PROTOTYPE EXPERIENCE WITH RUBBLE MOUND BREAKWATERS

K.J. MacIntosh* and W.F. Baird*

ABSTRACT

At the 19th ICE Conference in Houston in 1984 an alternative concept for the design of rubble mound breakwaters was introduced. This concept has the objective of providing a least-cost structure by optimizing the use of locally available materials and utilizing simple construction procedures. Contractors' bids demonstrated that significant cost savings could be achieved, when compared to the cost of traditional designs.

Considerable prototype experience has now been obtained with this concept of breakwaters. Breakwaters have been built using the concept in Canada, the United States, and Iceland since 1984 and have been subjected to storms and ice action.

Prototype observations have supported the performance predicted during the design process. In this paper surveys of a breakwater taken after construction and after storm action are presented. In addition to wave action, this breakwater has also been subjected to extensive ice action. The response of the breakwater has been monitored and observed and is discussed.

INTRODUCTION

In 1984, Baird and Hall described an alternative procedure for designing a rubble mound breakwater. The objective of the design procedure is to maximize the use of local materials and to give consideration to construction procedures with the intent of minimizing cost.

It is useful to consider that successful rubble mound breakwater designs, providing protection from extreme storms, may extend from the use of one layer of large stones to sand beaches. Considering this "family" of breakwaters there is, of course, a point where there occurs extensive movement of the "stones" or sand grains that must be considered in the design process. However, stones at least one-fifth the weight of conventional armor stones (placed in two layers) can be used without any continuing movement of stones occurring, even at the head of the breakwater.

* W.F. Baird & Associates Coastal Engineers Ltd., 38 Antares Drive, Suite 150, Ottawa, Canada, K2E 7V2

Baird and Hall (1984) describe breakwater designs where continuing movement of stones does not occur. The designs specify armor stones significantly smaller than armor stones required for two layer conventional armor designs. Stability is achieved by increasing the width of the armor layer and through interlocking of the armor stones at the surface of the breakwater.

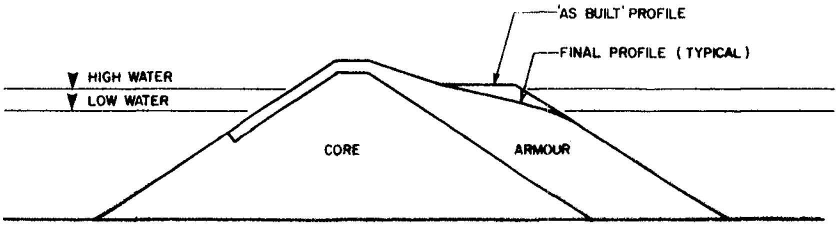
This alternate design using smaller armor stones is based on the observation that if the armor layer is built to significantly greater thickness than that of two stones, much smaller stones are required to provide stable protection against wave action. Therefore, the thickness of the armor layer for a specific breakwater is determined based on the gradation of the available armor stones and the incident wave climate.

The relatively high porosity of the mass of armor stones allows the waves to propagate amongst the stones and dissipate their energy over a large area within the wide armor layer. In a conventional two stone armor 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 armor 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 mass of armor stones.

The mass of armor stones also increases its stability as a result of wave action. Wave action causes consolidation and a resulting increase in shear strength of the mass of stones. Motion of some stones at the surface results in "nesting" of the surface stones. 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 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 armoring of the outer layer of the stones.

These designs have allowed the engineer to use the most appropriate stones for the selected location. This has allowed complete utilization of local quarries at some locations, and has allowed the use of material produced as a by-product of an existing quarry operation at another.

The basic design consists of a core, which may consist of the lower fraction of the quarry yield, and the armor, which may consist of the upper fraction of the quarry yield, as shown in Figure 1.



EXAMPLE OF BREAKWATER WITH WIDE ARMOUR LAYER (BERM)

Figure 1

Breakwaters based on this design concept have been built at a number of locations. They are summarized below.

Codroy, Newfoundland.

The breakwater was designed to use the yield of a local quarry with stones ranging from 0.5 to 4.0 tonnes. The depth limited design wave height was 6 m. Construction was completed in the fall of 1984. Although no recorded wave data exists, it is expected that the design wave conditions have occurred on more than one occasion since construction.

Iceland

Seven breakwaters have been designed using this concept, by the Icelandic Harbour Authority, since 1983.

Helguvik Bay, Iceland

The breakwater was designed to use the yield of a local quarry which provided 1.7 to 7 tonne stone. The design significant wave height was 6 m, with depths renging from 25 to 30 m. Construction began in the spring of 1986 and is expected to be completed by the fall of 1987.

Racine, Wisconsin

The breakwater was designed to use the yield of a local limestone quarry. Stone sizes ranged from 0.14 to 2.7 tonnes. The design significant wave height was 4.4 m, with depths ranging up to 7.5 m. Construction was completed in November 1986.

