CHAPTER 25

AKMON ARMOUR UNIT FOR COVER LAYERS OF RUBBLE MOUND BREAKWATERS

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A new specially shaped concrete block, the "Akmon", to be used as armour unit for protective cover layers of rubble mound breakwaters is presented.

The characteristics as have been derived from laboratory tests are compared with those of various other types of blocks.

Some considerations are given on the design procedure for cover layers, as it appears that this procedure has an influence on the block-type and -weight to be chosen.

If armour units have to be placed at random, which is in many cases an imperative necessity, the akmon appears to be one of the most suitable blocks developed up till now.

For two different breakwaters, the results are given of model investigations concerning the stability under the attack of waves generated by a wave board and wind.

INTRODUCTION

One of the designs of "Rijkswaterstaat" for the new harbour mole at IJmuiden was a rubble mound breakwater with a protective layer of concrete blocks. For this design the laboratory investigated different types of blocks with regard to stability against wave attack. First a series of comparative tests was conducted in a wave flume with regular paddle-generated waves. In these tests quarry stone was compared with cubes and other types of artificial blocks, some of which are given in figure 1.

Because of the restricted time only the three most promising blocks cubes, tetrapods and akmons were used for the second series of comparative tests which was conducted in a wind flume. Especially the akmon (Greek for anvil, see figure 2) appeared to have excellent qualities with regard to stability and porosity of the cover layer. Meanwhil however, important progress was made in the handling of stone-asphalt mixtures below the water level and the rubble mound breakwater appeared to be in this case no longer competitive. Then the investigations were stopped in an advanced stage.

The results were used for the design of other breakwaters invest gated by the laboratory and some data of the investigations are also given below. Moreover some general considerations are given with regard to the design procedure and especially the comparison of different type of blocks from an economical point of vue.

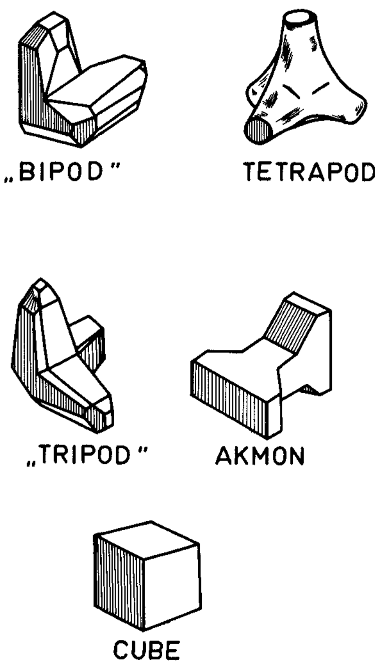

Fig. 1. Complete armour units.

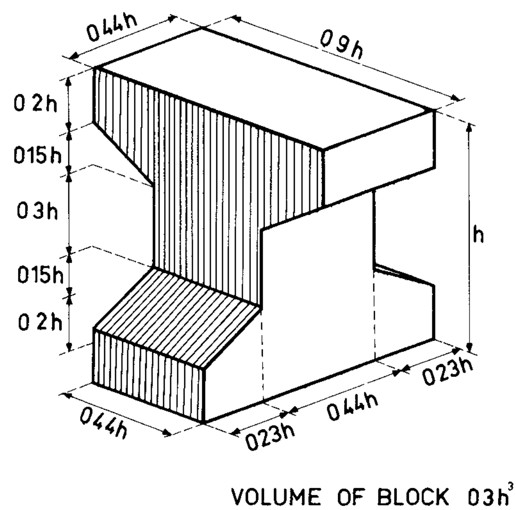

Fig. 2. Akmon armour unit.

