

CHAPTER 165

Scale Effects on Stability and Wave Reflection regarding Armor Units

by

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ABSTRACT

In the studies on stability of the armor units and reflection from those, there are some indications on scale effects which are included in the results of small scale experiments. In this study, the fact has been confirmed with large wave flume test, and estimated the critical Reynolds Number where was no scale effect. And by this result on the stability of armor units, we can evaluate the results in small and middle scale test, and can correct the minimum weight of armor units. So we can design the breakwaters and seawalls rationally and economically.

However, it has not been confirmed the critical Reynolds Number where the influence of scale effect on reflection became negligible.

1. INTRODUCTION

In recent years, according to enlargement of thermal and atomic power station sited on coastal regions in Japan, breakwaters and seawalls which protect harbour facilities have been constructed in the areas with water depth of more than twenty meters, so it is necessary to design armor units rationally and economically.

Especially, the concrete Blocks (armor units) which are used for decreasing the wave force and reflection waves are main structural materials of breakwaters and seawalls, and in deeper areas, many volume of armor units are necessary and the proportion of their cost to the total construction cost is not few.

To design the armor units which are used for coastal structures, it is important to decide the shapes and weight of armor unit considering following three points of view,

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- (1) the hydraulic characteristics on stability to the wave force and wave reflection
- (2) the relation between the shape of armor units and the strength of concrete
- (3) the geological characteristic of sea bed soil in the site.

And in respect to the stability on armor units in (1), hitherto, it have been used to estimate the minimum weight of armor units with Hudson's¹⁾ formula. And in this formula, the coefficient K_D was conducted from the result of small scale tests on rubble mound.

However, since he proposed in 1958, now, from the review of actual damage examples, it has been pointed out that the value of K_D had been conservative a little.

And Thomsen²⁾ et al. (1972) have investigated about scale effects on stability of rubble mound and some kinds of armor units, and they have pointed out the existence. However, there is almost no study about scale effect on stability of armor units which are widely used in Japan. And in the investigation by Alf Torum³⁾ et al, they have conducted the model test about the revival of damaged breakwater in site. And they reported that there was no scale effect on the deformation of the cross section.

Thus, it has not been obtained to get a general consensus about this theme. And more data about this investigation are needed⁴⁾.

We have already investigated the scale effect on stability and reflection of armor units using model tests in small and middle wave flume.

Now, we are going to clarify the hydraulic characteristic of armor units with large wave flume, and to detect the hydraulic range where influence of scale effect on stability and reflection ratio become negligible. And if the range or criteria of these scale effect are made to clarify, various results obtained from small model tests will be more applicable.

2. EXPERIMENTAL METHOD AND DIMENSION

The small wave flume is 20m long, 0.6m high and 0.3m wide, and middle wave flume is 77m long 1m high and 0.9m wide. And we have investigated about scale effect in these wave flumes.

The weights of model armor units used in these tests ranged from 16g to 300g. The large wave flume is 205m long, 6m high and 3.4 wide. And it can generate a maximum of 2m wave height. Figure-1 shows the profile of this flume.

Figure-2 shows an example of cross section model in the test.

The each dimension of model cross section was decided with the scale in proportion to prototype. Three kinds of the armor units were used in the experiment and these weights range from 2kg to 50kg.

The armor units were put at random with two layers thickness.

