CHAPTER 51

THE ECONOMIC VALUE OF A NEW BREAKWATER ARMOUR UNIT 'DOLOS'

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ABSTRACT

The Dolos, a new type of armour unit which closely resembles a normal ship's anchor, was developed and tried out under field conditions on the main breakwater of East London harbour. Since these full-scale Dolosse proved very successful, tests were made in a wave channel to compare the stability of Dolosse with other known types of armour blocks. The test results showed that the Dolos is outstandingly stable, and since manufacture and random placing of Dolosse offers no particular difficulties it is concluded that in many cases the use of Dolosse in armour layers may lead to more economical solutions for rubble mound breakwater and shore protection works.

INTRODUCTION

Rubble mound breakwaters are normally protected against damage from storm waves by a cover layer of very heavy armour units or breakwater blocks. If natural rock blocks were to be used for this purpose, the required unit weight may be in the order of 40 tons and more. Rocks of this size are difficult to obtain and almost impossible to handle on any large scale. It is, therefore, quite understandable that harbour design engineers and research workers alike have done their utmost to develop smaller concrete blocks which, due to their particular shape, would form an interlocking cover layer of much higher efficiency. As a result many different types of blocks have been developed, varying in geometric shape from the simple rectangular or cubular block to highly complicated shapes such as tetrapods and hexapods.

A new type of armour unit for breakwaters and coastal protection works, named 'Dolos', was developed by the senior author. A number of Dolosse were tried out under field conditions on the main breakwater at the Port of East London, South Africa. The results of these full-scale tests appeared promising and it was decided that, in order to obtain more comparative data, Dolosse, rectangular blocks, tetrapods and tetrahedrons be tested comprehensively in the wave channel of the Council for Scientific and Industrial Research in Pretoria.

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Armour unite are normally dumped at random. Due to their particular shape it is possible, however, to pack the Doloese in a regular pattern. Teete were, therefore, made with both randomly dumped and regularly packed Dolosee, although it wae realized from the etart that it would be extremely difficult, if not impoesible, to realize the latter in practice.

EXPERIENCES WITH DOLOSSE IN PRACTICE

Construction on the main breakwater at East London commenced in August 1873, with the tipping of rubble on the foreshore. However, little advance was made until the first 25-ton* rectangular block wae placed into the eea in March 1876. Thereafter, the breakwater was constructed ae a mound formed by rectangular blocks weighing from 15 to 30 tons each, topped with a 36-ft wide concrete cap reaching to 16 ft above LWOST** and a seaward parapet of 5 ft 6 ine high. By 1884, 1,500 ft of breakwater had been completed and the structure wae ended off with a round head. Between 1911 and 1917 the breakwater wae extended a further 776 ft using 40-ton rectangular blocks placed at random while the end portion was raised to 19 ft above LWOST. In 1935 the third and final stage of conetruction commenced. The breakwater wae extended by a further 1,000 ft, aleo to 19 ft above LWOST using 33-ton blocks. This work wae completed in 1939 and the breakwater is now 3,276 ft long.

DEVELOPMENT OF THE 'DOLOS'

The eeaward face of the breakwater was at one time protected with a random layer of 33-ton rectangular blocke over a length of 1,000 ft on the eeaward end of the breakwater and with 41-ton blocks over the remainder. During 1944 a severe storm breached the breakwater some two hundred feet from the end, carrying away a considerable number of 33-ton protective armour blooke. The breakwater was repaired and the whole seaward face protected to a height of 24 ft above LWOST with 41-ton rectangular blocke plaoed at random to an approximate slope of $1\frac{1}{4}$ horizontally to 1 vertically. In 1963, i.e. nineteen years afterwarde, it wae estimated that the outer half of the breakwater had loet at least fifty per cent of its seaward random block protection, while a few sections were almost stripped bare to the original mound oore. It wae, therefore, evident that the exieting rectangular 41-ton armour blocke did not provide a stable protection and, if the high oosts of replacement were to be brought down to a reasonable figure, eome other type of armour block would have to be used.

Coneideration was given to various known typee of specially shaped blocks but, due to reetrictione (patent righte) and the coste involved, it was decided rather to develop some other original form. Wooden models were

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* 1 Ton = 2,000 lb.

** Low Water Ordinary Spring Tide.

made of numerous block shapes based on the idea, firstly, that they should form a cover layer with a high void to solid ratio, to facilitate dissipation of wave energy and, secondly, that each block should be linked with others to form a knitted composite structure, rather than a loose group of individual blocks. Moreover, the block should have enough mechanical strength to withstand the rigours of rough handling when being placed on the breakwater, and the shape should be such that the blocks can be manufactured economically.

The shape that seemed to satisfy these requirements best was the 'Dolos', an anchor shaped block with dimensions as shown in Figure 1. The name 'Dolos' (plural 'Dolosse') was given to the block because of its South African association. The name refers to the knuckle bones of a sheep or goat, used by children as toy oxen in the old trek (pioneering) days, and also to the small bones used by African witchdoctors for divining.

Packing and placing tests of the wooden models on various slopes were carried out and it was found that due to the anchor shape of the Dolos one leg always hooks into the underlayer, while due to the legs being tapered towards the ends the blocks are wedged tightly between other blocks, thus forming a good interlocking structure. Preliminary tests were also carried out to determine whether a more economical result could not be obtained by laying the blocks to pattern. However, it soon became evident that, in practice, the task of laying to pattern on rough slopes, battered by an ever-moving sea, would be virtually impossible.

It was then decided to manufacture some full-size Dolosse and to test these blocks on the East London breakwater.

MANUFACTURE OF DOLOSSE

At this early stage no laboratory tests had been carried out, but it was nevertheless decided to select a size of Dolos that was less in weight than that which would have to be used for other well known types of blocks and, at the same time, would be large enough to interlock with the remaining rectangular blocks on the breakwater face. The selected size was an eleven-foot high block (h = 11 ft) weighing $19\frac{3}{4}$ tons. The waist was slightly thicker than the dimension 0.3 h which is shown in Figure 1. It was brought to a round figure of 3 ft 9 ins (i.e. 0.34 h). The slight thickening of the waist for the larger sizes of Dolosse is considered a reasonable adjustment to cope with the higher stresses in the concrete during handling.

The hexagon cross-section, shown in Figure 1, was preferred to a circular one for ease of making the shuttering and extracting the Dolos from the mould. In practice, this section is near enough to a circular one to prevent undesirable concentrated flow, resulting in high run-up, and reflection of wave energy on large flat surfaces. The moulds were built up of 3/16-inch thick mild steel plate panels flanged and ribbed around all edges and bolted together. These casings are fixed permanently in one position with their lower halves in a pit and with the upper surfaces left open to receive the concrete mix (see Figure 2).

The Dolos is lifted from its mould within 18 to 24 hours after casting, depending on air temperatures. In order to remove the cast Dolos, one section of the mould on the horizontal leg is folded back and the upper section is removed in one piece, while two vertical joints on the lower vertical leg are merely loosened to break the suction (see Figure 2). This system of removing the casting from the mould shortly after pouring concrete considerably reduces the required number of moulds and, consequently, the size of the casting yard.

The following concrete mix (by volume) was used:

1 Portland cement	2.66 stone, $\frac{1}{4}$ inch to dust	graded aggregate
1 Slagment	2.66 stone, $\frac{3}{4}$ inch to $\frac{1}{2}$ inch	
2 Sea sand	4.00 stone, $1\frac{1}{2}$ inch	

In order to ensure an initial strong resting toe at the bottom of the vertical leg, the first mix poured into the mould has cement substituted for the slagment. Sufficient water is used to provide a stiff workable mixture, which is compacted with a small pencil vibrator. The mixture is a strong one, but this is considered necessary in order to develop a high mechanical strength in the Dolos and in order to minimise chemical and abrasive attack on the concrete. Slagment was originally used because it is cheaper than cement and presents less storage problems. Since the South African Railways Research Laboratories have recently thrown some doubt on the good properties of slagment when used under alternating wet and dry conditions in the sea, Portland cement will, in future, replace slagment. However, Dolosse placed on the breakwater two years ago have as yet shown no signs of chemical deterioration.

HANDLING AND PLACING OF DOLOSSE

A frame consisting of three pieces of scrap rails (80 lb per yard) tack welded together is placed along the central axes of the three legs of the Dolos mould (see extreme right Figure 2). Two steel rope lifting loops are wound around the central rail while the ends project out of the mould providing lifting eyes after casting the block (see Figure 2). In this way it is possible to lift the blocks out of the moulds only one day after casting. A study of eye-bolts cast into old blocks and concrete structures at East London harbour many years ago had shown that the metal has only corroded to slightly below the concrete surface. No damage had been suffered by the concrete when the cover around the protruding steel was thick enough. It is, therefore, felt that corrosion of the lifting loops protruding from the Dolosse will cause no significant damage to the concrete.

The freshly cast Dolosse are carefully placed in a nearby curing yard and left there for seven days. Thereafter they are closely packed in the final curing yard and left for a minimum period of 21 days (total minimum curing time 28 days).

