CHAPTER 178

DOLOS ARMOUR DESIGN CONSIDERATIONS

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ABSTRACT

The dolos armour unit has been used all over the world and, although most projects have been successful, there have also been some major failures. When moved around, armour units in general and the rather slender dolosse in particular are prone to structural damage and when dolosse break through the shank, one is left with very unstable pieces of rubble. It is shown in this paper that a safe and economic dolos structure can be obtained if the correct design process is followed. The "optimum" design is based on a reasonable degree of dolos movement which must be established in detailed and representative model tests.

To ensure that the dolosse can withstand these movements, prototype dolos behaviour must be monitored, and such monitoring must be supplemented by representative structural tests, analytical studies and special prototype measurements.

To increase the structural strength of dolosse, the waist to height ratio can be increased and some (simple) form of reinforcing can be included.

1. INTRODUCTION

Much thought has been given to the design of rubble mound breakwaters and considerable effort has gone into obtaining a better understanding of the processes at work and the design techniques after the initial major failures of the Bilboa breakwater in 1976 (35 m depth, 65 t concrete blocks) and the Sines breakwater in 1978/79 (up to 50 m depth, 42 t dolosse; Zwamborn, 1979). In the ten years since these failures progress has been made, particularly in identifying the relevant parameters and in defining the many problems which remain to be solved regarding wave climate, model studies (wave structure interactions), material strength and geotechnical aspects (PIANC, 1985).

Much research will still have to be done on these aspects before a fully reliable design procedure can be developed. In the meantime, however, breakwaters have to be designed with the techniques that are available and particular attention will have to be given to **sensitivity analysis.** This means that the design of the structure should be checked for **realistic variations in the relevant parameters.** The results of this analysis will provide data on the risk of failure or major damage and, at the same time, give an idea of the cost involved in reducing/increasing this task.

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These remarks apply to rubble mound breakwaters in general, whether covered with rock armour, simple-shape concrete units (cubes) or complicated-shape units (dolosse) but particularly to the rather slender **dolos armour units.**

It is generally accepted that dolosse have a high hydraulic stability and, in many cases, they offer the most economical solution for breakwaters/shore protection works. Incorrect application of dolosse, however, has resulted in excessive damage due to armour unit breakages.

2. DESIGN APPROACH

There are three different approaches to achieving a safe dolos structure design, namely:

(i) **"No Movement" Design**
In this case the units have to be made to withstand the **in situ** static loads only and the stability can be based on comprehensive and representative hydraulic model tests, using conventional unbreakable model dolosse.

(ii) **"No Breakage" Design**
With this approach the dolosse have to be made "unbreakable" by heavy reinforcing, in one form or other, and stability can be checked by conventional hydraulic model tests aimed at determining acceptable profile changes or unit displacements (the long-term durability of the units/reinforcement must also be considered).

(iii) **"Optimum" Design**
This approach is aimed at a practical and safe design at minimum costs. This is achieved by accepting certain dolos movements, including rocking, and ensuring that the units can withstand these movements without breakage (minimal breakage).

"No Movement Design

Static loading tests on 15 t and 30 t **unreinforced** dolosse have shown that these dolosse can carry 4 to 6 times their own weight under the worst possible loading condition without breakage (Grimaldi and Fontana, 1984).

As no particular problems have been encountered in handling unreinforced dolosse up to 50 t in the casting and placing process (breakages did not exceed 1 to 2 per cent) and because the direct wave forces are of the same order or less than the dead weight forces, a dolos armour consisting of several layers can be designed safely on the basis of hydraulic model test results if these show that there is no significant movement (rocking). In determining the "no movement" criterion, however, **detailed tests** would have to be done, taking into account:

a) realistic and representative design conditions, particularly for waves (wave spectrum/groupiness),
b) possible variation (reliability) of design conditions,
c) storm duration and cumulative effects
d) near-shore effects,
e) variation in test results,
f) the extent of the structure and

g) three-dimensional effects.

Because the "no movement" criterion basically mean that the design must be based on H_{max}, the result could become rather uneconomical.