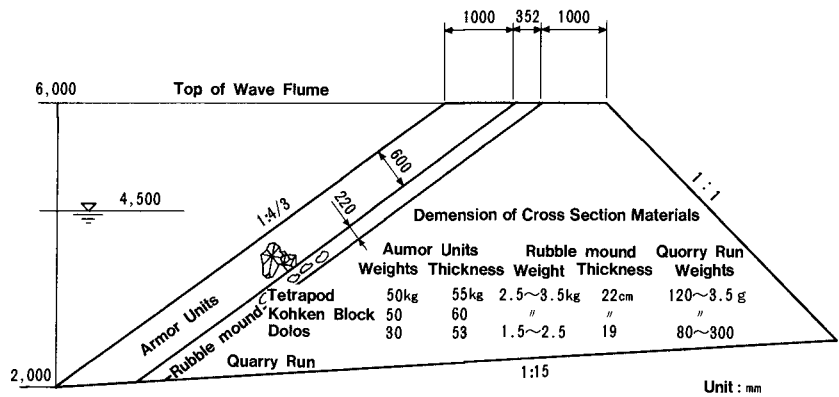
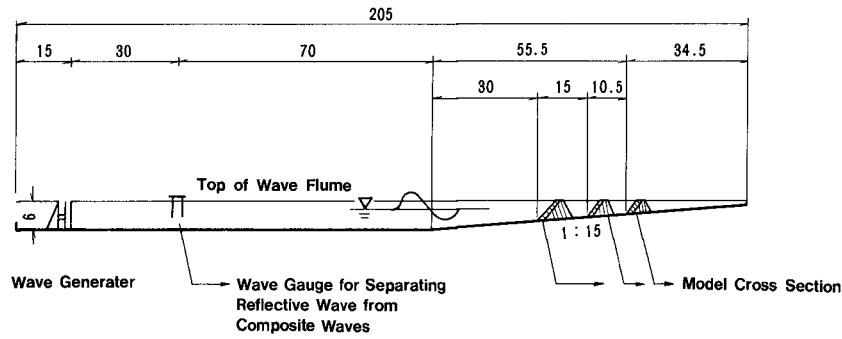


Figure-2 Model Cross Section

Figure-3 shows the shapes of the armor units in the experiment.

The experimental waves are regular waves which are broken at the toe of cross section. To avoid the occurrence of multi-reflection wave in flume, generated waves were stopped in about 2 minutes once a time and were continued to a setting duration. Incident and reflection wave height were measured by the method of separating reflection wave from composite waves at uniform water depth in the flume.

To decide the judgement criteria of the armor units stability, damage percentage was defined as the ratio of removed armor units numbers to the all armor units which were exposed to the wave actions. And the word "removed" means that an armor unit moved over the length of the armor unit height. And using this definition, the removal of up to one armor unit is considered to be zero damage in this experiment. Breaking wave heights H_b which cause 0% and 2% damage were searched in each model cross section.

Table-1 shows conditions of all experiments. The movements of armor units were observed by video camera and eyes. And run-up heights on surface layer were observed by wave height recorder which was set on the slope.

Test Dimension

Large Wave Flume 205m (Length) 6m (Height) 3.4m (Width)

Test Wave Wave Height up till Breaking Wave (max 1.85m)
Period 2.3sec~6sec

Name of Armor Units

Tetrapod	2.16kg	6.81kg	20.85kg	49.34kg
Dolos	1.99kg	9.66kg	29.37kg	
Kohken Block	2.05kg	6.61kg	19.65kg	49.58kg