The Dolosse are finally transported onto the breakwater in railway trucks and placed by a 40-ton capacity travelling Titan crane having a maximum reach of 65 ft. The blocks are placed over the existing 41-ton rectangular blocks to an average slope of about $1\frac{1}{4}$ to 1. The lifting loops are not used for this operation but the Dolosse are slung around their middle sections by means of an ordinary wire rope sling with a trip hook fixed at one end.

DOLOSSE PLACED ON THE EAST LONDON BREAKWATER

A small number of the $19\frac{3}{4}$-ton Dolosse were placed in a line (not interlocked) on a section of the foreshore near the root of the breakwater to test the individual characteristics of the blocks. They were subjected to breaking waves up to 18 ft in height and, although only seated on small loose round boulders, they moved very little by swinging sideways and tending to "dig in". They showed no tendency to roll or glide away as happens to rectangular blocks.

By the end of 1965 approximately 450 Dolosse had been placed at random around the end of the breakwater and along a short section of its seaward face (see Figure 3). It was found during the first onslaught of a severe storm that Dolosse, which were not completely stable yet, moved into more secure positions and a general "settling down" of the Dolosse occurred, forming a permanent and better packed group. After this initial settling no subsequent movement has been observed and the blocks have now withstood the severest storms, with estimated wave heights of up to 25 ft, of two winters, while during the first winter (1964), five 41-ton rectangular blocks were swept over the breakwater cap, at a section where there was no Dolos protection.

During a storm or 'heavy seas', and particularly when the wind is blowing in the same direction as the waves, it is quite impossible to traverse the breakwater due to large amounts of water splashing over the top, and due to strong clapotis. On one occasion when the waves were estimated to be of the order of 20 ft high, the only manner in which the light at the end of the breakwater could be reached was by means of a steam locomotive. At the round head, which is protected by Dolosse, it was possible to walk about the breakwater deck with perfect safety, and only a light spray brought over by wind was experienced (see Figure 4).

No damage of any sort, including erosion, has been observed in any of the Dolosse over a period of two years and, although many blocks fell and slid four to five feet during placing, none of them suffered any damage except for minor chipping of the edges.

DESIGN CRITERIA FOR BREAKWATER COVER LAYERS

A schematic cross-section of a rubble mound breakwater is shown in Figure 5. The main body or core of the breakwater may consist of normal quarry run material. This core is covered by rocks of various sizes (so called 'underlayers') over which armour units forming the final cover layer are placed. In Figure 5, the required rock weights as given by Hudson[1] are all expressed as a proportion of the equivalent block weight (W_e) of the armour units. The equivalent block weight is defined as the weight of quarry stone which provides the same protection as the particular armour unit (having a weight W) to be used. Although Hudson's approach is quite acceptable when using known armour units, it will become clear later that in the case of Dolosse it may be better to define the size of the stone in the underlayer as a proportion of the actual weight (W) of the Dolos.

In order to arrive at an economic breakwater cover layer design, factors such as design wave height, stability of blocks, porosity of the cover layer, shape factor of the blocks and wave run-up should be taken into account. These factors are dealt with in more detail in the following sections.

DESIGN WAVE HEIGHT

Figure 6 is a typical diagram for the Cape Town area showing the frequencies of occurrence of deep sea maximum wave heights ($H_{o\ max}$) for five directions. The frequency of occurrence lines are based on just under one year's records collected by the Division of Sea Fisheries research vessel Africana II in deep sea, using the N.I.O. accelerometer type wave recorder. It is realized that the recording period is short, but since no better information on waves in South African waters is available at present, the lines shown in Figure 6 are the only basis for design (at least for the West and South coast of South Africa) until such time as more wave data become available. Similar wave data are being collected for other places on the South African coast at present.

While Figure 6 refers to deep sea wave heights, the design wave height (H) for a particular location on the coast is easily determined from these deep sea wave characteristics by using the well known refraction analysis[2] and after taking into account the effect on wave height of the reduced water depth in front of the breakwater[3].

REQUIRED BLOCK WEIGHT AND STABILITY FACTORS

The required weight of an individual armour unit may be determined from the following formula given by Hudson[1]:

$$W = \frac{\gamma_s H^3}{K_D \Delta^3 \operatorname{cotg} \alpha} \qquad (1)$$

where W is the block weight, γ_s the specific weight of the armour unit, H the design wave height, Δ the relative density of the block ($\Delta = (\gamma_s - \gamma)/\gamma$ where γ is the specific weight of water), α the slope angle (see Figure 5) and K_D the stability factor. For the cases where no damage is allowed at all the stability factor (K_D) is defined by equation (1) when H is the wave height at which damage just starts. Stability factors for the <u>no-damage</u> and <u>no-overtopping</u> criteria as given by Hudson[1] are shown in Table I. These values are reported to apply only to the trunk of the breakwater (not for breakwater heads) and where the waves do not break just before the structure. Moreover, since the influence of factors such as irregularity of waves, methods of placing the units and permeability of the rubble mound structure are all combined in the single parameter K_D it is necessary to use some care when applying model K_D values for prototype design. Based on a very limited amount of full-scale field data Hudson suggests a minor adjustment of K_D values for full-scale block design.

TABLE I. STABILITY FACTORS (K_D) ACCORDING TO HUDSON

Armour Unit	Method of placing	K_D	
		Model Values	Recommended for full-scale
Quarry stone	random, double layer	3	3
Tetrahedrons	" "	5.5	-
Tetrapods	" "	8	8
Hexapods	" "	10	9
Hexapods	uniform, single layer	22	-

Paape et al[4] have shown that the stability factor can be expressed as a function of the damage. Much larger values for K_D are found to be applicable when a few per cent of damage is considered acceptable. In this case the cost for the required maintenance will have to be weighed against extra capital investment when using larger armour units to arrive at the most economical design.

POROSITY, THICKNESS OF COVER LAYER AND REQUIRED NUMBER OF BLOCKS

The porosity (P) is defined as the percentage voids of the total volume of the cover layer. A high porosity of the armour layer is beneficial since wave run-up as well as the total concrete volume required in the cover layer are reduced.

The thickness (r) of an armour cover layer may be defined as:

$$r = n\ C\ V^{1/3} \tag{2}$$

where n is the number of layers, C a shape factor which is related to the packing density of the blocks, and V the volume of the block.

The required number of blocks (N) to cover a unit area is then found from:

$$N = n\ C\ \left(1 - \frac{P}{100}\right)\ V^{-2/3} \tag{3}$$

Since the number of blocks required to cover a given area of the breakwater slope is proportional to the shape factor (C), low values of C should be aimed at in block design.

WAVE RUN-UP

The wave run-up (R) determines the crest height of a non-overtopping breakwater (see Figure 5). High porosity results in a reduced wave run-up. Block shape also affects wave run-up.

MODEL TESTS

Tests were made in the outdoor wave channel of the Council for Scientific and Industrial Research. This channel is 4 ft wide, 3.5 ft deep and has a total length of 111.5 ft, the effective length (distance between wave paddle and model breakwater) being about 90 ft. Waves are generated by a paddle which is driven by an electric motor through a variable speed hydraulic transmission. In front of the wave generator is a wave filter which absorbs, to a large extent, waves reflected by the model. Wave heights of between 4 and 14 inches and wave periods of between about 0.5 and 5 seconds could be produced with the available equipment.

Three different sizes of model Dolosse (weighing 993, 427 and 185 gr. respectively), two sizes of rectangular blocks (1,262 and 929 gr.), model tetrapods (834 gr.) and tetrahedrons (594 gr.) were tested in the wave channel[5]. The three types of Dolosse were not exactly geometrically similar. The values given in Figure 1 are the mean dimensions of the three types of Dolosse and, in fact, they agree closely with the geometry of the medium size ones. The thickness-to-height ratio was 0.34 for the large size, 0.27 for the small size and 0.31 for the medium size Dolosse. The large sizes were thus relatively heavier whereas the small ones were about 25 per cent more slender than the large ones. Due to this, a slight difference in behaviour regarding stability could be expected.

TEST CONDITIONS

All armour units were tested on a slope of 1 in 1.5 and were generally put down in two layers dumped at random on an underlayer of quarry stone. The weight of the underlayer stone was $\frac{1}{4}$ of that of the medium size Dolosse or 0.1 of that of the large size rectangular blocks. The cover layer reached from 1 ft below to 1 ft above mean water level. At lower levels quarry stone, having a weight of about twice the medium Dolos weight, was used in the primary cover layer. In the case of the Dolosse, tests were also made with the blocks placed on a regular pattern as a single layer.

Two types of armour units were tested simultaneously side by side in the flume. Wave heights were increased in steps of about 2 ins from 4 ins to 14 ins, each step constituting a test run. Separate series of tests were carried out for wave periods of 1.2, 2 and 3 seconds. The water depth in front of the model breakwater was 2.5 ft to still water level in all cases.

"Damage" was assessed in the main tests in terms of the movement of a block over a distance greater than 2 ins (called 'damage'). This concept of damage was later broadened to include those blocks which rocked to and fro to such an extent that structural damage would probably occur and the blocks would be lost effectively for wave absorption (called 'total damage'). These features were recorded by visual observation during each test and a check was provided by taking photographs before and after each test. Per cent damage was calculated in terms of the total number of blocks placed on the face.

