DOLOS STABILITY
EFFECT OF BLOCK DENSITY AND WAIST THICKNESS

by

D J P Scholtz, J A Zwamborn and M van Niekerk*

ABSTRACT

Model tests were done with dolosse having the same shape and volume, but with different **block densities,** to determine the effect of block density on stability and to check whether the theoretical third-power relationship between block volume and relative block density is valid.

From these tests it can be concluded that the higher the density of the block material the greater the stability becomes. Although the individual scatter is appreciable, the average results indicate that the stability of dolosse is inversely proportional to a power of about 2,3 of the relative density, which is significantly less than the theoretical power of 3.

Model tests were also carried out on dolosse having the same mass and volume but with different **waist-to-height ratios** to determine the effect of waist-to-height ratio on the stability of a dolos armour.

From the results of these tests it can be concluded that the stability of the armour decreases with increasing waist thickness, particularly for relatively high waist ratios.

1. INTRODUCTION

The dolos armour unit has been used widely for harbour and shore protection works in various parts of the world (Zwamborn et al., 1980). Dolosse appear to provide an effective and economic means for protecting many small and medium-sized coastal structures, but, as these units are being used for increasingly larger projects in greater water depths and in more severe wave climates, serious doubts have emerged especially on, amongst other factors,

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* Coastal Engineering and Hydraulics, National Research Institute for Oceanology, CSIR, Stellenbosch, Republic of South Africa

the structural behaviour of the units. The obvious answer to the more severe wave climates is to increase the unit size or mass. However, when the size of the dolos is increased, tensile stresses also increase which may result in breakages.

There are two possible solutions to this problem, namely, (1) reinforcing and (2) increasing the waist-to-height ratio of the units. This paper deals with model tests carried out to determine the effect on the stability of the dolos of increased waist thickness.

According to theoretical stability formulae, the mass of the armour block is inversely proportional to the third power of the relative block density (PIANC, 1976). It is, therefore, attractive and, in certain cases imperative (Standish-White and Zwamborn, 1978), to use a higher than normal block density. Some doubt has been expressed, however, about the validity of this proportionality as applied to dolosse (Zwamborn and Beute, 1972) and tests with regular non-breaking waves were, therefore, done to determine the effect of relative block density on the stability of dolosse (Zwambron, 1978 and 1980 and Zwamborn and Van Niekerk, 1982).

It is generally accepted that when the linear dimensions of a dolos block are increased to obtain a heavier block with better stability, the stresses in the block will increase if the shape of the block remains the same. To overcome this increase in stress the waist of a dolos must be thickened if reinforcing is not used. Zwamborn and Beute (1972) suggested that the following waist ratio for a dolos with a mass W be used:

$$r = 0{,}34 \sqrt[6]{W/20}$$

It was, however, uncertain what the effect of an increase in waist ratio would be on the stability of the armour; it was decided, therefore, to do tests to determine this effect.

2. TEST FACILITIES

Tests on both the block density and the waist thickness of the dolos were done in the 160 m long (effective length), 3 m wide and 1,1 m deep wind-wave flume in Stellenbosch (Figure 1). Only regular waves which were produced by a translatory wave board were used. Waves were recorded with temperature-compensated probes and wave height meters connected to standard chart recorders and/or an electronic microprocessor which processed the outputs from the probes to yield the heights of the incident and reflected waves and the reflection coefficient. During the wave calibration stage, the waves were measured at the place at which the model slope would be positioned in the stability tests. During the actual tests, the waves were measured from a moving trolley in front of the model.

