CHAPTER 83

Stability of High-specific Gravity Armor Blocks

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Abstract

The stability coefficient of the well-known the Hudson formula, K_D, has been established by many laboratory tests for various types of armor blocks with a range of specific gravity 2.16~2.47 representative of normal concrete. Design manuals for coastal structures do not describe the adoption of high-specific gravity armor blocks for use in field construction. To examine the effect of specific gravity on stability of Tetrapods, then a laboratory test was conducted by using Tetrapod models of different weights which are composed of five values of specific gravities. Temporal changes of damage ratio arranged test conditions that satisfy the Hudson formula do not coincide among each other, depending on wave period and specific gravity. The effect of the specific gravity on their stability is discussed. As a result, it is found that the relationship between the stability and the specific gravity is considerably affected by the surf similarity parameter and Reynolds number.

Introduction

The stable weight of armor units which are used in the cover layer of groins, breakwaters and wave absorbing works is evaluated by the Hudson formula (1959). The Hudson's stability coefficient of armor blocks made from a normal concrete with specific gravity of about 2.30, such as Tetrapod and Dolos, have been determined on the basis of laboratory tests. These tests have been performed using a wide range of experimental conditions for wave height, wave period, and structure slope, using regular waves. As for the use of the armor blocks on beaches and coast lines, there are the following problems and needs:

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armor bloeks, that is to say, the maximum weight of Tetrapod as a armor bloek is 784 kN (80 tf) at the present time, but this weight becomes unstable for wave heights over 9 m for seaward slopes of 1 on 4/3 of typical breakwaters.

(2) When large scale eonstruction equipment such as floating cranes or derrick barges are difficult to move the place such a far detached-island, then small size and more stable armor blocks have to be used.

(3) Construction site with limited storage spaee for armor blocks.

(4) Armor bloeks in a eorner or head of breakwaters, groins or wave absorbing works receive the eomplex wave aetion due to the eombined wave-flow indueed due to waves. Then, thus parts a weak point in armor blocks and are easily broken.

(5) To hold the natural beauty of beaehes, eoastlines, and harbors, smaller and stable armor blocks are required.

For these problems and needs, high-speeific gravity armor bloeks are eonsidered more suitable. These armor blocks are smaller than the same weight units made from normal eonerete. They are more stable against waves. Also it is possible to reduce strueture size by using these armor blocks.

A manufacturing method for producing high specific gravity armor blocks is made possible by mixing a heavy stone, or crushed or grained iron ore such as pyrite into the concrete. The "heavy stone" concrete reaches specific gravity of about 2.7~2.8. In the iron ore concrete mixture, the specific gravity becomes greater than 3.0. Sueh high-speeific gravity armor bloeks have been already put to a praetieal use in Japan.

Previous investigation of the high-speeific gravity armor bloeks, Zwamborn (1978) discussed the effect of specifie gravity as the ratio of armor unit volume to wave height based on the past laboratory data that had been performed using rubble- stones of different specific gravity by Kydland and Sodefjed, and dolosse of different specific gravity by Gravesen and Sϕrensen. Zwanborn reported that by rearranging some test data with dolosse of different specific gravities (2.4, 2.75 and 3.05), the dimensionless wave height, $(V/H^3)\cot\theta$, based on block volume, V, wave height, H, and slope angle of armor layer, θ, is proportional to the speeific gravity in water to -3.0, -3.0 and -4.0 power for 1, 2, and 5 per eent damage, respectively. But in the Hudson formula, its exponent value is constant (-3rd power) and well accepted. The authors (1992a, 1992b, 1994) have been carrying out the laboratory study using Tetrapod models of various sizes and specifie gravities in order to investigate the effect of speeifie gravity on the stability for waves. On the basis of the tests results, this paper diseusses the effeet of speeifie gravity, surf similarity parameter, and Reynolds number as a function of the block-size and wave charaeteristie. Reeently, Takeda et al. (1993) diseussed the relationship between stability and specific gravity, based on the laboratory tests using high-specific gravity armor bloeks. He pointed out that the wave period eonsiderably affeets the stability-speeifie gravity relationship.