North Bay, Ontario

A stockpile of waste stone from a previous construction project was used as the source of material for the North Bay breakwater. Stones weighing between 4 and 250 kg (the maximum weight available) were used to construct the breakwater. The structure is located in depths up to 5 m, with a design significant wave height of 1.5 m. Construction was completed in November 1984.

The experience gained by the authors with their involvement with the design, construction and monitoring of these breakwaters is described below.

TRANSPORTATION

Restrictions and cost premiums associated with transportation of armor stones have been found to be important considerations in the design of a breakwater. Trucks and procedures for transportation also vary from location to location depending on the local construction requirements.

In Ontario, Canada, for example, highway trucks will carry stones below a certain size range (approximately 500 kg) without charging a premium. For stones larger than 1 ton, flat-beds are generally used. It is found that 2 to 5 tonne stones represent an ideal weight range where full loads can be obtained. A premium is charged for other sizes.

In Racine, highway trucks with special rock boxes were used that could carry any sized stone up to 2.7 tonnes. In North Bay it was possible to use highway trucks with regular boxes because of the smaller stone size. At other locations such as Helguvik Bay, it was possible to use off road trucks for construction of the breakwater and no restrictions or problems were encountered.

QUARRY OPERATIONS

Generally, there are two situations to consider in the design process. Either a quarry is to be operated specifically for the breakwater construction, or a product of an existing quarry operation will be used.

In either case, the weight gradation of the quarry or available quarried material is estimated and the breakwater is designed to optimize the use of these materials. Each design provides for the simple division of the quarry yield into two fractions, the armor stone and the core material.

During construction, the essential requirement is to verify that the actual gradation being obtained is similar to that assumed in the design process. Monitoring of the gradation of the armor is required with the procedure used depending on the stone weight. For relatively small stones, satisfactory results have been obtained by taking representative samples and establishing the gradation of the sample. For large stones (for example, greater than one tonne), in addition to establishing the gradation of representative samples, it is also useful to count the number of stones in selected trucks and compare this to the total weight of the load (which is measured by a weigh scale).

There will be a unique number of stones to weight ratio for any defined gradation.

Quarry operations are simple because a particular size of stone is not being selected. The armor stones may be produced by a screening process or by removal of all stones above a specified weight. Both processes have been successfully used in prototype situations as discussed below.

The North Bay breakwater design consisted of using all the stones available above 4 kg. The removal of the material less than 4 kg, completed with a grizzly operation, was required to provide sufficient voids for wave energy dissipation in the armor layer. Some difficulties occurred in developing an efficient grizzly operation; however, the problems associated with the removal of the small stones were eventually resolved. Because of the size of the breakwater and amount of stone available it was not necessary to build a core. It was more economical to build the entire breakwater cross-section of one stone gradation.

In Helguvik Bay, a quarry operation was set up on the rock bluff directly adjacent to where the breakwater is under construction. The rock was blasted and then sorted using hydraulic excavators. Then, depending on the stage of construction, the stone was trucked to an armor stock pile or trucked directly to the breakwater for placement. This efficient operation is shown in Figures 2 and 3.

PLACEMENT

Experience with armor placement has been obtained with the use of bulldozers in an essentially "dump-and-push" operation, and with cranes.

Both have been successfully used, although there is a limit to the stone weight that can be effectively moved by a bulldozer during breakwater construction. Bulldozers were used at Codroy, Racine, and North Bay for moving armor stone. With larger armor stones, such as at Helguvik, a crane operation can proceed very quickly because there is no requirement to carefully locate and place each stone in the armor layer. Contractors have found that a crane operation can easily keep up with the truck supply. If a crane operation is implemented then it is important that a well designed grab be used, appropriate for the size of stones to be handled.

Figure 2 Quarry Operation Adjacent to Breakwater Construction

Figure 3 Breakwater Construction

ARMOUR SPECIFICATIONS

The essential specifications for the armor are as follows:

1) The stones must be durable, or the durability must be known and accounted for in the design process,

2) The gradation of stone weights must be the same as that specified,

3) The voids must not be contaminated with undersized material since it is essential that the permeability of the armor be maintained.

The propagation of waves and the dissipation of their energy within the mass of armor stones is very evident and an important test of the correct construction of the armor. The propagation of waves up to the core can be seen and heard provided that the voids have not become filled with undersized material.

