CHAPTER 154

STABILITY AND STRUCTURAL BEHAVIOUR OF STRENGTH IMPROVED DOLOSSE

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ABSTRACT

Stability model tests and prototype breakage tests were done to provide data for the optimum design of dolos breakwater armouring.

Stability tests with irregular waves were done with dolosse with waist ratios of 0,33, 0,36, 0,38, 0,40 and 0,43 and breakwater slopes of 1:1,33, 1:1,5 and 1:2. All model dolosse had a mass of about 80 gr and were placed at a 'normal' density, Ø = 1,00. The results showed that regular waves with $H_{reg} = 1,1\ H_{mo}$ must be used to get similar damage. Also, a significant reduction in stability is evident for dolosse with larger waist-to-height ratios and for the shorter period waves (Figures 4 and 5).

Some 50 9 t dolosse, without reinforcing and with different types of simple rail reinforcing, were tested for breakage behaviour, using a specially developed cushioning device to closely represent breakwater conditions. The results showed that unreinforced dolosse can withstand falls up to 1,5 m, without breakage and X or double-V rail reinforced units about double this height.

The results of these tests, together with specific model tests, were used to design an effective protection for the Table Bay main breakwater. The tests indicated the use of 25 t dolosse (minimum) but, because of the shallow waterdepth, the toe dolosse of the repair slope were reinforced (double-V rail reinforcing), stabilized by 75 mm steel chains, and bitumen grout will be placed to reduce their movements.

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INTRODUCTION

Procedures for the design of safe and economic dolos structures have been described by Zwamborn and Scholtz (1986). Three different design approaches were described, namely:

(i) "No Movement" Design;
(ii) "No Breakage" Design; (based on 'unbreakable'units)
(iii) "Optimum" Design; using strength improved dolosse.

Low cost dolos strength improvement can be achieved by increasing the waist-to-height ratio, in other words, to make the dolosse thicker, and by using simple types of reinforcing, for example scrap rail reinforcing.

To assist with the design over 800 stability tests were done with regular and irregular waves, using model dolosse with five different waist ratios. Moreover, unreinforced 9 t dolosse and dolosse reinforced with three different types of rail reinforcing were used to check their structural behaviour under simulated 'near breakwater' loading conditions to acceptable degrees of movements for different types of dolosse.

These results, together with a series of site-specific stability tests, were used to design the major repair works for the Table Bay main breakwater at Cape Town, Republic of South Africa.

2. DOLOS STABILITY TESTS

Stability tests on dolosse with different waist-to-height ratios (r = 0,33, 0,38 and 0,43) reported by Scholtz et al (1982) showed a marked decrease in stability for the larger waist ratios, particularly for $r > 0{,}38$. Later tests by Burcharth et al (1986) indicated little influence of the waist-to-height ratio on dolos stability, particularly for the smaller damage values. To resolve this issue, a comprehensive test programme using irregular waves and 80 gr dolosse with waist-to-height ratios of 0,33, 0,36, 0,38, 0,40 and 0,43 has been carried out.

Test Facilities and Model Layout

The stability tests were carried out in a 127 m long by 3 m wide and 1,1 m deep test flume equipped with Seasim irregular wave generators, including an absorption system to reduce re-reflections. The flume was divided into three 0,75 m wide test channels leaving two narrow dummy channels on either side. Details of the test dolosse were as follows: W = 78 to 81 g, specific density 2,34 to 2,40 and r = 0,33 to 0,43.

The standard 'mean' dolos packing density was used for all the tests, that is, Ø = 1,00 (number of dolosse per unit area, $N_n = Ø_n V^{-2/3}$, where V is the block volume and n the number of 'layers', Zwamborn and Van Niekerk, 1982) and 538 dolosse were placed on each of the 0,75 x 0,75 m^2 test areas (Figure 1). The underlayers consisted of 16,5 g selected stone, that is W/5 g.