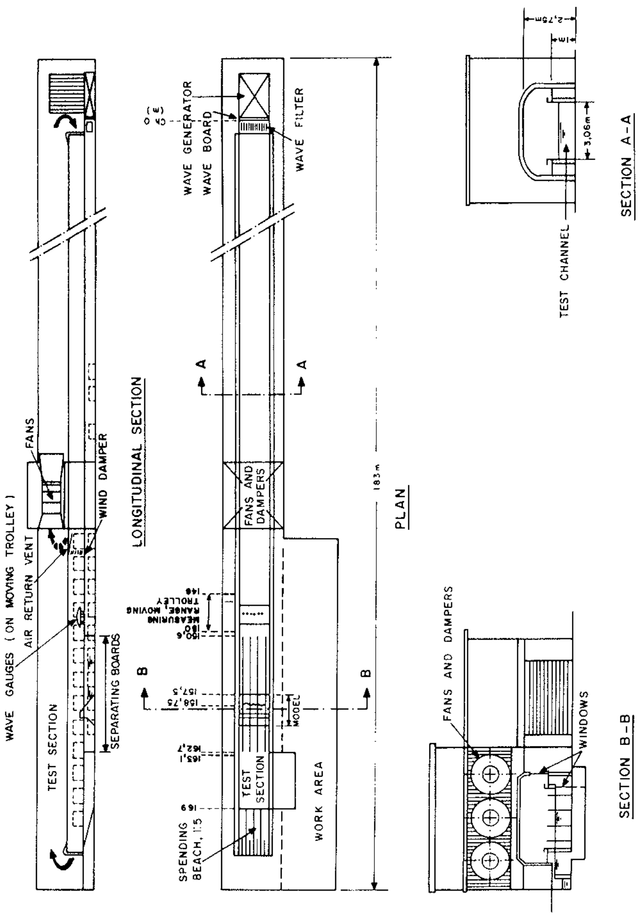


Figure 1 General layout of wind wave flume

3. MODEL LAYOUT

The flume was divided into three 0,75 m test sections leaving a dummy channel of about half that width on either side of the sections (Figures 2 and 3). The breakwater core was built of loose bricks and clean 6 mm stone. The underlayer consisted of 16,5 g sorted stone and the layer thickness was 43 mm. The top armour layer consisted of dolosse with a volume of about 35 × 10^{-6} m^3 during the block density tests and dolosse with a mass of about 81 g during the waist ratio tests. In both test series a 'mean' packing, ϕ = 1,00 was used where (Zwamborn, 1980):

$$N_n = \phi_n V^{-2/3}$$

with N = number of dolosse per unit area
V = block volume
n = number of 'layers'.

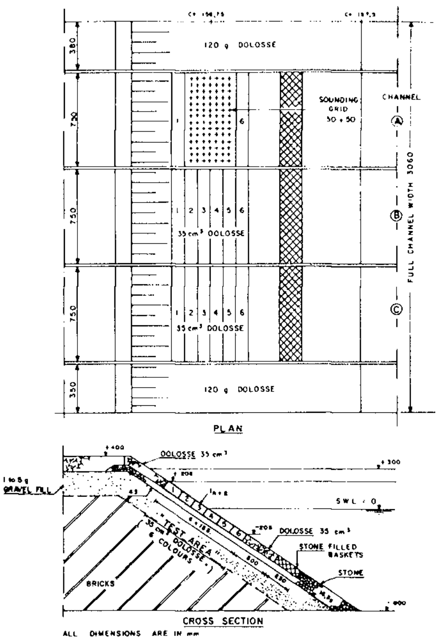


Figure 2 Model layout

Figure 3 General model view

The slope of the model was 1:1,5 and the depth of water was 0,8 m.

The test areas were 750 × 750 mm and the model dolosse were placed in six 125 mm (about 2 h, where h is the dolos height) wide bands of different colours, three above and three below still-water level, that is, 208 mm below to 208 mm above water (about 1,5 H_d, where H_d is the 'design wave height', Zwamborn, 1980).

4. TEST CONDITIONS AND PROCEDURES

All tests were done with regular waves of 1,75 s period, water depth of 0,80 m, and each test series consisted of 24 'bursts' of 2,5 min wave action for each wave height, namely, 49, 66, 83, 100, 117, 135, 152, 168, 185, 203, 221, 237 and 253 mm for the density tests and 75, 95, 115, 135, 146, 157, 173, 189 and 206 mm for the waist ratio tests. In the density tests the test series were repeated six to nine times and with the waist ratio tests nine repeat tests were done. During the repeat tests the test channels were alternated to eliminate the effects of the channels on the results.

With the above wave conditions the range of Ursell parameters used was 0,79 to 4,05 and of Iribarren number 2,9 to 6,6. Damage refers to the test section shown in Figure 2.

5. TEST RESULTS

5.1 Effect of Block Density

The initial tests with armour with block densities of 2,31; 2,41 and 2,57 indicated that increasing the density results in an increase in stability, but no clear relationship between dolos stability and block density could be established (Zwamborn, 1978 and 1980). Because of this, further tests were done with a much wider range of block densities, namely, γ_s = 1,81 to 3,02 (Zwamborn and Van Niekerk, 1982). The results of the latter tests will mainly be referred to in this paper.

