CHAPTER ONE HUNDRED SIXTY FIVE

Rehabilitation Methods for Damaged Breakwaters

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Abstract

A number of studies have been undertaken recently to select optimum methods for rehabilitating damaged breakwaters in the Mediterranean and in the Atlantic Ocean. This paper outlines the approach to these studies and discusses the relative merits of the various concepts considered for repairing the damaged structures. Based on case studies of two projects, the paper also shows how the principle concepts have been successfully applied.

1. Introduction

In recent years many deep-water breakwaters, protecting ports at exposed locations around the world, have exhibited damage to their armour systems or have in some cases suffered complete failure of whole sections. Studies have been carried out to define the causes of these failures and to select the most satisfactory method for rehabilitation in each case.

The optimum method for the rehabilitation of a breakwater depends on many factors which necessarily include:

- the cause of failure (inadequate design, unsatisfactory construction, or extreme environmental conditions)
- the degree and nature of the damage
- the geometry of the structure
- the local topography
- the availability of construction materials and equipment
- the acceptable level of risk to port operations or other facilities

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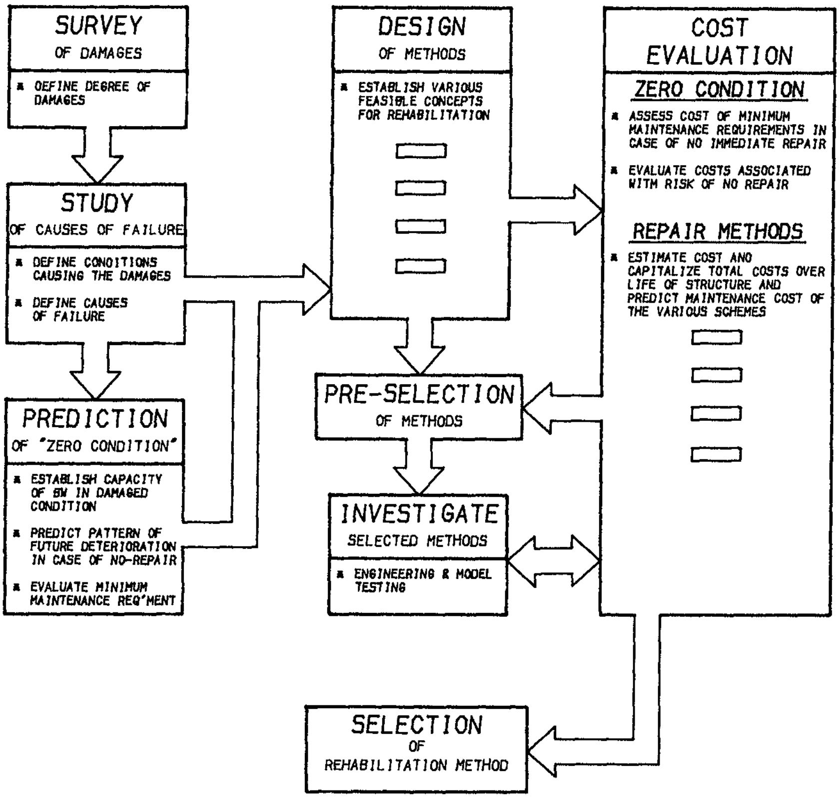


FLOW DIAGRAM

EVALUATION OF

REHABILITATION METHODS

FIGURE 1

- future requirements for port expansion or other construction works
- financial resources, cash-flow details and requirements on local and foreign elements of the rehabilitation costs

The basis for the evaluation of rehabilitation measures may be termed the "zero-condition" in which no immediate repair work is carried out. Under such a condition, the further deterioration of the breakwater is predicted and the likely additional financial burden, due to any associated restrictions in port operations or damage to other facilities, is assessed.

The general approach to a project study, in order to develop a satisfactory rehabilitation scheme, is shown in Figure 1. This indicates that the first step is to carry out a detailed survey of the historical damages to the breakwater. Wherever possible, this should be directly equated with the history of local environmental conditions. In addition, the causes of damage or failure should be determined as accurately as possible.

Together with the assessment of the "zero-condition", various feasible concepts for rehabilitation are developed, which provide possible permanent solutions. After a pre-selection the most attractive solutions are refined and optimized utilising laboratory model test studies.

The final selection of possible solutions and the "zero-condition" are then re-evaluated taking into account costs and all further relevant aspects including local availability of materials and plant and owner's cash flow policy.

This paper discusses this approach, for the study of any breakwater rehabilitation, in more detail and presents various concepts for repair. Examples of the application of the principle concepts outlined are shown, using case studies of projects along the Atlantic Coast.