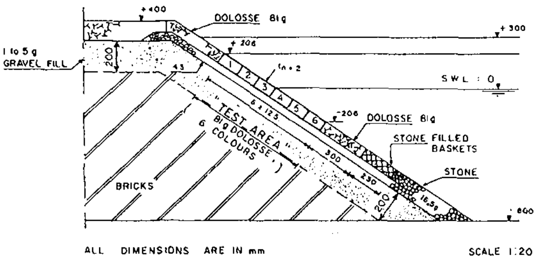


FIG. 1: MODEL CROSS-SECTION

Test Wave Conditions

Wave Spectrum	T_p (s)	Target Wave heights, H_{mo} (mm)							
Jonswap	1,25	31	50	69	90	112	129		
	1,50	30	50	69	90	109	128	155	
	1,75	30	51	72	93	113	134	152	163
	2,00	31	51	72	91	111	129	149	161
PM	1,75	31	52	72	92	113	130	146	

Wave heights were measured 5,55, 5,80 and 6,20 m away from the model slope. Re-reflections of wave energy from the wave paddles was avoided by using the Seasim wave generators' absorption system. The incident and reflected wave spectra for the above test conditions were determined by the three-point method based on the least square technique reported by Monsard and Funke (1980).

Test Procedures and Damage Criteria

The model dolosse were placed at the prescribed packing density in one operation from the bottom upwards. The tests were carried out similar to the previous tests with regular waves, that is, each wave height interval (see test wave conditions) was tested for 60 min after which the damage was determined. All test series (up to 8 wave heights) were repeated between 3 and 8 times.

Damage was determined by recording displaced units (observations during the tests and using still photography) and rocking units (observations and single exposure cine camera technique). The following damage criteria were used:

(a) displacement (movement over at least a distance h)
(b) continuous rocking or full roll-over
(c) intermittent rocking (two-thirds of the test time)
(d) occasional rocking (one-third of time or less)

The test results have been presented relative to these criteria. 'Total' damage is defined as (a) + (b) + (c).

Test Programme

The following tests were carried out using up to 8 characteristic wave heights for each test series (test numbers):

Slope	Spectrum	$T_p(s)$	r = 0,33	r = 0,36	r = 0,38	r = 0,40	r = 43
1:1,5	JS	1,75	W_2 to 9	W_2 to 9	A_7 to 9	W_2 to 9	A_7 to 9
	JS	2,0	P_1 to 3	P_1 to 3		P_1 to 3	
	JS	1,5	P_4 to 6	P_4 to 6	A_4 to 6	P_4 to 6	A_4 to 6
	JS	1,25	P_7 to 9	P_7 to 9	A_1 to 3	P_7 to 9	A_1 to 3
	PM	1,75	PM_1 to 3	PM_1 to 3		PM_1 to 3	
1:2	JS	1,75	A_{13} to 15		A_{13} to 15		
1:1,33	JS	1,75	A_{10} to 12		A_{10} to 12		

Test Results

The mean results of the tests for different **waist ratios** at a slope of 1:1,5 are shown in Figure 2, together with the earlier test results for regular waves. A significant reduction in stability (wave height) for dolosse with larger waist ratios is evident from this figure. When rocking units are added to the displaced units, damage was found to increase by 100 per cent for r = 0,33, 80 per cent for r = 0,36 and 50 per cent for r = 0,40.

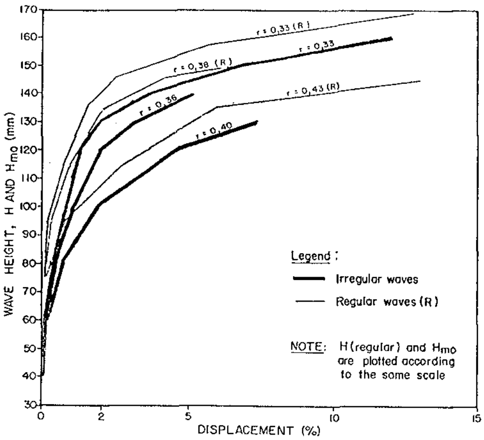


FIG. 2: EFFECT OF WAIST RATIO, REGULAR VERSUS IRREGULAR WAVES

It can also be derived from Figure 2 that **regular** waves of wave height H_{reg} = $1,1H_{mo}$ cause the same damage as irregular waves with a characteristic wave height H_{mo}. Brorsen et al (1974) concluded from model tests on dolosse that similar damage is caused when $H \simeq 0,8\ H_s$ but after checking their results this was found to be incorrect; it should have been $H \approx 1,25\ H_{mo}$ (the same error is carried through in Burcharth et al, 1986).