"No Breakage" Design

The other extreme would be to ensure that the dolosse are **unbreakable** under prototype loading conditions. In this case the design can be based on conventional hydraulic model tests which have to prove that armour displacement will be within acceptable limits, for instance, Figure 1 indicates K_D factors between 25 and 30 for 1 to 2 per cent displacement. **Detailed tests,** as described above, will be necessary to ensure a safe design. The results of these tests could also be used to optimise the design, that is to minimise the total cost (capital investment plus maintenance cost).

This approach is the easiest with regard to model testing but there are two major problems, namely, to determine the **prototype loading conditions** and to make the dolosse **unbreakable** for these conditions without losing the coast advantage of the units' high stability.

Extensive tests have been done with different types of reinforced dolosse (Burcharth, 1981 and Grimaldi and Fontana, 1984). The test results showed limited improvement in impact strength with from 30 kg/m³ up to 120 kg/m³ (0,4 to 1,6 per cent by volume) **steel fibres,** that is, an increase in drop heights from about 20 to 150 per cent at "failure" (major damage and/or breakage). **Conventional steel reinforcement** of 77 to 138 kg/m³ (1 to 1,8 per cent by volume), however, was found to make the dolosse virtually unbreakable. Although first crack formation occurred at drop heights only about 50 percent higher than for unreinforced units, serious damage (major cracking and spalding which exposed the main reinforcing bars) occurred for drop heights 4 to 8 times those of the unreinforced units (0,8 to 1,6 m for 30 t dolosse at Gioia Tauro). Moreover, tests at Gioia Tauro, where a 30 t dolos with a waist ratio of 0,37 and reinforced with conventional steel reinforcement (77 kg/m³ or 1 per cent by volume) was dropped on the breakwater core, showed no serious cracks up to a drop height on 10 m. Although the **in situ** loading is not known, one would intuitively consider this dolos to be strong enough (mechanically) to withstand the **in situ** forces caused by movements/rocking.

Drawbacks of conventionally reinforced dolosse are additional **cost** (50 to 100 per cent more expensive, which could make dolosse unattractive in many applications) and the possibility of **corrosion** causing possible deterioration of the units with time.

"Optimum" Design

It seems obvious that there should be an "optimum" design between the two extremes discussed above whereby a certain amount of **movement/rocking is accepted** while the dolos units are made strong enough to withstand these limited movements without increasing their cost too much.

As early as 1972 it was suggested that the **waist-to-height ratio** (r) of larger dolosse be increased according to:

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

where W is the mass of the dolos in tons, to compensate for the higher stresses occurring in larger dolosse (Zwamborn and Beute, 1972). A simple analysis showed that, when using this formula, dolos stresses would remain about the same with increased dolos mass (Zwamborn, **et al**, 1980). The more rigid structural analysis by Burcharth (1981a) supports this finding (Zwamborn, 1985). The beneficial effect on the structural strength of the dolos was also confirmed by prototype tests on 15 to 30 t units at Gioia Tauro (Grimaldi and Fontana, 1984).

It is obvious that, to get greater unit strength, even larger waist-ratios could be used. However, stability tests with regular waves on dolosse with waist ratios of 0,33, 0,38 and 0,43 showed a gradual reduction in stability for the larger waist ratios, which was to be expected. The reduction in stability from r = 0,33 to 0,38 was relatively small but the test results indicate a significant reduction in K_D for dolosse with r = 0,33 to 0,43 (Scholtz, Zwamborn and Van Niekerk, 1982). As a waist ratio of 0,43 corresponds to an 82 t dolos unit, there is still considerable scope in using the waist ratio in the optimisation of the design (Burcharth, 1981b). Structural performance of dolosse can also be significantly improved by proper mix design and good quality control (Zwamborn, **et al**, 1980).

Single central scrap **rail reinforcement** was used in the original East London dolosse, mainly to lift the units out of the mould. In the redesign of the Gioia Tauro breakwaters (Grimaldi and Fontana, 1984) it was decided (1979) to introduce single-scraprail reinforced 30 t dolosse in the more critical areas on the breakwater heads for extra safety and to reduce maintenance (27,4 kg/m³ steel or 0,35 per cent by volume). Subsequently, the designers (Polytecna Harris of Milan) developed the so-called **double-V rail reinforcement** which consists of a frame with four scraprails in the dolos trunk and one scraprail each in the flukes (53 kg/m³ steel or 0,7 per cent by volume). This solution proved to be both very effective and economical; the critical drop heights were found to come fairly close to those of the conventionally reinforced units while the possibility of corrosion was minimized and the extra cost for the reinforcing was reasonable (extra cost for double-V reinforced dolosse being about 60 per cent in Italy and about 26 per cent in South Africa).