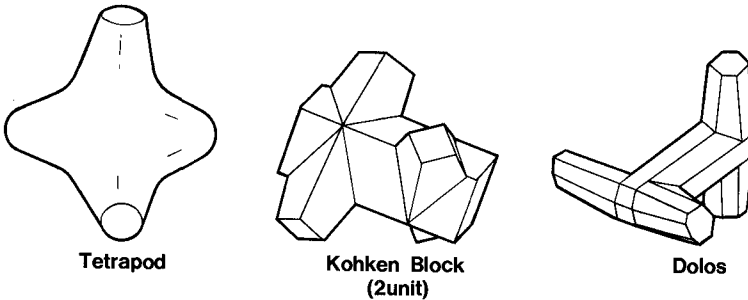


Figure-3 Dimensions in Tests and Shapes of Armor Units used in Large Wave Flume

Table-1 Conditions for large flume tests

Test No.	armor units	Weight(kg)	Section	depth(m)	Period(sec)	Wave Height(m)
1-1	TeTrapod	2.16	I	0.50	2.3	0.043 ~0.48
1-2	"	2.16	"	0.50	3.0	0.46 ~0.49
1-3	"	2.16	"	0.45	4.0	0.49 ~0.51
2-1	Kohken Block	2.05	I	0.50	2.3	0.44 ~0.48
2-2	"	2.05	"	0.50	3.0	0.495~0.50
2-3	"	2.05	"	0.45	4.0	0.495~0.51
3-1	Dolos	1.99	I	0.65	2.3	0.52 ~0.575
3-2	"	1.99	"	0.60	3.0	0.57 ~0.61
3-3	"	1.99	"	0.60	4.0	0.62 ~0.66
4-1	Tetrapod	6.81	II	0.80	2.5	0.70 ~0.76
4-2	"	6.81	"	0.70	3.5	0.75 ~
4-3	"	6.81	"	0.70	4.5	0.80 ~0.84
5-1	Kohken Block	6.61	II	0.80	2.5	0.70 ~0.74
5-2	"	6.61	"	0.70	3.5	0.75 ~
5-3	"	6.61	"	0.70	4.5	0.83 ~0.85
6-1	Tetrapod	20.85	III	1.30	3.0	1.05 ~1.12
6-2	"	20.85	"	1.30	4.0	1.18 ~1.25
6-3	"	20.85	"	1.20	5.0	1.17 ~1.26
7-1	Kohken Block	19.65	III	1.30	3.0	1.13 ~1.20
7-2	"	19.65	"	1.30	3.5	1.02 ~1.17
7-3	"	19.65	"	1.30	4.0	1.25 ~1.30
8-1	Dolos	9.66	III	1.10	3.0	0.84 ~0.90
8-2	"	9.66	"	1.00	4.0	0.97 ~1.05
8-3	"	9.66	"	1.00	5.0	1.05 ~1.15
9-1	Tetrapod	49.34	IV	1.70	4.0	1.50 ~1.51
9-2	"	49.34	"	1.50	6.0	1.60 ~1.63
10-1	Kohken Block	49.58	IV	1.80	4.0	1.50 ~1.59
10-2	"	49.58	"	1.50	6.0	1.63 ~
11-1	Dolos	29.37	IV	1.80	4.0	1.39 ~1.58
11-2	"	29.37	"	1.70	5.0	1.53 ~1.65
11-3	"	29.37	"	1.70	6.0	1.55 ~1.76

3. RESULT AND CONSIDERATION

(1) Characteristics of Experimental Wave

The sea bottom slope below model in large flume is 1:15. Before the stability test, characteristics of generated wave were observed.

Figure-4 shows the relation between breaking wave height H_b and breaking depth h_b in the large wave flume.

In figure, curves show outline of progressive waves on each sea bottom slope, obtained from general small and middle flume tests.

And dotted points show experimental values in this large flume.

These values show good coincidence and the ratio of H_b/h_b are distributed within 0.8 and 1.2..

