CHAPTER ONE HUNDRED SEVENTY THREE

THE DESIGN OF BREAKWATERS USING QUARRIED STONES

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1.0 Introduction

The majority of rubble mound breakwaters built in North America that use quarried stones in their armour layer contain either one or two layers of armour stone, one or two filter layers and a core of quarry run.

Preparation of a design normally involves use of the Hudson equation and may be supported by physical model tests. Once the design wave conditions are defined the size of armour stones are only a function of the outer slope of the breakwater.

In this paper an alternative approach to the design of quarried stone breakwaters is discussed. The basic principal involved in this concept is the use of locally available materials. It is established that the greater the thickness of the armour layer, the smaller the stones that are required to provide stable protection against wave action. Therefore, the thickness of the armour layer for a specific breakwater is determined by the gradation of the available armour stones and the incident wave climate. The final cross-section makes allowance for the practical considerations of breakwater construction. New concepts for breakwaters that have resulted from the use of this alternative design procedure are described. Construction of these breakwaters in 1983-84 has demonstrated that significant cost savings are obtained.

2.0 Traditional Design

The traditional design approach is described in many texts, and in greatest detail in the U.S. Corps of Engineers Shore and Protection Manuals (4). A breakwater design that may result from the use of this procedure is shown in Figure 1.

A number of possible difficulties with the construction of this design can be identified and include the following:

- Large Armour Stones Required. At many locations the wave climate dictates (through the design formula) large stones that may be very expensive to obtain or are not available.

  In the latter case the designer must specify concrete armour units which will significantly increase the cost of the project.

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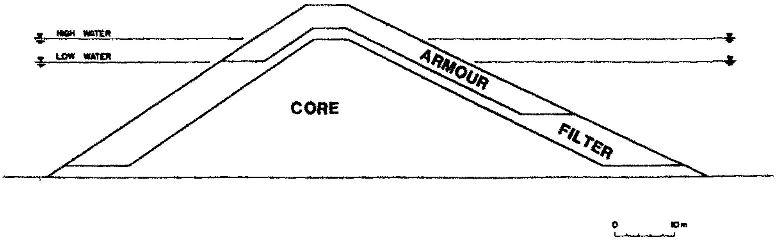

Figure 1. Example of Conventional Armour Stone Breakwater

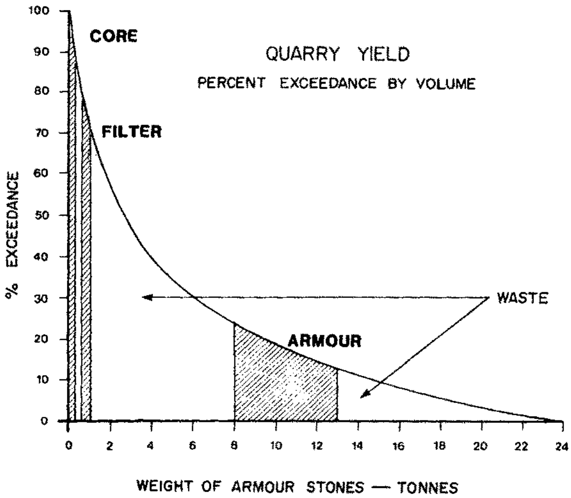

Figure 2. Quarry Yield and Stone Weights Required By Conventional Breakwater

- Wastage at the Quarry. The volume of armour and filter stones of the specified weights used may represent only a small percentage of the volume that must be quarried to obtain these stones. This problem is illustrated in Figure 2, which shows the yield of a typical quarry and the range of stone weights that can and cannot be used for a breakwater. This breakwater is designed for a significant wave height of 5 m and has a front slope of 2 horizontal to 1 vertical.

  The relative proportions of material required to build this breakwater in 12 m of water are compared to the relative proportions of the usable volumes of the quarry yield in Table 1. In this example, overproduction of armour stones will be required to produce the required volume of core material, although quite often the converse is true.

- Costly Quarry Operations. The quarry operation must be geared to produce armour stones, filter stones and core material. This may require differing blasting procedures. All other material that results from the quarried operations must be sorted and placed in a waste pile.

