DOLOS PACKING DENSITY AND EFFECT OF RELATIVE BLOCK DENSITY

by

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ABSTRACT

Accuracy and compatibility of measuring and testing techniques are discussed briefly and a *plea* is made for *standardization* to avoid, as far as possible, deviations in test results of different laboratories. One of the main causes of these differences is inconsistency in Dolos *packing densities* and corresponding layer thicknesses or shape factors. In an attempt to alleviate this problem three placing densities, namely 'light', 'mean' and 'dense' have been defined and their physical properties determined. Flume tests with regular waves, and Dolos armour units at these packing densities, showed very little difference in stability and, considering practical limitations during construction, it is suggested that the 'mean' packing density be used for a 'first design', followed by proper model tests. The results of tests with model Dolosse using three different *unit densities* were inconclusive and further tests using a wider range of densities are underway.

INTRODUCTION

The 'Dolos' breakwater armour unit is now used widely for harbour and shore protection works in various parts of the world.[20] Model tests on the stability of Dolosse have been carried out at several laboratories but differences in *definitions* and *test techniques* often preclude a direct comparison of the results.

There is, for example, considerable difference of opinion about the *number of Dolosse* required to form a so-called 'double layer' of armouring blocks[20,11,3,7] and, because the number of Dolosse per unit area affects the economy as well as the stability of a structure, an attempt is made to define more clearly various packing densities. Some tests have also been done to determine the effect of the packing density on the stability of a Dolos armouring, as well as its possible influence on wave run-up.

According to all the known stability formulae, the armour block mass is inversely proportional to the *relative block density* to the third power[14] and it is, therefore, attractive and, in certain cases imperative[16], to use a higher than normal block density. Some doubt has been expressed, however, about the validity of this proportionality in the case of Dolosse[19] and some tests with regular non-breaking waves were, therefore, done to determine the effect of relative block density on the stability of Dolosse.

ACCURACY AND COMPATIBILITY OF MEASURING TECHNIQUES

Definitions and test methods should be completely compatible if comparisons

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are to be made between the results of tests on models done in different laboratories and when test data are to be compared with prototype data. This is of particular importance in the case of porosity of the armouring, the block shape factor or the layer thickness, and the damage recorded after wave action.

The *porosity* can be determined in two different ways, firstly, by placing, say, 5 to 10 layers of Dolosse in a container of known dimensions and filling the voids with water ('real' porosity) and, secondly, by determining the percentage voids in the container or of the model slope, from the difference of the 'total volume' and the volume of the Dolosse ('fictitious' porosity). A representative water level, in the case of the container tests, or the thickness of the armour, in the case of a model slope, can be judged by eye (to achieve a reasonable accuracy, 5 to 10 layers are used) or can be determined with the more reliable sounding technique.[3,5]

Both methods are used to determine porosity [11,18] and a comparison of the values obtained by these methods showed a consistent difference of 3,5 per cent, which is caused by the protrusion above the water surface of parts of the Dolosse. It is thus important to define the basis or method of measurement when values for porosity are given.

The U.S. Army Engineer Waterways Experiment Station (WES) developed a standard *sounding technique* in the early 1950's to measure the extent of damage to stone dumped randomly on a breakwater slope. The size of the original sounding disc was increased for Dolosse to 1,14 $V^{1/3}$ with a grid spacing of 1,5 $V^{1/3}$, (V is the block volume) to obtain an armour layer thickness "which visually appeared to represent an acceptable two-layer thickness."[3] This technique was found to be very useful in determining the average armour thickness; repeat packing and sounding tests in a container showed a maximum variation of $\pm$ 3 per cent but repeat soundings of the same packing on Dolos slopes showed a variation of only $\pm$ 1½ per cent). The *shape factor* $C = t/n\ V^{-1/3}$(t being the measured thickness of n layers) follows directly from the armour layer thickness and the block volume and its value is therefore of the same accuracy.

A further check was made of the influence of the grid size and the disc diameter on the measured armour thickness. Container tests showed that for a *grid size* of up to double that specified, that is 3 $V^{1/3}$, the thickness is hardly affected, the difference being less than 1 per cent . The layer thickness, however, is reduced slightly, almost linearly, for smaller *disc sizes*, i.e. a disc of one third of the size causes a reduction of just under 10 per cent. The latter should be taken into account when doing *prototype soundings* because normally, a relatively small plate or ball is used which would make the Dolos layer *appear* to be say, 10 per cent, thinner.

A comparison was also made between the *damage* measured according to the WES sounding technique and the damage derived from records of individual blocks which had been displaced. Repeat soundings showed that a 'damage' of 4 per cent (sum of the negative differences) could be obtained even before there had been any wave action. Thus the sounding technique cannot be expected to provide damage figures to an accuracy better than about 4 per cent which is considered a serious drawback, particularly as regards localised damage. Compared with this, measurement of the movement of individual Dolosse provides a much more detailed and accurate record of damage because the movement of each Dolos can be recorded; with say 500 Dolosse in the test section, damage increments of 0,2 per cent can be differentiated.

In the past, blocks which were seen to be *rocking* continuously were sometimes also included in the measurement of damage because these blocks were assumed to have broken. Compared with the blocks which moved out of position (displaced units) the number of rocking blocks observed was quite small and, since the visual observations were rather subjective, the rocking was often neglected. Observations through glass-sided flumes have indicated, however, that considerable rocking movements do take place and a quantitative measuring technique was therefore developed to record these movements. The technique consists of *time-lapse cine pictures* of the Dolos slope, taken at the time when the wave trough has reached its lowest point on the slope. Subsequent projection of the film clearly shows the change in Dolos positions, representing Dolos movements between successive waves, on the entire exposed slope. The results are analysed by marking and counting the blocks separately which shows

- *continuous rocking or full roll-over* (no displacement)
- *intermittent rocking* (about two-thirds of the time)
- *occasional rocking* (about one-third of the time)

Present knowledge of the Dolos strength is insufficient to define acceptable degrees of rocking and it is *suggested* that, for the time being, all the above modes of movement be recorded separately, together with the number of displaced units, as discussed above. A more detailed description of the measuring techniques is given elsewhere[22].