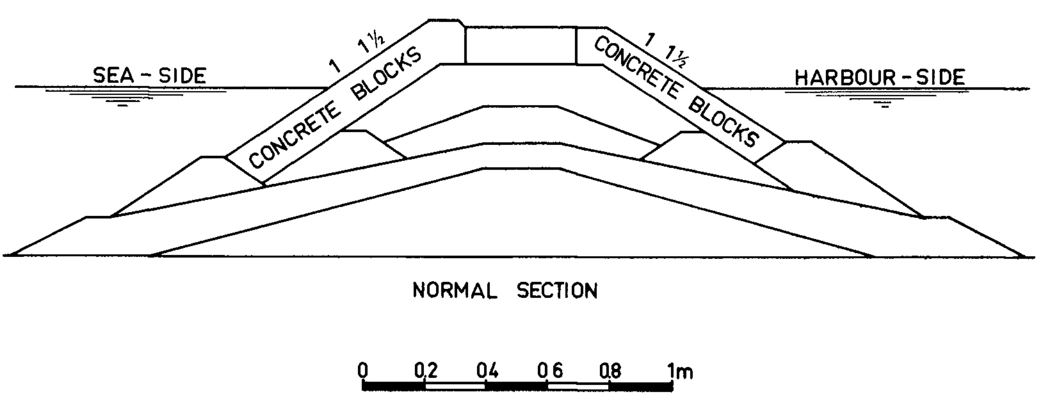

Fig. 3. Model of IJmuiden breakwater as used for comparative tests.

CHARACTERISTICS OF THE ARMOUR UNITS

The comparative tests started with six different armour units: quarrystone, cubes, tetrapods, "tripods", "bipods" and akmons.

The volumes and specific weights of the different types were the same. Sketches of the artificial blocks are given in figure 1. As the akmon (the Greek word for anvil) was found to be the most promising of the new types that were investigated, a detailed sketch of this block is given in figure 2.

The number of blocks required for covering a certain area with a double layer, placed pell-mell, can be expressed as:

$$N = C.A.V.^{-2/3}, \quad \text{in which:}$$

N is the number of blocks in a double layer on a surface A.
V is the volume of one block.
C is a coefficient, depending on the shape of the blocks.

A similar formula is given by the Waterways Experiment Station (W.E.S.) (see reference 2, page 11) and values of C for various shapes of blocks can be derived from the data presented in the report mention above. The results obtained by W.E.S. and the authors are as follows:

Armour Unit	$C_{W.E.S.}$	$C_{HYDR.LAB.}$
Quarrystone	1,24	1,22
Modified cube	1,16	-
Tetrapod	1,0	1,03
Quadripod	1,0	-
Hexapod	1,22	-
Tribar	0,92	-
Akmon	-	0,90
Cube	-	1,18
"Tripod"	-	1,05
"Bipod"	-	1,08

The results obtained for tetrapods are in accordance with those given by SOGREAH (3).

Needless to say that the amount of stone or concrete required to construct a cover layer is, for the same blockweight, proportional to the value of C.

A quick, but somewhat rough impression about the porosity of a number of stone layers was obtained by filling a box with blocks, placed at random. The dimensions of the box were about 5 x 6 x 6 times the "diameter" of a block.

For the different types of blocks tested, the results are as follows:

	Akmon	Cube	Tetrapod	"Tripod"	"Bipod"	Quarrystone
Porosity (%)	60	47	53	53	51	45

For akmons the porosity of a double layer was determined by measuring the thickness of the layer by means of a sounding rod, equipped with a ball and socket foot, in order to obtain a result comparable with the W.E.S. (2).

The foot was circular with a diameter of one-half times the diameter of the blocks. In this way the porosity was found to be 55%.

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COMPARATIVE TESTS

REGULAR WAVES

Models - The first series of comparative tests for the design of IJmuiden breakwater were carried out in a wave tank, 2,5 m wide and 29 m long and equipped with a wave board, generating regular waves. In front of the wave machine a filter was provided in order to reduce the waves reflected by the models. In this flume five sections (fig. 3), each 0.5 m wide and covered with different types of armour units were tested simultaneously by gradually increasing the wave height.

These wave heights were measured at different places in front of the breakwater by a parallel wire resistance gauge and recorded by a pen recorder. From the records the incident wave height was determined. The wave period was kept at 1.4 sec.

The slope was 1 : 1.33, 1 : 1.5 and 1 : 1.6 (only for the first slope enough results are available). The waterdepth was as indicated in fig. 3, namely 0.27 m at the toe of the breakwater but in front of the breakwater there was a slope of 1 : 5 till a depth of 0.42 m. The blocks had a mean density of 2200 kg/m^3 and a volume of $38 . 10^{-6}$ m^3.