Thus, investigations on the stability of high–specific gravity armor blocks have been not insufficient up until the present time. Design manuals for coastal structures do not describe the adoption of high–specific gravity armor blocks for use in field construction. The effect of the specific gravity on armor unit stability, therefore, must be further investigated.

Advantages of high–specific gravity armor blocks

The effect of the specific gravity on the resistance against wave action is possible to be calculated using the Hudson formula. Assuming that the Hudson's stability coefficient K_D is a constant for Tetrapod (8.3), the slope angle of armored structure is a constant, the unit weight of normal concrete w_c is 22.54 kN/m^3 (2.3 tf/m^3), and the unit weight of water w_c is 9.8 kN/m^3 (1 tf/m^3), then, we can obtain the ratio of the design wave height for high–specific gravity armor block, H/H_c to the change of the relative specific gravity against the normal concrete, S_r (=w_r/w_w), from the Hudson formula assuming that both blocks are the same size (l_B=const.). Where w_r, w_c and w_w are the unit weight of any specific gravity armor units, normal concrete, and water, respectively. The effect of S_r on H/H_c, the resistance against wave action is shown with a solid curve in Fig. 1. The results show the relative block weight W/W_c of high–specific gravity to normal concrete, which is also shown with a broken line curve in Fig. 1. Here H and H_c are the design wave height of any specific gravity and normal concrete, respectively. It can be seen from this figure that H in the armor blocks of specific gravity S_r=3.0 is possible to resist about 1.5 times wave height, H_c, for the normal concrete of the same size. However, this finding holds only when K_D–values are the constant though the specific gravity ranges.

Laboratory test

To examine the effect of specific gravity on stability of Tetrapod, models of different weight were used, composed of five different values of specific gravities (1.82, 2.30, 2.77, 3.40, 4.27). A total of 21 different Tetrapod models were used. The range of Tetrapod models used varied between a vertical height of l_B=3.29~16.6 cm and a weight of W=0.27~22.85 N (27.7~2329.6 gf). The sizes and weights of Tetrapod models used in the laboratory tests are listed in Table 1. Model weights on each row (A, B, C, D, and E) within this table are obtained for each specific gravity

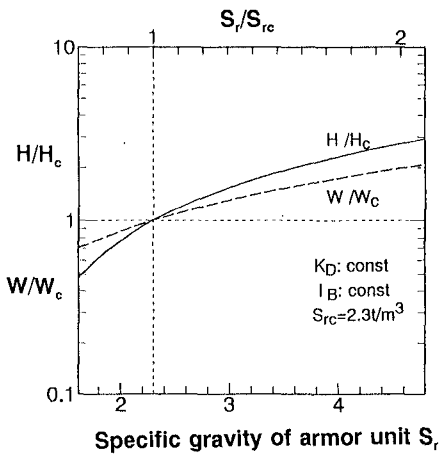


Fig. 1. Effect of specific gravity on stability of armor blocks for waves

Table 1. Specific gravities, sizes and weights of Tetrapod models

Marks of model	Class Nos. of specific gravity	5	4	3	2	1	Design Wave height at 1%-damege H(cm)
	W_r/W_w	1.82	2.30	2.77	3.40	4.27	
A	ℓ_B (cm)	7.16	4.52	3.29			8.6
	W (gf)	186.4	58.9	27.7			
B	ℓ_B (cm)	9.04	5.68	4.14			10.8
	W (gf)	372.7	117.8	55.4			
C	ℓ_N (cm)	12.24	7.72	5.68	4.14	3.08	14.7
	W (gf)	931.8	294.4	141.8	68.0	34.2	
D	ℓ_B (cm)	16.62	10.48	7.72	5.68	4.14	19.9
	W (gf)	2329.6	736.0	354.6	174.1	85.4	
E	ℓ_N (cm)		14.15	10.48	7.72	5.68	26.9
	W (gf)		1811.0	886.4	435.2	218.6	
F	ℓ_N (cm)		8.28				15.7
	W (gf)		368.0				