Waves produced by the mechanical wave generator were of the regular type comparable, to some extent, with regular swell in nature but not with storm waves. Due to the great depth in front of the structure waves only broke on the model breakwater itself. Hudson[1] found that for the shallow water case, when waves break just before the structure, somewhat lower stability factors than the standard values (Table I) must be applied. Since the aim of the present study was to compare the behaviour of the Dolosse with that of other armour units only, it was considered acceptable to limit the tests to the deep water case using regular waves. However, for full-scale application in a particular situation possible effects on block stability of irregular waves (wave spectrum) and shallow water should be taken into account.

RESULTS OF STABILITY TESTS

The stability factor which is typical for a particular type of block follows from equation (1) viz.:

$$K_D = \frac{H^3}{V\ \Delta^3\ \cot g\, \alpha} \tag{4}$$

For a particular armour unit having a volume V and a relative density Δ placed on a breakwater face of slope α, K_D is thus proportional to H^3. For the 0%-damage case the value of H was taken to be the wave height at which damage just started (comparable with Hudson's no-damage case, see Table I). In addition to the 0% or no-damage values for K_D as defined above, one can also define K_D values for x%-damage ($x > 0$), which are, of course, associated with higher waves (height $H_x > H$). In these cases H_x must be substituted in equation (1) to obtain K_{D_x}.

The test results for 'total damage' are summarised in Figure 7 where K_D values are plotted against per cent 'total damage'. An important point is how the test results compare with previously published ones. Test results obtained at Delft for cubes and tetrapods, as reported by Paape et al[4], are therefore also shown in Figure 7. The results obtained in Delft for cubes are seen to be in very close agreement with the CSIR's tests on rectangular blocks. The same holds for tetrapods for the lower (and thus the more important) percentages of total damage. It is, therefore, concluded that the agreement with previously published results is quite satisfactory, bearing in mind the possible minor differences in test conditions (e.g. initial packing of the blocks) inherent in this type of investigation. Hence the test results for the new Dolos block may be relied upon with confidence.

Hudson[1], in Table I, refers to K_D values for the 0%-damage case only. Comparable values for K_D extracted from the CSIR's results are shown in

Table II.

TABLE II. CSIR'S STABILITY FACTORS (K_D) FOR THE 0%-DAMAGE CASE

Armour Unit	Method of placing	K_D	
		Damage	Total damage
Rectangular blocks	random, double layer	2.5	2.3
Tetrahedrons	" "	1.5	1.2
Tetrapods	" "	6.5	2.5
Dolosse	" "	40	24
Dolosse	uniform, single layer	25	20

The K_D values of Table II for tetrahedrons and tetrapods are much smaller than those given by Hudson (Table I). However, the 0%-damage stage is extremely difficult to decide upon. It is, therefore, quite possible that at the stage which Hudson seleoted as 0%-damage some minor damage had, in fact, taken place. For instance it is seen from Figure 7 that the values of K_D for $1\frac{1}{2}$%-damage compare very well with Hudson's values. This clearly demonstrates the deficiencies of the no-damage criterion and emphasizes the importance of determining the actual damage which takes place for each particular wave height[4].

The validity of the model K_D values for random Dolosse ($K_D = 24$) is confirmed by the experience with the $19\frac{3}{4}$-ton Dolosse on the East London breakwater head. These blocks withstood, without moving, 25-ft high waves and with $\gamma_s = 150$ lb/ft^3, $\Delta = 1.34$ (seawater) and cotg $\alpha = 1.25$ this means a K_D value of 19.6 or more. Since a slightly smaller stability factor may be expected for the breakwater head compared with the trunk of the breakwater the agreement with the model value is considered good.

It is clear from Figure 7 that Dolosse are much more stable than the other types of blocks. Since the required block weight is inversely proportional to K_D the high values of K_D for Dolosse mean that smaller individual units may be used for a particular design wave height. The rapid increase of the K_D value after a few per cent of damage emphasizes the strong tendency of the Dolosse to interlock, thus forming a semi-monolitic cover layer of great stability.

Although the Dolosse packed to pattern seem to compare very favourably with other blocks dumped at random and, in fact, the zero-damage K_D values were found to agree closely with the K_D value for uniformly placed hexapods (Dolosse, K_D = 25 to 20, hexapods K_D = 22, see Tables I and II), a serious disadvantage of the packed Dolosse was found to be that once damage has started the coherence of the structure is lost and total failure results. This makes the use of packed Dolosse much more risky compared with any type of armour unit dumped at random and since placing to pattern on real breakwaters is virtually impossible, the results on packed Dolosse are considered to be of academic value only.

POROSITY VALUES

Porosity figures for cover layers of different type blocks are compared in Table III.

TABLE III. POROSITIES OF COVER LAYERS IN PER CENT

Type of block	Hudson[1]	Paape et al[4]	CSIR	Accepted
Cubes	47	47	-	
Rectangular blocks	-	-	50	50
Tetrapods	50	53	55	53
Tetrahedrons	-	-	60	60
Dolosse (random)	-	-	60	60
Dolosse (packed, single layer)	-	-	41	41

Porosity determinations at CSIR were repeated several times and very consistent results were obtained. The porosity of randomly dumped Dolosse is high. Consequently a significant reduction in run-up is to be expected and in fact was noted in the tests in comparison with other types of blocks.

SHAPE FACTORS

Values for the shape factor (C) were determined by using equation (3). The results are compared with other available information in Table IV.

TABLE IV. SHAPE FACTORS (C) OF ARMOUR UNITS

Type of block	Hudson[1]	Paape et al[4]	CSIR	Accepted
Cubes	1.1	-	-	
Rectangular blocks	-	-	1.0	1.0
Tetrapods	1.0	1.0	1.0	1.0
Tetrahedrons	-	-	1.2	1.2
Dolosse (random)	-	-	1.3	1.3
Dolosse (packed)	-	-	1.2	1.2

The required number of blocks for a given block weight is proportional to C (equation 3) and thus a low value of C is desirable. The high value of C for Dolosse means that for a given block size the cover layer is relatively thick ($r = n\ C\ V^{1/3}$, equation 2) which may well be an explanation for the excellent stability of the Dolosse. Whether the high value of C is a serious defect regarding the overall economics of the Dolos is examined in a later section on economics.

WAVE RUN-UP

Results of measurements of wave run-up for the various blocks are shown in Figure 8. As could be expected from the high porosity figure the Dolosse, dumped at random, showed slightly smaller run-up figures than all other types of blocks. Although the tetrahedrons have the same porosity as the Dolosse (viz. 60 per cent) the run-up values are somewhat greater. This is probably due to the relatively large flat surfaces of the tetrahedrons.

Since the worst conditions should be considered, it is clear that the peak values of the various run-up curves shown in Figure 8 (for critical wave steepness) determine the necessary breakwater crest height (for no-overtopping). These peak values are summarised in Table V.

TABLE V. MAXIMUM RELATIVE WAVE RUN-UP

Type of block	Rectangular block	Tetrapods	Tetrahedrons	Dolosse (random)	Dolosse (packed)
R/H	1.00	0.90	0.98	0.83	0.90

For a design wave height H = 25 ft a reduction in breakwater height of over 4 ft is effected if random dumped Dolosse are used instead of rectangular blocks.

ECONOMICS OF DOLOSSE FOR COVER LAYERS

The cost of a breakwater cover layer for a particular design wave height depends on:

(a) The weight of the individual blocks (taking into account equipment available for handling the units; this is of particular importance in maintenance);

(b) The total concrete volume required per unit area of cover layer;

(c) The number of blocks;

(d) The wave run-up;

(e) The manufacturing costs (cubes being much easier to make than tetrapods) including possible royalties; and

(f) The method of placing (random is much simpler than placing in a regular pattern).

These factors are discussed in more detail in the following paragraphs.

BLOCK WEIGHTS

Block weights have been calculated for the various armour units as a function of the design wave height. The results of these calculations are shown in Figures 9 and 10. Four different percentages of damage, viz. 0, 2, 5 and 10 per cent were considered separately. It follows from Figures 9 and 10 that under all conditions Dolosse, when dumped at random, can be made far lighter than any other type of block. For 0%-damage Dolosse may be about 1/10th of the weight of rectangular blocks or tetrapods and for 2- and 5%-damage about 1/6th.

For example, with a design wave height of 25 ft and assuming 2%-damage to be acceptable, the following block weights (in tons) are required:

Rectangular blocks	50	Tetrahedrons	45
Tetrapods	35	Dolosse (random)	7.5

Although it is rather difficult to define the actual saving it is clear that the smaller block weights for Dolosse are a great advantage, in particular for use at small harbours and in remote areas, where heavy handling equipment is not available, and for repair work in which case permanent equipment for maintenance work can be much less elaborate and much lighter.

Hudson[1] expressed the sizes of the quarry stone in the underlayers as proportions of the equivalent weight of quarry stone in the cover layer (W_e, see Figure 5). Since the test results for rectangular blocks are virtually the same as those which Paape et al[4] found for quarry stone the line depicting K_D values for rectangular blocks, in Figure 7, may safely be accepted for quarry stone as well. For the above example (rectangular blocks or quarry stone - 50 t, Dolosse - 7.5 t) the size of the underlayer blocks should thus be 5 tons according to Hudson. However, compared with the 7.5 ton Dolosse this is considered to be impractically large and it is proposed that the size of the underlayer stone should rather be 1/4 to 1/6th of the Dolos weight (1/4 to 1/6 W), and not 0.1 W_e.