- Difficult to Construct. Placing continuous layers of armour and filter stones to specified tolerances for location and slope below water requires very careful supervision and inspection, which may be restricted by poor visibility. This may be very problematic in deeper water and/or at locations where there is little calm weather. Construction problems may also be associated with requirements to place core, filter and armour material in close succession to avoid damage to a partly built breakwater by wave action. The supply of materials along the breakwater can cause major logistical problems.

- Speed of Construction. The rate of placement of armour stones on a traditional breakwater is limited by crane operations, which are relatively slow.

The conventional design procedure based on the Hudson formula provides very little flexibility to the designer to overcome these problems and provide what could be a more cost effective design.

3.0 Alternative Design Approach

The basis of the design procedure described in this section is the optimization of the use of locally available material and the preparation of a design that requires relatively simple but effective construction methods.

The objective of the design process is to prepare a least cost and stable breakwater.

In order to develop the design, the following procedure is used:

i) Study the properties of locally available stones.

ii) Define the range of sizes of the locally available material, typically the gradation of curve of a quarry.

TABLE 1

COMPARISON OF RELATIVE PROPORTIONS OF MATERIAL VOLUMES REQUIRED FOR BREAKWATER TO THE USABLE QUARRY YIELD

	Percent of Breakwater Volume	Percent of Usable Quarry Yield
Armour	25	36
Filter	25	26
Core	50	38

TABLE 2

COMPARISON OF STONE SIZES POSSIBLE WITH BERM DESIGN AND CONVENTIONAL DESIGN

Design Significant Wave Height (Metres)	Range of Armour Stone In New Design (Tonnes)	Stone Weight For Conventional Design (Tonnes)	
		Slope	
		1:1.5	1:2
4	0.2 - 1.1	7.1	5.3
6	0.7 - 3.5	24	18
8	1.8 - 8.4	57	43

Note: The size of armour stones used in the proposed concept should be dictated by the yield of the local quarry and may be larger than shown. The above indicates possible lower limits that may be considered.

iii) Use the smaller fraction of the available material for the core of the structure, as illustrated in Figure 3.

iv) Use the large fraction of the available material for the armour, as illustrated in Figure 3.

v) Determine the shape and dimensions of the armour protection, which typically involves increasing the thickness of the armour layer, so that during design wave conditions, a stable structure is obtained. This activity is completed using physical hydraulic model studies. As the dimensions of the armour protection are determined, the relative sizes of core material and armour material (items iii and iv) will vary to accomodate changes in the relative percentages of armour stone and core material required.

vi) Finalize the geometry of the cross-section of the armour to allow for simple construction operations.

The design concept that has resulted from this approach contains armour stones placed in the form of a horizontal berm as illustrated in Figure 4. It is the horizontal dimension "L" that is to be determined in the model studies. This dimension is a function of the armour stone gradation and incident wave height. In Figure 4 comparison is made between a conventional breakwater and this alternative design when designed for the same wave conditions. This breakwater concept has the following features.

- The armour stones can be less than one-fifth the weight of the stones required in a conventional design, as illustrated in Table 2. However, the important point is that the concept is intended to make use of the available stones and not necessarily the use of smaller stones.

- Maximum use of quarry yield, as illustrated in Figure 3.

- Simple Design. Filter layers and toe scour protection berms are usually not required.

- The quarry operation consists only of blasting and sorting the stones into two categories (the larger fraction and the smaller fraction).

- The breakwater can be built using land based equipment only. In most cases a dump and push operation can be utilized and no crane placement is required. Plenty of room is available on the breakwater for construction roads. Wave action during construction is relatively of little concern.

- Construction tolerances can be relaxed and the requirement for extensive underwater inspection can be replaced by relatively simple surveys.