Various relatively cheap methods to improve the strength of dolosse have been discussed above. Unfortunately, it is not possible to define the exact dolos strength required when a certain amount of moving/rocking is allowed to occur under design conditions. Prototype observations have provided reasonable proof that dolos structures designed on the basis of a few per cent (2 to 3) total damage (displacement plus rocking) performed satisfactorily. There is no doubt that strength-improved (e.g. scraprail-reinforced) units will be able to withstand considerably greater movement/rocking but more observations and (full scale) tests are needed to confirm the effectiveness of these improvements, that is, to arrive at the "optimum" design.

3. STABILITY MODEL TESTS

The results of a comprehensive series of dolos stability tests for regular waves are shown in Figure 1. The figure shows damage as a function of

model wave height for different degrees of dolos movements, that is, displacements and rocking. For easier use of the data, a scale for the Hudson stability factors (K_D) has been added.

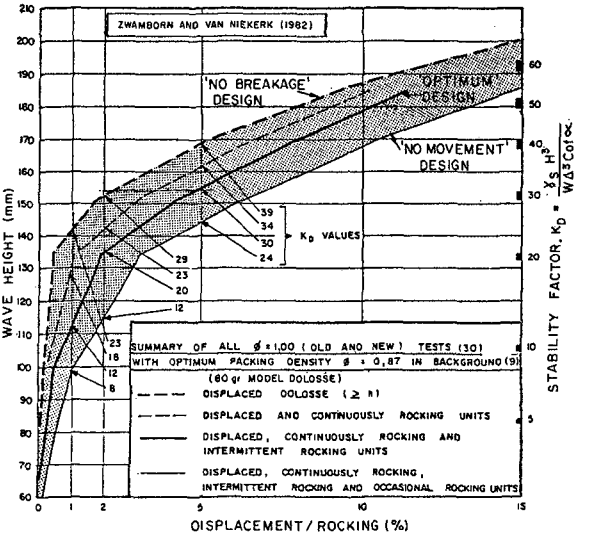


Figure 1: Damage (Displacement/Rocking) versus wave height/stability factor

A similar test programme for irregular waves, under otherwise identical conditions, is underway at present. Results of these tests will become available during 1987.

Although the results shown in Fig. 1 may be used for a first design, detailed and preferably three-dimensional model tests of a specific application using representative wave conditions are a prerequisite for a good design. In these tests, dolos motions/accelerations should be determined as accurately as possible. Dolos motions can be recorded with the now well-known cine and overlay techniques. Alternatively, more advanced measuring techniques can be used to measure accelerations and stresses in individual model armour units but a large number of units would have to be instrumented for each test condition to get statistically reliable results and these results will have to be compared with prototype measurements, as planned in Table Bay and Crescent city (Howell, 1986).

4. PROTOTYPE DOLOS BEHAVIOUR

Details of the behaviour of dolos structures around the world, including ten South African structures, are included in a report entitled "Survey of Dolos Structures" (Zwamborn and Van Niekerk, 1981) which was used extensively for the later survey carried out for PIANC (PIANC, 1985). Further data, for selected South African projects, covering the period 1979 to 1982, are included in Zwamborn (1985) while an update of these projects is given below.

Prototype monitoring in other parts of the world include measurements at Gioia Tauro, Italy (Grimaldi and Fontana, 1984), monitoring of the 2 t dolos breakwater at Cleveland, USA (Markle and Davidson, 1984) and the planned extensive monitoring programme at Crescent City, USA (Howell, 1986).