REQUIRED CONCRETE VOLUME IN COVER LAYERS

The volume of concrete required for armour units per unit area of cover layer is given by (see equation 3):

$$Q = N\,V = n\,C\,(1 - \frac{P}{100})\,V^{1/3} \tag{5}$$

Since the block volume $V = W/\gamma_s$ and the block weight W is a function of the design wave height H (equation 1) it follows that Q is also a function of H. This functional relationship is shown in Figures 11 and 12 for each of the 0-, 2-, 5- and 10%-damage cases.

From the test results it was found that randomly dumped Dolosse show up favourably with respect to porosity but unfavourably regarding the shape factor. However, the thickness of a Dolos cover layer for a given design wave height is relatively small since light (and thus small) individual blocks may be used. Consequently the total volume of concrete required is so much reduced that this volume is still significantly smaller than for any other type of block (see Figures 11 and 12).

The direct saving in concrete volume is about 50 per cent for the 0%-damage case and about 40 per cent for the 2-, 5- and 10%-damage cases when randomly dumped Dolosse are used instead of one of the other types of blocks.

Although packed Dolosse appear to be even more favourable, as was mentioned earlier this result is not considered to be of practical value.

For the case of a design wave height of 25 ft and 2%-damage (see example for block weights), the required concrete volumes (in cu.ft/sq.ft) are:

Rectangular blocks	8.6	Tetrahedrons	8.0
Tetrapods	7.2	Dolosse (random)	4.8

REQUIRED NUMBER OF BLOCKS

For a given design wave height the required number of armour units per unit area of cover layer is found from:

$$N = \frac{Q}{V} = \gamma_s \frac{Q}{W} \tag{6}$$

whereby Q and W are read off against the particular value of H in Figures 9 to 12.

Since in the case of Dolosse the block weight is about 1/6th of that of other block types and because the concrete volume for Dolosse is about 50 per cent smaller, the number of blocks will generally be approximately three times larger.

From equation (5) it follows that the required concrete volume in the cover layer for a particular block shape is directly proportional to the third root of the block weight, i.e.:

$$Q = K_1 W^{1/3} \tag{7}$$

where $K_1 = n\ C\ (1 - \frac{P}{100})\ \gamma_s^{-1/3}$ (constant).

The number of blocks, however, is inversely proportional to the two-third root of the block weight, i.e.:

$$N = K_2 W^{-2/3} \tag{8}$$

with $K_2 = \gamma_s K_1$.

A 25 per cent increase in concrete volume (Q) will thus result in a reduction in the number of blocks (N) of about 50 per cent. Under certain circumstances, depending on the relation between labour and material costs, it may therefore be more economical to use slightly larger blocks than necessary in order to effect a relatively large reduction in the number. However, in practice this can only be done for the smaller block sizes because a 25 per cent increase in concrete volume would effect a 100 per cent increase in block weight, which could cause the blocks to become too large to handle. Moreover, in the case of Dolosse, the number of blocks is virtually proportional to the concrete volume for block sizes greater than 6 to 8 tons. The possibility of reducing the overall costs by reducing the number of Dolosse is thus limited to the sizes smaller than 6 to 8 tons.

WAVE RUN-UP

Since the height to which the cover layer reaches above still water level depends on the wave run-up, R (see Figure 5) the reduction of the run-up in case of Dolosse effects a direct saving of about 8.5 per cent in the cost of the armour layer compared with rectangular blocks and about 3.5 per cent compared with tetrapods.

BLOCK MANUFACTURING AND PLACING COSTS

Manufacturing and placing costs will of course depend very much on local conditions. It is obvious that rectangular blocks are easier to manufacture than most special shape blocks, but because the rectangular blocks have to be extremely heavy, handling will be much more costly.

As was described in the first part of the paper, when dealing with full-scale Dolosse, no particular difficulties were encountered with the manufacturing of Dolosse, while placing of these blocks was found to be quite simple because they could be picked up easily with a simple sling arrangement. Dolosse are definitely not more difficult to make than, for instance, tetrapods or tetrahedrons. This is confirmed by the following approximate unit costs (Rand/cu.yd., including placing) which apply to recent harbour construction works in South Africa:

Boulders (Port Elizabeth)	(5 - 8 t)	11	Tetrahedrons (Cape Town)	(3 t)	12.5
Rectangular blocks (Durban)	(30 - 40 t)	8	Dolosse (East London)	($19\frac{3}{4}$ t)	12
Tetrapods (Cape Town)	(8 t)	19			

The rectangular blocks, tetrapods and Dolosse were made Departmentally, whereas the tetrahedrons were made under contract.

Although steel frames were put in the $19\frac{3}{4}$-ton Dolosse to provide sufficient support to the cast-in wires for lifting the 'green' blocks out of the moulds, it has been found recently that the rail reinforcing is not required. Two pieces of steel wire cast into each block have been found to be sufficient for lifting purposes.

THE ECONOMIC VALUE OF DOLOSSE

When using Dolosse a saving in concrete volume in the cover layer of about 40 per cent, compared with other block types, can thus be obtained. Assuming roughly equal unit costs (which seems to be correct for all but rectangular blocks) this means a direct saving in manufacturing costs of about the same order.

For Dolosse a block weight of about 1/6th of that of other block types will normally be sufficient. Obviously this is a great advantage but, on the other hand, a larger number of blocks will have to be handled. For the construction of new harbours and in the case of small harbours, where large equipment for handling blocks is not available, the advantage of the smaller blocks would, of course, outweight by far the extra handling due to the greater number of blocks.

Apart from the direct saving in cover layer costs, when using Dolosse, due to the reduced wave run-up a further saving is effected because the whole breakwater structure can be made lower. Moreover, since the size of the quarry stone in the underlayers should be related to the size of the blocks in the cover layer it follows that with the much smaller Dolosse a saving in size of the stone and the thickness of the underlayers may be possible.

It is thus concluded that in many cases the use of Dolosse in armour layers will be very economical.

OPTIMUM COVER LAYER DESIGN

For optimum cover layer design it will be necessary to establish which design wave height, with corresponding recurrence period and acceptable percentage of damage, will yield the minimum total annual cost (including interest on capital, capital redemption and maintenance cost).

An economic analysis was made for Dolosse based on the following assumptions:

(a) The SE waves shown in Figure 6 are determinative for the breakwater design (this is probably the case for the East London main breakwater);

(b) Wave height between deep sea and the breakwater are not materially affected by refraction or shoaling;

(c) The redemption period may be accepted to be equal to the recurrence period of the wave height used for the determination of the required block weight;

(d) The interest rate on capital is 6 per cent per annum; and

(e) The basic cost of the cover layer is assumed to be proportional to the concrete volume.

With the aid of Figures 11 and 12 the annual costs for the 0-, 2-, 5- and 10%-damage cases were determined, the results being shown in Figure 13. Both total (including maintenance) and capital costs are shown, the latter being cumulative, for the higher damage cases.

The optimum design wave height is seen to be almost independent of the acceptable damage and lies between 35 and 40 ft (recurrence periods of 25 and 100 years for SE waves). Accepting a wave height of 37.5 ft as the optimum (recurrence and thus also redemption period of 50 years), it follows from the Inset on Figure 13 that the minimum annual cost would be obtained if the design value for acceptable damage was made 4 per cent.

CONCLUSIONS

The performance of Dolosse, both in the model and in nature, was found to be excellent in comparison with other specially designed breakwater blocks. The outstanding stability of the blocks can be ascribed to their particular shape, which encourages interlocking to a very great extent. The good performance and economy of a double layer of randomly dumped Dolosse in comparison with other blocks is evidenced in particular by:

(a) Smaller block weight for a particular design wave;

(b) A reduction in total amount of concrete in the cover layer; and

(c) Smaller wave run-up.

Dolosse, therefore, appear to be very economical to use in cover layers and for shore protection works. This seems particularly the case for smaller harbours, where no heavy cranes may be available.