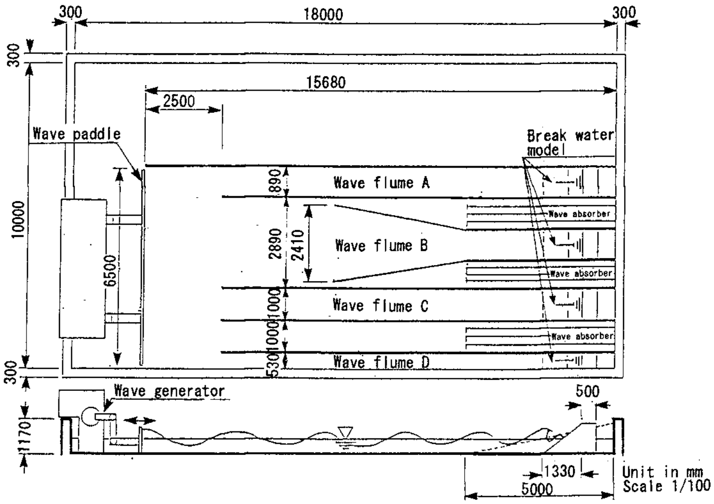


Fig. 2. Wave flumes to minimize the multiple wave reflection

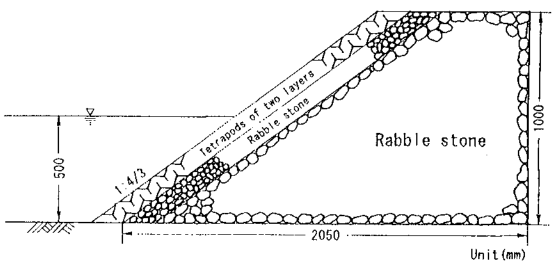


Fig. 3. Breakwater model armored with Tetrapods of two-layer

Table 2. Experimental conditions

Waves	Water depth (cm)	50.60
	Wave height (cm)	5~40
	Period (sec)	1~3
	Wave steepness Ho/Lo	~0.14
Tetrapods	Specific gravity w_r/w_w	1.82, 2.30, 2.77 3.40, 4.27
	Weight (gf)	34.2~2329.0
	Vertical height (cm)	3.08~16.6.0
Breakwater	Front slope of cover layer	1:4/3
Slope of Sea-floor		horizon
Wave operation time (min) (Wave numbers t/T)		50~70 (80~2000)

by giving K_D=8.3 (in 0<Damage ratio≤1%), cotθ=4/3, w_w=9.8 kN/m^3 (1 tf/m^3), and given a constant Hudson formula design wave height. The design wave height of the models in each row of Table 1, becomes nearly equal, despite difference in specific gravity.

As shown in Fig. 2 the wave basin was divided into the seven flumes, each having a free water zone of 2.5 m in front of the wave paddle. Model breakwaters used in the stability test were constructed within every other flume. The control flumes had wave absorbing net-mats, which were set on a slope of 1 on 10 used to minimize the multiple wave reflection which takes place between wave paddle and breakwater model in normal flumes. In the laboratory test, regular waves were generated continuously on the Tetrapod model for a total of about 1,500 waves under no-overtopping conditions. The 1,500 waves are equivalent to prototype wave action of about 4 hours for a wave period of 10 sec. Wave flume B was constructed with a geometry to increase wave height. Each Tetrapod model was constructed randomly in two layers, on a slope of 1 on 4/3 as shown in Fig. 3. Laboratory test conditions are summarized in Table 2. The damage progression of Tetrapod models was observed continuously by a 8 mm Video-camera. The damage rate, defined as the ratio of the number of blocks that moved to the total number of armor blocks in the two layers, was measured with a display playing back the Video.

