leg (Photo-2).

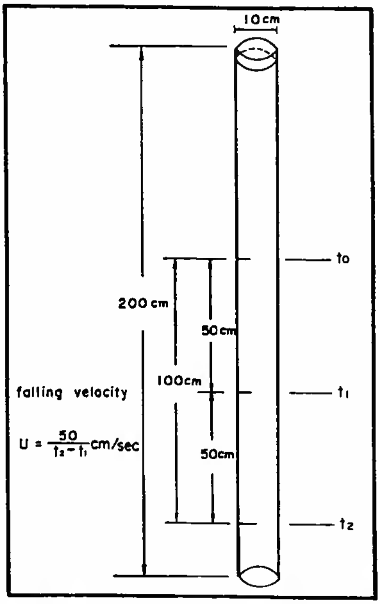

Fig. 3 Test on Falling Velocity

Photo-1 Test Instrument of Falling Velocity

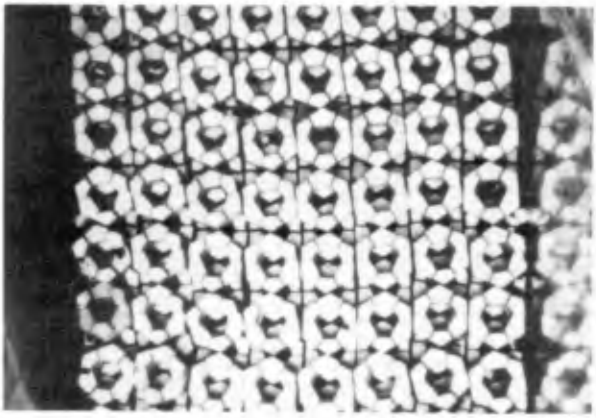

Photo-2 Model Blocks

The value of falling velocity of every model block obtained by measuring average of 30 repeated experiments, defferent weight of 4 blocks to be tested. These value were substitute to equation (13) and obtained C_D as table-2.

$$(\rho_s - \rho) \, g \, V = \frac{1}{2} \rho \, g \, v^2 \, C_D \, V^{2/3} \quad \text{------------} (12)$$

$$\Rightarrow C_D = 2 \left(\frac{\rho_s - \rho}{\rho} \right) g \, \frac{V^{2/3}}{v^2} \quad \text{------------} (13)$$

Where V = Volume of armour blocks

v = falling velocity

Using value of μ and C_D substitute to equation (10) and (11), it was calculated for varying relative depth d/L and wave steepness H/L and then plotted on theoretical curve in Fig. 4.

Table-2 Test Data of Drag Coefficient

Types	Wa (grf)	Ww (grf)	$\forall$ (cm^3)	γ (grf/cm^3)	U (cm/sec)	C_D
HOLTRIPOD	74.9	42.5	32.56	2.282	59.2445	2.286
HEXA-HOLLOW TRI-LEG	46.1	30.1	20.00	2.310	58.6809	2.024
	67.4	45.0	29.43	2.290	59.8402	2.180
	84.9	57.5	37.00	2.295	60.7334	2.293
	110.9	72.5	48.70	2.277	61.3556	2.428
	137.6	79.1	59.70	2.305	63.9164	2.447

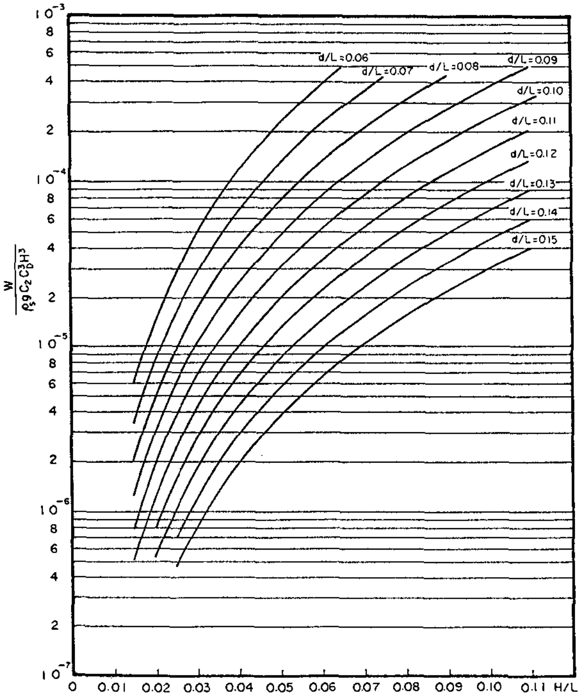

Fig. 4 Theoretical curve from eq. (10),(11)