Most test were done with a **Jonswap** type of spectrum but comparative tests with a PM spectrum showed similar stability results for the various waist ratios.

A comparison of the effect of different breakwater **slopes** for r = 0,33 and 0,38 is given in Figure 3. For dolosse with r = 0,33 and 2 per cent displacement, the H_{mo} values are 116, 130 and 140 mm for slopes of 1:1,33, 1:1,5 and 1:2 respectively, thus somewhat increased stability for flatter slopes. In the case of r = 0,38, the differences in stability are seen to be much smaller.

Test results showed a significant reduction in stability for the shorter wave period (T_p) values, for instance, for r = 0,33 and Jonswap spectra with T_p = 2,0 and 1,25 s resulted in 2 per cent displacement K_D values of 22 and 13 respectively. Similarly, for r = 0,40, K_D values of 12 and 6 were found.

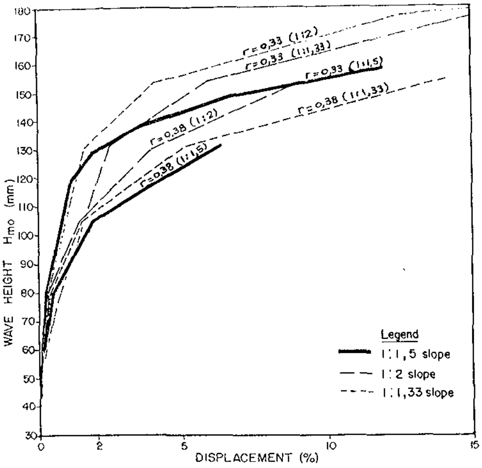


FIG. 3: EFFECT OF BREAKWATER SLOPE, IRREGULAR WAVES, T_p = 1,75 s

The overall test results are presented in Figures 4 and 5 which show the stability factors

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

with H_{mo} = wave height;

$$\Delta = \frac{\gamma_s}{\gamma} - 1;$$

γ and γ_s = specific density of water and model dolosse

and α = breakwater slope angle;

versus the Irribarren number,

$$\xi = \frac{\tan}{(H_{mo}/L_o)^{0,5}}.$$

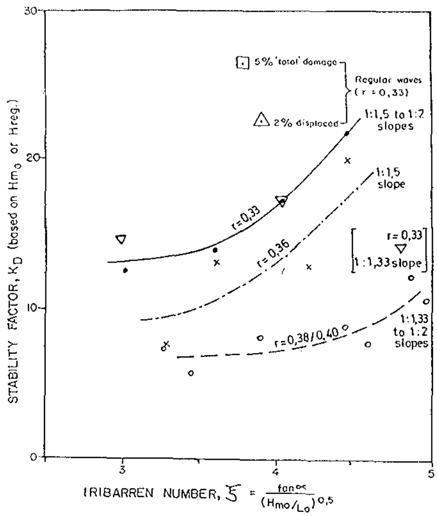


FIG. 4: STABILITY FACTORS FOR PRELIMINARY DESIGN - 2% DISPLACEMENT OR 5% 'TOTAL' DAMAGE

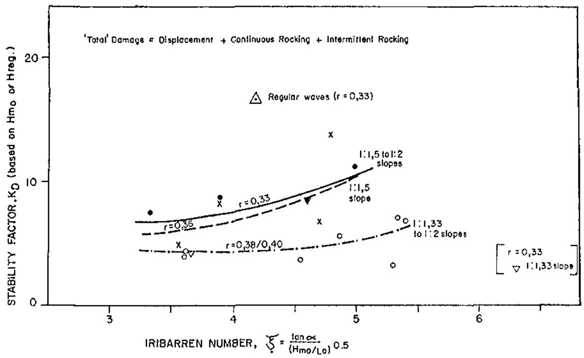


FIG. 5: STABILITY FACTORS FOR PRELIMINARY DESIGN - 2% 'TOTAL' DAMAGE

Figure 4 is based on 2 per cent displacement. This figure also represents the 5 per cent total damage quite well. Figure 5 is based on 2 per cent 'total' damage.