In order to be able to make a comparison the results were plotted as a function of the wave height as defined by Hudson (1) (2) viz. the average height of the highest one third of the waves in the wave trains. Then the highest waves which occur when starting and stopping the wave machine are approximately 12% higher. This, however, does not mean that the tests may be considered as being identical to Hudson's.

Results - The results of the stability tests are plotted in fig. 4 with K_D as a function of the damage. K_D is the damage coefficient:

$$K_D = \frac{H^3}{V \Delta^3 \text{ cotg } \alpha}$$

with H = wave height, causing a certain damage.

V = volume of the block.

$$\Delta = \frac{\rho_s - \rho_w}{\rho_w} .$$

ρ_s = density of the stone.

ρ_w = density of the water.

α = angle of inclination of the slope.

For some blocks also results with cotg α = 1.6 were obtained. Then K_D generally is greater, but the small number of tests does not lead to a definite conclusion whether the function of α in the Hudson formula (1) is somewhat optimistic for the steeper slopes.

WIND WAVES

Models - For the second series of tests for the design of IJmuiden breakwater a wind flume was used, 4 m wide and 100 m long equipped with a wave board and an electrically driven fan blowing wind over the entire length of the flume. The fan is provided with adjustable vanes by means of which the air current can be regulated up to a wind velocity of 20 m/sec. Here the same method of measuring wave heights was used and the wave attack is oharacterized by H_{15} being the wave height exoeeded by 15% of a series of waves.

Although it is possible to raise in the windflume by wind only a spectrum of wave heights as will oocur in nature, the wave period is limited. When the scale of the model requires a period exceeding this limit, the waves are generated by wind combined with the wave board. This means that somewhat less higher waves occur. The more the period exceeds the limit, the greater this deviation oan be, but generally it is still acoeptable. Especially for the investigation of Umuiden breakwater this meant no draw-back, because in the limited depth present the highest waves were broken before reaching the structure, but for general application the results are not suitable.

The waterdepth in these tests was 0.27, 0.30, 0.33 and 0.36 m. The density of the blocks was 2600 kg/m^3 and the volume of the blooks was 50.10^{-6} m^3.

Results - Damage coefficients were obtained for three types of blocks on a slope of 1 : 1.5 in a waterdepth of 0.27 m with a wave period of 1.1, 1.4 and 1.8 sec of whioh 1.4 seo was the most dangerous period.

K_D		Akmons	Cubes	Tetrapods
Damage	0%	4.8	3.5	4.7
	1%	11	7	9
	2%	12	8	11
	5%	± 17	± 14	± 15

REMARK

Because doubt was expressed whether the stability of the akmon might be mainly due to its sharp edges comparative tests were performed with normal akmons, tetrapods and akmons of which the sharp edges were rounded off. In these tests, with oblique and normal wave attaok, the "rounded off akmons" showed no signifioant difference with the normal akmons, although the blocks were rounded off much more than is found to happen with concrete blocks in prototype breakwaters. So it may be conoluded that the stability characteristics of the akmon are due to its principal form and not to its sharp edges.

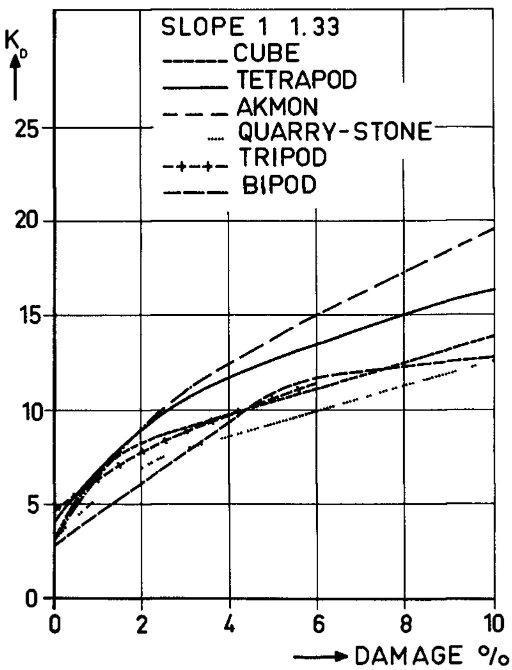

Fig. 4. Test results with regular waves.