DIFFERENT PACKING DENSITIES

Definitions

The definition of the packing density of breakwater armour blocks is the *number of units* (e.g. Dolosse), N, per unit area of slope. The packing density may be expressed as follows :

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

with $\emptyset_n$ is the packing density parameter being related to the number of layers (n), the shape factor (C_n) and the 'fictitious' porosity (P_f) as follows : $\emptyset_n = nC_n(1 - P_f/100)$.

The layer thickness can be expressed as follows :

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

where τ_n is the layer thickness parameter also related to the number of layers (n) and the shape factor (C_n), i.e. $\tau_n = n\,C_n$.

Differences of up to 35 per cent in the value of $\emptyset_{n=2}$ (double layer) are quoted in the literature.[11,17] Because the number of armour units per unit area, and thus the value of $\emptyset$, has a direct bearing on the economy of the structure and is also expected to influence both the stability as well as the safety of the breakwater, it was decided that a clear and unambiguous *definition* for the packing density of a *single randomly placed layer* of Dolosse was needed urgently. The following definitions are therefore proposed (see Fig. 1) :

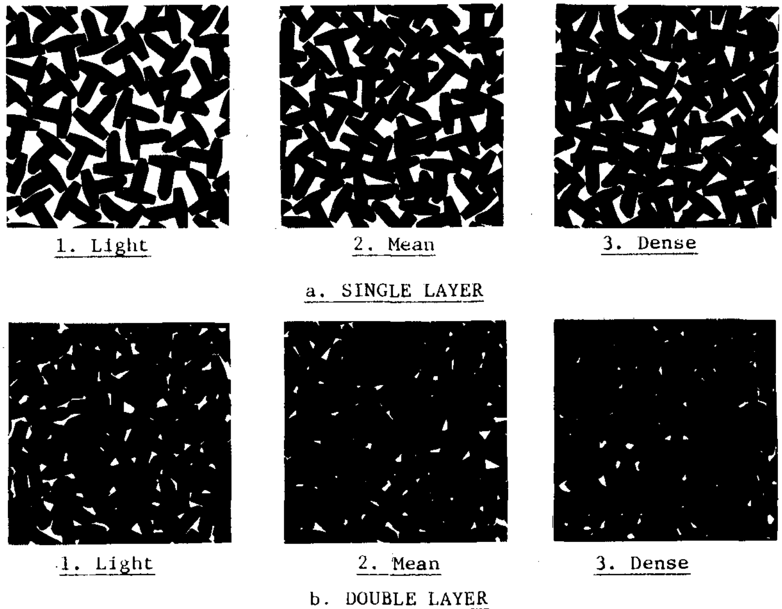


FIG. 1 PACKING DENSITIES

light packing – all Dolosse rest on the underlayer with two points (Fig. 1.a.1)

mean packing – average packing density judged to provide a proper first layer cover (Fig. 1.a.2)

dense packing – every Dolos touches the underlayer with at least one point (Fig. 1.a.3)

Packing tests

To determine the $\emptyset$ values for the above packing densities, a total of 65 packing tests were done by 8 different persons using a 0,5m by 0,5m area ($A = 0{,}25\ m^2$) and Dolosse with a height $h = 60$ mm ($V = 35{,}6 \times 10^{-6} m^3$).

The following results were obtained :

Packing	Tests	Mean no. Dolosse ($N_{n=1}A$)	Variation max./min.	$\emptyset_{n=2} = 2N_{n=1}V^{2/3}$
light	23	96	± 5	0,83
mean	20	115	± 8	1,00
dense	22	133	± 8	1,15

As was to be expected, there is a reasonably large variation between the individual packing tests but, on average, the results were found to be very consistent even with the large number of people involved in the tests. *It is thus concluded that, given the above definitions, the three packing densities are reproduceable to an acceptable degree of accuracy.*

For a breakwater armouring, a 'double layer' of Dolosse is required, that is, $2N_{n=1}$. The corresponding $\emptyset_{n=2}$ values are included in the last column of the above table.

Placing technique

The packing densities, N, discussed above refer only to the number of units per unit area and *not* to the possible differences in *placing density*, i.e. differences in the number of units per unit of volume. Although it was found in the laboratory to be possible to achieve different placing densities,[18] this is quite impractical in the prototype; the placing density will depend on the placing technique and conditions during placing and can, therefore, not be prescribed.

Since it is not considered possible to achieve a specific placing density in the prototype, a *standard technique* is used in the model whereby the Dolosse are held by the shank and dropped in position from a height of between h to 2 h. This is considered reasonably representative of prototype placing techniques.

On the model slopes, the Dolosse were always placed in *one operation* (full layer thickness) from the bottom upwards. A better interlocking is achieved in this way.

Porosity and layer thickness

The *physical properties*, namely, 'real' (P_r) and 'fictitious' (P_f) porosities, layer thickness (t) and shape factor (C), were determined for the light, mean and dense packing densities using the results of 12 container tests and 10 tests each for the light and dense packing and 34 tests for the mean packing on a 1 in 1,5 model slope. The average physical properties of Dolosse at different packing densities were found to be as follows :

Packing density	$\emptyset$ (n=2)	Porosity in per cent				Relative armour layer thickness			
		Container tests (n=5)		Model slope (n=2)		Container tests (n=1 to 5)		Model slope (n=2)	
		P_r	P_f	P_f		$\tau_{n=2}$	τ_1 n>2	$\tau_{n=2}$	$C_{n=2}$
light	*0,83*	*55,0*	*52,8*	*51,8*		*1,79*	*0,85*	*1,72*	*0,86*
mean	1,00	55,0	50,9	51,5	51,5	2,06	0,94	2,04	1,02
dense	*1,15*	*55,0*	*51,4*	*52,3*		*2,41*	*1,14*	*2,42*	*1,21*

The 'real' porosity is seen to be independent of packing density which is to be expected. Variations in the fictitious porosity are small and follow no particular trend so that the average value of 51,5 per cent, which applies to both the container and model slope tests, can safely be accepted for all three packing densities.