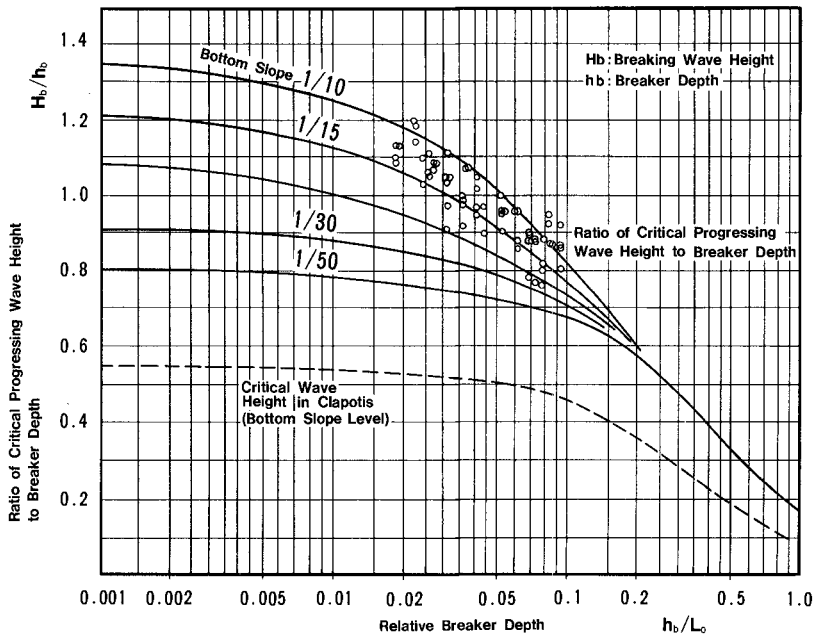


Figure-4 Characteristic of Breaking Wave in the Test

(2) Wave Run Up

Figure-5 shows wave run up heights by which 0% and 2% damages were caused. In figure, curves show the wave run up on smooth surface and the layer covered with armor units at slope of $\tan \theta : 3/4$ by the method of the temporary slope which was proposed by T. Saville⁶⁾.

Figure-5 shows that the values of wave run up in the experiments are almost below the values in smooth surface but are distributed in fairly higher location than the values in the case of layer covered with armor units. Considering that the curves by Saville's method were obtained from the results in small scale tests, it is recognized that there are scale effects in this behavior.

So it is necessary to consider the relation between the stability of armor units and wave run up.

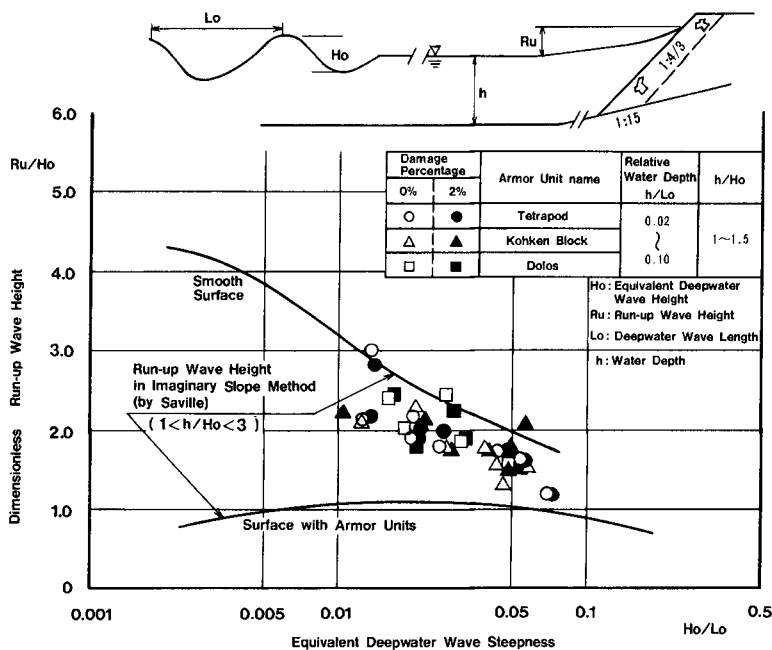


Figure-5 Wave Run-up in the Test Cross Section

(3) Stability of Armor Units

The results of experiments on the scale effect of stability of armor units are shown in Figure-6. The axis of ordinate indicates the stability number N_s . And N_s mean the ratio of wave force which act to

armor units and the resistance force of armor units.

And N_s is defined as following equation.

$$N_s = \frac{H_b \cdot \gamma^{1/3}}{W^{1/3} \cdot (S-1)} \dots\dots\dots (1)$$

Where, H_b : breaking wave height at the point where the toe of model section is set after (cm)

γ : the specific weight of the armor units (g/cm^3)

S : the ratio of γ to the specific weight of water

W : the weight of one armor unit (g)

Further, the K_D value in Hudson formula in the case of which cross section slope is θ degree are defined as following equation.

$$K_D = \frac{N_s^3}{\cot \theta} \dots\dots\dots (2)$$

The transverse axis indicates the Reynolds Number which show the influence of the force by fluid viscosity around the armor units. In this Reynolds Number, the terms in water particle velocity are estimated first by long wave velocity $C: \sqrt{gh}$, g : gravity acceleration, h : depth, and further, h are displaced by breaking wave height H_b which is nearly equal to h . And the terms of length are estimated by the volume of the armor unit to the one-three power.