Test results

A temporal damage change of Tetrapod models attributed to the difference of specific gravity based on test data, is shown in Fig. 4. The damage to the Tetrapod models of each different specific gravities should be similar to each other. These Tetrapod models (A-3, A-4, A-5) are listed the same row of Table 1. The design wave height of these armor units is nearly equal. However, these damage curves differ due to specific gravity. As to a reason for the difference,

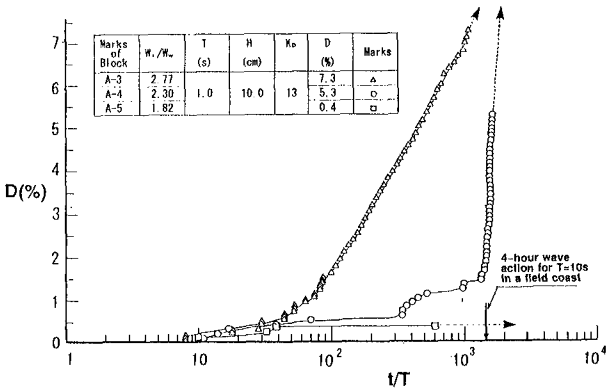


Fig. 4. Temporal damage changes due to the difference of specific gravity

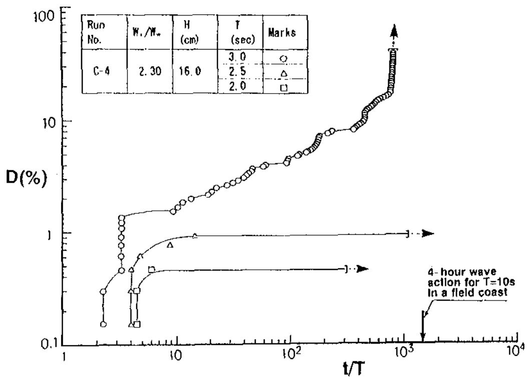


Fig. 5. Temporal damage changes due to the difference of wave period

Table 3. Damages of detached breakwaters, groins, and seawall with Tetrapods due to storm waves in Japan

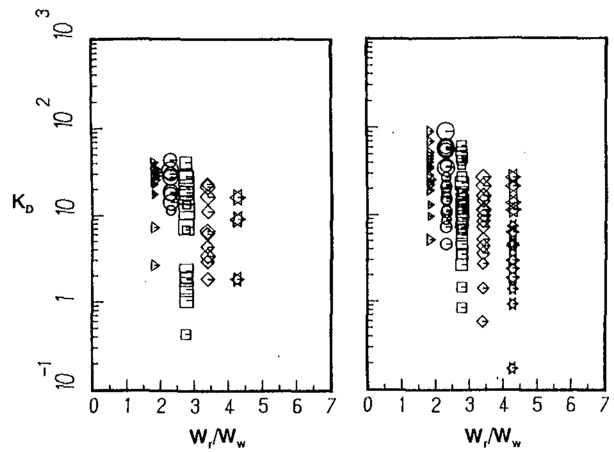
Locations of port and harbour in Japan	W (tf)	T (s)	Damage ratio (%)	$H_{1/3}$ (m)	K_D	R_e	ξ	Remarks
Hamana	3	13	50	5.6	64.6	6.7E+06	4.3	Typhoon 7219
Hamada	20	13	50	8.0	23.6	1.6E+07	3.6	Depression, Jan. 1971
Simoda	8	12	30	5.0	14.4	9.3E+06	4.2	Typhoon 7010
Simoda	16	12	30	5.0	7.2	1.2E+07	4.2	Typhoon 7020
Nobeoka	13	14	50	4.0	4.7	9.6E+06	5.4	Typhoon 7123
Miyazaki	8	14	50	4.0	7.4	8.3E+06	5.4	Typhoon 7119
Miyazaki	5	14	50	4.0	11.8	7.1E+06	5.4	Typhoon 7119