2. Damage Survey and Causes of Failures

A detailed survey of a damaged breakwater is an essential element in establishing the cause or causes of the damage. The damage events are listed in Table 1. The external events which may be the direct causes of damage or failure of a breakwater are also listed.

Parallel with the breakwater survey the environmental conditions causing the damage have to be established using measurements, observations and, if necessary, hindcasting methods. In this respect, the severity of the event causing damage should be established as a matter of prime importance.

TABLE 1

DAMACE EVENTS

External Events	Minor Damages	Major Damages	Failure Damages
Water level	Scour of Foreshore	Damage Front Armour	Settlement Sliding and Overturning of Crown Wall
Waves	Erosion of Toe Filter	Damage Rear Armour	
Currents	Venting thru Breakwater	Settlement of Core and Subsoil	Erosion of Underlayers and Core
Tsunamis	Instable Front Berm	Sliding Failure of Slopes and Subsoil	Gradual Deterio-ration of Mound
Earthquake	Washing Out of fines	Erosion and up-lift of backfill	
		Breakage of Parapet wall	

This study of the extent and causes of failure should also include the comprehensive collection of data on the design and construction stages. In this respect, major aspects to be investigated include:

- quality, extent and accuracy of the design studies
- possible neglect of any failure modes
- design parameters and safety factors
- differences between the design and the as-built condition of the breakwater

The damage or failure of a breakwater is frequently due to a combination of circumstances rather than to any single factor and it is important to identify as accurately as possible the precise causes of such damage of failure. If this is not done, there is a high inherent risk that further damage or failure will occur for the same unidentified reasons.

3. Study of the "Zero-Condition"

The severeness of a damage to a breakwater may be classified between two extreme conditions which are:

a) damage of a nature which does not increase the risks of further damage/failure, and

b) critical damage which places the breakwater at serious risk to further damage/failure.

Clearly, if the nature of any damage invokes a risk of complete failure, immediate measures will be required. In certain cases, however, the risk of further deterioration of a damaged breakwater may be small and the rate of further deterioration may be low. As an example of this, it is possible that a low percentage of armour units are found to be broken due to rocking and displacement. It is even possible that conditions exist which encourage further compaction of all units (so that they are less subject to rocking and displacement) whereby the broken units continue to be part of an integrated armour system. Under such conditions, the risks of further deterioration are diminishing.

A higher percentage of broken units may create serious weak spots in the armour. The broken units will not all be interlocked with the adjacent units and may be lifted. The secondary layer of armour will then be subjected to direct exposure. Such a condition will require repair, possibly by periodic replacement of broken armour units with new units.

The predictions of future damage can be verified through simulations by model tests, but it should be noted that many factors influencing the causes of failure are difficult or impossible to model. Most scale models are only concerned with the hydraulic behaviour of the armour and with immediate erosion problems. They do not address long term problems such as the loss of fine materials of the core material.

In order to establish the zero condition as a standard of comparison for other alternatives, an evaluation should be carried out in accordance with the following scope:

- define the damages
- investigate the causes of the damages
- evaluate the effect of the damage on the causes
- make a prediction of further damages in time
- estimate the risk of complete failure of the damaged area
- investigate the effect of the complete failure on the overall function of the breakwater with respect to port operations and safety
- evaluate the costs resulting from failure of part of the breakwater with respect to restrictions in port operations and damage to other port structures.

Relevant aspects to be taken into account in the comparison with other alternatives are:

- Owner's investment plan

- Project planning concerning port expansion or reconstruction work

- Availability of construction material and plant in the area

4. Rehabilitation Methods

4.1 General

The technical feasibility of methods of rehabiliation is related to the causes of the failures encountered and the extent of the damage. With respect to the extent of the damages, a classification is given in Table 2. This table shows a classification of damages resulting from hydraulic instability of the armour system.

The correlation between the percentage of displaced units and the description of damage given is based on average conditions.

TABLE 2

Classification of Damage	Percentage of Displaced Units	Description of Damage
(i) Minor	0 - 3%	A few individual units of top layer displaced, but no gaps in top layer larger than 4 units, bottom layer intact.
(ii) Moderate	3 - 5%	No gaps in top layer larger than 6 units, slight displacements of bottom units only
(iii) Major	5 - 30%	Top layer removed over large area, bottom layer over not more than 2 units.
(iv) Total	Over 30%	Armour and underlayers removed over large area, exposure of core material.

Typical concepts for repair (Methods 1 to 4) are set out below. Their application must be considered in the light of the causes of the damage or failure encountered. Figure 2 presents a diagram illustrating applications of each of these rehabilitation concepts. Each concept is related to the degree of damage and the magnitude of the external event (expressed in period of recurrence) which caused the damage.