So, in this study Reynolds Number are defined as following equation,

$$Re = \left(\frac{\gamma_f}{\mu} \right) \left(\frac{W}{\gamma} \right)^{1/3} \left(\frac{H}{g} \right)^{1/2} \dots\dots\dots (3)$$

where, γ_f : the weight in unit volume of water (g/cm^3)

μ : viscosity coefficient of water ($\text{g} \cdot \text{sec/cm}^2$)

W : the weight of one armor unit (g)

g : gravity acceleration (cm/sec^2)

And wave period T are indicated by nondimensional style, $gT^2/(W/\gamma_f)^{1/3}$. In Figure-6, the results in each kind of armor units which weights range from 16g to 50Kg are plotted.

And the results in smaller than 300g weights have been obtained already from small and middle wave flumes⁷⁾.

Figure-6 shows that according to the Reynolds Number increasing, stability Number of each kind of armor units tend upward too, and this feature indicate the scale effect on the stability of armor units. However, where the Reynolds Number take more than nearly 4×10^5 , that means the experimental armor unit weights are more than 6.8kg in the case of any armor unit, it is found that the values of N_s approach to a constant value. However, the influence of wave period to the stability of the armor units is not so obvious and as the result, the values of N_s in long waves is smaller rather than in short waves. It is considered that, to this tendency, experimental waves were all limited to the breaking wave at the toe of cross section.

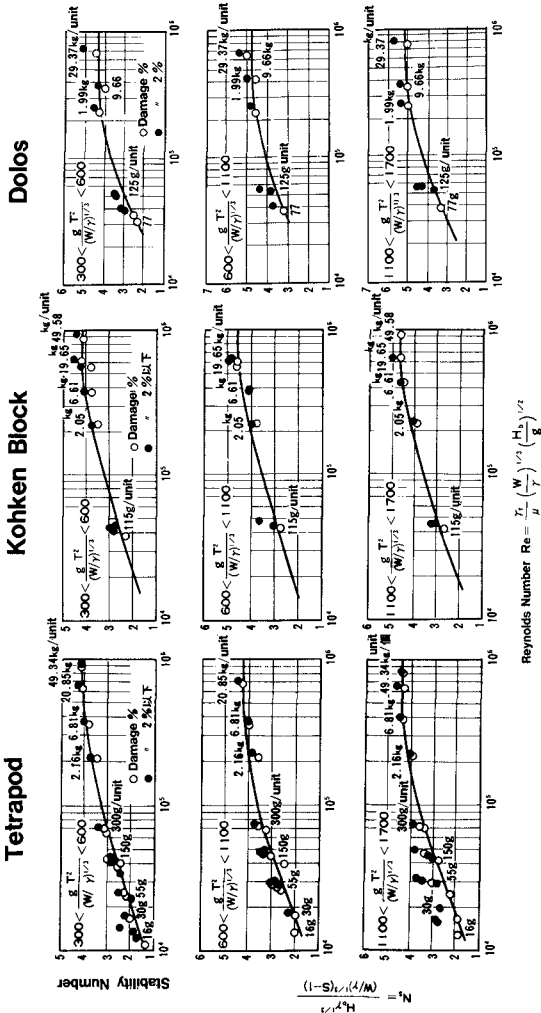


Figure-6 Relation between Stability Number and Reynolds Number

And the long waves breaker at that point are generated in shallower depth than in short period wave breaker. So it is concluded in this study long period wave energy attacking cross section is smaller than short period wave.