ACKNOWLEDGEMENT

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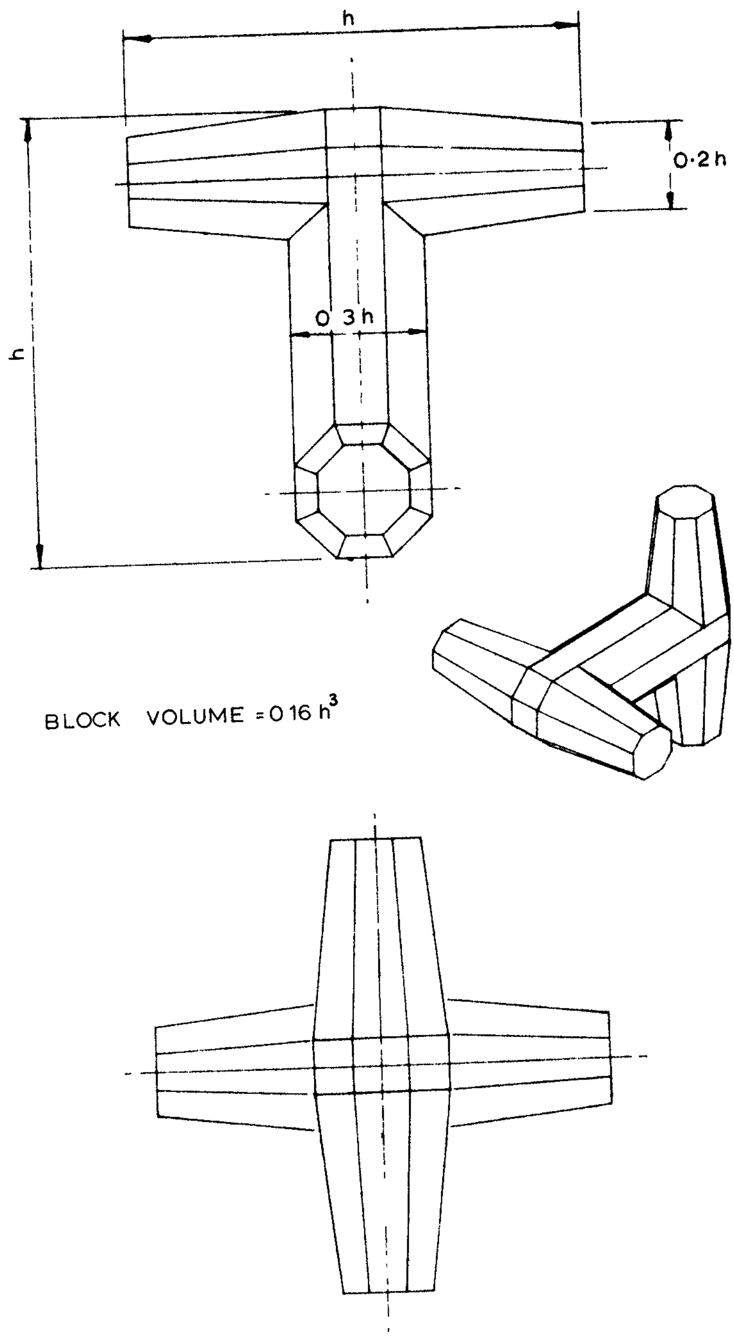


Fig. 1. Breakwater block 'Dolos'.

Fig. 2. Lifting a 19-3/4-ton Dolos from its mould.

Fig. 3. Breakwater head protected with 19-3/4-ton Dolosse.

Fig. 4. Difference in run-up and splashing between rectangular blocks (background) and Dolosse (foreground).

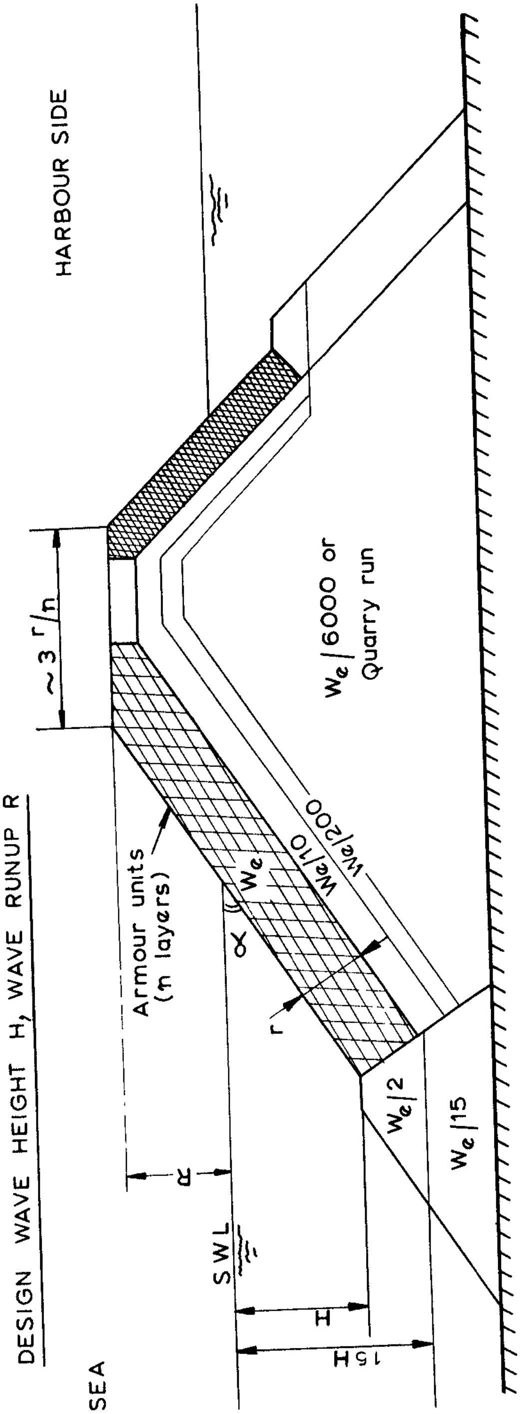


Fig. 5. Schematic cross-section of rubble mound breakwater.

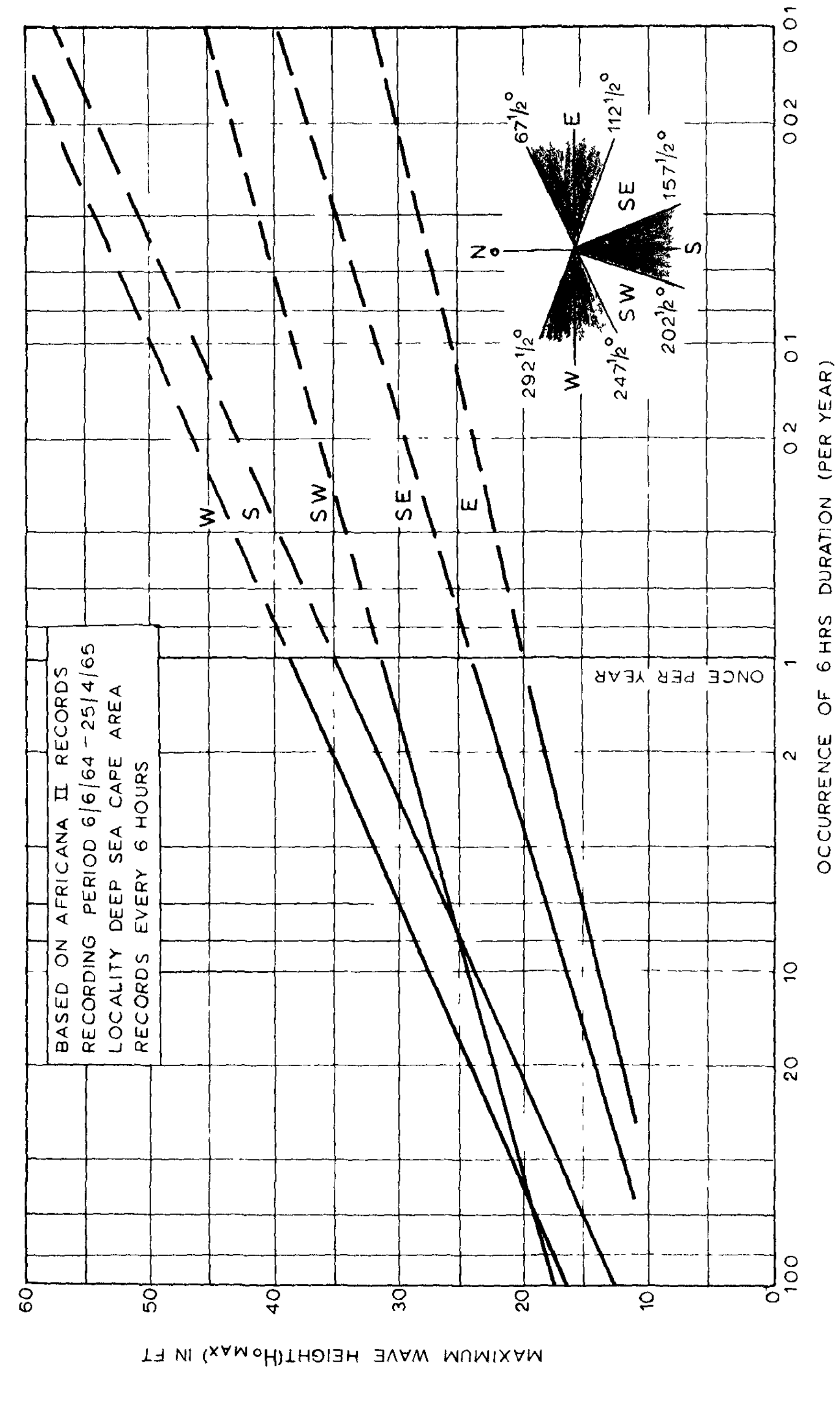


Fig. 6. Design wave heights, Cape Town area.