Richards Bay Breakwater

The Richards Bay main breakwater is protected with 5 t, 20 t and 30 t dolosse placed to slopes of 1 in 1,5 and 1 in 2. This breakwater was completed in Frebruary 1976 and has been monitored at regular intervals since 1978. The monitoring was concentrated on the above-water part of the dolos armour, with the 20 t dolosse on the trunk and the 30 t dolosse on the head of the breakwater. Techniques used were vertical and horizontal photography, visual observations and profiling with a spherical cage, made of reinforcing steel, with a diameter of 2,5 m (0,6 h, were h is the dolos height).
The following survey and storm data have become available since the 1982 review (Zwamborn, 1985):

Breakwater Monitoring		Storm Data						
Date	Type of Survey	Date	H_{s-r} (m)	T_p (s)	Direction (°deep sea)	H_{s-b} (m)	H_{max} (m)	Tide (m+CD*)
24-6-83	Vertical photography	17-2-84	4,3	11,9	140	5,3	10	0,4
		9-4-84	4,0	9,7	117	2,5	5	1,0
		10-4-84	4,1	10,7	147	4,4	8	0,8
		27-4-84	4,5	13,5	140	5,4	10	0,9
		30-5-84	4,3	22,3	160	5,4	10	1,0
4-7-85	Vert. photo. (large scale)	12-7-85	4,1	7,5	120	2,6	5	0,8
24-6-86	Vert. photo.							

*Chart Datum

Only storms with significant wave heights exceeding 4 m have been included in this table. The wave heights (H_{s-r}) and the wave periods (T_p) were recorded by waverider anchored in the 20 m water depth, about 1,5 km seaward of the south breakwater head. Wave directions were recorded by wave clinometer. H_{s-b} values are the wave heights directly in front of the breakwater head, determined from actual measurements made in the original physical model during three-dimensional breakwater stability tests. Because the wave height measurements apply to a 6-hour period, $H_{max} = 1,9\ H_{s-b}$ (Longuet-Higgins, 1952). Most of the storms occurred at high tide. The depth at the breakwater head decreased from the original -17 to -12 m CD about 300 m from the breakwater head. This means that at high tide (+1,8 m CD) the maximum breaker height can be about 0,9 x 13,8 = 12,4 m (Jackson, 1968).

Detailed analyses of a section of the breakwater head on which were placed 1 045 30 t dolosse with a waist-to-hight ratio of 0,36 were possible with the use of large-scale vertical photographs. The results of these analyses can be

summed up as follows ("damage" is taken as the sum of the lost and broken units):

Monitoring Date	Storm Data (H_{s-r} > 4 m)		Damage (%)*			
	Date	H_{max} (m)	Lost	Broken	Moved	"Damaged"
28-6-79	24-7-79	8				
	17-4-80	10				
18-6-81	17-8-81	9	0,6	0,8	0,8	1,4
5-12-81	-	-	0	0,2	0,2	0,2
5-6-82	-	-	0	0	0	0
24-6-83	-	-	0,4	0,4	0,2	0,8
	17-2-84	10				
	9-4-84	5				
	10-4-84	8				
	27-4-84	10				
4-7-85	30-5-84	10	0,8	0	0	0,8
24-6-86	12-7-85	5	0	0	0	0
TOTAL OVER 7 YEARS			1,8	1,4	1,2	3,2

*Damage above Low Water based on 500 30 t dolosse

Gansbaai Harbour

The Gansbaai harbour breakwater, described in Zwamborn and Van Niekerk (1981), was repaired between 1979 and 1982 with 505 20 t and 1 630 25 t dolosse at slopes of 1 in 2 and 1,75 respectively. The performance of these dolosse was closely monitored by regular visual observations, including underwater diver surveys, during construction and after the occurrence of large waves (Zwamborn, 1985).

The following data on conditions since completion of the repair work were made available to the Fisheries Development Corporation (no local wave data available after 1982):

Breakwater Monitoring			Storm Data						
Date	Dolos Breakages (%)		Date	H_{s-r} (m)	T_p (s)	H_{s-b} (m)		H_{max} (m)	Tide (m+CD)
	20 t	25 t				WSW	11°N of W		
July 1982	0,2	0,1	12-7-82	3,4	12	1,7	6,0	8	0,6
			17-7-82	3,7	18	2,3	6,4	8,5	1,2
			29-7-82	4,2	14	2,6	6,7	8,5	0,9
April 1984	-	0,25							
May 1984	1,2	0,7	15-5-84	10,8	15,5	(Slangkop)		8,5	1,5
TOTAL	1,4	1,05	Breakages over about 4 years*						

*Some repair work was done after the 16th May 1986 storm.