Figure-7 shows the stability of each kind of armor units with the expression H_b/D in stead of Stability Number N_s in transverse axis in Figure-6.

Where H_b is breaker height in the stage of stability criteria and D indicates two layers thickness of each armor units. In Figure-7, variable amounts which indicate the scale effect on the each armor units are concentrated on the same curved line.

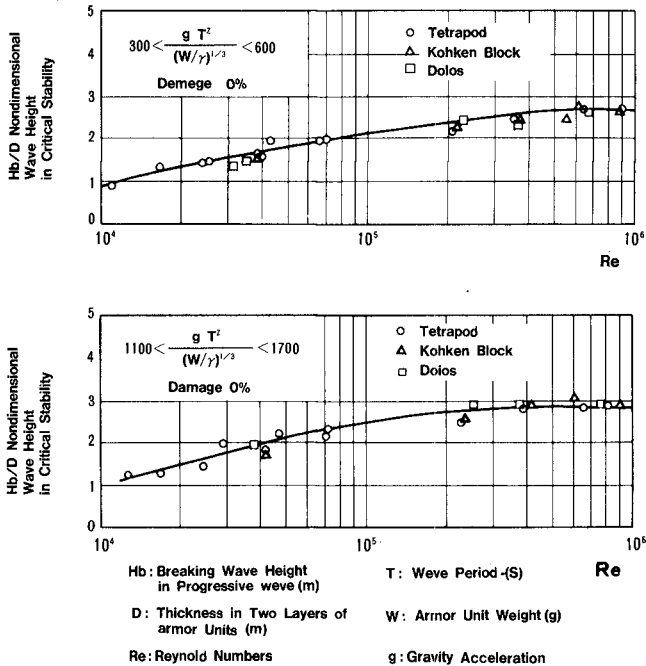


Figure-7 Relation between Reynolds Number and nondimensional wave Height in critical Stability considered Thickness in Two Layers of Armor Units

In this investigation, it was known that the shapes of armor units are connected with the stability of the armor units than that of rubble mound even if interlocking matter were included.

And the value of H_b/D will give the outline in design of the armor units. To give the correct value of Stability Number N_s in prototype from results in small scale experiment.

Figure-8 is presented by rewriting.

Now, Figure-6 and this expression was quoted from Thomsen²⁾. For example, if the armor units in weight 100g has been used in test, it will be reasonable in prototype design to take 1.45 times N_s . In Figure-8 the results of rubble mound in CERC are shown, and it's tendency is similar to our results.

And the results of small scale tests will be more applicable by using this result.

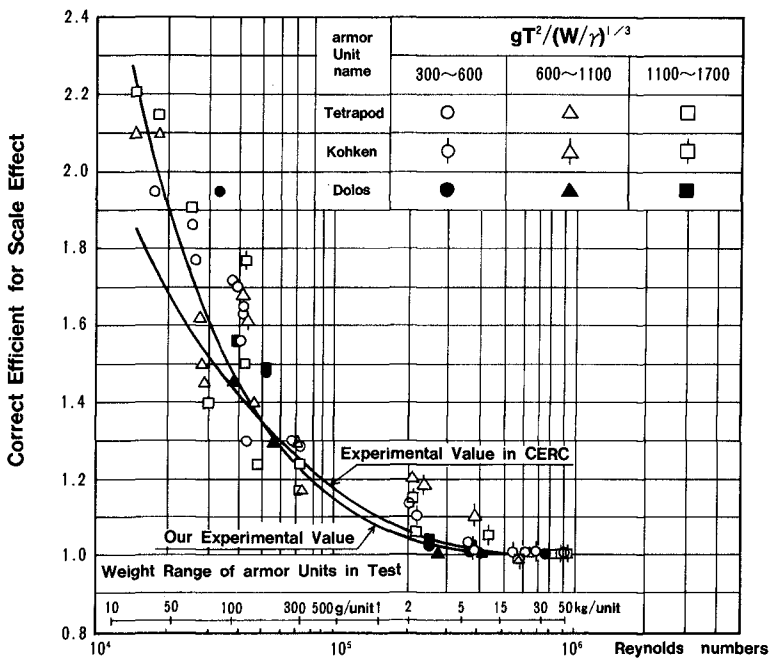


Figure-8 Correct Efficient of Stability number using Re number in no scale Effect