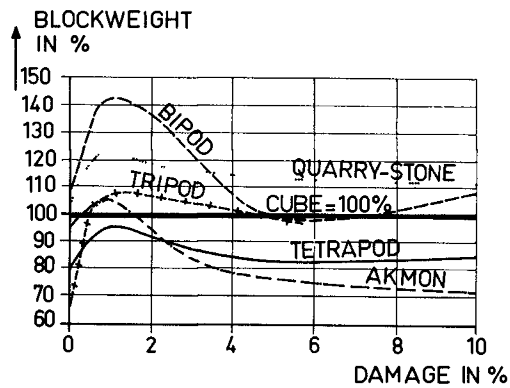

Fig. 5. Required block weight compared with cubes.

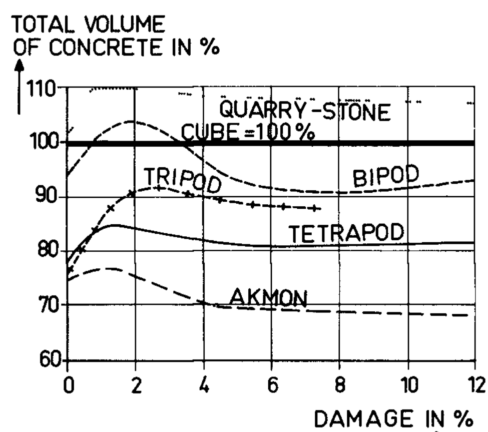

Fig. 6. Required volume of concrete compared with cubes.

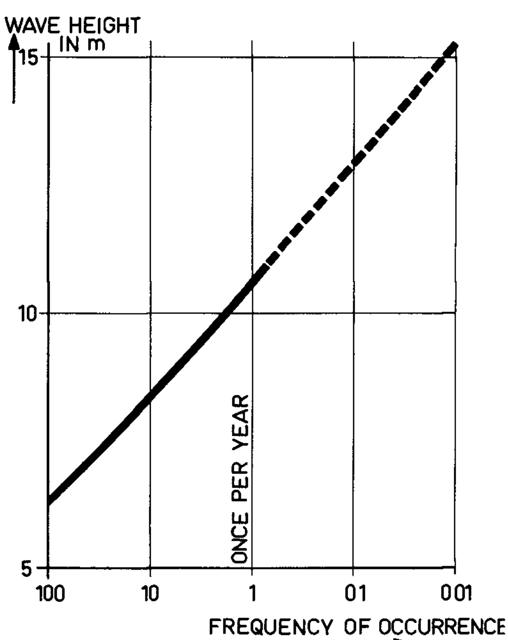

Fig. 8. Frequency of occurrence of individual wave heights near the Dutch coast.

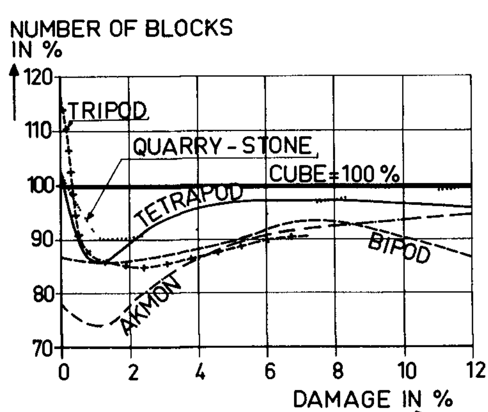

Fig. 7. Number of blocks required in comparison with cubes.

DESIGN PROCEDURE FOR COVER LAYERS

GENERAL CONSIDERATIONS

Some considerations are given below on the design procedure for cover layers, as it appears that this procedure has an influence on the block-type and -weight to be chosen.

One of the most important requirements for the design of a breakwater is of course that the investment and costs of maintenance are minimum.