- The performance of the breakwater when subjected to waves exceeding the design condition is significantly better than the performance of a conventional structure exposed to similar conditions. The structure

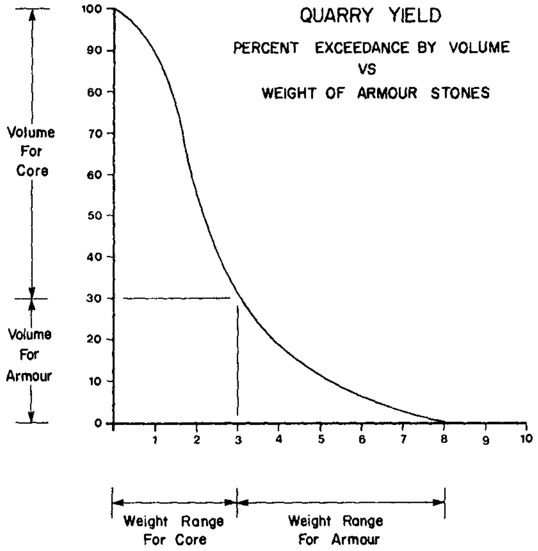

Figure 3. Quarry Yield and Stone Weights Required By Berm Breakwater

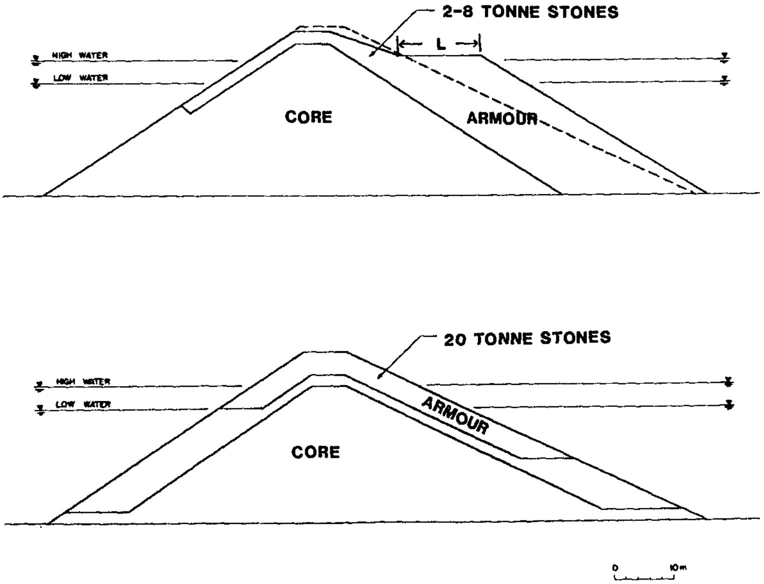

Figure 4. Example of Berm Breakwater Compared to Conventional Breakwater

will not fail in a rapid catastrophic manner.

- The total volume of the structure, compared to a conventional structure, depends on the depth of water and the size of stones available. Typically, it may be 10 to 20 per cent greater in depths of 10 to 20 metres.

- The cost of construction of this breakwater in Canada has been found to be between 50 and 70 per cent of the cost of an equivalent traditional structure.

The improved performance of the structure compared to conventional structures is achieved because of the permeable berm of armour stones that consolidates into a well 'nested' and armoured surface. In the following discussion the main armour protection, which is in the form of an armour stone berm, is referred to as the berm.

The relatively high porosity of the berm allows the waves to propagate into the armour stones and dissipate their energy over a large area within the berm. In a conventional two stone armour layer, the flow produced by the incident wave is restricted by the relatively impermeable filter and core and, consequently, there are large velocities produced by the wave uprushing or downrushing within the narrow armour layer. In the berm the flow has a larger area into which it can move and as a result localized velocities are greatly reduced thereby decreasing the external hydrodynamic forces applied to the stones. A considerable increase in stability is achieved as a consequence of this dissipation of wave energy within the permeable berm of armour stones.