Koeberg Cooling-Water Intake Basin

The breakwaters forming the Koeberg intake basin are protected with 6 t, 15 t and 20 t dolosse placed at a slope of 1 in 1,5 (Zwamborn and Van Niekerk, 1981). Some 2 295 20 t dolosse were used to armour the main breakwater from chainage 750 to 912 m, which includes the head. The entire main breakwater has depth-limiting design conditions; the depth at its head is -8 m CD and waves with $H_s \geq 3,2$ m were assumed to start breaking on the head (H_{max} = 6,4 m). This means that the design waves (6,4 m breaking waves) occur on average 15 days per year, which was taken into account in deciding on acceptable damage criteria.

The following data have been collected since the previous review (Zwamborn, 1985):

Breakwater Monitoring			Storm Data (H_{s-r} > 3 m)				
Date	Type of Survey	Damage (20 t)	Date	H_{s-r} (m)	T_p (s)	H_{max} (m)	Tide (m+CD)
11-11-81	Horizontal photography						
	(37 storms)		2-1-82 to 10-6-83	3,2 to 5,9	8,8 to 15,5	5,7 to 6,9	0,2 to 1,8
14-6-83	Visual Inspection (9 storms)	(No change)					
			25-6-83 to 31-1-84	3,6 to 5,4	11,9 to 15,5	5,6 to 6,5	0,4 to 1,3
	("100 year" storm)		16-5-84	6,7	15,5	7,4	2,5
29-5-84	Visual, above and below water (11 storms)	0,44					
			29-6-84 to 5-10-84	3,4 to 7,2	11,9 to 18,3	5,9 to 6,6	0,5 to 1,4
17-10-84	Horizontal photography	(No change)					

Concluding Remarks

Prototype measurements of dolos behaviour have provided evidence that 30 t dolosse with a waist ratio of 0,36 placed on the Richards Bay breakwater head can withstand 10 m waves with only about 3 per cent "damage". Applying Figure 1, the expected total damage would be 3 per cent displacement plus all types of rocking, or about 2 per cent when excluding occasional rocking (heavy line in Figure 1).

The newly placed 20 and 25 t dolosse at Gansbaai (waist ratios 0,34 and 0,35 respectively) have withstood four storms with waves reaching 8,5 m with only 1,4 and 1,05 per cent breakages respectively (including the underwater part). For this wave height, Figure 1 indicates 2,5 and 2 per cent "total damage", or 1,5 and 1 per cent excluding occasional rocking, for the 20 and 25 t units respectively.

The 20 t dolosse at Koeberg (waist ratio 0,34) showed little damage (only 0,44 per cent for the "100 year" storm of May 1984) over a period of three years when 6 and 7 m breaking waves attacked the breakwater on 58 occasions. For these wave heights, Figure 1 would indicate 1 per cent "total damage" or 0,5 per cent excluding occasional rocking.

These observations, together with experience in the USA (Markle and David-

son, 1984), provide evidence that well-designed dolos structures (that is, considering different dolos movements) can withstand severe and sustained wave action with nominal damage. However, considerable damage has occurred in certain cased which emphasizes the need for a special and detailed design effort for major dolos projects.

5. STRUCTURAL TESTS ON DOLOSSE

Drop Test on Solid Concrete

In the foregoing, reference has been made to structural tests which provide invaluable data regarding the relative strengths of dolosse of different design, concrete quality and reinforcing. A standard drop test on a solid concrete base has been proposed for dolosse by Burcharth (1981a). Burcharth found that trunk breakage occurred for drop heights (centre of gravity) of 0,12 to 0,17 m using 1,5, 5,4, 10 and 20 t unreinforced dolosse.

The results of similar drop tests carried out at Gioia Tauro, Italy, on 15 t (r = 0,32) and 30 t dolosse (r = 0,37) (Grimaldi and Fontana, 1984) showed a considerable improvement in dolos strength with time (pozzuolana cement was used), the positive effect of the larger waist ratio of the 30 t units, the limited benefit of the steel fibres and the effectiveness of, particularly, the double-V reinforcement.