Details of the model dolosse were as follows (based on 35 dolosse per density):

Model dolosse	W(g)	V($10^{-6}m^3$)	γ_s	h(mm)	r
Mean Max deviation (%)	62 ±1,45	34,2 ±1,46	1,81 ±0,83	59,6 ±0,5	0,32 ±1,5
Mean Max deviation (%)	83 ±3,25	34,8 ±2,59	2,39 ±2,15	59,2 ±0,4	0,33 ±5,3
Mean Max deviation (%)	106 ±2,55	35,1 ±1,56	3,02 ±1,10	60,1 ±0,25	0,32 ±1,7

The characteristics of the dolos armour for each test before wave action determined with the standard sounding technique (Zwamborn, 1978 and 1980), are given in the following table:

Test series D1,75		10	11	12	13	14	15	Mean
γ_s = 1,81	$t_{n=2}$ (mm) $C_{n=2}$ P_f (%)	75,6 1,16 56,8	68,5 1,05 52,3	72,2 1,11 54,8	70,0 1,07 53,3	68,6 1,05 52,4	71,3 1,09 54,2	71,0 1,09 54,0
γ_s = 2,39	$t_{n=2}$ (mm) $C_{n=2}$ P_f (%)	73,4 1,12 55,5	69,2 1,06 52,8	68,9 1,06 52,6	71,1 1,09 54,1	66,7 1,02 51,0	70,5 1,08 53,7	70,0 1,07 53,3
γ_s = 3,02	$t_{n=2}$ (mm) $C_{n=2}$ P_f (%)	71,1 1,09 54,1	73,8 1,13 55,7	67,2 1,03 51,4	71,5 1,10 54,3	67,1 1,03 51,3	70,8 1,08 53,9	70,3 1,08 53,5

In the above tables:

W = dolos mass
V = dolos volume
h = dolos height
γ_s = specific block density
r = waist-to-height ratio
t_n = layer thickness
C_n = shape factor
= $\phi_n/n(1-P_f/100)$
P_f = fictitious porosity

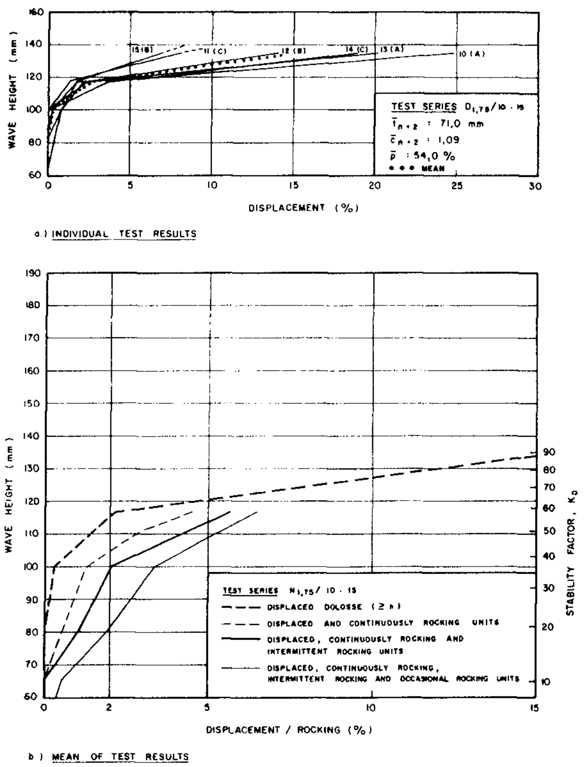


Figure 4 Test results with very light dolosse $\gamma = 1{,}81\ t/m^3$

The test results are plotted in Figures 4, 5 and 6 which show (a) the individual test results for displaced dolosse and (b) the mean results for displaced and rocking units. These figures show a considerable increase in 'damage' if the number of rocking units are included.