The berm also increases its stability as a result of progressive wave action exceeding a threshold that will cause motion of the stones in the berm. The berm is consolidated as a result of nesting of stones and this increases the shear strength of the berm. This nesting process also results in an increase in the frictional restraint on individual stones. Depending on the size of stones available and the design wave conditions, movement of stones on the outer surface may occur to varying degrees. Movement takes place during the early stages of exposure to wave action. The stones eventually find a geometrically similar space in the berm surface into which they nest. The result of this process is a natural armouring of the outer layer of the berm. A typical armoured profile is illustrated in Figure 5, where it can be seen that the final profile has been consolidated to approximately 85 to 90 per cent of the as-placed volume.

Although the final shape of the cross-section may be similar to the 'S' shape profile reported by other investigators (3), there are several subtle differences. The berm does not change profile below a certain depth. Stones are not rolled out of the top of the berm and carried down to the seabed. The berm is consolidated because the stones that move eventually find a geometrically similar void into which they nest. Also, the profile of the berm is quite regular through the water line, typically in the order of 1:5, whereas an 'S' shaped profile tends to have a curvature to it in the region of the waterline.

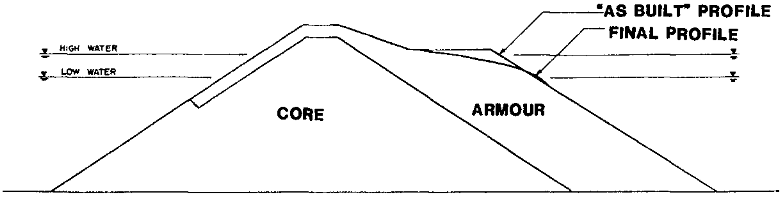

Figure 5. Profile Development on Berm Breakwater

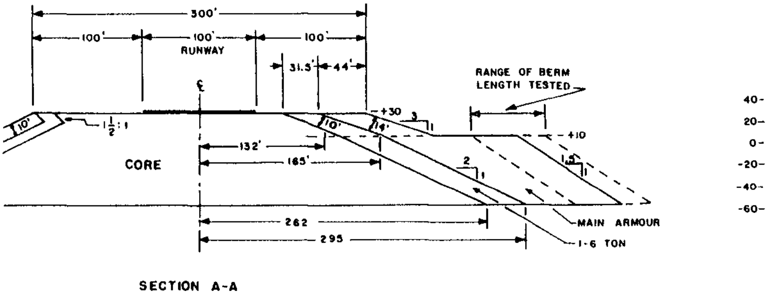

Figure 6. Cross-section of Unalaska Design

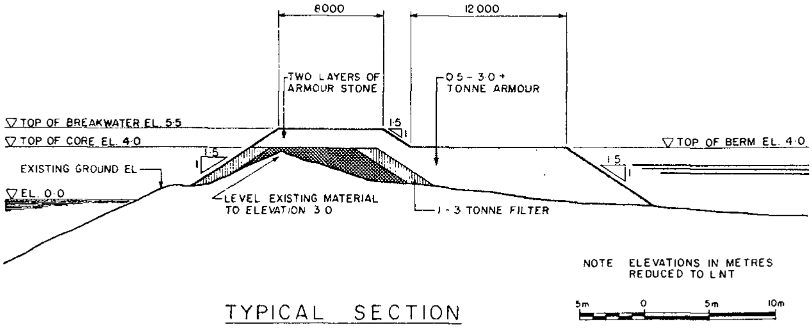

Figure 7. Cross-section of Codroy Breakwater

A formula to assist with the design of this concept of breakwater cannot be introduced because of the site specific nature of each design.

4.0 Summary of Recent Experience

In the following section some designs that have been developed are summarized.

i) Runway Extension, Unalaska, Alaska

Protection against a design significant wave height of 10.5 m was required for a runway extending into a maximum water depth of 17 m. The armour consisted of a 23 m wide berm of 3.5 to 17 tonne stones. This design is reported in references (1) and (2). The cross-section is illustrated in Figure 6.

This design was prepared for Dames & Moore, Anchorage, who were responsible to the State of Alaska for this project.

ii) Helguvik Bay, Iceland

The breakwater was designed for a significant wave height of 6 m in a water depth of 20 m. The armour consisted of a 14 m wide berm of 1.7 to 7 tonne stones.