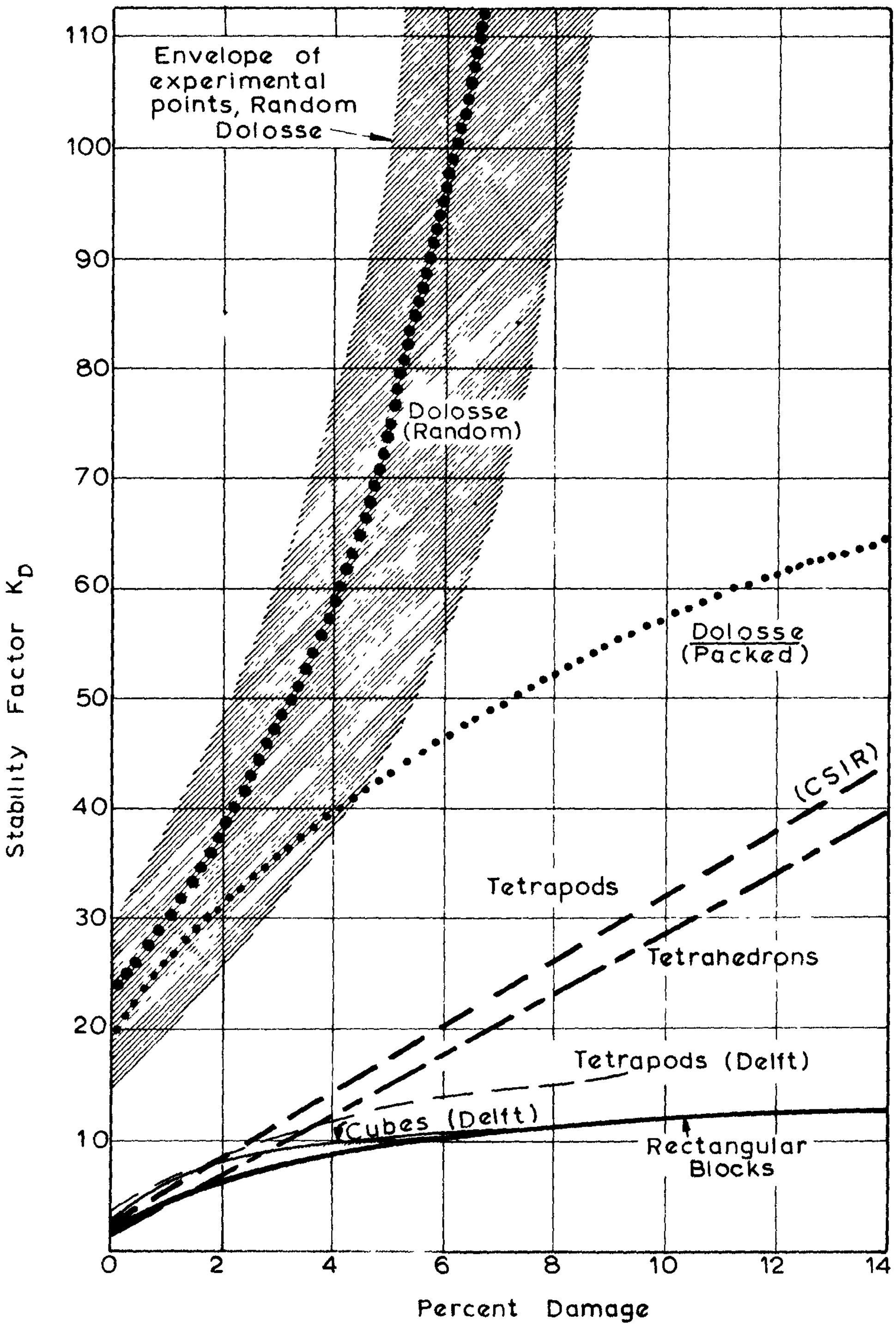


Fig. 7. Stability factors versus total damage.

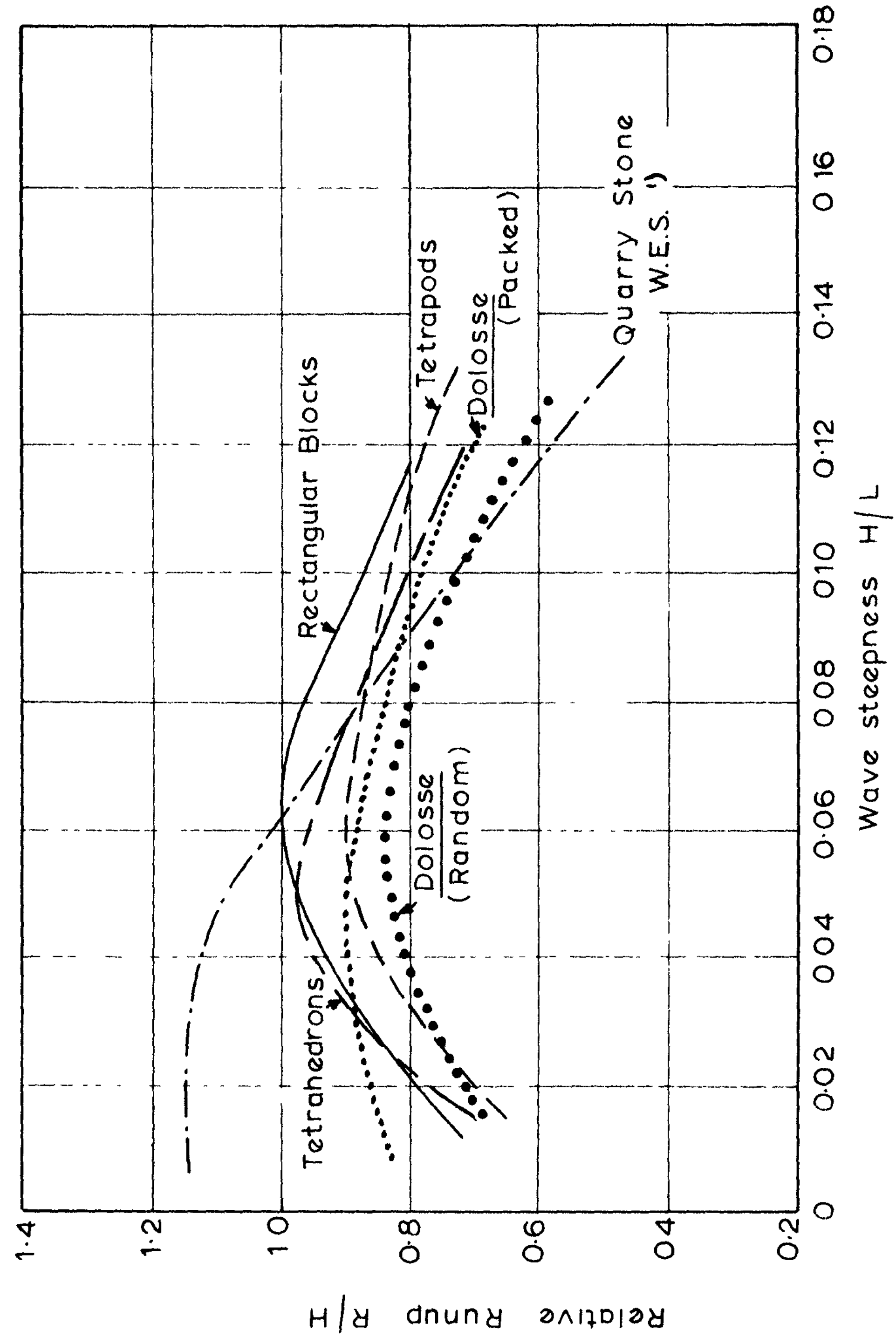
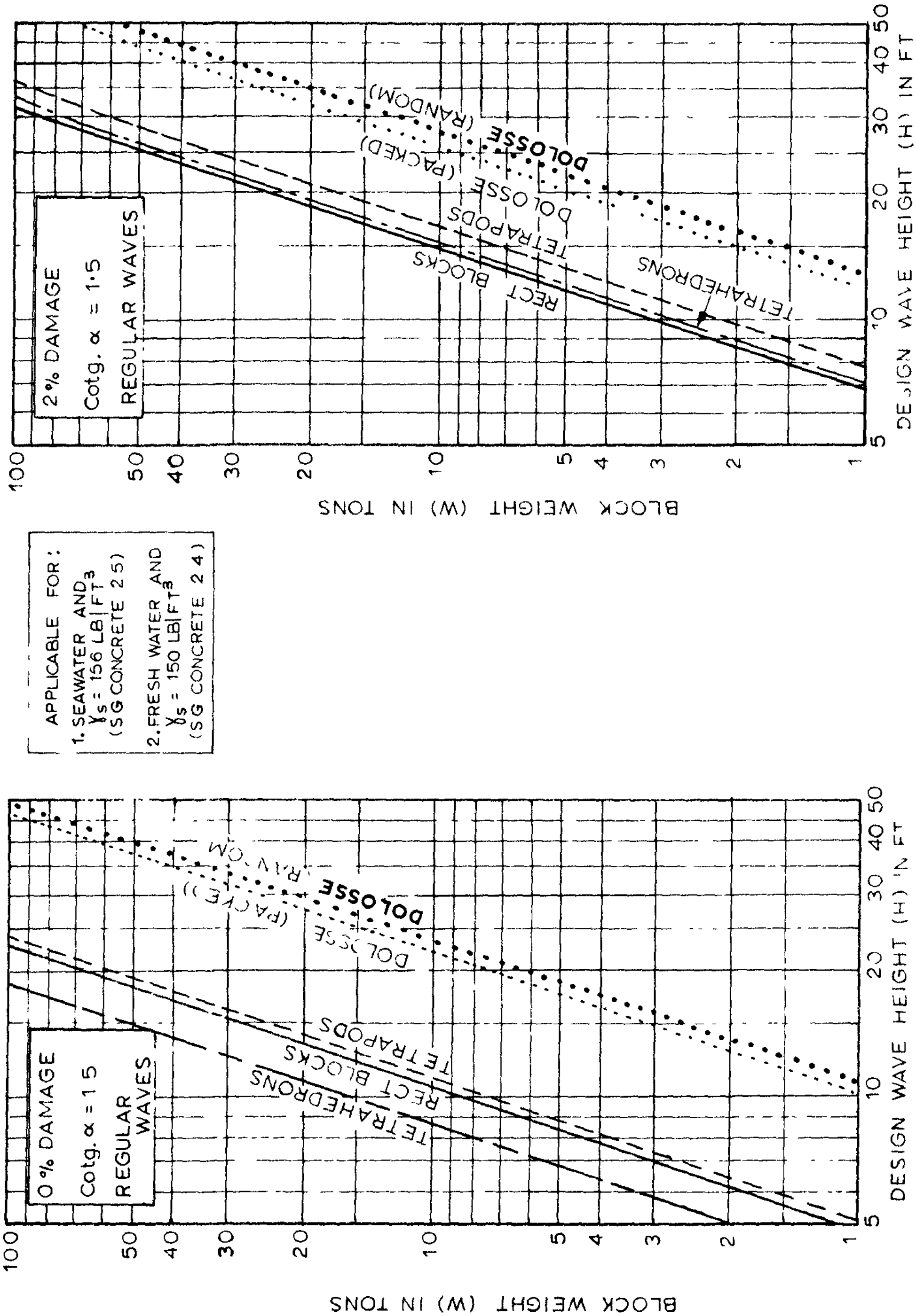