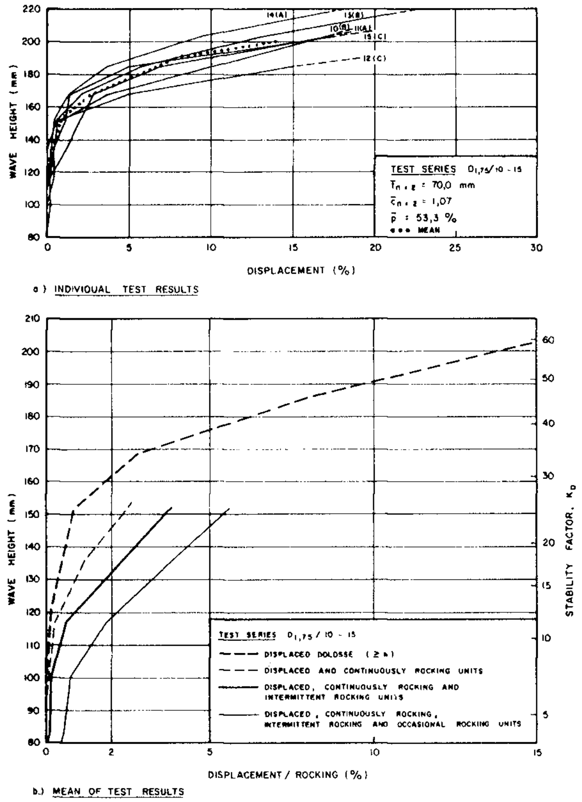


Figure 5 Test results with normal density dolosse $\gamma = 2,39\ t/m^3$

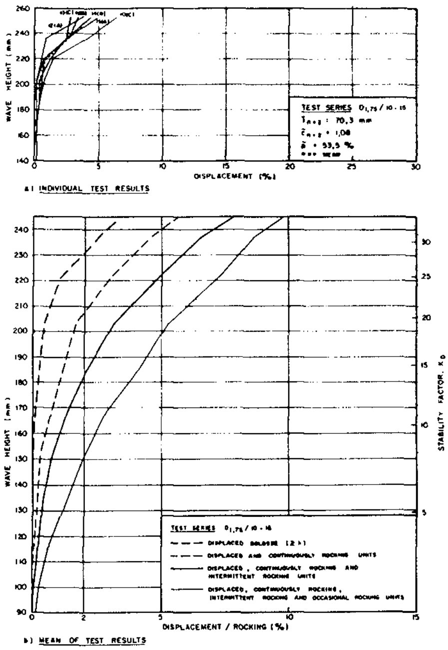


Figure 6 Test results with very heavy dolosse
$\gamma = 3{,}02\ t/m^3$

The areal distribution of damage along the slopes is shown in Figure 7.

The mean and extreme values for displaced dolosse are compared in Figure 8. The mean values obtained in the initial tests are also shown in this figure from which it is clear that:

(i) initial and present test results compare reasonably well, particularly for the lower damage ranges;

(ii) there is a considerable increase in stability with increase in the density of the dolosse; and

(iii) an increase in damage from 1 to 5 per cent occurs for dolosse with

γ_s = 1,81 for a 13 per cent increase in wave height;
γ_s = 2,39 for a 15 per cent increase in wave height; and

γ_s = 3,02 for a 17 per cent increase in wave height.

The reserve stability for the heavier units is thus slightly greater but this is not considered to be very significant.

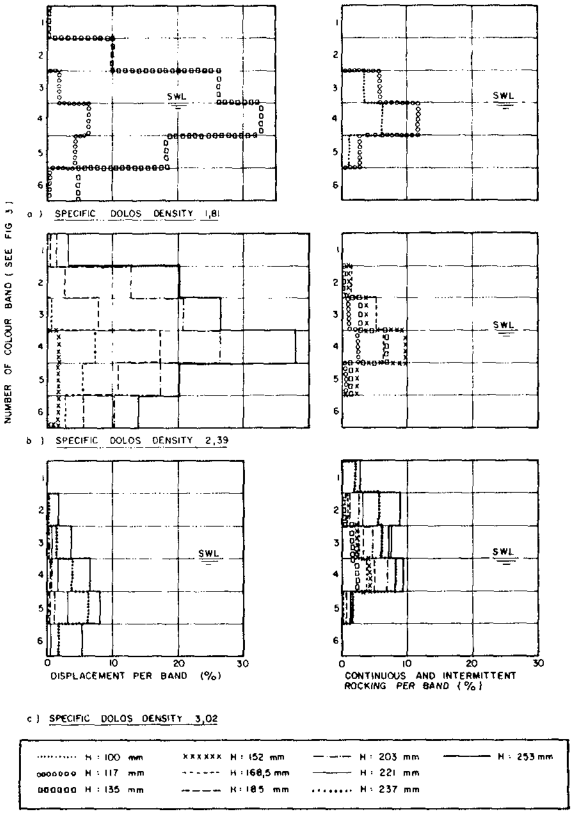


Figure 7 Block density tests - mean areal distribution of damage

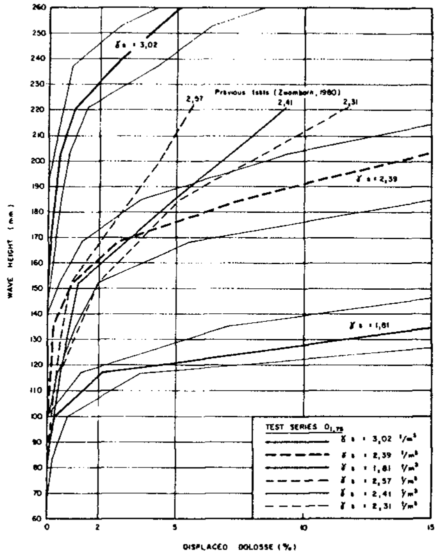


Figure 8 Comparison of mean and extreme test results for all unit densities tested

5.2 Effect of Waist to Height Ratio

Details of the model dolosse were as follows:

Model dolosse	W(g)	V(10^{-6}m^3)	γ_s	h(mm)	r
Mean	80,9	34,50	2,34	59,3	0,33
Standard deviation	0,72	0,605	0,035	0,19	0,003
Mean	81,2	33,95	2,39	56,4	0,38
Standard deviation	2,30	0,785	0,047	0,18	0,004
Mean	80,4	33,47	2,40	52,9	0,43
Standard deviation	1,98	0,698	0,052	0,17	0,004

The characteristics of the dolos armour for each test before wave action, determined with the standard sounding technique, are given in the following table:

Test series R		1	2	3	4	5	6	7	8	9	Mean
r=0,33	$t_{n=2}$ (mm)	69,9	68,2	63,9	67,8	73,5	69,5	67,4	66,5	67,4	68,2
	$C_{n=2}$	1,07	1,05	0,98	1,04	1,13	1,07	1,03	1,02	1,03	1,05
	P_f (%)	53,4	52,3	49,0	52,0	55,7	53,2	51,7	51,0	51,7	52,2
r=0,38	$t_{n=2}$ (mm)	-	67,4	64,8	61,9	69,8	61,6	66,6	65,1	60,1	64,7
	$C_{n=2}$	-	1,04	1,00	0,96	1,08	0,95	1,03	1,00	0,93	1,00
	P_f (%)	-	52,0	50,0	47,7	53,6	47,4	51,4	50,3	46,1	49,8
r=0,43	$t_{n=2}$ (mm)	62,4	59,9	56,6	62,1	62,7	59,9	61,6	57,4	56,0	59,8
	$C_{n=2}$	0,97	0,93	0,88	0,96	0,97	0,93	0,96	0,89	0,87	0,93
	P_f (%)	48,3	46,2	43,1	48,1	48,6	46,2	47,7	43,9	42,4	46,1

The individual and mean test results of nine repeat tests for waist ratios r = 0,33; 0,38 and 0,43 are presented in Figures 9, 10 and 11.

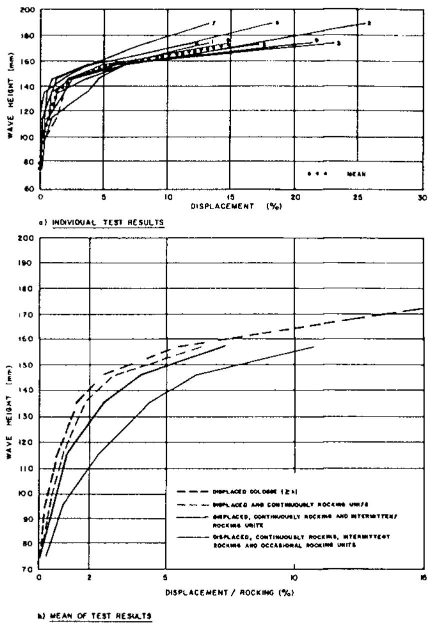
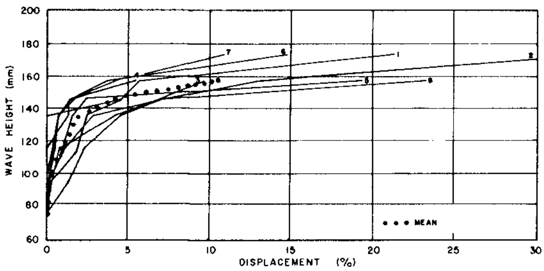
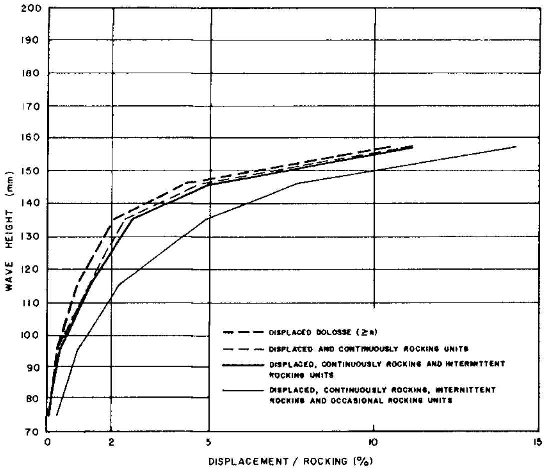