In the container tests, every layer was sounded from n = 1 to n = 5. The results showed that the *first layer* was always significantly *thicker* than the following layers because the first layer is packed onto underlayer stone in which the cavities are much smaller than they are in a Dolos layer. Thus $\tau_{n=2}$ is seen to be greater (about 7%) than $2\tau_1$

where t_i refers to the thickness of one layer in a multi-layer packing (n>2). The same applies to the shape factor, C, which is found simply by dividing t_n by n. This should be borne in mind when the armouring in the above table, consists of *more than two layers* (n > 2). The model slope double-layer thickness and corresponding shape factor values are seen to agree closely with the container values.

The above physical properties apply strictly only to Dolosse with r = 0,33 but it was found that there is no significant difference in porosity or layer thickness for Dolosse with waist ratios varying from 0,30 to 0,35 and they can therefore *safely be used* for all Dolosse with *waist ratios* within this range.

For a normal *double layer*, the number of Dolosse per unit area follows from $N_{n=2} = \emptyset_{n=2} V^{-2/3}$ but for a large *mound* of Dolosse, consisting of many layers, the packing density per unit of volume (N') becomes :

$$N' = N/t = (1 - P_r/100)V^{-1} = 0,45/V$$

because P_r = 55,0 for all three packing densities.

For a structure of *irregular shape* (e.g. breakwater head) in which a *double layer* of Dolosse is used, the number of units per unit of volume may be useful :

$$N'_{n=2} = N_{n=2}/t_{n=2} = 0,485/V$$

which is also independent of packing density accepting P_f = 51,5.

Comparison with previous data

Previously reported data on required *number of Dolosse* and corresponding *layer thicknesses* are compared in the following table :

Source	Year	$\emptyset_{n=2}$	$\tau_{n=2}$
(a) Merrifield and Zwamborn[11]	1966	1,04	2,6
(b) CERC, SPM[17]	1973	0,74	2,0
(c) Silva and Foster[15]	1974	0,73	2,00
(d) Davidson[5]	1976	0,67	1,60
(e) Vonk[18]	1976	1,15	2,36
(f) Vonk[18]	1976	1,08	2,12
(g) Vonk[18]	1976	0,86	2,00
(h) Zwamborn[20]	1976	1,0	2,2
(i) Carver and Davidson[3]	1977	0,83	1,88
(j) Carver and Davidson[3]	1977	0,62	1,24
(k) Present paper : *light*	1978	0,83	1,72
(l) (based on soundings) *mean*	1978	1,00	2,04
(m) *dense*	1978	1,15	2,42

It is clear from the above that smaller layer thicknesses generally go with lower packing densities which is to be expected because $\emptyset = (1 - P_f/100)\tau$ with P being constant (thus intermediate values for $\emptyset$ and τ can be interpolated linearly. Most of the data compare reasonably well, except (a), (b) and (c) for which the τ values are relatively too high. In the tests described in (a) very roughly cast cement Dolosse were used for the original tests. Subsequent tests (h), (k), (l) and (m) were all done with smooth P.V.C. models.

All the Dolos applications in South Africa (involving a total of some 120 000 Dolosse) and several large schemes elsewhere (e.g. High Island Water scheme[9] and Sines Harbour[12]) were built in accordance with a value $\emptyset \simeq 1$ whereas in the U.S.A. and Australia values as low as $\emptyset = 0,67$ and, more recently, $\emptyset = 0,83$ are used, the latter being the same as the 'light' packing density defined in this paper.

Optimum packing density

Three packing densities have been defined above and the corresponding physical properties determined. The question now is, which density should be used for a particular harbour design?

Obviously, a low packing density reduces the initial cost. On the other hand, some test results indicate that stability of the armour is improved when the number of Dolosse is increased[3,18]. There are also practical aspects to be taken into account; when a low packing density is used, placing accuracy and control must be very good, otherwise there is a possibility that the armour will have weak spots in it right from the beginning. It is interesting to note that in several instances, *during construction*, the armour was judged to be incomplete or too irregular after the theoretical number of Dolosse had been placed. This occurred, inter alia, at the Cape Town harbour extensions where some 10 per cent cent more Dolosse were used ($\emptyset \simeq 1,13$), for the Port Elizabeth shore protection[20] where 2 per cent more Dolosse were used ($\emptyset = 1,06$) and for the Sines breakwater[21] where the number of units was increased from $0,16/m^2$ ($\emptyset = 1,04$) to $0,18/m^2$ ($\emptyset = 1,17$), that is about 13 per cent more than the theoretical number.

A decision on the packing density to be used should be reached by carefully *weighing up* the initial capital cost, maintenance cost, practical considerations (construction methods and constraints) and the economic effects (interruption in port operation) of a part or complete failure of the structure. In order to be able to perform this type of economic analysis, it will be necessary to know the effect on the stability of different packing densities. Because of the complete lack of comparable data, it was decided to carry out some tests using the three packing densities discussed above.

MODEL TESTS ON EFFECT OF PACKING DENSITY ON STABILITY

Although, as discussed in the previous section, researchers have used various packing densities in stability tests it is virtually impossible, because of the differences in test conditions and the interpretation of damage, to compare directly the results of tests done by different laboratories.

Some *comparative tests* were done, however, by Vonk[18], both with a 1 in 1,5 and a 1 in 2 slope. He found a significant *improvement* in the stability of a Dolos armour by increasing the packing density about 25 per cent from $\emptyset_{n=2} = 0,86$ to $\emptyset_{n=2} = 1,08$, particularly for the 1 in 1,5 slope. Carver and Davidson[3] also report on some tests carried out with Dolosse on a 1 in 1,5 slope using different packing densities. They report a decrease of about 50 per cent in the stability factor, K_D, for a decrease of 25 per cent in the number of Dolosse (from $\emptyset = 0,83$ to $\emptyset = 0,62$) and an increase of 27 per cent in K_D for an increase of 11 per cent in N (from $\emptyset = 0,83$ to $\emptyset = 0,92$)*. Silva and Foster[15] found little difference in

* Carver and Davidson[3] ascribe this improvement to the fact that the Dolosse were packed in a *pattern* but, considering the improvement in K_D for $\emptyset = 0,62$ to $\emptyset = 0,83$, the further increase in K_D could also be ascribed to the increased number of Dolosse.

the initiation of motion of the units but, at higher damage levels, there was a significant increase found with a higher packing density.