considcrations must bc givcn to the fact that stability is affected by the specific gravity. Selecting identical wavc heights from thc test data in the same sizc Tetrapod model, a temporal damage changc is shown for each wavc pcriod in Fig. 5. Damage curves, generally, must be similar to each othcr regardless of the differencc in wave periods. Hudson's (1959) stability coefficient is indcpendent of wave period. But from Fig. 5 it is rccognized that stability bccomes a function of the wave pcriod.

From field data, we can investigate damage ratio, significant wavc height, and block weight of Tetrapod. Thc tcchnical report by Takeyama and Nakayama (1975) reported on damage of failurc of coastal structures by large waves in Japan. These field data are listcd in Table 3. The field data includcs thc effects of oblique incident waves, deflection wavcs, and scour in or around the toe of brcakwatcr slope. The damage ratios shown in this tablc, then, are considerablc largc (range from 30% to 50%). Hudson's stability cocfficient in this tablc is obtaincd by converting wave hcight to equivalent significant wave height. Regular waves were converted based on the equation, $H= 1.5H_{1/3}$. This equation follows thc cquations proposed by Fan et al. (1983) and Tanimoto (1985) as

$$H=1.4H_{1/3} \quad \text{(Fan et al.)} \qquad (1)$$
$$H=(1.5\pm0.37)H_{1/3} \quad \text{(Tanimoto et al.)} \qquad (2)$$

The evaluated surf similarity parameter ξ and Rcynolds number R_e are also listed in Tablc 3.



(a) Rocking only (b) Damage ratio, D=0~1%

Fig. 6. The relationship between K_D-values and specific gravity in two types of damages

Effect of specific gravity on stability

The rocking only (no-damage) and the 0~1 % damage are selected from the laboratory test data. Fig. 6 shows these data which show the relationship between Hudson's stability coefficient, K_D, and the specific gravity in water, S_r-1. In this figure, the K_D-values scatter wildly for the difference in the specific gravity in water. The effect of the specific gravity on stability (rocking only and 0~1% damage) can not be clearly established from this figure. In the Hudson formula, the stability coefficient K_D should be constant because it should considerably depend on the shape of armor units. Therefore, the stability coefficient must be independent of the change of specific gravity. But K_D-values scatter wildly for the different S_r-1 values as shown in Fig. 6. Then the Hudson formula may not satisfy the test data.

Theoretical discussion

As above discussed, the effect of the specific gravity on the stability disagrees with the Hudson formula. As this reason it is considered that many factors affect Hudson's stability coefficient, including effects due to wave steepness, relative depth, Reynolds number, drag coefficient, acceleration of wave motion etc. as described by Hudson (1959).

Reviewing the Hudson formula, the stability coefficient K_D is expressed by;

$$K_D=\frac{w_r H^3}{W(S_r-1)^3\cot\theta} \tag{3}$$

where, W is the weight of armor unit, w_r is the unit weight of armor unit, H is the design wave height, S_r ($=w_r/w_w$) is the specific gravity of armor unit, w_r is the unit weight of armor unit, w_w is the unit weight of water, θ is the angle of structure slope measured from horizontal in degrees, and K_D is the stability coefficient varying primarily with the shape of the armor units, degree of interlocking, damage rate, etc.

The behaviors of armor units is affected by slope angle, wave breaking, wave runup, and rundown, and is sensitive to the surf similarity parameter ξ,

$$\xi=\frac{\tan\theta}{\sqrt{H/L_o}} \tag{4}$$

where L_o is the wave length in deep water.