Minor damage to a breakwater, is generally only noticed if the condition of the breakwater is regularly inspected. If damage is found, repair and strengthening measures may be necessary to avoid the risk of initiating a chain of events which leads to a major failure. If such a risk is not expected, it may be more economic to use the zero option and leave the damage unrepaired.

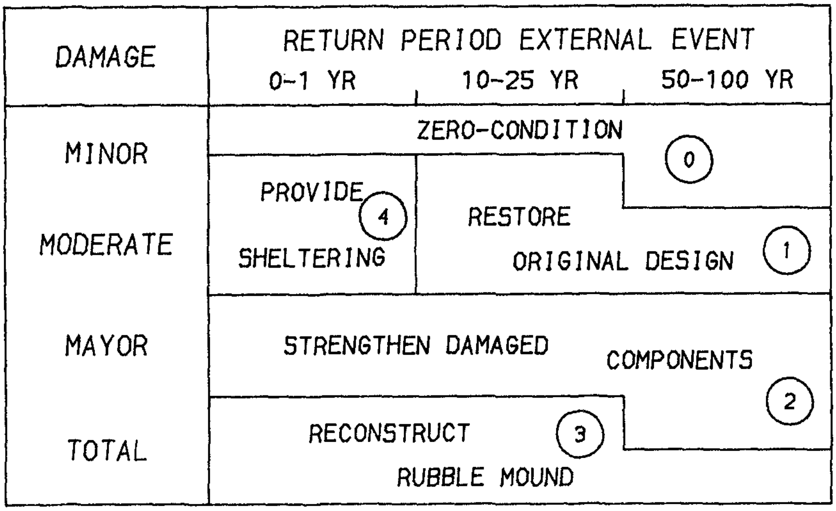


FIGURE 2

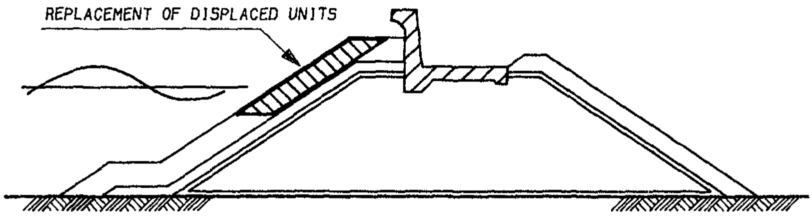
It is often difficult to strengthen individual components of a breakwater to avoid future minor damage. For example, repair is complicated if venting through the breakwater results in washing out of fine particles of the core material due to large permeability and insufficient filtering of the underlayers. In such cases the consequential risk of a major damage to the structure may be minimized by strengthening other components.

4.2 Repair by replacement of units (Method 1)

Damages classified under (i) and (ii) of Table 2 may be repaired by replacement of units of the same type and size, provided that such damage has been caused by events resembling the design conditions.

The feasibility of replacing the individual units should be considered case by case. Usually, if the units are of the interlocking type, the undamaged original units on the slope above the gap caused by the displaced damaged units, will need to be removed and replaced to provide adequate interlocking between individual elements.

Because the displaced units have most likely been removed from above or just below the water-line, the method of repair can in most cases be carried out with lifting equipment placed on the breakwater, provided that space is available. (Ref. Figure 3)



METHOD 1
FIGURE 3

If the original units were too light, it may be possible to use reinforced units of the same type. This has the advantage that the units will be heavier and give better resistance against impacts due to initial movements and rocking. The amount of reinforcing steel may however be considerable and the solution may prove expensive. Moreover, the life of the reinforced units may be shortened by corrosion of the reinforcement when seawater seeps through cracks in the concrete. Compared with other possible repair methods, the use of steel reinforcement is seldom an attractive solution.

If heavier replacement units are preferred, a slight increase in dimensions can give a considerable increase in weight. It is likely however that this method will require continuous maintenance over a long period and will only be attractive if lifting cranes and labour are readily available when maintenance works are needed. The method can be economically attractive because:

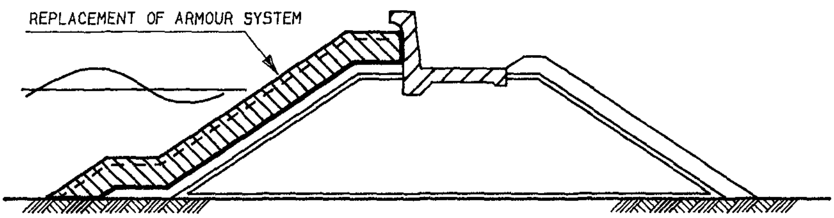
a) only those areas of the slopes and head of a breakwater, which are critically exposed, will be repaired and the areas where no damage occurs are left untouched

b) the high direct investment costs are low and those costs required for the repair are spread over a long period