To examine the results abovementioned, numerous experiments have been carried out in the regular wave flume of Tainan Hydraulics Laboratory, National Cheng-Kung University, Taiwan, as Photo-3. A channel 75 m long, 1.0 m wide and 1.2 m deep was equiped with a hingeplate wave generator near one end, wave height and period were measured with resistance gages, amplifier and recording oscillograph. The cross section of test model as Fig. 5, and test conditions as table-3.

Photo-3 Wave flume

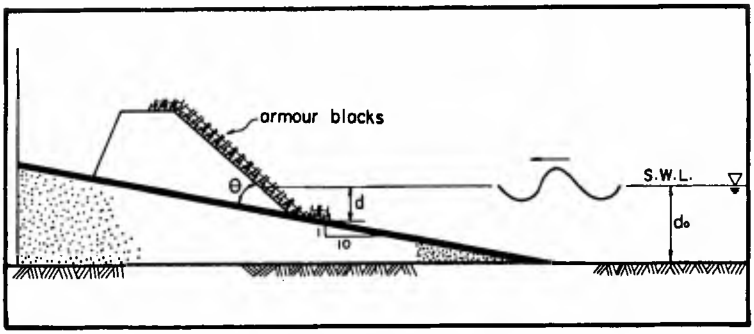

Fig. 5 Dike cross section in the wave flume

Table-3 Testing wave conditions

Testing wave Conditions	Wave Height Ho (cm)	wave periods T (sec)			water depth d (cm)	do
	10 — 26	1.0	1.3	1.6	15.0 cm	50 cm
		1.8	2.0	2.14	25.0 cm	60 cm

Fig. 6 shows the experimental results graphically simultaneously with calculated results of equation (11).

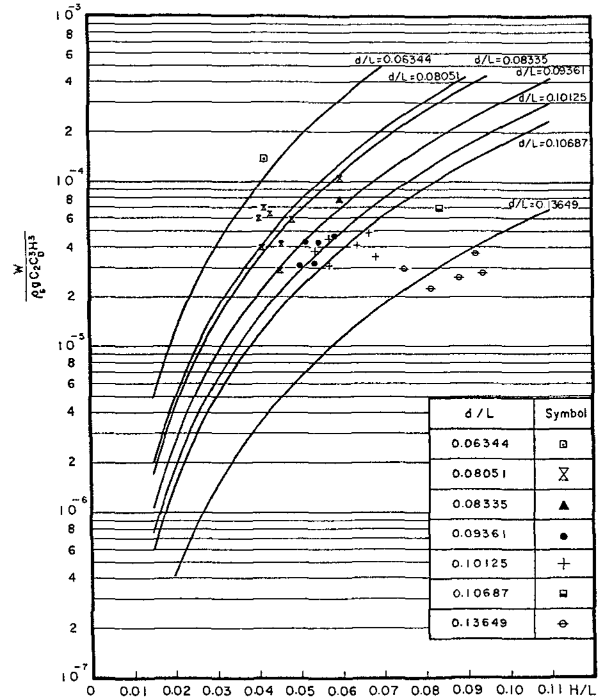

Fig. 6 Experimental result

CONCLUSIONS

1. According to abovementioned analytical calculations and experiments, equation (10) namely

$$W = \rho_s \; g \; C_2 \; C_D^3 \; H^3 \; (H/L)^3 / [\sinh (4\pi d/L)]^3$$ is to be applied

in practical design, while C_2 in equeation (11) is known for the same type of blocks and definite design profile, the coefficient μ and C_D should be determined by the experiments having been performed by the authors.