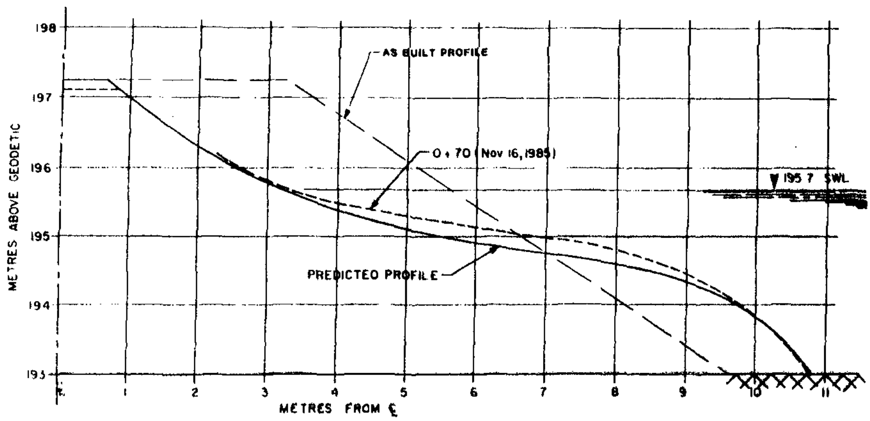
CORE SPECIFICATIONS

The core has been specified to contain any material not required for the armor. Filter layers have not been specified. In all of the very extensive model tests that have been completed (with geometric scales varying from 1:25 to 1:50), leaching of core material into the armor was not observed. However, a specification for a maximum percentage of fines, for example the percentage by weight of material less than 1kg, should be developed.

It is proposed that an appropriate percentage of allowable fines would be in the order of 30 per cent, as opposed to the 5 or 10 per cent specified for conventional breakwaters.

MONITORING

As noted in Baird and Hall, 1984, consolidation and change in the profile of the armor will occur when subjected to wave action. Prototype results from the North Bay breakwater reveal an accurate prediction of the expected profile by comparing it to the prototype profile measured after the breakwater was subjected to numerous storms. An example of the cross-section surveyed on the breakwater at North Bay, the as-built profile and the profile predicted from model test results are shown in Figure 4.



COMPARISON OF PREDICTED & MEASURED PROFILES

Figure 4

ICE

A field monitoring program of ice interaction with the North Bay breakwater was undertaken during the winter of 1984-85.

Because of the small armor stone size on the North Bay breakwater, there was concern about the effects of ice interaction with the structure. Therefore, a detailed field investigation was undertaken during the structure's first winter in service.

The objectives of this study were to:

1) Gather data on ice-breakwater interaction using surveying techniques, photography, and other general observations.

2) Determine the structure and origin of the various ice types present around the breakwater and relate the results to the meteorological data for the site.

3) Study the formation of ice and temperature profiles within the breakwater, by designing and installing an array of thermocouples (temperature sensors) to assess the extent of ice growth within the structure.

4) Analyze the collected data and develop relationships between the various parameters.

5) Provide an assessment of the ability of the breakwater to withstand interaction with ice.

The study program consisted of several measurement and observation techniques including: temperature measurements throughout the horizontal and vertical profile of the breakwater; surveys of the external profile of the breakwater structure and of the surrounding shore and ice profiles; determination of the properties and characteristics of the ice adjacent to the breakwater using crystallographic techniques; and measurement of water column temperature profiles.

In addition to the measurements noted above, visual observations were made of the modes of failure of ice on the breakwater and the relationship of water level changes to failure modes. The visual observations of ice-structure interaction were documented using field notes, photography and video recorders, as presented in MacIntosh (1985).

The investigation provided several interesting results concerning the response of the breakwater to ice action.

1) No significant ice inclusions formed within the berm due to the combination of heat provided by the lake water and insulation from the snow and ice, overlying the breakwater. Consequently, the voids within the breakwater were never filled with ice.

2) Failure and deterioration of the ice surrounding the breakwater occurred in such a manner that the ice did not move any stones from the breakwater either by plucking or by pushing. The buildup of spray ice on the surface of the breakwater was not sufficient to create any substantial loads or influence the stability of the breakwater slope.

3) The profile developed by wave action on this breakwater was advantageous in protecting the breakwater against damage from ice.

Overall, it appears that the berm type breakwater is not significantly affected by the interaction of fresh water ice with the structure. However, additional monitoring of the performance of the berm design under ice loadings, especially at other locations, is recommended. Extreme ice conditions not covered in the North Bay study may occur in the future although the ice conditions of 1984-85 were considered to be above average severity.

CONCLUSIONS

Prototype experience with rubblemound berm breakwaters has supported the performance predicted during the design process and led to the development of more efficient, cost effective construction techniques. Each berm design construction project, completed to date, has had a unique set of construction procedures. Variations in the quarry operations, transportation methods, placement of armor and core materials, and monitoring of gradations have provided a better understanding of what methods are the most beneficial in each situation. Although each breakwater construction project completed in the future will also be unique, the experience gained during the construction of the breakwaters described in this paper is extremely valuable. The application of this knowledge to both the design and construction aspects of future projects will translate into more efficient and lower cost breakwater construction projects.

REFERENCES

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