Thus, it appears that an *increase in the number of Dolosse* per unit area *improves stability*. Test data, however, are very sketchy and comparative tests were, therefore, done in the wave flume in Stellenbosch.

In the above, the stability factor is defined by Hudson's formula[17], namely,

$$K_D = \frac{\gamma_s H_D^3}{W \Delta^3 \cot\alpha}$$

where γ_s is mass density, H_D is design wave height, W is block mass, Δ is relative block density i.e. $\gamma_s/\gamma-1$, γ is mass density of water and α is breakwater side slope.

Test facilities

The tests were done in the 160 m long (effective length), 3 m wide and 1,1 m deep wind-wave flume in Stellenbosch. Only *regular waves* were used for this test series which were produced by the translatory wave board. Waves were recorded with temperature compensated probes and wave height meters connected to standard chart recorders. During the wave calibration stage, the waves were measured where the model slope was to be positioned in the stability tests (that is, near the intersection of the still water line and the top of the model slope) and a quarter wave length in front. During the actual tests, the waves were recorded from a trolley moving at an approximately constant speed over a distance of two wave lengths in front of the model.

FIG. 2 MODEL VIEW

Model lay-out and design

The flume was divided into *three* 0,75 m wide *test sections* leaving two narrow dummy channels of about half that width on either side (see Fig. 2). The core was built of clean 6mm (about 4 g) stone, the model slope was 1 in 1,5 and the water depth 0,8m.

The particulars of the *model Dolosse* were as follows (based on accurate measurements of a representative sample of 170 Dolosse) :

Model Dolosse	W(g)	$V(10^{-6}m^3)$	γ_s	h(mm)	r
Mean	81,2	35,0	2,32	59,2	0,33
Max.deviation(%)	± 3,3	± 3,0	± 2,6	± 0,4	±5,3

The 'test areas' were 750 x 750 mm^2 and 436, 526 and 605 Dolosse were placed in these areas representing a *double layer* of 'light', 'mean' and 'dense' packing respectively. They were placed in six 125 mm (about 2h) wide bands of different colour, three above and three below still water level, i.e. from 208 mm below to 208 mm above water. Taking K_D = 25 ('first design' value[20]), the design wave height for the model Dolosse follows from Hudson's formula, viz. H_D = 144,5 mm and the *area considered for damage* thus extended from 1,44 H_D above to 1,44 H_D below still water level. Above and below the 'test area', additional 81,2 g Dolosse were placed, but these were not considered for damage.

The underlayer stone mass used was W_u = 81,2/5 = 16,2 g. Sorted stone with a mean mass of 16,5 g was used. The thickness of the underlayer follows from $t_u = nCV^{1/3} =$ 43mm, using n = 2, C = 1,15 and γ_s = 2,64[20,17].

Test conditions and procedures

After the stone had been smoothed out the underlayer was profiled using the standard sounding technique on a 50 mm grid (see Fig. 12.a). The Dolosse were then placed in one operation, working from the bottom upwards, and were sounded on the same grid. The mean difference between the two soundings provided the *average layer thickness*, and the 'fictitious' porosity. The entire Dolos cover was replaced after each test series.

A test series consisted of 24 'bursts' of 2½ min. or a total of 60 min. of wave action for each wave height increment, viz. 83, 100, 117, 134,5, 152, 168,5, 185, 203 and 221. The wave period for the entire series was constant at 1,75 s (the Ursell parameter, $U = HL^2/2d^3$ where L is wave length and d is waterdepth, varied between 1,33 and 4,05; the Iribarren number, $\xi = \tan\alpha/\sqrt{H/L_o}$ where L_o is the deepwater wave length, varied from 5,06 to 2,90 while for H_D = 144,5 mm, ξ_D = 3,83 which represents the least stable condition according to Bruun and Günbak[2]).

Displacement of any units was recorded after each 2½ min 'burst'. Small movements and *rocking* were recorded continuously by the cine technique, except during wave 'bursts' numbers 8 and 16 when the cine camera was used to record the maximum wave *run-up*.

Test results on stability of different packing densities

Because of the inherent variation in tests of this nature, 10 virtually identical *repeat runs* were made using the above-mentioned wave heights. Although a few tests were carried on until complete destruction, most of the test series were stopped when between 20 and 30 per cent damage had been reached, to reduce the time required for reconstruction of the slopes.

The *test results* are shown in Fig. 3 where the percentages of displaced Dolosse are plotted against wave height for each test. The results show considerable differences, particularly for the 'mean' packing density. The more consistent result for the 'light' packing could be ascribed to an, on average, somewhat better interlock between the Dolosse but the 'dense' packing results are equally consistent so that this explanation does not appear to hold.

The *average results* for the three packing densities are shown in Fig. 4. This figure shows the somewhat surprising result that all three packing densities display about the *same stability* and, on the basis of the present tests, stability does not appear to increase with the number of Dolosse, as was expected. There is, however, a difference in the type of collapse of the armour, i.e. the 'light' and 'mean' packing densities collapse more suddenly than the 'mean' and 'dense' packings respectively.

These differences, however, show up only for damage well exceeding 15 per cent.