Gioia Tauro Free Fall Test

The standard drop test is carried out on a rigid base and failure is virtually due to impact loading only. In a breakwater armouring, a dolos will either drop on underlayer stone or on another dolos, both of which will probably move under the impact. A dolos breakage test which more closely represents conditions on an actual breakwater, should, therefore, include a realistic yield comparable to movement of the underlaying dolos and/or stone. Further drop tests and free fall tests were, therefore, done at Gioia Tauro onto a 50 to 1 000 kg rock fill bed and onto the breakwater core (Figure 2).

Test on Rock Test on Core Material

Figure 2: Free-fall tests with 30 t dolosse

The mean results of the tests on 30 t dolosse as interpreted by the author, are given below:

Age (months)	No. Repeat Tests	Type of test	Test bed material	Reinforcement type (kg/m³)	Failure or Damage	
					Fall Height L (m)	Impact Velocity V (m/s)
2,5	2	drop	rock	-	2,4*	5,9*
3,5	1	drop	rock	Twisted fibres (75)	2,4*	5,9*
2,5	3	free fall	rock	-	1,5	5,4+
3,5	2	free fall	rock	Twisted fibres (75) and steel fibres (95)	2,5	7,0
2	1	free fall	rock	Double-V (53)	2,6	7,1
2	2	free fall	core	Double-V (53)	2,5/5,0	7,0/9,9
2	1	free fall	core	Conventional (77)	10	14

*Maximum possible lifting height, no visual damage.

The most significant result of these tests is that the critical fall heights with a realistic yield are about 10 times greater than for the rigid-base case which means that unreinforced dolosse should be able to withstand considerable movements/rocking without breakage, a fact which is born out by prototype observations.

Controlled Yield Tests on 9 t Dolosse

Because tests on rubble are difficult to control fully and because the inclusion of a certain yield is essential to get results more directly comparable with the actual breakwater situation, a test technique by which the impact deceleration is controlled by a given yield has been developed for full scale tests on 9 t dolosse at Cape Town. The test configurations shown in Figure 3 were used for the Table Bay tests, that is, the swing test configuration.

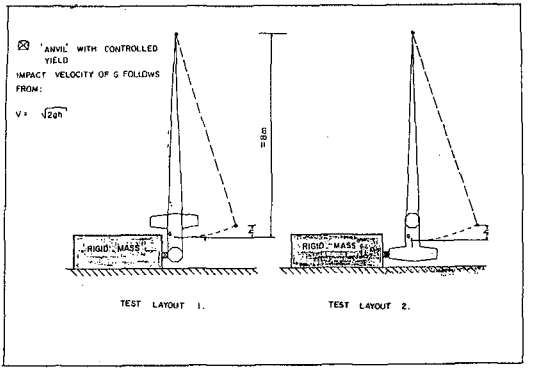
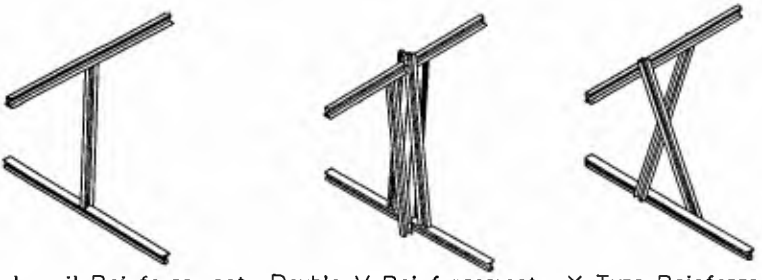


Figure 3: Dynamic Impact Test Arrangements

The height of the 9 t test dolosse was 2,9 m and the waist-to-height ratio was 0,30. The units were made of 40 MPa concrete (28 days). The tests included dolosse without reinforcing and with three types of 43 kg/m **scrap rail reinforcing**, that is a single central rail, the so-called double-V reinforcing designed by Grimaldi and Fontana (1984) and the X-type reinforcing developed by the NRIO (see Figure 4).



Single-rail Reinforcement Double-V Reinforcement X-Type Reinforcement

Figure 4: Rail Reinforcement in 9 t Dolosse

The purpose of the tests, carried out in co-operation with the South African Transport Services, were:

a) to develop a test procedure closely resembling conditions in a breakwater armour;

b) to determine the effectiveness under representative loading conditions of the different types of reinforcement;

c) to determine the effect of repeated impact loading, and

d) to decide on the type and extent of reinforcing for the 25 t dolosse to be used for the breakwater repair.