Figure 9 Test results with r = 0,33



a) INDIVIDUAL TEST RESULTS



b) MEAN OF TEST RESULTS

Figure 10 Test results with r = 0,38

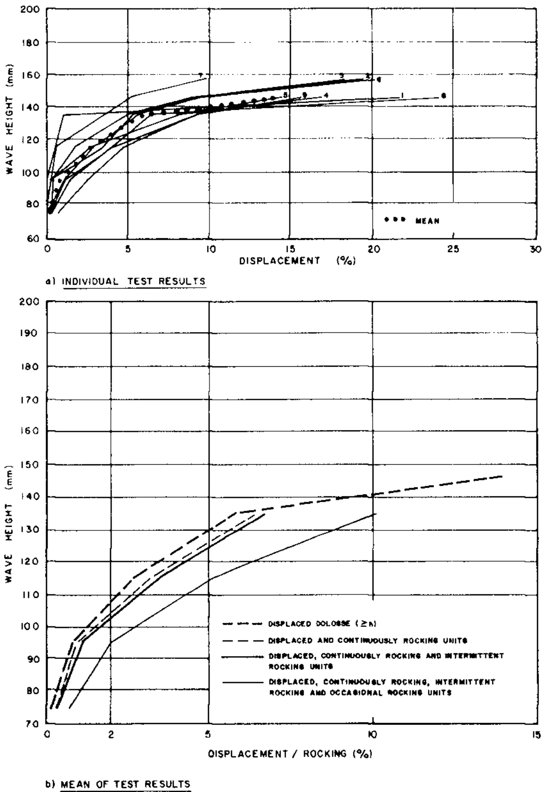


Figure 11 Test results with r = 0,43

The mean values for displaced dolosse for the three waist ratios tested are shown in Figure 12 for comparison. This figure indicates that there is a marked decrease in stability with r increased from 0,33 to 0,38 and a considerable decrease in stability with r increased from 0,38 to 0,43.

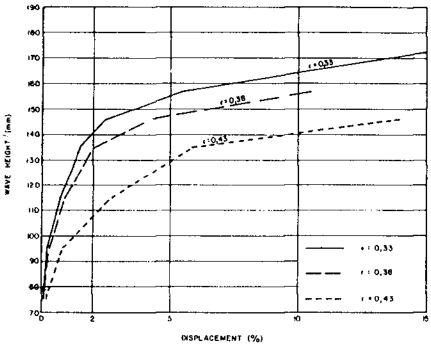


Figure 12 Comparison of mean test results for waist ratios tested

6. INTERPRETATION OF TEST RESULTS

6.1 Effect of Block Density

The basic stability equation may be written

$$\frac{V}{H^3} f(\alpha) = \frac{1}{K} \left(\frac{\gamma_s}{\gamma} - 1\right)^x = \frac{\Delta^x}{K} \quad \text{(Zwamborn, 1978 and 1980)}$$

This equation converts into the Hudson stability formula when $f(\alpha) = \cot \alpha$, $V = W/\gamma_s$, $x = -3$ and the constant $K = K_D$.

Since in the model tests the breakwater slope was always 1 in 1,5 ($\tan \alpha$), the effect of the slope, α, cannot be checked. By disregarding $f(\alpha)$ in the above equation, the tests with different γ_s values make it possible, however, to check the correctness of the remainder of the formula. Figure 13 shows the results of the initial tests (Zwamborn, 1978 and 1980) and of the new tests (Zwamborn and Van Niekerk, 1982) plotted as $V/H^3 \cot \alpha$ as function of $\gamma_s/\gamma - 1$ for 1, 2, 5 and 10 per cent damage (displaced dolosse).

Initially, curves were drawn through the test results excluding those for $\gamma_s = 1,81$ and these curves appeared to support the theoretical third power relationship, that is, $x \approx -3$, for $\gamma_s > 2,3$ t/m^3 (Zwamborn and Van Niekerk, 1982). However, a statistical analysis of the test results showed that a significantly better fit was possible when all test results are included, with the following resulting values for x and K (Figure 13):

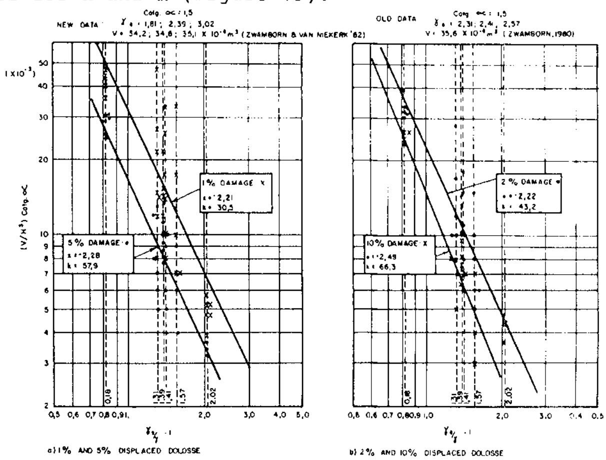


Figure 13 Relative dolos volumes versus relative density

Statistical values	Dolos displacements (%)			
	1	2	5	10
$-\bar{x}$	2,21	2,22	2,28	2,49
95% conf. lim.	1,18 to 3,24	1,78 to 2,66	1,92 to 2,64	1,87 to 3,11
$\bar{K}$	30,5	43,2	57,9	66,3

The mean value of the power x is therefore -2,30 (95% confidence limits 1,89 to 2,71) and not -3,0 and it thus appears that the theoretical equations (PIANC, 1976) and also Hudson's stability equation does not hold for dolosse, with respect to the effect of block density.