(4) Correction of Coefficient K_D

From experimental investigation on the stability of the armor units by irregular wave⁸⁾ which has been conducted by one of authors, it is known that there is a relation shown following equation between regular wave height H and irregular wave significant wave height $H_{1/3}$, which cause the same damage up to several percentage.

that is $H = 1.2 H_{1/3}$ (4)

And this result is shown in Figure-9.

Now, using this relation, experimental results are revised, and the K_D , coefficient in Hudson Formula (1), are corrected. And the result of correction are shown in Table-2. According to Table-2, it is expected to increase the K_D coefficient to the range of 1.6~3.6 times, that is, to lighten the minimum weight of the armor units.

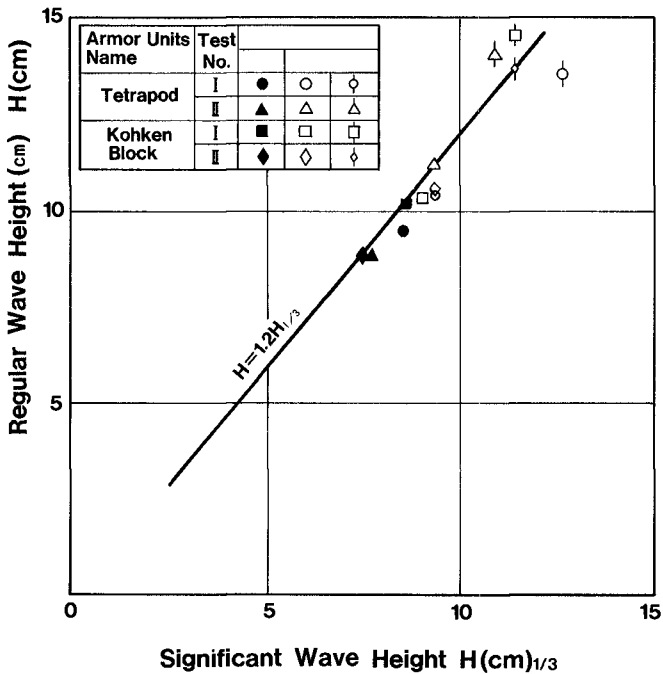


Figure-9 Relation between Regular Wave and Irregular Wave in Same Damage

Table-2 Correct K_D Value with Test Results (0% Damage)

$$gT^2/(W/\gamma)^{1/3} \quad 300 \sim 600$$

$$Re > 4 \times 10^5$$

Armor Unit Name	Hb/D	Ns	K_D	Correct Value by Irregular Wave	K_D in Present Method
Tetrapod	2.71	4.05	49.8	28.8	8
Kohken Block	2.64	4.05	49.8	28.8	8
Dolos	2.64	4.45	63.9	36.9	22

Ns: Stability Number $Ns = Hb/(W/\gamma)^{1/3}(S-1)$

Hb: Breaking Wave Height

D: Thickness in Two Layers of armor Units

(5) Scale Effect on Reflection Coefficient

It has been conducted to compare the reflection coefficient of the armor units in small and large scale tests likewise as stability test.

Figure-10 shows the results in comparison.