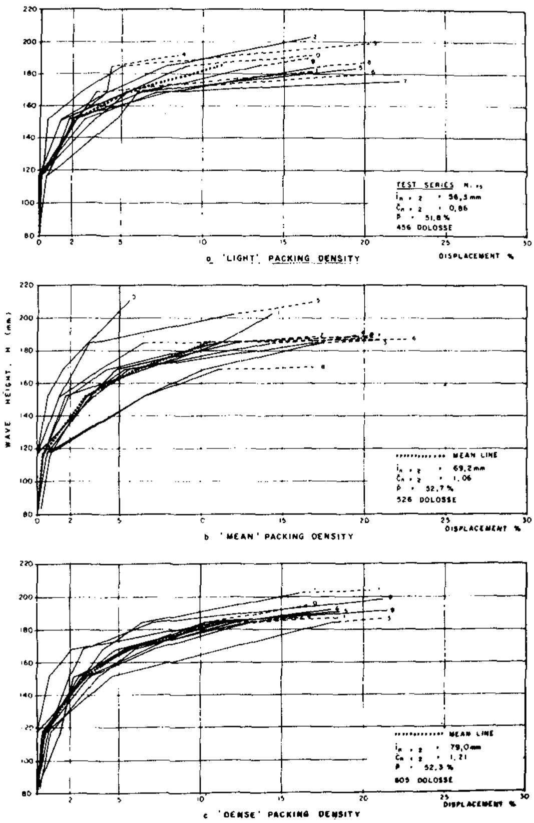


FIG. 3 PACKING DENSITY TESTS, DOLOS DISPLACEMENT VERSUS WAVE HEIGHT

Figure 5 gives the percentages of displaced units as well as the *continuously* and *intermittently rocking* Dolosse. These results were derived from the time-lapse cine measurements. The percentages are not too much greater for the higher damage values but, at the 2 per cent displacement level, the increase due to continuous rocking is seen to be about 50 per cent while continuously plus intermittently rocking units add about 100 per cent to the damage caused by displacement. Although the percentage increase is somewhat smaller for the 'dense' packing, this is not considered to be very significant (see Fig. 5).

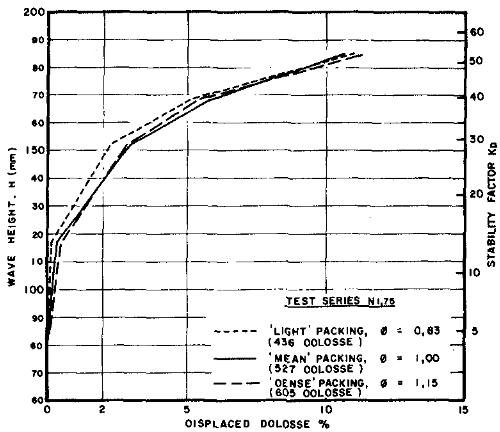


FIG. 4 COMPARISON OF MEAN TEST RESULTS FOR 'LIGHT', 'MEAN', AND 'DENSE' PACKING DENSITIES

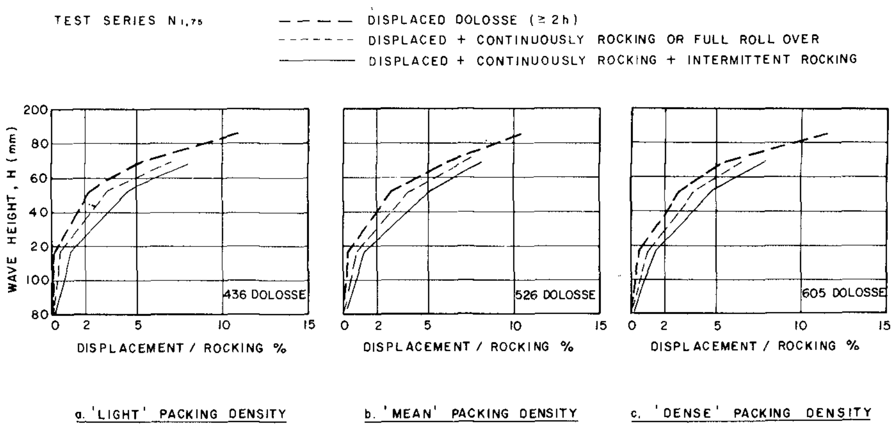


FIG. 5 PACKING DENSITY TESTS, MEAN DISPLACEMENT AND ROCKING VERSUS WAVE HEIGHT

The stability factors, K_D given in the following table, also show the lack of increased stability for higher packing densities :

Packing density	'Light', Ø=0,83			'Mean', Ø=1,00			'Dense', Ø=1,15		
Damage (%)	2	5	10	2*	5	10	2	5	10
K_D(displ.)	26,9	39,3	(50)	22,2	36,5	50,3	22,2	37,9	49,9
K_D(displ.+rock.)	16,6	30,2	-	15,4	28,5	-	15,2	29,7	-

The K_D factors, based on displacement, compare with the lowest values reported by Merrifield and Zwamborn[11] and are in reasonably good agreement with Carver and Davidson's more recent results[3] (K_D = 33 for 5% damage, Ø = 0,83, best-fit line). The K_D values based on displacement plus continuous and intermittent rocking are seen to be considerably smaller, particularly for the small percentages damage.

As indicated before, the results are somewhat surprising in that there is *no obvious improvement* in stability for the higher packing densities. The question thus arises whether it is worthwhile to use these higher densities. There are several reasons, however, against using the 'light' packing density, Ø = 0,83, namely :

- a large portion of the armour lies underwater so that it is difficult to ensure the 'ideal' packing necessary with the 'light' packing density;
- breakage of more than three Dolosse in a cluster will cause loss of stability with the 'light' packing[4];
- there is little reserve in the structure, particularly in the case of possible breakage of units;
- the wave run-up is about 5 per cent larger than that for 'mean' packing density (refer following section).

Considering the anchor shape of the Dolos, it would appear that the *optimum* *layer thickness* could be $t_{n=2} = \underline{h}$. In this case, maximum interlocking could be achieved if a certain percentage of the Dolosse came to rest with their shanks about perpendicular to the breakwater slope, acting as anchors. Based on the average measured layer thicknesses, the corresponding packing density would be $N = 0,9\ V^{-2/3}$ ($\emptyset = 0,87 \approx 0,9$). Even so, depending on the type of structure, the method of placing and the quality of the control, it would be prudent to allow for about 10 per cent extra units to ensure an even packing density in practice, increasing the above packing density to $N = 1,0\ V^{-2/3}$, that is, 'mean' packing density.

Areal distribution of damage

The average damage per Dolos colour band, for 10 repeat tests, is shown in Fig. 6. This figure shows the percentages damage due to displaced Dolosse as well as for the continuously plus intermittently rocking units.