Fig. 8. Wave run-up.


2% DAMAGE
Cotg. α = 1·5
REGULAR WAVES
DOLOSSE (RANDOM)
DOLOSSE (PACKED)
TETRAPODS
RECT BLOCKS
TETRAHEDRONS
BLOCK WEIGHT (W) IN TONS
DESIGN WAVE HEIGHT (H) IN FT
APPLICABLE FOR :
1. SEAWATER AND γs = 156 LB/FT3 (SG CONCRETE 2.5)
2. FRESH WATER AND γs = 150 LB/FT3 (SG CONCRETE 2.4)
0% DAMAGE
Cotg. α = 1.5
REGULAR WAVES
DOLOSSE (RANDOM)
DOLOSSE (PACKED)
TETRAPODS
RECT BLOCKS
TETRAHEDRONS
BLOCK WEIGHT (W) IN TONS
DESIGN WAVE HEIGHT (H) IN FT

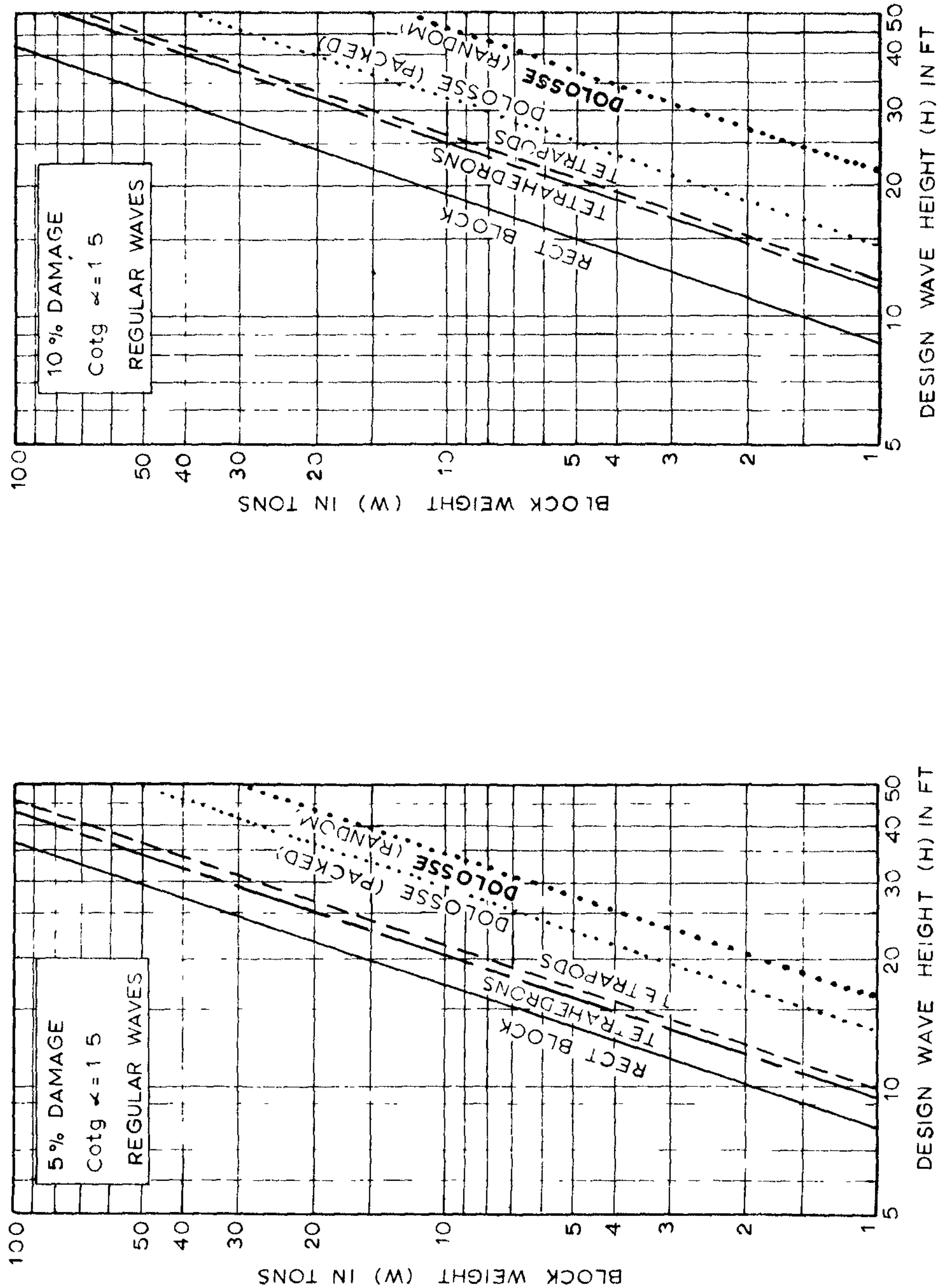


Fig. 10. Block weights for 5 and 10 per cent total damage.

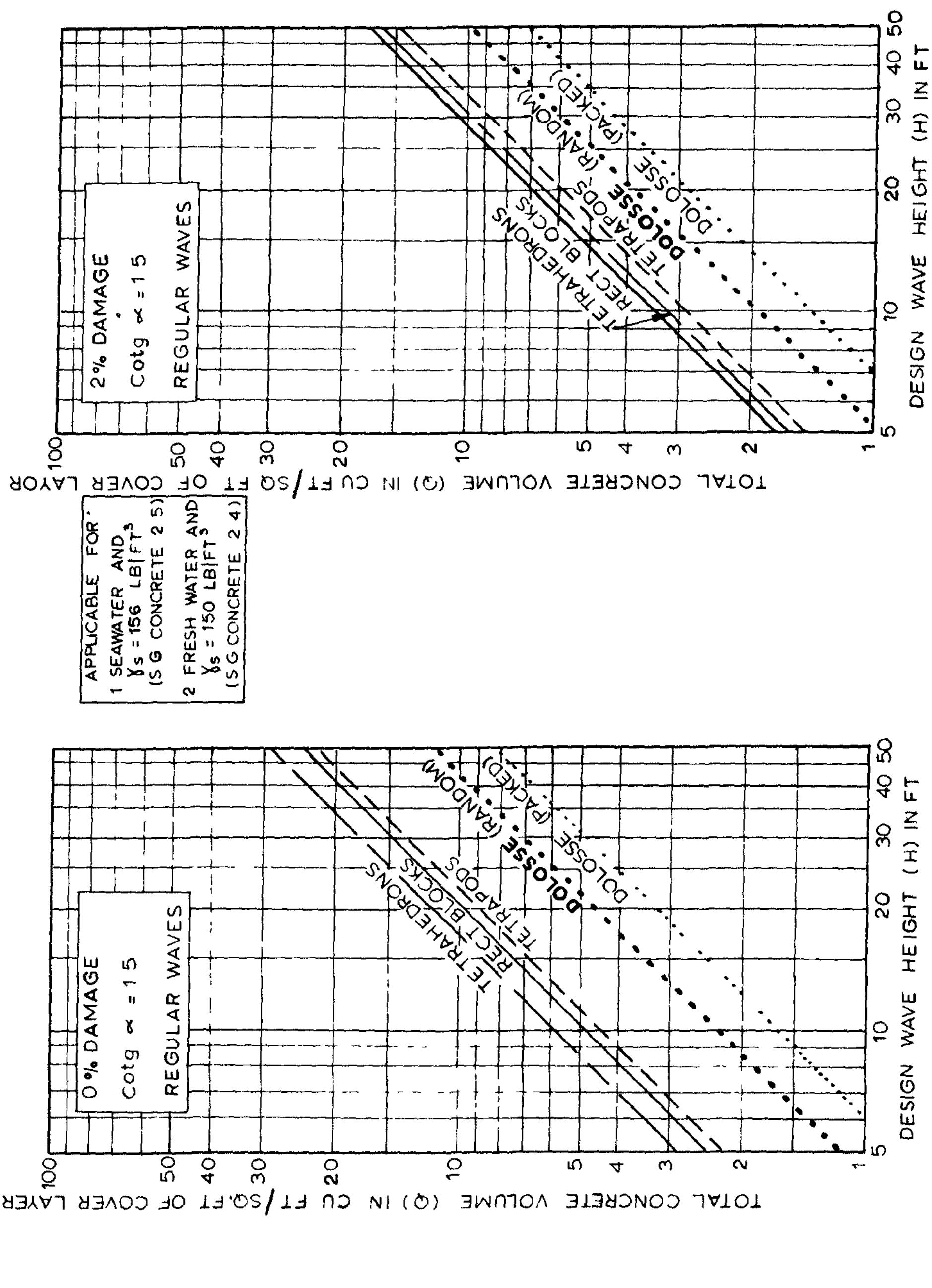


Fig. 11. Required concrete volume for 0 and 2 per cent total damage.