These figures display clearly the significant effects of the increased waist ratio's (reduced K_D values), and the wave period (low K_D values for shorter wave periods with minimum values for $2,5 < \xi < 3,5$. These figures also show the effect of irregular waves (H_{mo}) versus regular waves (H_{reg}) (Scholtz et al, 1983).

Figures 4 and 5 could be used for a first design, as a guide using Figure 4 (2% displacement or 5% total damage) for high quality strength reinforced dolos projects and Figure 5 (2% total damage) for lower quality and unreinforced dolos applications.

It should be mentioned here that the significant reduction in stability of the 'thicker' dolosse found in these tests contradicts the results reported by Burcharth et al (1986) which is inter alia thought due to different dolos packing densities and the small dolosse used by Burcharth (30 g), that is, possible scale effects.

3. STRUCTURAL TESTS ON DOLOSSE

To check on the structural strength of various types of simple reinforced dolosse, a series of breakage tests on 9 t dolosse were done at Cape Town.

Structural tests on dolosse were done elsewhere by dropping the units on a solid concrete base (drop test) or by letting a concrete ball hit the dolos (pendulum test). These test are effective in showing relative strengths, for instance, to show the effect of increased waist-to-height ratio's (Burcharth, 1981). However, the results of these tests cannot be used directly for the actual breakwater situation because the 'rigid'-base test is not representative for the breakwater armouring where a dolos, when moving, will drop on underlayer stone or on other dolosse that will move (yield) under the impact. A test procedure, closely representing the actual breakwater situation was therefore developed for the Cape Town tests.

Purpose of the Tests

The main purposes of the structural tests were:

(a) to develop a test procedure, closely resembling the conditions in a breakwater armour, so that acceptable dolos movements can be defined better;

(b) to determine the effectiveness of different types of simple reinforcement;

(c) to determine the effect of repeated impact loading; and

(d) to decide on the type of reinforcing of the 25 t dolosse for the Table Bay breakwater repair.

Test Dolosse

The test dolosse were 9 t with h = 2,9 m and r = 0,30. The concrete density was 2,4 t/m^3 and the design compressive strength was 40 MPa at 28 days. Test cubes showed strengths between 37 and 54 MPa while the equivalent cube strength based on cores, taken after 2 years (when the dolosse were tested) were found to be 23 per cent higher. The average tensile strength was found to be 1/15 of this value, that is, 4 MPa.

Unreinforced and dolosse reinforced with single rails, double-V rails and X-rails were tested (Figure 6). Scrap rails of 43 kg/m were used for the reinforcement, that is, 85, 115 and 168 kg/m^3 respectively.

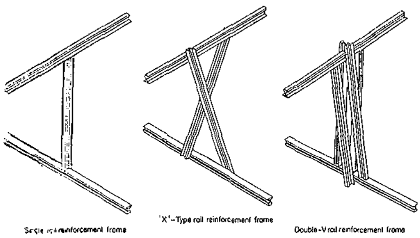


FIG. 6: TYPES OF RAIL REINFORCEMENT

Test Procedures

The basic swing test arrangement, (Zwamborn and Scholtz) was used for the tests. Various methods were tried to achieve a controlled yield and the best solution was found to be a set of three 250 mm long, 89 mm outside diameter and 4,05 mm thick pipes as an 'anvil' or 'cushioning' device (Figure 7).

The cushioning device was calibrated by comparing the deceleration of an impacting 9 t dolos in the swing test with that of a similar dolos which was dropped on 0,5 to 3 t breakwater underlayer stone and on other 9 t dolosse. The deceleration were measured with PCB Piezotronics shock accelerometers with a range of 500 g and a resolution of 0,01 g (Figure 8).