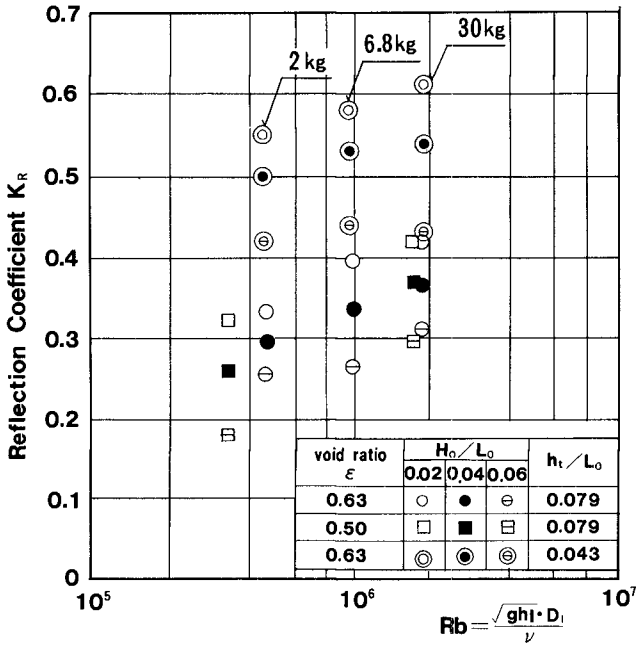
The axis of ordinate indicates the reflection coefficient and transverse axis indicate the Reynolds Number R_b which is composed with the long wave velocity, the height of the armor unit and kinematic viscosity also as stability investigation.

The value of R_b is about one and half times of the value of Re in equation (3) in the case of tetrapod and in small wave steepness R_b is larger than Re , because the term gh_L is larger than the term gh_b .

Figure-10 shows the reflection coefficient in same wave steepness and same relative depth.

And if the Reynold's Numbers increase, that mean the case in larger armor units, the reflection coefficients have a little upward tendency.

And the deference is with in 10%. But it is not found to approach to a constant values according as Reynolds Number become high. So it is recognized that there is scale effect on the reflection, but the deference in small and large scale is little.



Rb ; Reynolds Number

g ; Gravity Acceleration

h_i ; Water Depth

ν ; Coefficient of Kinematic Viscosity

D_i ; Height of Armor Unit

Figure-10 Scale Effect for Reflection Coefficient

4. CONCLUSION

(1) It was recognized from the experiments in small and large wave flumes that there were scale effects on the hydraulic stability and reflection regarding armor units.

(2) The influence of the scale effect on the stability becomes small and will be negligible in more than the Reynolds Number

$$Re : 4 \times 10^8$$

And this Number indicate that the armor unit weights are over than 6.8kg.

(3) It is expected that the minimum weight of armor unit can be calculated under nearly half value as compared with present design method, though irregular wave are considered.

(4) The scale effect on reflection coefficient of the armor unit are recognized in small and large scale tests, however, the deference is smaller than that of stability.

REFERENCES

- 1) Hudson, R. Y. : Laboratory investigation of rubble mound breakwaters. Proc. of the Amer. Soc. of Civil Eng. Journal of the Waterways and Harbours Division, Vol.85, No.WW3, Sept. 1959.
- 2) Thomsen, A. L., P. E. Wohnt and A. S. Harrison : Rip-Rap stability on earth embankment tested in large and small scale Wave tanks. CERC Technical Memorandum No.37, June 1972.
- 3) Tørum, A., B. Mathiesen and R. Escutia : Scale and Model effects in breakwater model tests. P.O.A.C., 1335pp., 1979.
- 4) Sorensen, T. and O. J. Jensen : Reliability of hydraulic models of rubble-mound breakwater as proven by proto-type measurements. The Dock & Harbour Authority, Vol.LXV, No.768, 155pp., March 1985.
- 5) Hydraulic Formulas 510p. 1985, edited by Civil Eng. in Japan.
- 6) Hydraulic Formulas 530p. 1985, edited by Civil Eng. in Japan.
- 7) T. Fujimoto, N. Abe, and H. Hasegawa : Experimental Study on hydraulic characteristics of wave dissipating concrete armor units.
Central Research Institute of Electric Power Industry Research Report 382001 1982.
- 8) T. Fujimoto : Effects of wave Irregularity on Stability of Concrete Armor Units.
Central Research Institute of Electric Power Industry Research Report 385008 1985.