The design was prepared for Bernard Johnson Inc. of Bethesda who were responsible to the U.S. Navy for this project.

iii) Codroy, Newfoundland

The breakwater was designed for a maximum wave height of 6.8 m. The armour consists of a 12 m wide berm of 0.5 to 4.0 tonne stones. This breakwater is illustrated in Figures 7, 8, and 9.

Construction was completed in the summer of 1984. The work was completed for the Department of Public Works of Canada.

iv) North Bay, Ontario

The breakwater is designed to protect a marina. The design significant wave height is 1.5 m and the maximum water depth is 5 m. The breakwater was built out of 2 to 750 kg stones.The breakwater is illustrated in Figure 10.

Construction was completed in the summer of 1984. The work was completed for the Department of Public Works of Canada.

v) Breakwaters in Iceland

Four breakwaters based on this concept were built in Iceland by the Harbour and Lighthouse Authority in 1983-84. Contractors were invited to bid on conventional designs as well as the berm design. The berm design was found to be significantly less expensive.

Figure 8. Codroy Breakwater After Construction. Breakwater Extends From Beach (in foreground) to an island

Figure 9. Berm of Codroy Breakwater During Construction Showing 0.5 to 4.0 Tonne Stones

5.0 Model Investigations

The designs described above, with the exception of the Icelandic Harbour and Lighthouse Authority breakwaters, were based on extensive model investigations. These studies involved in excess of sixty complete tests (simulating a full storm profile) in three dimensions using irregular waves at scales between 1:30 and 1:50, and have considered the following variables:

- stone sizes and gradations
- width of the berm
- wave attack at an angle to the breakwater
- changes in water levels
- duration of storm and storm profile
- more than one consecutive design storm
- angular and rounded stones
- crest elevation and overtopping

Verification of the prototype performance of these structures has been the subject of discussion during the review of all of these designs. Review of the literature shows that extensive prototype data describing the performance of quarried stone structures of a similar nature exist. Since the 1800's many breakwaters have been built by dumping all quarried material at the breakwater site. The breakwater at Cherbourg, France; Plymouth, England; Fishguard and Holyhead, Wales; Aldernay, Channel Islands; Port Elliot and Encounter Bay, Australia are some examples where a major part of the structure was built in this way. Extensive surveys of many of these structures exist, although difficult to obtain, and provide support to the performance of the structures observed in the model tests. The question is whether the hydraulic model studies undertaken of these site specific designs fully represent the prototype processes. Consequently, in the development of these designs the size of the model, the simulation of storm waves, and the properties of the stones were very carefully reviewed.

6.0 Conclusions

The following conclusions can be drawn:

i) The potential of quarried stones for protecting breakwaters from wave action is not realized with traditional designs.

ii) Quarried stones could be used at many locations where expensive and problematic concrete units have been used in the past.

iii) Significant cost savings compared to conventional structures can be achieved because of minimum wastage of available material, use of smaller stone sizes and simple construction methods. Cost savings of between 50 to 70 per cent of the cost of conventional structures have been achieved in Canada.

iv) Improved stability, compared to traditional designs, is achieved for wave conditions equal to, or exceeding, the design event.

v) The design for a specific project depends on the characteristics of the local quarry and the wave climate of the site.

vi) The traditional design with two layers of armour stones can be considered a special case of this more general concept.

7.0 References

1. Hall, K.R. and Baird, W.F., May 1982, "Offshore Runway Extension of Unalaska Airport, Alaska - The Development of Structures to Protect the Runway Extension From Wave Action Using a Hydraulic Model Study". Unpublished report prepared for Dames and Moore, Los Angeles.

2. Hall, K.R., Baird, W.F. and Rauw, C.I., 1983, "Development of a Wave Protection Scheme for a Proposed Offshore Runway Extension at Unalaska Airport, Alaska", Coastal Structures 83, Washington.

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4. U.S. Army Coastal Engineering Research Center, 1973. Shore Protection Manual, Volume II.

Figure 10. North Bay Breakwater During Construction. Construction Required Only Trucks and a Bulldozer