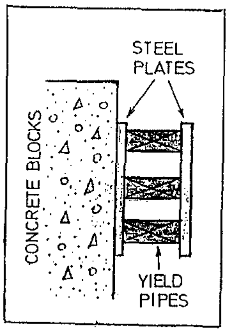


FIG. 7: CUSHIONING DEVICE

In this way, a test procedure was developed which closely represents the conditions in a breakwater situation where a dolos is lifted by the wave action and falls back onto the underlayer or on other dolosse (see also Zwamborn and Scholtz, 1986). Normally, the first fall height was 1,1 m which was increased in steps of 0,15 m to 1,7 m with unreinforced and 1,4 m with the reinforced units whereafter the step heights were increased to 0,3 m until the dolos broke or cracks occurred of at least 0,5 mm width or a fall height of 4,1 m was reached. Repeated impact tests were done using 80 and 64 per cent of the failure fall heights repeatedly, resulting in 90 and 80 per cent of the failure stresses.

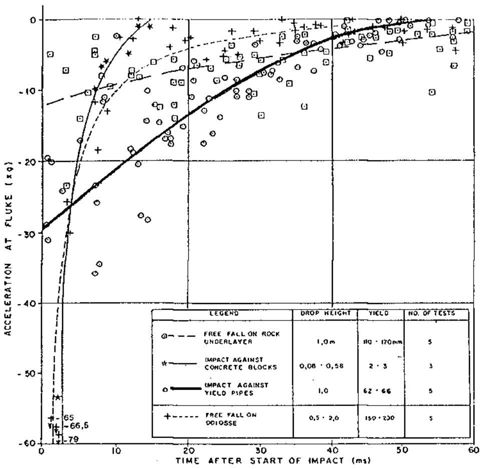


FIG. 8: CALIBRATION OF CUSHIONING DEVICE

Test Programme

The test programme included free-fall tests on rock (17 tests with 0,5, 1,0, 1,5 and 2,0 m fall heights) and free-fall tests on dolosse (5 tests with similar fall heights). Preliminary swing tests included tests against solid concrete blocks (3 tests, 10 to 15 t blocks) and tests using different pipe arrangements as cushioning device (21 tests).

The actual breakage tests included (a) head on swing tests, three dolosse each, unreinforced, single rail, X-rail and double-V rail; (b) side on swing tests, two dolosse each, as above; and (c) repeated impact, three unreinforced, one single rail, one X-rail and two double-V rail. A total of 51 9 t dolosse were used for the tests.

Test Results

Whereas unreinforced dolosse in a 'rigid' drop test break for fall heights of about 0,2 m, with a realistic yield, the critical fall heights were found to be well above 2 m. The failure fall heights found in the Table Bay tests compare very well with the Gioia Tauro tests (Grimaldi and Fontana, 1984).

With regard to the **rail reinforcing**, it is concluded from the test that:

- the single rail does not increase the dolos strength significantly, although breakage is retarded;
- the X-rail and double-V rail reinforcing increase the dolos strength by about 100 per cent (double fall height) and the dolosse were damaged but did not fail;
- since the double-V reinforcing requires about 50 per cent more steel, the **X-rail reinforced dolos** is the most cost/strength effective unit.

Also, since the critical drop heights for the 9 t Table Bay and the 30 t Gioia Tauro unreinforced and double-V reinforced dolosse are seen to be of the same order, it may be concluded that the reinforcing has the same degree of effectiveness independent of dolos size, provided the steel/concrete ratio (kg/m^3) is kept constant. With regard to **repeated impact loading**, the test results are shown in Figure 9 which is based on 200 kg dolos units (Burcharth, 1984).