4.3 Repair by replacement of Armour System (Method 2)

This method requires the replacement of the armour units by others of a different type and requires the removal of all original units. The method may be feasible if excessive maintenance to the original system is anticipated over the life of the structure, and capitalized costs of this maintenance exceed the cost of replacement. The underlaying material should suit the new armour units and must be checked for layer thickness and compaction. It may be necessary also to place a new layer of secondary armour, in which case an adjustment of the slope may be considered. (Ref. Figure 4)

This method has been applied in cases in which the original choice of armour units proved to be inadequate. In particular this may occur, regarding the structural strength of units with a sophisticated interlocking form. The original units were possibly selected because similar but smaller units proved to be successful for breakwaters in shallower water with less wave action. However, the extrapolation to deepwater breakwaters often yields unsatisfactory results because the larger units have insufficient strength.

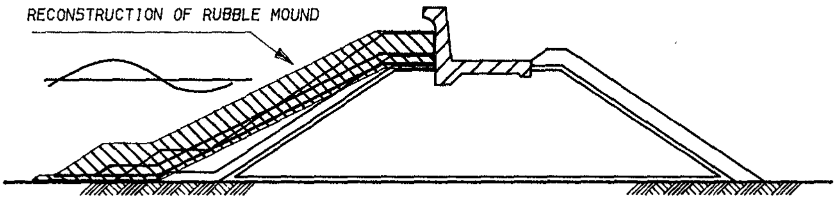


METHOD 2

FIGURE 4

4.4 Repair by reconstruction of rubble mound (Method 3)

This method involves removal of the original armour and underlayers and placement of new layers after preparation of well-compacted core material and the placement of a suitable filter between core and armour material. (Ref. Figure 5)



METHOD 3
FIGURE 5

This ultimate solution may prove necessary to overcome serious problems such as:

- geotechnical instability e.g. slopes which are too steep in relation to the internal friction of the core, the underlayer material or the sub-soil.

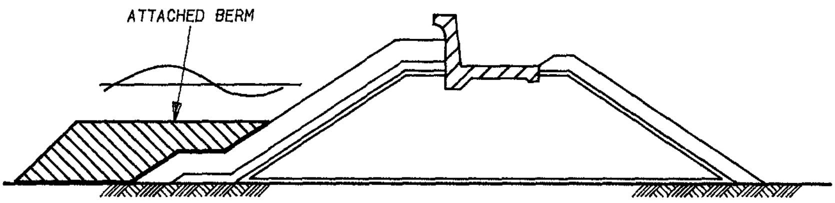
- undue settlements of prime armour and crown due to the loss of core material through the armour system, caused by a lack of adequate filters, or erosion of sub-soil material near the toe of the breakwater because of a lack of sub-soil protection.

4.5 Provision of sheltering against Critical Wave Condition (Method 4)

This method includes the following alternative solutions:

a) Provision of an Underwater Berm attached to the Breakwater:

This underwater berm should be designed to reduce the energy of the waves, which may be critical to the stability of the slope. (Ref. Figure 6)



METHOD 4 : PROVIDE FOR SHELTERING
FIGURE 6

b) Provision of a Detached Underwater Breakwater:

In this case the additional structure reduces the wave conditions in front of the damaged breakwater to an acceptable level.

It is of interest to compare the merits of the above different methods in specific cases of breakwater projects. For this purpose, two case studies are discussed in this paper.

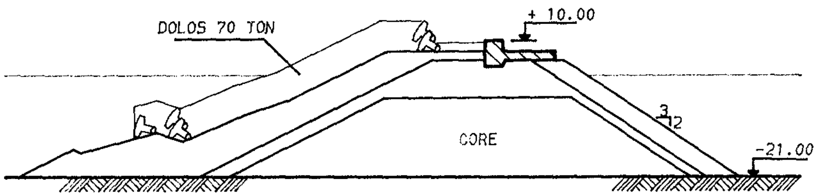
5. Case Studies

5.1 Case 1

This case study concerns a port along the Northern coast of Spain protected by two breakwaters.

The breakwaters are situated in waterdepths up to 20 m. The location is very exposed, in particular from north-westerly directions, but also from the North and occasionally from the East. Damage to the breakwaters occurred, however, under relatively quiet sea conditions. The first observations of damage were made soon after the completion of the construction of the breakwater. Damage was visually evident because armour units, which consist of 50 ton dolosse on slopes of 1:1.5 and 1:2, were broken.