In case that natural stones are applied, the possibilities given by the quarry are often determinative. When designing a cover layer of concrete blocks, the specific conditions for the breakwater concerned can be taken into account next to the general requirements. As such can be mentioned a.o.:

1. The blocks must allow the application of steep slopes, in order to reduce the material in the core. A practical limit is 1 : 1.5 to 1 : 1.3 depending on the core material and the wave motion during execution.

2. Manufacturing of the blocks shall be relatively easy.

3. It is often necessary to place the blocks at random, in case of building in a rough sea and in order to reduce the time for placing.

4. The covering of special points, such as bends and the head, must be possible without extreme difficulties.

The costs of realising a cover layer, as far as dependent on the shape of the blocks, are determined by:

1. The total amount of concrete which is required.

2. The weight of the individual blocks (in view of the equipment that is available).

3. The costs of manufacturing.

4. The number of blocks to be placed (number of moulds and manipulations).

The data required to evaluate the various types of blocks in the light of these factors, as far as can be derived from model tests are given below.

BASIC DATA FOR DIFFERENT TYPES OF ARMOUR UNITS

Slope - From the tests it appeared that the application of a slope of 1 : 1.33 is, in principle, possible for all types of blocks.

Method of placing - Although it is very difficult to reproduce in the model exactly the method of placing in nature (see (2)), a comparison can be made between the different types of blocks, based on model tests in which the blocks are placed at random.

<u>Block weight</u> - An estimate of the block weight which is required can be made based on the coefficients K_D given in the foregoing chapter The block weight is inversely proportional to the value of K_D. For comparison the results are given compared to the values for cubes, which have been set to 100%.

For armour unit X and cubes, the ratio of the block weights is $\frac{W_X}{W_C} = \frac{K_{DC}}{K_{DX}}$. In figure 5 this ratio is plotted as a function of the damage.

<u>Total volume of material</u> - The total volume of material in the cover layer of a certain area is: Q = N.V, in which N is the number of blocks at area A and V the volume of one block. It was derived that $N = C.A.V^{-2/3}$, hence:

$$Q = C.A.V^{1/3}$$

Compared to the values for cubes: $\frac{Q_X}{Q_C} = \frac{C_X}{C_C} \cdot \left(\frac{K_{DX}}{K_{DC}}\right)^{1/3}$.

This ratio is given in figure 6.

<u>Number of blocks</u> - From the formula $N = C.A.V^{-2/3}$ it appears that the number of blocks which is required can be expressed as:

$$\frac{N_X}{N_C} = \frac{C_X}{C_C} \cdot \left(\frac{K_{DX}}{K_{DC}}\right)^{2/3} .$$

The results are shown in figure 7.

From the results it appears that besides K_D the coefficient C has a great influence on the evaluation of the various types of blocks. A relationship between C and K_D is not yet established.

A difficulty in practice is that the influence of the block weight on the costs depends on the equipment available, which is normally not known until an advanced stage of the design.

The remarkable path of the curves between 0 and 2% damage is due to the relative great increase in the value of the coefficient K_D for cubes which was found between 0 and 1% damage. The influence of accidental conditions, however, increases for very small damage, so the reliability of the results becomes less.

<u>Restriction</u> - It must be noticed that the results which are presented here are based on tests with regular waves, and for a slope of 1 : 1.33 only. Data for general application for wind generated waves and other slopes are not yet available.

DESIGN CONDITIONS

Within the scope of this paper, a restriction is made to wave conditions under direct influence of the wind. Swell is not dealt with.

In case of deep water relative to the wave heights the wave conditions to be expected at the breakwater location have to be related to the frequency of occurrance. Consequently the damage criterion has to be expressed in terms of probability. Once the probability with which a certain damage is accepted has been chosen, the accumulative wave attack corresponding with this probability must be determined.

The accumulated wave attack can be defined as the sum of all wave conditions up to and including those generated by a storm which has the frequency of oocurrence equal to the probability with which damage is accepted. This definition implies that the probability on damage is a time dependent factor due to the accumulative effect. Moreover it is known that consolidation occurs under moderate wave conditions.