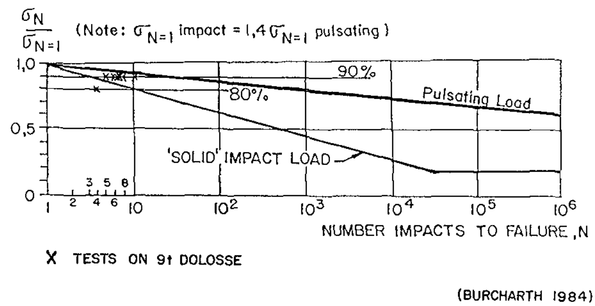


FIG. 9: REPEATED IMPACT LOADING

Burcharth's tests are based on a 'rigid' test layout and, as expected, the Table Bay results are seen to fall between the 'solid' impact load and pulsating load case, that is, in the breakwater situation, the dolosse will be able to withstand about **twice** the number of repeat loads (for example, 6 repeat loads at 90 per cent of the ultimate stress and 25 repeat loads at 80 per cent) compared with the 'rigid' case.

Application of Results

The test results can be used in the following way for the design of dolos armouring:

- single movements of unreinforced dolosse, with adjusted waist ratio (Scholtz et al, 1982) up to 1,5 m can be accepted;

- occasional rocking (less than one-third of the time) up to 0,5 m can be accepted for unreinforced dolosse;

- approximately double these values can be allowed when X or double-V reinforced units are used;

- intermittent (two-thirds of the time) and continuously rocking units will break in the case of unreinforced and crack in the case of reinforced units and must thus be accepted as eventual loss (included in 'total' damage).

4. TABLE BAY BREAKWATER REPAIRS

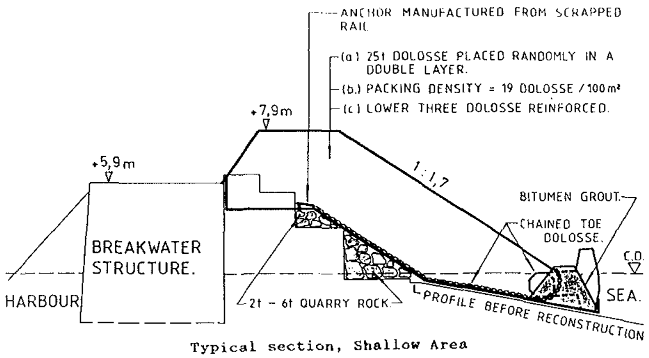
During the past two decades the seaward slope of the Table Bay harbour's main breakwater suffered appreciable damage, particularly during winter storms when the wave climate is more aggressive. Although repairs were carried out as required on an ad hoc basis, mostly by replacing missing or damaged armour units, it was suspected that the long-term effects of this maintenance work was not satisfactory.

Over the years the situation became progressively worse as the remains of broken armour units were left behind to form part of a conglomerate of various sizes of rock, rubble, gravel and sand. It became clear that the situation should be investigated in depth to ensure that the integrity of the breakwater was maintained and to curb the escalating maintenance cost. Because of the multitude of contributory factors it was concluded that the problem could best be investigated by modeling the existing situation. The complication of the accumulation of various types of debris extending for some distance seaward of the breakwater made any alterations to the existing shallow bed slopes at the breakwater almost impossible and certainly impractical.

Model Tests

It was decided to investigate different typical sections of the breakwater separately in a 3 m wide wave flume. At the selected scale of the model of 1/53, up to 160 m long breakwater sections could be studied in the flume. The 160 m long wave flume was equipped with an irregular wave generator capable of reproducing wave conditions up to and exceeding the 1 in 100 year design wave condition, that is $H_{mo} = 7,5$ m.

The finally adopted design consisted of a double layer of 25 t dolosse placed on the existing breakwater slope after partial clearing of the above-water part of the existing breakwater protection (see Figure 10). This solution which included a toe row of chained dolosse, showed a total damage (displacement > 0,5 m, dolos roll over and continuous rocking) of about 3% in the shallower part of the breakwater (- 3 m MSL) but about 20% for the deeper part (- 5 m MSL). For practical reasons, 25 t dolosse were used throughout but in the deeper section, the dolosse were all reinforced and two rows of toe dolosse were chained.



Typical section, Shallow Area

FIG. 10: TABLE BAY BREAKWATER REPAIR

Design Aspects

The dolos waist ratio was increased according to $r = 0,34\ (25/20)^{1/6} \simeq 0,36$ to strengthen the units.