Figure 5: Free-fall tests on 0,5 to 3 t rock.

To determine a realistic yield, representing the impact of dolosse on underlayer stone or other dolosse, the first test series involved dropping a 9 t (reinforced) dolos onto 0,5 to 3 t underlayer stone (Fig. 5). Decelerations on impact were measured during these tests with two PCB Piezotronics shock accelerometer with 500 g range, fitted on the trunk and on the top shank (Fig. 5).

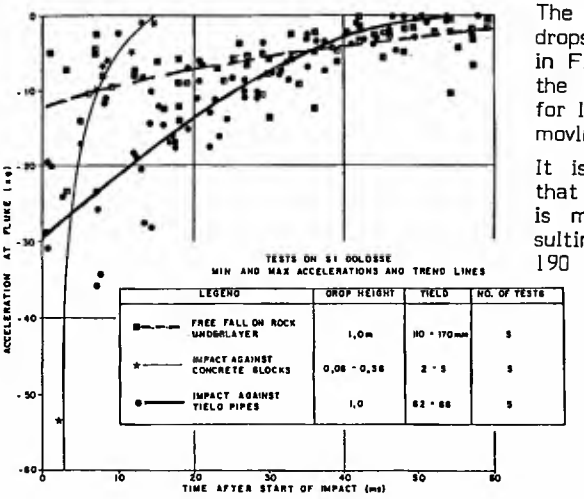


Figure 6: Comparison of accelerations for different test procedures

The results of 5 repeated drops, over 1 m, are plotted in Fig. 6, which also includes the recorded decelerations for impact against solid, non-moving concrete blocks.

It is clear from this figure that the impact on the rock is much more "gentle" (resulting in ayiled of 110 to 190 mm) than that against the rigid concrete blocks and thus, the **resulting stresses in the dolosse are therefore much smaller.**

Because the impact on rock will depend largely on the rock packing and will thus be variable (see spread of points in Fig. 6 for large impact time values), swing test were done using a representative "cushioning device". Considering that, in reality dolosse could either fall onto underlayer rock or on parts of other dolosse, a "cushioning device" consisting of three collapsible "yield pipes" (Fig. 7; 3 pipes: 89 mm OD, 4,5 mm thick and 250 mm long) was designed to give approximately twice the initial deceleration of the free drop-on-rock case but with a similar ultimate impact time of 40 to 60 ms. In this way, a conservative test condition was developed representing breakwater conditions quite realistically.

Figure 7: Cushioning Device

The actual test configuration is shown in Figures 8 and 9. The tests are still underway at present but preliminary results of the tests, according to the Test Layout 2 of Fig. 3, are given in the following table:

Figure 8: General Test Arrangement

Figure 9: Dolos (9t) at impact

Age (Months)	No. Repeat Tests	Type of Tests	Test Bed Material	Reinforcement (kg/m³)	Failure or Major Damage		Mean Yield (m)
					Fall Height (m)	Impact Velocity (m/s)	
19	3	Swing	Yield Pipes		2,3/2,6/2,9	6,7/7,1/7,5	0,16
12/15/18	3	Swing	Yield Pipes	Single Rail (85)	2,6/2,9/2,9	7,1/7,5/7,5	0,17
12	2	Swing	Yield Pipes	X-Rail (115)	3,5/3,5	8,3	0,18
18	2	Swing	Yield Pipes	Double-V (168)	3,8/4,1	8,6/9,0	0,18

The above results show:

(i) similar "failure" drop heights as found at Gioia Tauro,
(ii) the results of repeat tests do not differ much,
(iii) whereas unreinforced dolosse break in the "rigid" drop test for drop heights exceeding about 0,2 m, with a representative yield, the critical drop heights are well above 2 m,
(iv) there appears to be little difference between unreinforced and singrail reinforced dolosse but the latter will be damaged rather than fail,
(v) the double-V and X-type rail reinforcing increase the critical fall heights by 50 to 80 per cent and these are only damaged and did not fail.

Thus the **rail reinforcement** is found to be **very effective** in increasing the dolos strength and preventing dolos failure.