For the design, by calculation of modeltests, the disposal of a representative criterion for the wave conditions including the accumulative effect is essential. Experiments have shown that the total damage, caused by wave conditions generated by successive storms, cannot be derived from the sum of the contributions of the individual wave heights since the damage is not determined by one individual wave, however, depends on the composition of the series of waves.

For instance: the highest waves in a series with a significant height H_s = 4 m and a duration of 10 hours, can be the same as in a series with H_s = 5 m during 1 or 2 hours. The damage, however, is found to be different and in general greater in the latter case. Further researoh on this point is necessary.

At present the normal testing procedure in the windflumes is, that based on the distribution curve for significant wave heights in prototype a series of tests is carried out. In each series with a selected significant wave height, the wave height distribution from nature is reproduced as good as possible. Taking into account the duration of the storms it is tried to approach the phenomena in nature. A diffioult point in this procedure remains the reproduction of the effects of high waves in the very frequently occurring series, with smaller significant wave heights, i.e. long duration of tests.

It may be noted that a decision on the probability with which damage to the structure is accepted, cannot be made without oonsidering the rate of damage, as both the investment and the costs of maintenanoe are determinative.

Moreover, when a cover layer is built up of blocks placed at random, the blocks that had an unfavourable position will be removed first, after which the struoture is stable again for the same conditions. So a slight damage may be acceptable without repairing.

The foregoing considerations will be illustrated by an example.

EXAMPLE

For the moment we assume for simplicity that the damage can be related to the individual wave height.

Considering the conditions along the Dutoh coast the frequency of occurrance of individual wave heights can be represented approximately as shown in figure 8. When the design is based on 1% damage with a probability of on the average once in 15 years the oorresponding wave height is 13.7 m. The wave height corresponding with a frequency of occurrance on the average once in 100 years is 15.6 m, so 1.18 times higher.

The various quantities, in which the values for cubes are set to 100 for once in 15 years, are as follows:

Armour units	Block weight	Total amount of material	Number of blocks	Damage with a probability of 1% per year
Cube	100	100	100	$5\frac{1}{2}$ %
Quarry-stone	123	110	90	$4\frac{1}{2}$ %
Tetrapod	95	85	86	4 %
Akmon	105	77	75	$2\frac{1}{2}$ %

The last column gives an idea about the maintenance that is required.

Based on the criterion that 2% damage is accepted (without repairing) with a probability of once in 15 years, the following results are obtained:

Armour units	Block weight	Total amount of material	Number of blocks	Damage with a probability of 1% per year
Cube	100	100	100	9 %
Quarry-stone	118	109	92	8 %
Tetrapod	91	84	92	$7\frac{1}{2}$ %
Akmon	92	74	81	$5\frac{1}{2}$ %

Needless to say that the probabilities given above are arbitrary.

BREAKWATERS WITH AKMONS

The results of the comparative tests led to the designs of some breakwaters investigated by the laboratory. At the time of these investigations the above described design procedure was not developed so far that application in details was possible. As a criterion the significant wave height with a probability of 5% per year (prototype) was chosen to effect a damage of about 1%.

For the first design this resulted in a significant wave height between 0.102 and 0.108 m with an average duration of the storm of 1.3 hours (values on model scale). In the tests the breakwater was exposed to wave attack with a gradually increasing significant wave height up to 0.108 m and more. In view of the damage criterion of 0-1% the damage was sensitive to small variations. For this reason the duration of some storms was exaggerated. The wave heights greater than 0.108 m were applied in order to get an idea about the damage during storms with a probability less than 5% per year (prototype).

In the tests the waterdepth was 0.20 m. With a slope of 1 : 1.75 and a density of the concrete of 2400 kg/m^3 the volume of the block, based on a rather safe value of K_D had to be 40.10^{-6} m^3. The wave period was 1.4 seconds.

Four series of tests were performed on a normal section and the head as given in figure 9 and 10. For illustration a review of the tests is given below:

Test 1. Normal section (figure 9).