Breakage of dolosse continued with time. Three years after the construction, over 3000 units were found broken, 17% of the total number of one breakwater and 25% of the total number on the other. In the areas with the greatest concentration of breakage the percentage was almost 50%. In addition, major cracks in the concrete crownwall of the South breakwater were found at several locations as a result of differential settlements.

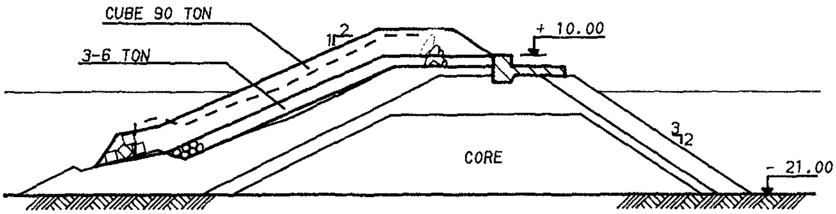


EXISTING SECTION-N.B.
FIGURE 7

A study was undertaken covering an extensive scope including a re-evaluation of the wave climate at the particular location, site investigations, investigations of the causes of failure and evaluation of possible rehabilitation of the breakwaters.

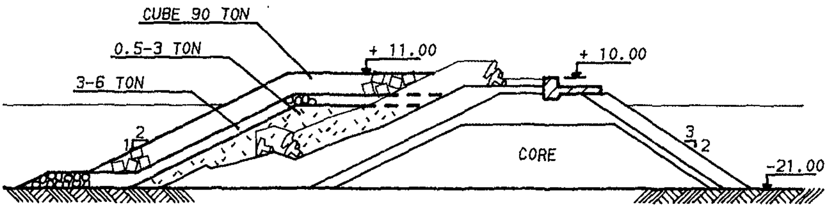
Six alternative methods for rehabilitation of the North breakwater, of which the existing section is shown in Figure 7, were studied:

(1) Removal of the existing 50 tons dolosse and replacement with a double layer of 90 ton concrete cubes placed at random. New rock armour underlayers would be placed. (Ref. Figure 8).



NEW SECTION N.B. - ALT.1
FIGURE 8

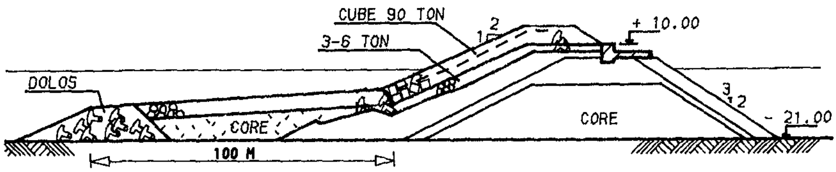
(2) Placement of a rock dike against the existing section and the voids between the dolosse would be filled with fine quarry run material or gravel whereby the existing dolosse would be left in place. Subsequently, new concrete armour similar to that considered for the first alternative would be placed over the rock dike at a slope of 1 to 2. (Ref. Figure 9).



NEW SECTION N.B. - ALT.2
FIGURE 9

(3) Installation of a berm at the toe of the breakwater to a level of about one third of the water depth whereby the dolosse would be left in place. New armour would be placed above the berm.

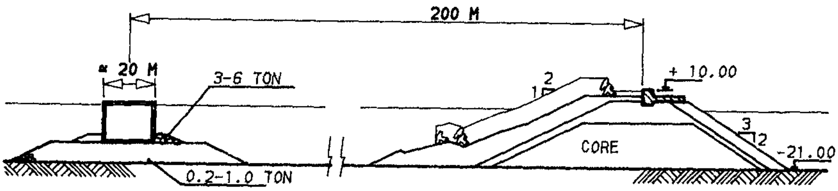
(4) Installation of a wide berm attached to the breakwater as in alternative 3, but of sufficient size to absorb wave energy and thus reduce the energy acting on the slope of the breakwater. The dolosse would be left in place, except on the breakwater slope above the berm where the dolosse would be replaced by 60 ton solid cubes where necessary. (Ref. Figure 10).



NEW SECTION N.B. - ALT.4
FIGURE 10

(5) Installation of an underwater breakwater in front of the existing breakwater at a distance sufficient to break up the waves before they reach the existing breakwater, which in principle remains unrepaired. The underwater breakwater would be designed such that the energy of the broken waves or, if unbroken, smaller waves would not cause further damage to the existing breakwater.