A comparison of earlier dolos tests (Zwamborn and Beute, 1972) also indicated a higher value of the power of the relative density (x > -3). Moreover, comprehensive tests on natural stone by Kydland and Sodefjed (Zwamborn, 1978) gave the following results (1 in 1,5 slope):

Power	Kydland		Sodefjed
	1% damage	4% damage	1% damage
-x	2,00	2,08	2,40

Thus the mean value for dolosse, x = -2,30, compares reasonably well with the values for natural stone and it appears from this that the theoretical and Hudson's formulae **generally** overestimate the effect on stability of increased block density.

If the Hudson formula is adjusted for dolosse according to the above results, to determine the density effect, namely,

$$W = \frac{\gamma_s H^3}{K \Delta^{2,3} \cot \alpha}$$

corresponding values for K must be used and **not** the previous K_D values based on the Hudson formula. Values for K have been calculated for the test results and are plotted in Figure 14 as function of damage (per cent displacement). The data points for the different densities tested are all seen to fall in a relatively narrow band and the mean values can be used as first estimates for the 'stability factor', K.

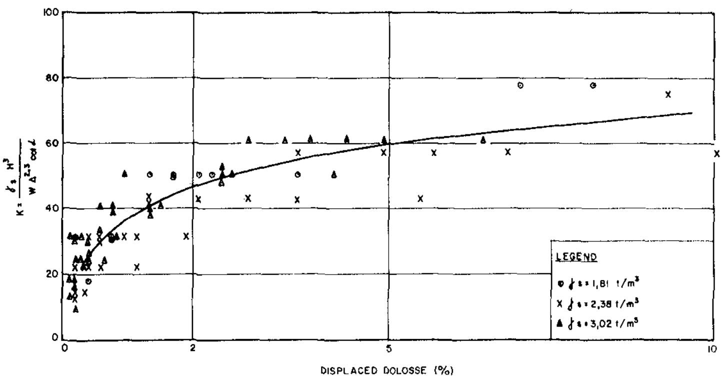


Figure 14 Comparison of stability factors, K, for different unit densities

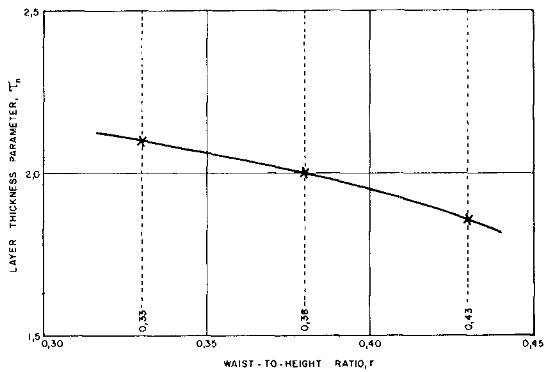
6.2 Effect of Waist-to-height Ratio

The test results show two effects of an increase in waist ratio, first, on the layer thickness and porosity and, second, on the stability of the dolosse. The layer thickness, shape factor and fictitious porosity are seen to decrease slightly with an increase in waist ratio from 0,33 to 0,43 (see Section 5.2). Since all dolosse had the same volume, this reduction was expected. The layer thickness is defined by:

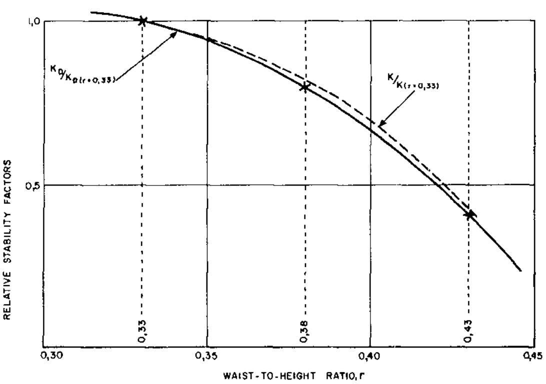
$$t_n = \tau_n V^{1/3}$$

where $\tau_n = nC_n$ = layer thickness for n layers. The following average values were found (see Figure 15a):