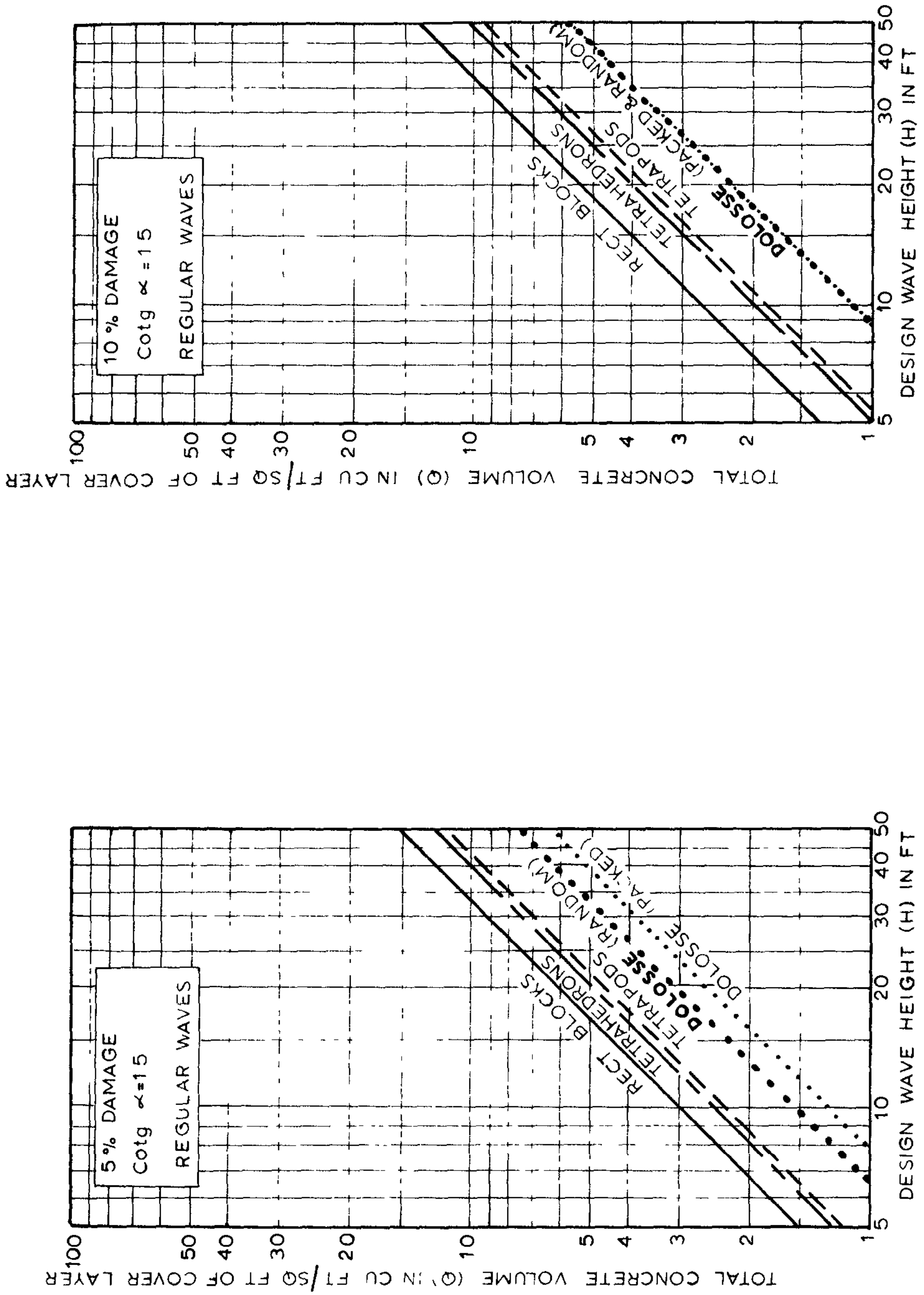


Fig. 12. Required concrete volume for 5 and 10 per cent total damage.

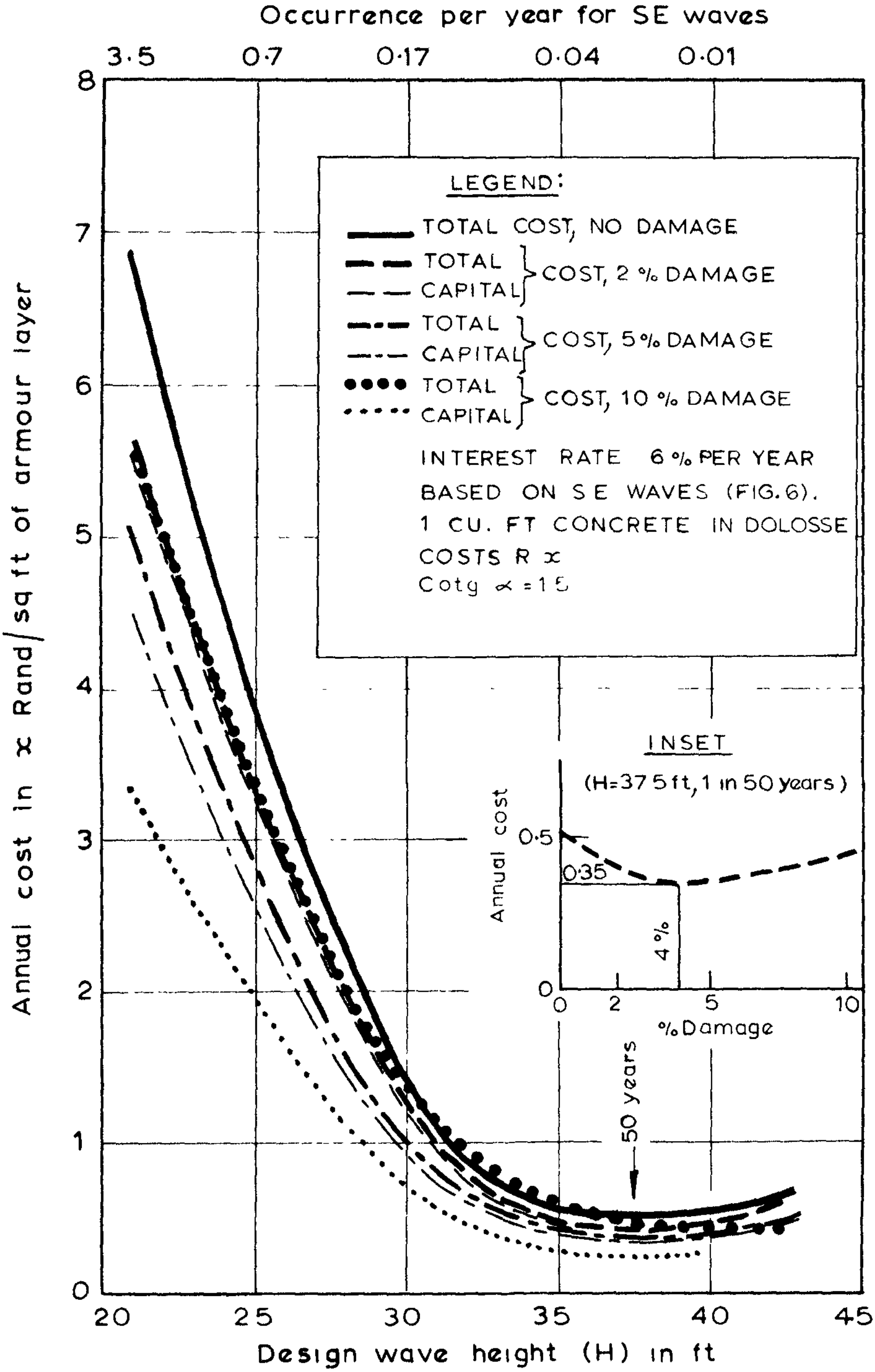


Fig. 13. Optimum design for Dolosse dumped at random.