2. From the outcomes of calculations and experiments, it is obvious that wave length has marked effect on the design weight of armour blocks. In experiments, the influence of relative depth even greater than steepness. This reality reveals the fact that to determine the weight of armour block by wave height only will be deficient.
3. Based on this fundermental results, the authors will try to modify the value of drag coefficient C_D for futher studies, such that measuring flow condition of armour block under the design wave length, for practical application.

NOTE, DEFINITION

W	:	armour block design weight	(kgf/m^3)
ρ_s	:	mass density of block	(kg/m^3)
ρ	:	mass density of sea water	(kg/m^3)
K_d	:	stability of Hudson's formula	
θ	:	slope engle of riprap facing offshore	
H	:	wave height at the location of the breakwater without wave breaking	(m)
K'	:	stability coefficient of Irribarren's formula	
C_D	:	drag coefficient	
μ	:	friction coefficient between blocks and mounds	
g	:	acceleration due to gravity	(cm/sec^2)
Wa	:	armour block's weight in air	(grf)
Ww	:	armour block's weight in water	(grf)
f	:	friction force	(grf)
V	:	volume of armour block	(cm^3)
U,v	:	falling velocity	(cm/sec)
γ	:	specific Weight of armour blocks	(grf/cm^3)
H_o	:	wave height of testing wave conditions	(cm)
T	:	wave period of testing wave conditions	(sec)

d : water depth in the toe of dike (cm)

d_o : deep water depth of testing wave conditions (cm)

REFERENCES

1. Bruun, P. & Johannesson, P., Parameters Affecting Stability of Rubble Mounds. Journal of the Waterways Harbors and Coastal Engineering Division, No. WW2, P.141-164, 1976.
2. Benjamin P.J.Chi, F.L.W.Tang, S.W.Twu, J.S.Hwang, Design and model Studies for the New Types of Concrete Block. Taiwan Hydraulics Laboratory of National Cheng-Kung University, Taiwan, R.O.C. Published Bulletin No. 54, 1982.
3. Kuo-Quan Chen, Design of Coastal Protection for Hsieh-Ho Power Plant, Taiwan, R.O.C., China port & Harbor Engineering Consultants Report of 1972.
4. Kuo-Quan Chen, Planning and Design of Port of Shen-Ao oil Harbor, China Port & Harbor Engineering Consultants, Report of 1977.
5. Kuo-Quan Chen, Design of Breakwater of Port of Kai-Yuan, Taiwan, R.O.C, China Port & Harbor Engineering Consultants, Report of 1980.
6. F.L.W.Tang, S.W.Twu, R.C.Kao, J.M.Leu, The Hydraulic model Tests of Sheltering Effect and Structural Stability of Breakwaters for the Unloading Pier of 4th. Nuclear Power Plant, T.P.C.. Tainan Hydraulics Laboratory of National Cheng-Kung University, Taiwan, R.O.C., Published Bulletin No. 79, 1985.
7. J.W.Van der Meet & K.W. Pilarczyk, Stability of Rubble Mound Slopes under Random Wave Attack. Proc. of 19th. Conf. on Coastal Engineering, ASCE, PP. 2620-2634, 1984.
8. Katsutosh Tanimoto, Tadahiko Yagyu, Yoshimi Goda, Irregular Wave Tests For Composite Breakwater Foundations. Proc. of 18th Conf. on Coastal Engineering, ASCE, P.P. 2214-2162, 1982.
9. Kao, Ruey-Chy, H.H.Hwung, W.T.Hwung, The Studies of Stability and Dissipation Efficiency on the Hexa-Hollow Tri-Leg Concrete Block. Tainan Hydraulics Laboratory of N.C.K.L., Bulletin No.91, 1986.
10. Mol, A, R.L.Groeneveld, A.J.Waanders, Safety and Reliability of Breakwaters. Proc. of 19th Conf. on Coastal Engineering, ASCE, P.P. 2451-2466, 1984.

11. Pilarczyk, K.W. & Boer, K. den, Stability and Profile Development of Coarse Material and Their Application in Coastal Engineering. Delft Hydraulics Laboratory, Publication No.293, 1983.

12. Twu, S.W., Ruey-Chy Kao, C.T.Wen, Model Studies on the Concrete Block of New Patterns. Tainan Hydraulics Laboratory of N.C.K.L., Bulletin No.87, 1986.