(6) This alternative is the same as the alternative 5 with the exception that the underwater breakwater would consist of a series of concrete caissons in lieu of a rubble mound structure. (Ref. Figure 11)



NEW SECTION N.B.-ALT.6
FIGURE 11

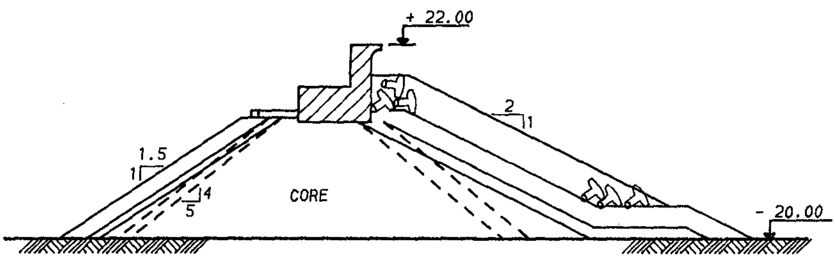
The relative costs of the various alternatives compared to the most conventional type of repair defined in Alternative 1, are 140, 165, 65, 105 and 200 percent for the alternatives 2 thru' 6 respectively. These cost indications are given for a random section of the breakwater in deeper water. The final solution for the whole of the breakwater can of course be a combination of various methods, whereby the overall costs can be optimized. Alternative 1 could be applied for the deep water section, while the dolosse removed from that deep water section could be used as berm material as per the Alternative 4 solution for those sections which are less exposed.

The cost of alternative 2, whereby the dolosse would be left in place, is relatively high despite the fact that removal is not required. An important contribution in the costs is the special provision for pumping gravel between the dolosse to ensure that the underlayer of the new armour and sublayers would be properly compacted with a porosity as required within the overall system.

The cost of the Alternative 6 is high but includes the cost for repair of the head of the breakwater in accordance with Alternative 1. This has been done because the underwater breakwater would not provide effective protection for the head.

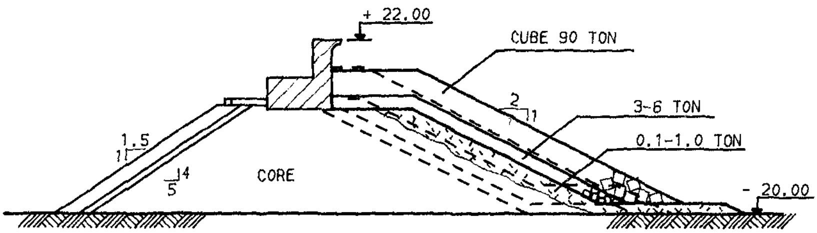
For both economical and technical reasons, the scheme finally selected for the rehabilitation of the North breakwater was in accordance with Alternative 1. The risk of exposure of the underlayers during construction, when the existing armour is removed, has been accepted.

For the rehabilitation of the South Breakwater, of which the existing cross section is shown in Figure 12, the possibilities were limited because this breakwater needed rehabilitation of the armour as well as strengthening to achieve better geotechnical stability. The alternatives considered were:



EXISTING SECTION - S.B.
FIGURE 12

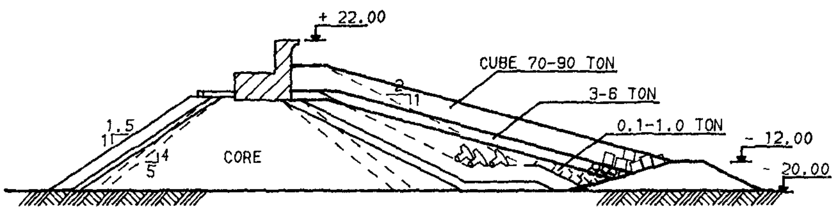
1) Removal of the dolosse and placement of filter material over the existing core material at a slope 1 to 2, placing of a new underlayer and the installation of solid block armour units in sizes varying from 50-90 ton. (See Figure 13)



NEW SECTION S.B. - ALT.1
FIGURE 13

2) A second alternative similar to the first, but with all new material placed at a slope of 1 to 3. The prime armour of block units would then be smaller than in Alternative 1. Furthermore, a berm at the toe of the seaward slope of the breakwater would be placed to a level of -12.0 m at waterdepth up to -20.0 m. (Ref. Figure 14)

The cost of the second alternative was estimated to be about 50% higher than the cost of Alternative 1. The second alternative was therefore selected for implementation.