Because of the hard nature of the sea bed it proved impractical to provide a proper toe berm for the breakwater slope and since this is a particularly vulnerable part of the breakwater, it was decided to introduce the following measures for the shallower part of the breakwater shown in Figure 10:

- rail reinforced dolosse were used for the lower three rows of the slope;
- to provide extra stability, the bottom row of reinforced dolosse were secured to the slope with chains;
- the practicality of using bitumen grout between the bottom rows would be investigated

Although the structural tests showed the X-type rail reinforcing to be most economical in terms of rail usage, the double-V type was used for the toe dolosse as the test results only became known during the construction period.

Manufacture of Dolosse

Concrete quality had to be very strictly supervised for the following reasons:

- the dolosse are expected to be subjected to higher than normal loads;
- due to practical constraints in the casting yard and to remain within the construction programme, dolosse were removed from the moulds after only 16 hours;
- to minimize the possibility of cracks which would allow the ingress of water to the rail reinforcing.

The concrete specified for the dolosse was a 40 MPa compressive strength mix with added pulverized fly ash and designed for maximum bending strength to counter the effects of early handling.

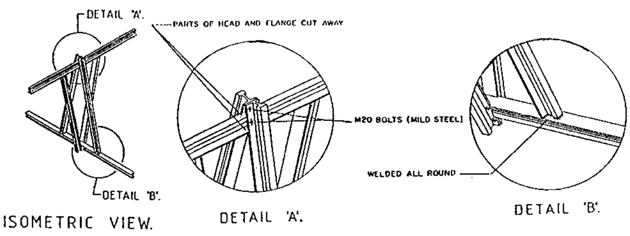


FIG. 11: RAIL REINFORCING (40 kg/m)

In most cases, 40 kg/m scrapped rails were used to manufacture the double-V type reinforcing frames (a few frames were made with 43 kg/m rails). Because of the number required (approximately 1500) the frames were built under workshop conditions using a combination of welding and bolting joints to facilitate the transport and on site assembly (see Figure 11).

Repair Work

Some of the factors that had to be taken into account in determining a placing pattern conforming to the design of the armour layer were:

(a) Only short lengths of the breakwater could be left exposed during the clearing phase of the reconstruction.

(b) As a result of the relative immobility of the rail mounted breakwater crane which operated from a movable section of track, provision had to be made for its protection against wave action during placing operations.

(c) The reach limitations of the breakwater crane had to be taken into account.

(d) The placing sequence of dolosse is important to ensure proper overlaying of the securing chains and proper interlocking between adjacent section of armour protection.

A typical placing pattern for one section, that is, one crane set-up position is depicted in Figure 12.

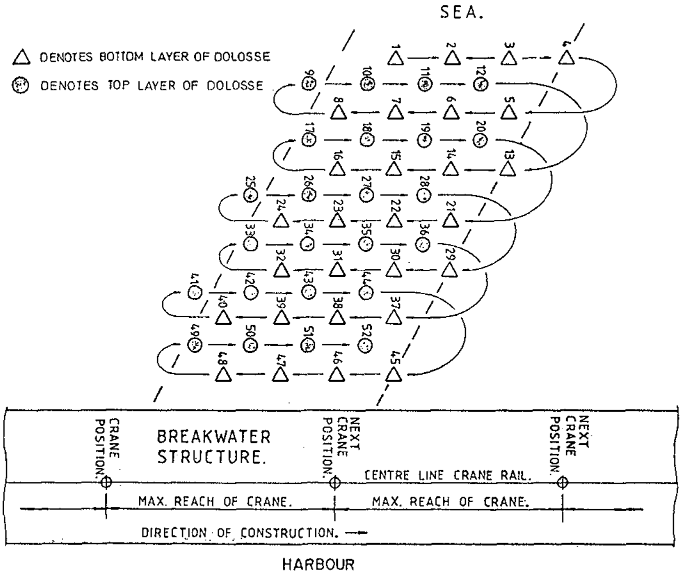


FIG. 12: DOLOS PLACING GRID

As the breakwater crane used for the reconstruction has built-in facilities for measuring angles and distance along the jib, the position of each dolos in the placing grid was translated to polar co-ordinates relative to each crane position. These polar co-ordinates were then used by the crane operator to locate the individual dolosse correctly. In practice it was found that after completing a section a visual inspection easily identified areas with obviously low packing densities, and additional units were placed where required. Generally the additional units amounted to approximately 4 per cent of the total number of units placed.