H_{15}	duration in model	results
0.06 m	1 hour	no damage
0.078 m	1.5 hrs	no damage
0.088 m	2 hrs	no damage
0.098 m	2 hrs	1% damage to akmon layer on sea-side slope
0.104 m	2 hrs	1% damage to akmon layer on harbour-side slope due to over-topping
0.108 m	0.7 hrs	no further damage
0.112 m	2.5 hrs	damage to harbour-side slope increased to 2% of the akmon layer
0.116 m	2 hrs	damage to harbour-side slope increased to 3% of the akmon layer

During wave attacks with H_s>0.11 m, the highest waves were breaking before they reached the structure.

Test 2. Normal section.

0.06 m	1 hour	no damage
0.072 m	2 hrs	no damage
0.10 m	6 hrs	no damage
0.11 m	4 hrs	no damage

Test 3. Normal section.

0.06 m	1 hour	no damage
0.078 m	1 hour	no damage
0.098 m	2 hrs	no damage
0.104 m	4 hrs	no damage
0.11 m	1.7 hrs	damage to harbour-side slope of the akmon layer due to over-topping 2-3%

The same procedure of gradually increasing the wave height was followed by testing the head and the results can be summarized as follows: Up to 0.10 m no damage occurred. With H_{15} = 0.11 m generally no damage occurred but in one test four blocks had rolled down. With H_{15} = 0.12 m four to six blocks had rolled down and with H_{15} = 0.13 m the damage increased to about fifteen blocks. From these tests and the probability of occurrance of different wave heights, the probability that a certain damage will be caused can be estimated.

For a second design the block weight was limited because of the available equipment. On model scale the maximum block weight was 0.16 kg. The waterdepth was 0.22 m and the design wave height was given by the highest wave possible in this waterdepth as waves higher than the maximum possible wave height in this waterdepth had to be expected with a probability greater than 5% per year (prototype). So for this design the normal design procedure could not be followed and the breakwater had to be stable for the maximum wave in the waterdepth present. The wave period was 1.4 sec.

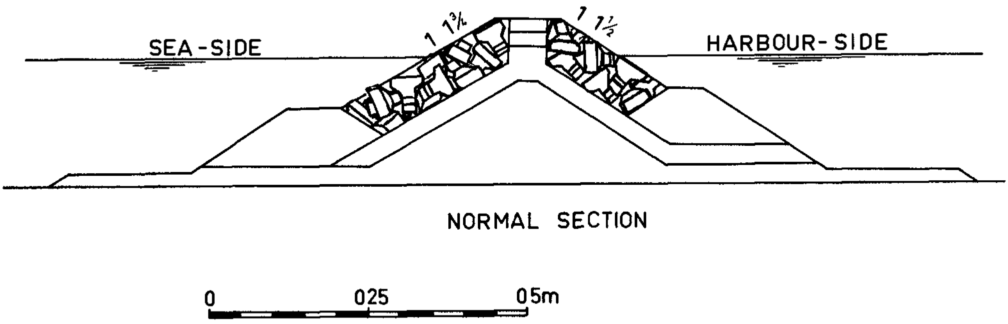

Fig. 9. Design of breakwater with akmons.

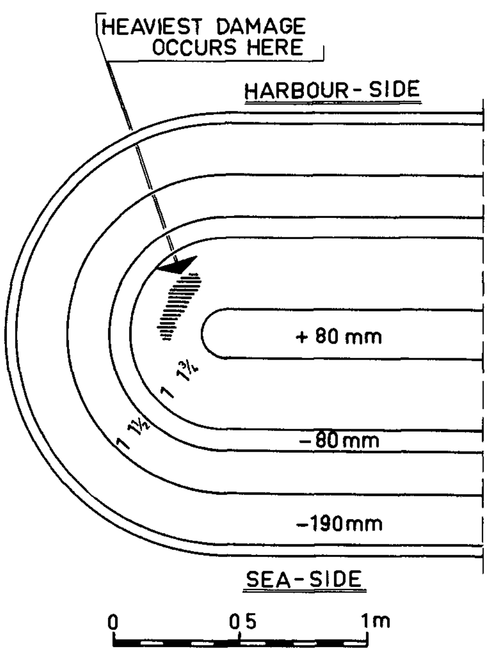

Fig. 10. Head of breakwater.