Hudson (1959), Dai and Camel (1969), and Sakakiyama and Kajima (1990) have pointed out that the stability of armor units is affected by the Reynolds number related the scale of laboratory tests. The Reynolds number is expressed using the velocity of wave motion and a characteristics length of the armor block as

$$R_e = \frac{\sqrt{gH}(W/w_r)^{1/3}}{\nu} \tag{5}$$

where ν is the kinematic viscosity, g is the acceleration due to gravity. Rewriting Eq. (3) using Eqs. (4) and (5), the stability coefficient K_D is expressed as follows:

$$K_D = \frac{R_e^2}{\xi^4 (S_r - 1)^3} C_R \tag{6}$$

where

$$C_R = \frac{L_o^2 \nu^2}{g} \left(\frac{w_r}{W}\right)^{\frac{5}{3}} \tan^5\theta \tag{7}$$

From Eq. (6), it is shown that the stability coefficient K_D is proportional to the –3rd power of the specific gravity in water, the –4th power of the surf similarity parameter, and the 2nd power of the Reynolds number.

Stability and Surf similarity parameter

Fig. 7 shows the relationship between K_D–values and the surf similarity parameter for the test data and the field data listed Table 3. In this Figure, the K_D–

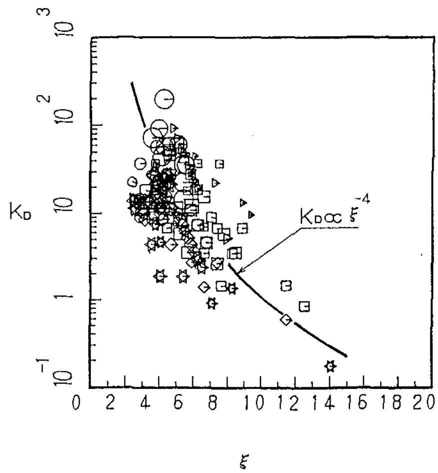


Fig. 7. The relationship between K_D–values and surf similarity parameter of test data and field data