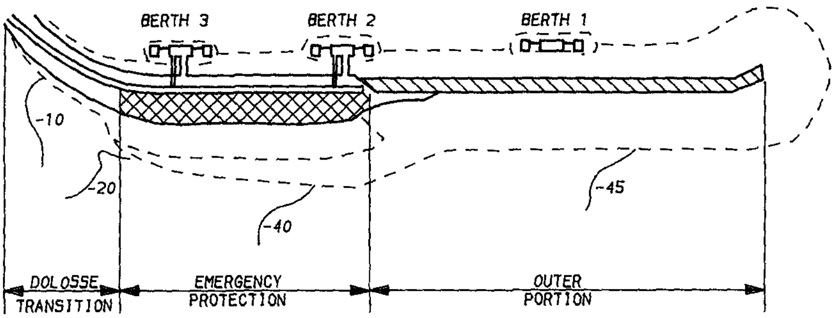
NEW SECTION S.B. - ALT.2
FIGURE 14

5.2 Case 2

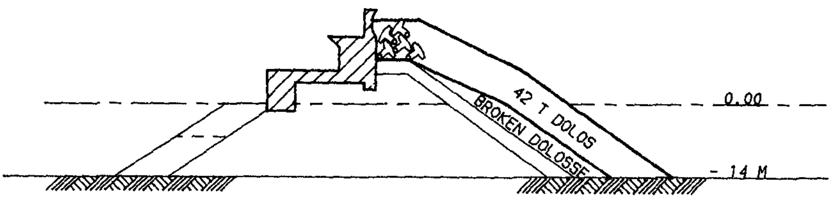
This concerns the West Breakwater of the port of Sines, Portugal, located at the Atlantic coast, which was severely damaged during two storms in the winter period of 1978-1979. Figure 15 shows the layout of the breakwater divided in three sections:

- the Section between berth 3 and the shore protected with dolosse (Figure 16)
- the Section between berths 2 and 3 previously repaired with new 90 ton Antifer type blocks (Figure 17)
- the outer portion, severly affected and at present unrepaired (Figure 18).

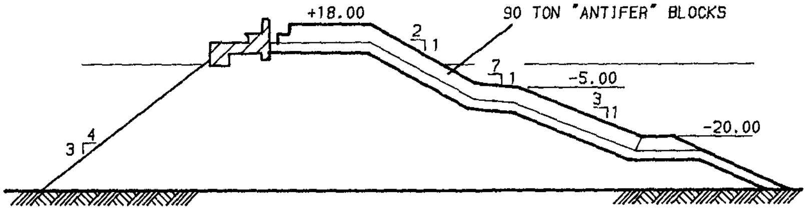
The history of the damage of the breakwater was extensively described in Reference 1. The study was commissioned to evaluate the



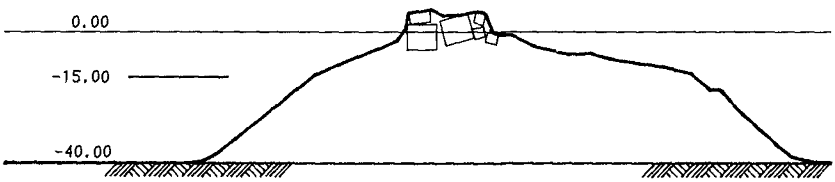
WEST BREAKWATER, SINES PORTUGAL
FIGURE 15



DOLOSSE SECTION
FIGURE 16



EMERGENCY REPAIR
FIGURE 17



OUTER PORTION, PRESENT SITUATION
FIGURE 18

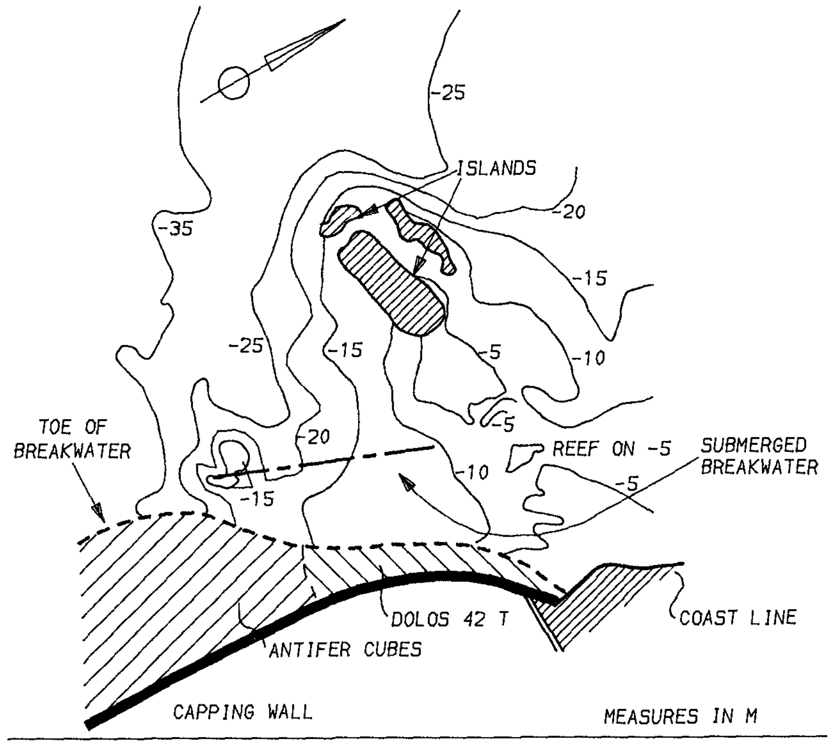
earlier repaired sections, to propose mitigating measures if necessary, and to develop a rehabilitation method for the outer portion. Preliminary results were presented in Reference 2.