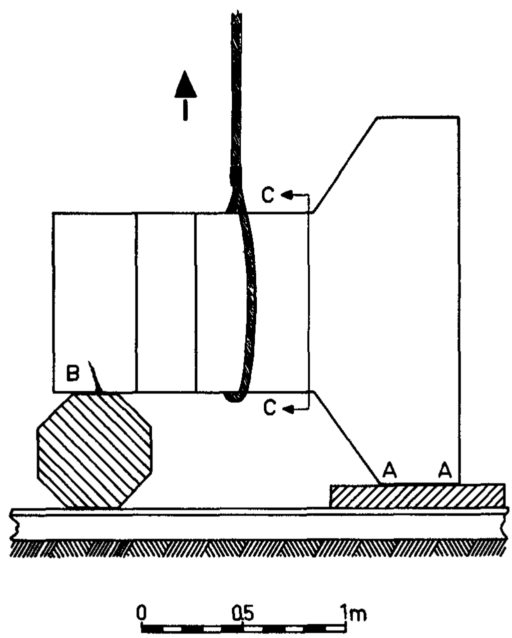

Fig. 11. Disposition of 6 ton akmon for test on mechanical strength.

With the given block weight and a density of 2450 kg/m^3 at first a slope of 1 : 1.5 was tried. Then until a significant wave height of 0.13 m no damage occurred but with 0.16 m wave height (measured in sufficient deep water at some distance from the breakwater toe) the damage was considered too much. A slope of 1 : 2 with a crest on + 0.16 m could meet the design criteria and in two tests only small acceptable damage of 0 to 2% occurred to the sea-side cover layer. Due to the limited waterdepth this damage will not be exceeded.

MECHANICAL STRENGTH OF THE AKMON

In order to get an idea about the meohanical strength of the akmons, which is important with regard to handling and plaoing of the blocks and with respect to oscillation or displacement under wave attack, tests were made on a block with a weight of 6 tons (see ref. 4).

The block was made of non-reinforoed concrete with 325 kg Portland cement per cubic metre and had a density of 2500 kg/m^3. After 24 hours the compressive strength of a test cube was 1.88 kg/mm^2.

After 5 days the strength of the block was tested by dropping it from increasing heights on a floor constructed as follows: On a bottom of sandy clay, I beams with a height of 0.15 m were placed close together. On this beams at one end a steel armour-plate, 0.10 m thick, and at the other end a reinforced concrete block, 0.5 m high, were placed, supporting the akmon (see figure 11). The block was lifted by means of a sling around the centre part and fixed to the hook of a crane which could be released suddenly, thus dropping the akmon on the armour-plate and concrete block. The damage caused to the akmon was thoroughly investigated. The results that were obtained can be summarized as follows:

Height of fall	Remarks
0.5 m	None
1 m	Slight damage to sharp angles (see A on figure 11)
1.5 m	Small crack visible at one side (see B)
2 m	Akmon broken in cross section C-C

Assuming for the moment that this single test may be considered as representative for the strength of the akmon, it may be expected that this block can withstand the forces excerted during handling and those caused by oscillation or displacement under wave attack.

CONCLUSIONS

- When designing a breakwater, the damage criterion has to be expressed in terms of probability. This criterion has to include initial damage and the damage that may possibly be of interest for maintenance.
- Once the probability with which a oertain damage is accepted has been chosen, the accumulative wave attaok corresponding

with this probability must be determined.

- Starting from the chosen damage criteria a comparison between the different block types can be made, based on economical and practical considerations.
- As a result it will appear that the akmon is one of the most suitable blocks developed up till now.
- From a test on the mechanical strength it appeared that the akmon is sufficiently strong for practical application.

ACKNOWLEDGEMENTS

The akmon was developed starting from a suggestion of Mr. J.G.H.R. Diephuis, Chief Engineer of the laboratory.

The authors wish to express their gratitude to Mr. C. Stigter who carried out part of the tests and to Mr. J.E. Prins, Chief Engineer of the laboratory for his help in compiling the report.

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PATENT

International patent applied for by the commissioners of the research, viz. "Rijkswaterstaat", The Hague and Royal Netherlands Harbour Works Co. Ltd., Amsterdam.