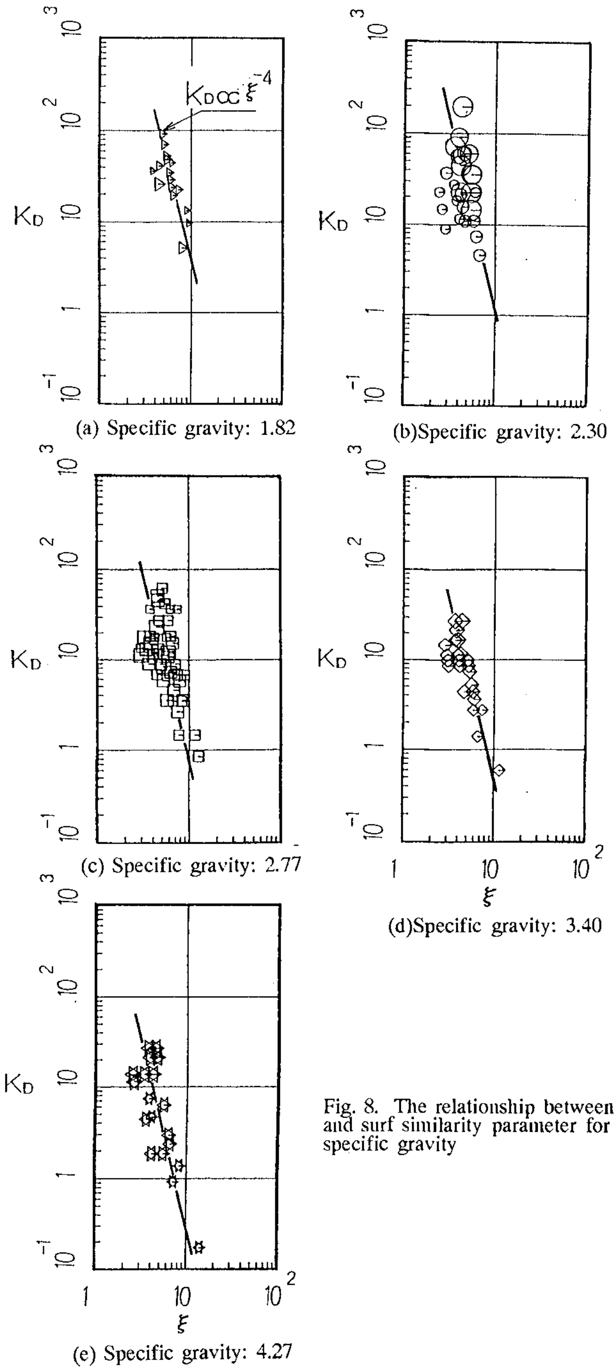


Fig. 8. The relationship between K_D-values and surf similarity parameter for each specific gravity

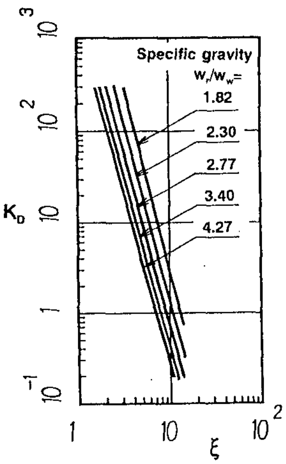


Fig. 9. The relationship between K_D-values and surf similarity parameter due to the difference of specific gravity

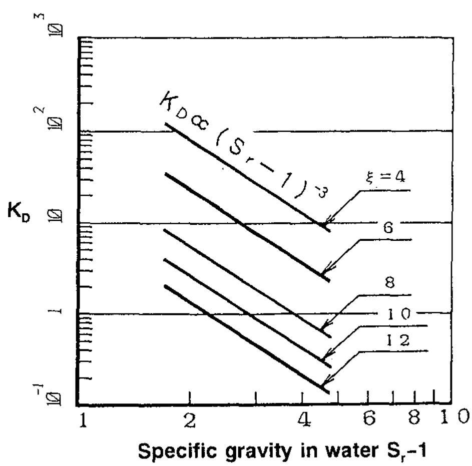


Fig. 10. The relationship between K_D-values and specific gravity in water due to the difference of surf similarity parameter

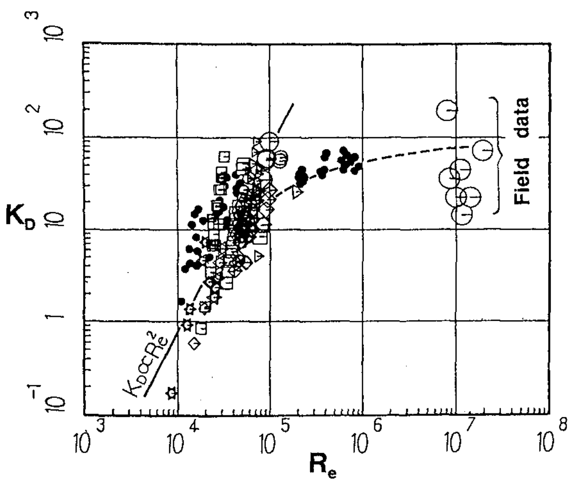


Fig. 11. Effect of Reynolds number on K_D-values

values agrees well with the solid curve expressing the relationship of $K_D \propto \xi^{-4}$in Eq. (6). The relationship between the K_D-values and the surf similarity parameter for each specific gravity are shown in Fig. 8(a)~(e), respectively. From these figures, the relationship between the K_D-values and the surf similarity parameter agrees well the solid line indicating the relationship of $K_D \propto \xi^{-4}$. Fig. 9 shows the relation of ξ to K_D arranged together from Fig. 8(a) to Fig.8(e) using the specific gravity as a parameter. Fig. 10 shows the relationship between the stability coefficient and specific gravity in water. This figure was obtained by rearranging Fig. 9 taking the surf similarity parameter as a parameter. From Fig. 10, it can be seen that the stability coefficient decreases with increasing specific gravity in water dependent on $K_D \propto (S_r-1)^{-3}$, as indicated in Eq. (6). From Fig. 10, stability is affected by the surf similarity parameter, and increases with decreasing the surf similarity parameter.