Burcharth (1984) has shown that repeated impact loading rapidly weakens the dolosse. For instance, impact failure will occur after three repeat loadings causing stresses of 10 per cent of the ultimate impact strength compared with 20 loadings in the case of a "pulsating" load/normal fatigue, see Figure 10.

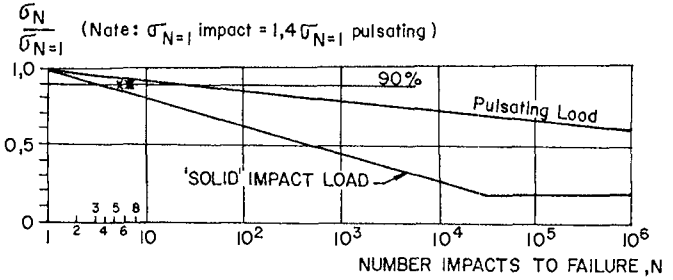


Figure 10: Average Results of Impact Tests on Dolosse (Burcharth)

The results of the first series of fatigue tests done on the 9 t dolosse are:

Type of Dolos	Number of tests	Fall Height	Number of impacts until failure
Unreinforced	2	2,0 m	5 and 7
Double V-reinforcing	1	3,2 m	7

These tests were done with a fall height of 80 per cent of the failure height and the results are plotted in Figure 10*. As expected, considering the inclusion of the cushioning device, the results fall between the pulsating and "rigid" impact lines which means that, in the breakwater situation the dolosse should be able to withstand about twice the number of impact loads predicted by the rigid impact test.

6. CONCLUSIONS

It is concluded that carefully designed dolos structures can withstand large waves with only minor (a few per cent) damage. Shortcomings in the design and/or construction and a lack of understanding of the structural limitations of dolosse can, however, result in significant damage or even local failure of the structure. A detailed and careful design process, as discussed above, will therefore have to be followed to arrive at a safe yet economical design.

An "optimum" dolos armour design should be based on a limited degree of movement using increased waist ratio and/or simple rail reinforcement to strengthen all the dolosse or only those in the more critical areas. Detailed information on **in situ** dolos movements and resulting structural dolos behaviour are required to achieve this. The results of measurements underway in South Africa and elsewhere should provide this information.

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*Burcharth (1984) assumed stresses proportional with square root of drop height, thus, for 80 per cent case, $\frac{\sigma N}{\sigma N=1} = \sqrt{0,8} = 0,9$

8. REFERENCES

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

BURCHARTH, H F (1981b). A design method for impact loaded slender armour units. Proc. ASCE Speciality Conference, New York.

BURCHARTH, H F (1984). Fatigue in breakwater concrete armour units. Report Laboratoriet for Hydraulic of Havnebygning, Aalborg.

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

HOWELL, G (1986). A system for the measurement of the structural response of dolos armour units in the prototype. Proc, International Conf. on Measuring Techniques, London.

JACKSON, R A (1968). Limiting heights of breaking waves and non-breaking waves on rubble-mound breakwaters. Technical Report No H68.3, WES, Vickburg.

LONGUET-HIGGINS, M S (1952). On the statistical distribution of the heights of sea waves. Journal of Marine Research, Vol XI, No 3.

MARKLE, D G and DAVIDSON, D D (1984). Breakage of concrete armour units; survey of existing Corps structures. Misc. Paper CERC-84-2, Vicksburg.

PIANC, (1985). The Stability of rubble mound breakwaters in deeper water. Supplement to Bulletin No 48 (1985), PIANC, Brussels.

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

ZWAMBORN, J A and BEUTE, J (1972). Stability of dolos armour units, ECOR Symposium, S71, Stellenbosch.

ZWAMBORN, J A and VAN NIEKERK, M (1981). Survey of dolos structures. CSIR Research Report 385, Stellenbosch.

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

ZWAMBORN, J A (1979). analysis of causes of damage to Sines breakwater. Proc. Coastal Structures 79, ASCE Speciality Conference, Alexandria.

ZWAMBORN, J A **et al** (1980). Dolosse: past, present and future? Proc. 17th ICCE, Syndney.

ZWAMBORN, J A (1985). Behaviour of Dolos Structures, particularly in regard to unit strenth. Proc. Workshop on Armour Units, CERC, WES, Vicksburg.