The conclusions of the study were as follows:

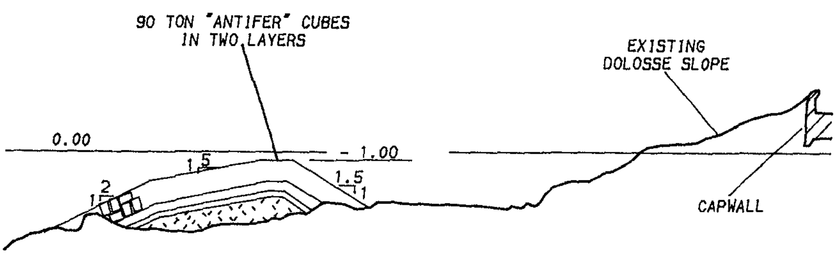
1. Close to the shore side of the breakwater the original section suffered hardly any damage. The repair should therefore be in accordance with Method 1 described above, and should be limited to replacement of new armour units where necessary. The units would then be of the same type as used in the original design.

2. The section armoured by dolosse, situated close to the previously repaired section, needed improvement. The most economic solution should involve closing the subsea trench south of the Perceveira Islands thereby eliminating the large waves which were penetrating through this trench from westerly directions. A plan and cross section are given in Figures 19 and 20.

3. The repair of the section between berths 2 and 3, where previous repairs had been made, should be in accordance with Method 2. The seaward slope should be modified by placing compact heavy cubes to a more gentle gradient.



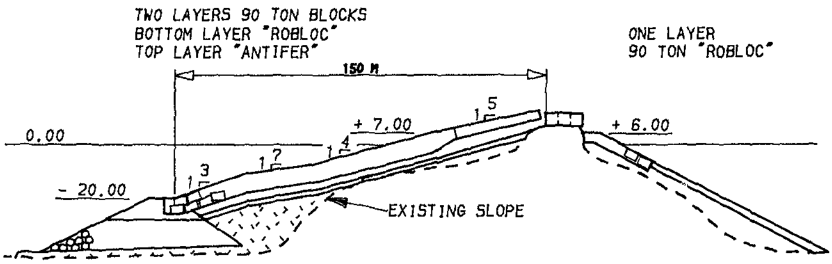
ALIGNMENT SUBMERGED BREAKWATER IN FRONT OF DOLOSSE SECTION
FIGURE 19



CROSS-SECTION IMPROVED DOLOSSE SECTION
FIGURE 20

4. The outer portion of the breakwater should be rehabilitated by constructing a new rubble mound over the damaged structure (Figure 21).

In addition, with regard to the last part of the outer portion of the breakwater, a cost-benefit analysis is currently being carried out. Indications are that full reconstruction of this part is not justifiable at present. However, to provide the necessary protection of the port, the crest level of this part of the breakwater may have to be maintained on mean sea level.



REHABILITATION OUTER PORTION
FIGURE 21

6. Conclusive Remarks

(1) Damage to a breakwater is often caused by a combination of events. Sufficient effort must be put into the rehabilitation study to recognise all causes so that the deficiencies of the breakwater can be correctly identified and satisfactory methods of rehabilitation can be selected.

(2) To provide a basis for cost comparison of any rehabilitation method, the "zero-condition" excluding repairs should be studied. This study should include the predictions of further deterioration, the analysis of the costs associated with the risk of a partial failure of the breakwater and the long-term

maintenance requirements to minimize such risks. In some cases it can be justified, technically and economically, to postpone the repair work to suit the owner's requirements or to integrate it in the construction planning of new port facilities.

(3) Simulation studies by physical or numerical models are an essential part of the overall study of a breakwater. Designers should be aware however of the limitations of such models. Overall conclusions must not be drawn from single model test results but from the interpretation of the study as a whole.

Reference:

1. A.S.C.E. "Failure of the Breakwater at Port Sines, Portugal", 1982.

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