As a further precaution to reduce dolos movements in the vulnerable toe area **bitumen grout** will be placed between the bottom rows. Factors such as a suitable grout mix, placing temperature and practical considerations will be confirmed by full scale tests. During preliminary on site experimenting it was estimated that a volume placing density of around 5 m^3 per linear meter of breakwater should be sufficient to provide an acceptable degree of dolos to dolos binding.

Exact details such as underlayer profiles, dolos slope profiles and the placing position of each dolos was kept during construction for as-built record purposes. These records will be invaluable for future performance monitoring of the armour protection.

5. CONCLUSIONS

A comprehensive series of stability tests with irregular waves showed a significant reduction in dolos stability, particularly for waist-to-height ratios exceeding **0,36**. This should be taken into account when the waist ratio of larger dolosse is increased to maintain sufficient strength.

The test results showed similar dolos stability for **slopes** between 1:1,33 and 1:2 for all dolos waist ratios except for r = 0,33 and a slope of 1:1,33 for which the stability is significantly less.

Wave period was also found to have a significant influence on dolos stability, that is, lower stability was found for smaller wave periods.

The inclusion of relatively simple **rail reinforcement** increases the dolos strength (fall height) by some 100 per cent and an optimum design of a dolos armour can be achieved by selectively using increased waist ratios and/or rail reinforcing in specific danger areas. The most cost effective rail reinforcement was found to be the **X-type**.

Detailed optimization studies were done for the repair of the Table Bay breakwater. Hydraulic model tests showed that a 25 t dolos armour would not be entirely stable in the toe area of the breakwater, which was situated only 3 to 5 m below water-level. By using a waist ratio of about 0,36, double-V rail reinforcement, anchor chains and bitumen grouting, a satisfactory practical solution was found for the essential and very difficult repair work for the Table Bay breakwater.

REFERENCES

BRORSEN, M, BURCHARTH, HF and LARSEN, T (1974). Stability of dolos slopes. Proc 14th ICCE, Copenhagen.

BURCHARTH, HF (1981). Full-scale dynamic testing of dolosse to destruction. Coastal Engineering, Vol 4, No 3, Amsterdam.

BURCHARTH, HF (1984). Fatigue in breakwater concrete armour units. Report Laboriet for Hydraulic of Havnebygning, Aalborg.

BURCHARTH, HF and BREJNEGAARD-NIELSEN, T (1986). The influence of waist thickness of dolosse on the hydraulic stability of dolosse armour. Proc 20th ICCE, Taipei.

GRIMALDI, F and FONTANA, F (1984). Redesign of main breakwater of Gioia Tauro (Italy). Proc Symp on maritime Structures in the Mediterranean Sea, Athens.

MONSARD, EPD and FUNKE, ER (1980). The measurement of incident and reflected waves in random wave experiments. Proc 15th ICCE, Hawaii.

SCHOLTZ, DJP, ZWAMBORN, JA and VAN NIEKERK, M (1982). Dolos stability, effect of block density and waist thickness. Proc 18th ICCE, Cape Town.

SCHOLTZ, DJP and ZWAMBORN, JA (1983). Effect of the waist thickness on stability of dolosse. CSIR Research Report 556, Stellenbosch.

ZWAMBORN, JA and VAN NIEKERK, M (1982). Additional model tests, dolos packing density and effect of relative block density. CSIR Research Report 554, Stellenbosch.

ZWAMBORN, JA and SCHOLTZ, DJP (1986). Dolos armour design considerations. Proc 20th ICCE, Taipei, Taiwan.