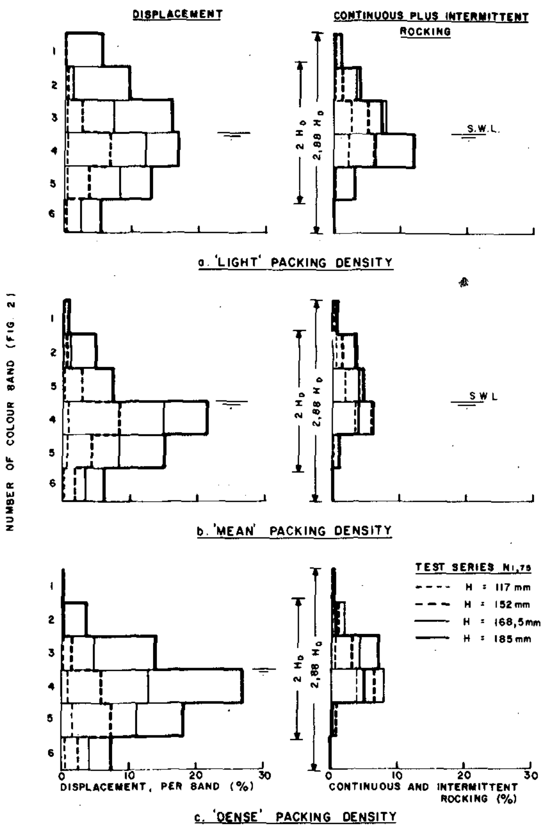


FIG. 6 PACKING DENSITY TESTS - MEAN AREAL DISTRIBUTION OF DAMAGE

The results show that the main damage areas are located *at* and *just below* the still water line but the 'dense' packing shows maximum damage in band 5 for the waves up to 152 mm. This is thought to be due to the increase in the quantity of run-down water caused by the thicker cover layer. As the wave height increases, the damage becomes more widespread, both below and above water. On average, the 'dense' packing sustained more concentrated damage near the water line whereas the 'light' packing showed the widest distribution of damage. The complete absence of rocking units in band 6 is not necessarily correct because this band remains normally submerged and is therefore excluded from the cine recording.

It is clear from the above that significant damage occurs outside the 2 H_D area normally considered and it is therefore *recommended* that damage be based on the area of the breakwater slope lying between <u>1,5</u> H_D *above* to <u>1,5</u> H_D *below still water level*.

Wave reflection and run-up

Some 100 *wave reflection* measurements for each of the three packing densities were used to compile Fig. 7a. There is seen to be very little variation in the average H_r/H values, that is, 0,27 to 0,30 and there is only a very small increase of reflection from the 'dense' to 'light' packing density.

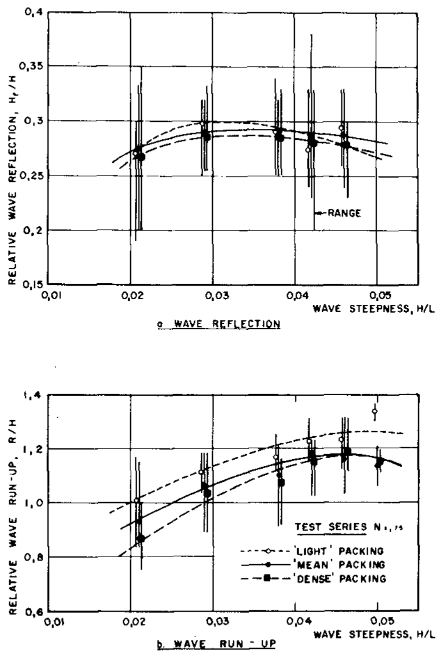


FIG. 7 WAVE REFLECTION AND RUN-UP VERSUS WAVE STEEPNESS FOR DIFFERENT PACKING DENSITIES

Wave run-up values measured by the time-lapse cine technique are shown in Fig. 7b. About 70 records for each packing density collected during 7 tests were used to plot this figure. The results show a *significant increase* in wave run-up for increase in wave steepness and for smaller packing densities.

The results for the 'mean' packing density compare well with those obtained previously by Zwamborn and Beute[19] and for the 'light' packing density with the results of Carver and Davidson[3].

MODEL TESTS ON EFFECT OF BLOCK DENSITY ON STABILITY

All available formulae to determine the mass of armour units include the third power of the relative block density in the denominator, which would indicate that the block mass can be *reduced considerably* if a high relative density is used. This has obvious advantages and, in particular cases, circumstances may *dictate* the use of high-density concrete[16].

A recent study of high-density concrete indicates that *high-strength* concrete can be produced using heavy aggregates, such as magnetite, goethite, hematite and ilmenite[6]. However, since higher density would result in increased tensile stresses in the armour units, a *thorough strength analysis* should precede the use of such high densities, particularly for large units.

Doubt has also been expressed about the validity of the third power relationship in the case of Dolosse because their stability is, at least, partly the result of the *interlocking* of the units and an evaluation of available test results indicated a power of the relative density below three[19]. It was therefore felt that a further investigation of the effect on stability of relative block density, was essential.

Basic stability equation

Castro and Iribarren (1938)[10] developed the first stability equation for rock armouring by equating the *drag force*, caused by the waves, with the resistance force, which depends on the *submerged mass* of the stone and the slope of the armouring. The basic form of their equation is :

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

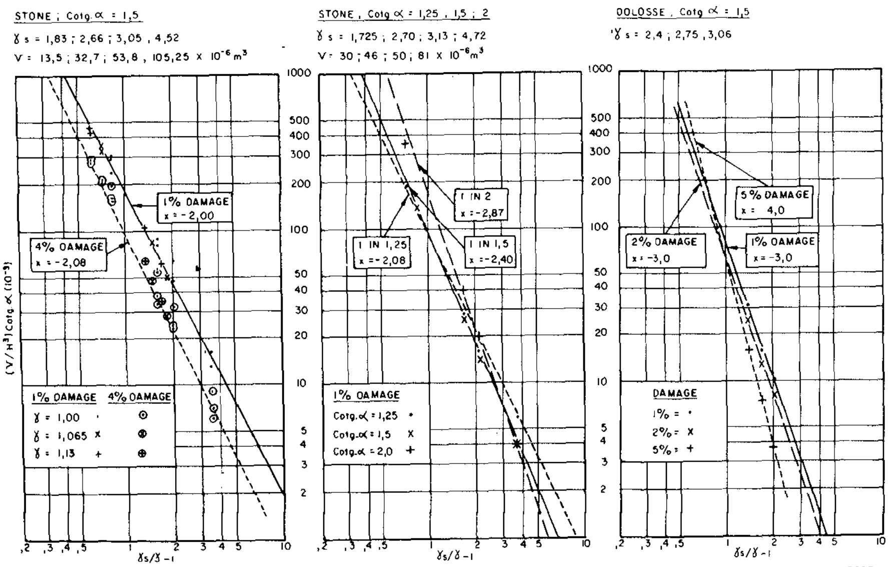
where $f(\alpha) = (\cos\alpha - \sin\alpha)^3$, K is a constant and $x = -3$. Many researchers have published variations to Iribarren's formula[14] but they all use the same basic form, except for the replacement of H^3 by H^2T in some of the formulae. The main difference between the various formulae is the different forms of $f(\alpha)$. The well-known Hudson furmula[17] is obtained by setting $x = -3$, $f(\alpha) = \cot\alpha$ and $V = W/\gamma_s$.