Waist-to-height ratio r	P_f (%)	$C_{n=2}$	$\tau_{n=2}$
0,33	52,2	1,05	2,10
0,38	49,8	1,00	2,00
0,43	46,1	0,93	1,86



a.) LAYER THICKNESS PARAMETER.



b) RELATIVE STABILITY FACTOR

Figure 15 Effect of increased waist ratio

Based on the test results, the relationship between the waist ratio (r) and the stability factors K_D and K are shown in Figure 15b. A marked decrease in stability occurs, especially when the waist ratio is increased to above 0,38. The reduction in stability is probably due to the loss in the interlocking ability of the units because of the thicker waist. If the waist ratio is increased further, the block will lose more of its interlocking ability and will ultimately resemble a cube which is totally dependent on its mass for stability.

Wave heights causing 2 per cent displacement in the model were converted to prototype values by adopting the waist ratio,

$$r = 0{,}34 \sqrt[6]{W/20}$$

suggested by Zwamborn and Beute (1972) and assuming γ_S = 2,40 and γ = 1,025. These results, presented in Figure 16, show that increasing the mass of dolosse above 40 t is much less effective in increasing stability then increasing the mass of dolosse below 40 t. It is also clear from this figure that the present data is insufficient to define the relationship between H and W and no attempt was therefore made to fit a curve through the data. To establish this relationship further tests will have to be done on dolosse with waist ratios of about 0,36 and 0,41.

Thus, when it is considered to use dolosse heavier than, say, about 40 tonnes it may well be more economical to use dolosse with reinforced thinner waists with correspondingly higher stability instead of a thick waist with lower stability. It must be stressed that Figure 16 is based on the relationship

$$r = 0{,}34 \sqrt[6]{W/20}$$

which was derived by accepting from prototype observations that 20-tonne dolosse with a waist ratio of 0,34 are strong enough to withstand stresses due to normal handling and design wave conditions. If, however, this would not be the case, for instance, a 15-ton dolos should rather have a 0,34 waist ratio, the W-H curve in Figure 16 will become lower.

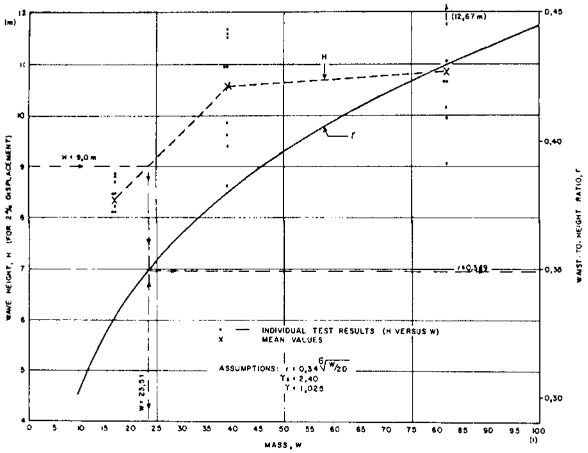


Figure 16 Relationship between H, W and r

7. CONCLUSIONS AND RECOMMENDATIONS

The initial tests with dolos armour with block densities of 2,31; 2,41 and 2,57 gave no conclusive results and further tests with dolosse with a larger range in block densities, namely, 1,81; 2,39 and 3,02 were done. These new test results showed clearly the effect of block density on the armour stability. The classic third-power relationship with regard to block density seems to over-estimate the effect of block density and a power of 2,3 was found to represent the test data better. The lower power agrees approximately with previous test results on natural stones and the theoretical stability equations, therefore, do not appear to represent the density effect correctly.

When high-density dolosse are used, care must be taken that they are at least as strong as the dolosse of normal density which can be achieved by increasing the waist-to-height ratio accordingly.

Test results showed that the stability of dolosse decreases as the waist ratio increases. Tests were done with dolosse with r = 0,33; 0,38 and 0,43 and K_D and K values for the latter two were found to be 20 and 60 per cent, respectively, smaller than the K_D value for dolosse with r = 0,33.

Further tests with waist ratios of about 0,36 and 0,41 would be needed to determine the reduction of stability more accurately.

Thus, when model tests are performed for a certain project, dolosse with the correct waist ratio must be used in the tests. If such dolosse are not available, the test results must be adapted to allow for the change in stability due to a different waist ratio tested.

To compensate for the larger tensile stresses in the heavier dolosse it has been suggested that the dolos waist ratio be increased according to the formula

$$r = 0{,}34 \sqrt[6]{W/20}$$

Because the stability decreases for the higher waist ratios, however, it was found that the stability of dolosse, designed accordng to this formula, increases very little when the mass exceeds about 40 t.

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