Sawaragi et al. (1983) pointed out that Iribarren's number reaches a minimum value around the surf similarity parameter of $\xi \approx 3$ due to the occurrence of wave–armor unit resonance on the basis of the laboratory tests of rubble mound breakwaters. Losada (1990) discussed the effect of the surf similarity parameter on the stability function, $\varphi=1/(K_D \cot\theta)$, by rearranging laboratory test data for various armor units. Then he pointed out that the stability function increases inversely proportional to decreasing surf similarity parameter. These findings are contrary to authors results as above discussed. The discrepancy between the authors and Losada may cause the reason that the range of the surf similarity parameter used and the size of armor unit model is not in agreement.

Stability and Reynolds number

It can be considered from Eq. (6) that the stability coefficient K_D is affected by the Reynolds number. Then, the relationship between the Reynolds number and the K_D–values of the zero damage test data and the field data listed in Table 3, is plotted in Fig. 11. This figure is also plotted with the dark circle indicating Tetrapods only from the paper by Simada et al. (1986), who investigated the stability of Tetrapods, Dolosse, and Koken–blocks. Theses armor units are made from normal concrete (w_c/w_w=2.30). The armor blocks had a weight range of W=0.16~484 kN (16 gf~49.39 kgf), and were tested in the medium and large wave tanks. It is shown from Fig. 11 that the K_D–values increase rapidly with increasing Reynolds number, up to $R_e=10^5$ which corresponds to small and medium test scales in the range of Reynolds number $R_e=8\text{x}10^3\sim10^5$. Over this value the K_D–values gradually reach a constant. The K_D–values fit well with the solid line indicating the relation of $K_D \propto R_e^2$. The K_D–values beyond $R_e=10^5$ deviates from the trend depicted by the solid line. Such changes in K_D–values may be caused by scale effects. This has been indicated by Dai and Camel (1969) and Shimada et al. (1986). A wider range of scales and numerous test data are needed to further the understanding of the affects of specific gravity and the surf similarity parameter as they related to K_D–values and the Reynolds number.

Conclusions

The effect of the specific gravity on the hydraulic stability of Tetrapod is examined on the basis of numerous laboratory test data. These data were obtained using the total of 21 different models composed five values of specific gravity;

1.82, 2.30, 2.77, 3.40, and 4.27. The discussion includes test and field data reported by another researchers. Conclusions drawn from the results obtained in this study are as follows:

(1) Hudson's formula does not include the effect of wave period. Then Hudson's stability coefficient must be independent of wave period. But this coefficient is considerably influenced by weave period.

(2) Trends are not seen for the relationship between K_D-values and specific gravity. But by arranging the relationship as a function of the surf similarity parameter, it is found that the K_D-values decrease with increasing surf similarity parameter, where $K_D \propto \xi^{-4}$.

(3) The relationship between the K_D-values and the specific gravity in water is shown by the relation, $K_D \propto (S_r-1)^{-3}$, when the surf similarity parameter is taken into account. The K_D-values decrease with increasing specific gravity.

(4) K_D-values from the test data correspond well to the 2nd power of the Reynolds number within a range of Reynolds number between R_e=$8x10^{-3}$~10^5. In $R_e \geq 10^5$, the K_D-values gradually reach a constant as Reynolds number increases. Therefore the stability of high-specific gravity armor blocks, is affected significantly by scale effects.

It should be remarked that the conclusions of (1), (2), and (3) are results that are discussed on the basis of the data of small and medium test scale included the scale effects.

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