The *inertial forces* on the armour units and *interlocking forces*, applicable to Dolosse, are not taken into account in the above formulae. The inertial force, which depends on the wave period, is estimated to be of the same order of magnitude as the drag force but the effect of interlocking is very difficult to quantify. Armour units are also not necessarily fully submerged when the combination of drag and inertial forces reaches a maximum, which would affect the right-hand term in the above equation.

Previous test results on the effect of unit density

Brandtzaeg has reported on *extensive tests* carried out by Kydland and Sodefjed using stone of different densities (1,725 to 4,72 t/m^3), fluids with different densities (1,0 to 1,13 t/m^3) and various breakwater slopes (1 in 1,25, 1 in 1,5 and 1 in 2)[1]. He plotted relative wave height versus relative unit density for various percentages damage, arriving at a linear relationship of the form $H/V^{1/3} = \xi(\gamma_s/\gamma - \Psi)$, where ξ and Ψ are constants. Although the test results fit in quite well with this equation, the equation has no physical basis and it yields wave heights greater than zero for $\gamma_s = \gamma$, which, of course, is impossible.

The Kydland test results were, therefore, plotted in Fig. 8.a in accordance with the above equation with $f(\alpha) = \cot\alpha$ for 1 and 4 per cent damage. Mean lines have been drawn through the test points which show a *remarkably good fit* for $x = -2{,}00$, $K = 5{,}3$ and $x = -2{,}08$, $K = 9{,}5$. Hudson ascribes the disagreement with his own formula ($x = -3$) to *scale effects*, because the stability number should be independent of the density. This conclusion, however, appears to be *incorrect* in view of the results shown in Fig. 8.a.



a. KYDLAND TEST RESULTS FOR ROCK AT 1 IN 1,5 SLOPE
b. SOOEFJED TEST RESULTS FOR ROCK AT DIFFERENT SLOPES
c. GRAVESEN TEST RESULTS WITH DOLOSSE AT 1 IN 1,5 SLOPES

FIG. 8 RELATIVE UNIT VOLUME VERSUS RELATIVE UNIT DENSITY

Sodefjed's test results are plotted similarly in Fig. 8.b for 1 per cent damage. This figure shows different values of x, varying from - 2,08 to - 2,87, for the different breakwater slopes. Thus although it is again found that x > - 3, the x values do not agree with Kydland's data. Moreover, the variation of x with slope indicates that f(α)= cotα does not fully represent the slope effect (replacing cotα by $(\cos\alpha)^3$ did not reduce the spread of the lines while $(\cos\alpha - \sin\alpha)^3$ made the spread distincly worse[14]).

Some test results with Dolosse of different densities were reported by Gravesen and Sørensen[8]. These are plotted in Fig. 8.c indicating values of x = - 3,0, - 3,0 and - 4,0 for 1, 2 and 5 per cent damage, respectively. The data, however, are very limited and the drawing of general conclusions should be reserved until more test results become available.

Test facilites, model lay-out and design

The tests were done in the same facilities described before and the models were built in the same position in the flume (see Fig. 2). Three models were again tested side by side, namely Dolosse with specific densities of 2,31, 2,41 and 2,57. The model slopes were 1 in $1\frac{1}{2}$ and the water depth was again 0,8 m.

Details of the model Dolosse, based on representative samples of 50 Dolosse for each density, are given in the following table :

Model Dolosse	W(g)	V($10^{-6}m^3$)	γ_s	h(mm)	r
Mean Max. deviation(%)	81,4 ± 2,1	35,3 ± 3,0	2,31 ±1,9	59,2 ± 2,4	0,33 ± 5,2
Mean Max. deviation(%)	84,8 ± 2,3	35,2 ± 2,8	2,41 ± 2,1	59,4 ± 2,5	0,33 ± 4,8
Mean Max. deviation(%)	92,0 ± 2,5	35,8 ± 2,0	2,57 ± 2,1	59,5 ± 2,1	0,33 ± 3,7

The slope area considered for damage was 750 x 750 mm^2 on which 513 Dolosse were placed ('mean' packing, $\emptyset$ = 1,00). The 'test area' extended from 255 mm below to 161 mm above still water level (1,76 H_D to 1,11 H_D respectively). Below and above the 'test area', 120 g Dolosse were used while the underlayer was 43 mm thick, consisting of 11,4 g stone.

Test conditions and procedures

The same basic test procedures were followed as for the packing density tests. The tests were all done with regular waves of 1,75 s period using 2½ min wave 'bursts' up to a total of 1 hour per wave height.

Tests No's D1 to D 3 and D 8 and D 9 were run with gradually increased wave heights whereas a sudden increase in wave height was used for Tests No's D 4 to D 7[22].

Test results on Dolosse with different densities

A total of nine tests were done and the *test results* are shown in Fig. 9 which also shows the mean results for the six *progressive* tests. Considerable variations in the results of individual tests are again evident but the variations are seen to be less for the higher unit density. The 'suddenly' increased wave height tests show, on average, less stability for the 2,31 t/m^3 unit density (Fig. 9.a) but for the other two densities, the results of these tests *agree very well* with the mean of the 'progressive' increase tests (Figs. 9.b and c).

The comparison of the *mean lines* in Fig. 10 show an improvement in Dolos stability for increased unit density, which was expected. Although damage was below 2 per cent, the results compare very well with the results of the different packing density (N) series, for greater percentages damage the D series show greater stability (compare Figs. 4 and 10), which is thought to be mainly due to a shorter test time, i.e. larger wave height steps.[13,22]

To check on the correctness of the *basic stability equation* the relative Dolos volumes were plotted, versus the relative submerged block density , similar to the plots in Fig. 8, and mean lines were drawn for the 1, 2, 5 and 10 per cent damage cases (displaced Dolosse). The *variation* in individual test results, however, was found to be much greater than for the Kydland and Sodefjed test data (based on stone) and no definate conclusion could be drawn from these test results with regard to the correct value for x. The large variation is probably *typical for Dolosse* because of the inherent differences in packing and subsequent interlocking, which does not apply to the same extent to stone.

It was therefore *concluded* that although increased unit density does increase Dolos stability, further tests with a greater range of unit densities are necessary to determine the correct relationship between stability and unit density. These tests are under way at present.[22]

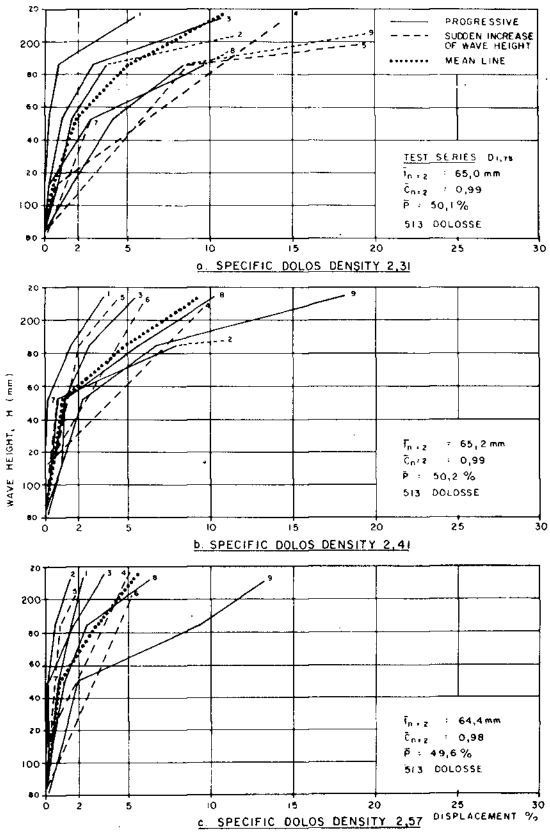


FIG. 9 DOLOS DENSITY TESTS, DOLOS DISPLACEMENT VERSUS WAVE HEICHT

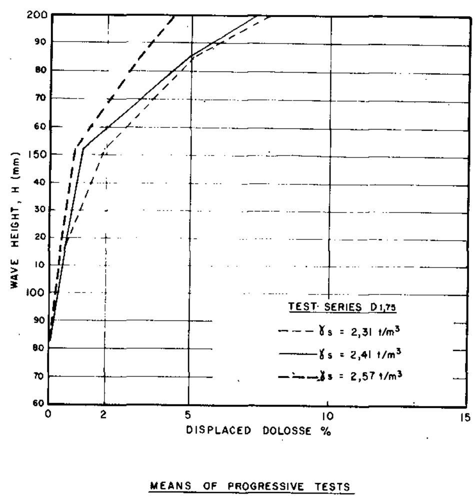


FIG. 10 COMPARISON OF MEAN TEST RESULTS FOR 2,31 ;2,41 AND 2,57 SPECIFIC DOLOS DENSITIES

CONCLUSIONS AND RECOMMENDATIONS

It is absolutely essential to *standardize measuring and testing techniques* to make test results on Dolos stability compatible. Detailed proposals for standardization are made elsewhere[22] but the main problem areas were found to be inconsistency in definitions and measurements of packing density, porosity, layer thickness (shape factor) and damage criteria which have led to unavoidable differences in reported test results from different laboratories.

Three *packing densities*, namely 'light' ($\emptyset$ = 0,83), 'mean' ($\emptyset$ = 1,00) and 'dense')$\emptyset$ = 1,15) have been defined in this paper and the corresponding layer thicknesses were found to be 1,72, 2,04 and 2,42 $V^{1/3}$, respectively, with a porosity of 51,5 per cent, independent of packing density.

Stability tests with a wave period of 1,75 s using these three *packing densities* showed little difference in damage, both based on displaced and displaced plus moving (rocking) units, the stability factor, K_D, being, on average, 24 and 16, respectively, for 2 per cent 'damage'. Wave reflection was found to be between 27 and 30 per cent, independent of placing density, but a difference of between 10 and 20 per cent was found between the wave run-up of the 'light' and 'dense' packing, depending on the wave steepness.

Taking also practical considerations into account, it is *recommended* that the 'mean' packing density be adopted for the 'first design' of a Dolos structure which should be checked by hydraulic model tests, preferably three-dimensional tests. Realistic wave conditions (e.g. irregular waves) should be reproduced in these tests and both displaced and rocking units should be carefully monitored. Tests should preferably include total destruction to determine the inherent safety of the structure.

Tests with model Dolosse having *different unit densities* (2,31, 2,41 and 2,57) showed greater stability for the higher densities but further tests with a greater unit density range are necessary to determine the relationship between stability and unit density.

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NOMENCLATURE

A = area
C = block shape factor
d = water depth
h = Dolos height
H = wave height
K_D or K = stability factor
L = wave length
n = number of armour layers
N = packing density or number of blocks per unit area
N' = number of blocks per unit volume
P_f = $(At - NV)/At$ = 'fictitious' porosity
P_r = voids volume/At = 'real' porosity
r = Dolos waist to height ratio
t = armour layer thickness
U = $HL^2/2d^3$ = Ursell parameter
T = wave period
V = Dolos volume
W = Dolos mass
x = exponent of relative density function, Δ

α = breakwater slope angle
ψ = constant
ϕ = $NV^{2/3}$ = packing density parameter
γ = specific density of water
γ_s = specific density of Dolosse
τ = $tV^{-1/3}$ = layer thickness parameter
ξ = $\tan\alpha/\sqrt{HL_o}$ = Iribarren number; also constant
Δ = $\gamma_s/\gamma - 1$ = relative block density.

Subscripts -

D indicates design value
i indicates single layer
n is the number of layers
o means deep sea value
u relates to underlayer