

Berm Breakwaters, Fifteen Years Experience

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Abstract

Berm breakwaters have been designed and constructed in Iceland since 1983. Over twenty rubble mound structures of the berm type have been constructed so far, fourteen were new structures, whereas the remaining six were improvements or repairs of existing breakwaters. During 1998 two berm breakwaters are being extended. Further two structures will be built every year for the next 2-3 years.

Although some of the berm structures in Iceland have already experienced the design or near to design wave conditions, only minor profile changes have been observed. Valuable experience has, however, been learned from the inspection of the reshaped profile of one structure.

The initial idea of berm breakwaters was that they should be wide voluminous structures, built of two stone classes with a wide size gradation. The Icelandic type of berm breakwaters has however been developed into a less voluminous, more stable structure, where large emphasis is put on maximising the outcome of the armour stone quarry and utilising this to the benefit to the design.

Introduction

At the Icelandic Maritime Administration (IMA) a variant of the original berm breakwater constructed of one or two stone classes has been developed. This variant can be described as “a tailor-made size graded berm” (Sigurdarson et al, 1996). The berm structure is build up of several size-graded layers. The largest stones are placed on top of the berm and some times also at its front, where they will be most effective in order to reinforce the structure, Figure 1. Smaller stones are used in the inner layers of the berm, even smaller than in the original berm breakwater, increasing the utilisation of the quarried material. The reinforcement of the berm has made it possible to reduce the berm width, which reduces the volume of the structure. The use of larger stones more narrowly graded on top and at the front of the berm has been

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proved in model tests to decrease reshaping of the berm (Sigurdarson et al, 1998). This is due to a combination of larger permeability and the ability of the structure to swallow the wave more rapidly.

Development of design process

The design process for berm breakwaters in Iceland has been developed through the years in close co-operation with all partners involved, designers, geologists, supervisors, contractors and local governments. At the same time, the designers have been directly involved in the hydraulic model studies and supervision of the construction of the breakwaters. Instead of looking at the berm as a mass of stones, the design focuses more on each unit. It has become clear that "no construction unit is as far from being standardised as the armour rock in the primary cover layer with regard to form, strength and durability" as stated by Viggoesson (1990).

Wave load and possible quarry yield

The design philosophy of berm breakwaters aims at optimising the structure with respect to wave load and possible yield from an armourstone quarry. The estimated yield from an armourstone quarry is used as an integrated part of the design process in an attempt to optimise the utilisation of the quarry.

Collaboration between designer and geologist

Close collaboration between the designer and geologist in the preparation of berm breakwater projects has been proven very effective over the years (Smarason et al, 1998). This has resulted in better designs and better use of the quarried material. This collaboration gives the designer the chance to fully utilise all rock classes from the quarry and has often resulted in 100% utilisation of the quarries. Close co-operation between the geologist, the project supervisor and the contractor is often



Figure 1. The Bolungarvik breakwater in 1995 two years after construction.

necessary to achieve maximum results in the quarry. Blasting and sorting of armourstone is by no means an easy task and slight alteration of spacing and tilt of drillholes may at times help to improve blasting results. It has to be realised that the contractor and the buyer should work as a team aiming for the same goal. Experienced contractors rely on the predicted quarry yield curves in their bidding.

The origin of the Icelandic Berm Breakwater

In the late seventies and early eighties many researchers and engineers were occupied with the idea of equilibrium slope and the importance of permeability (Bruun and Johannesson, 1976). Lessons were learned from 19th century breakwaters, like the breakwaters in Plymouth, England, and Cherbourg, France. These breakwaters were built by dumping all quarried material at the breakwater site. It was stated that when "maturing" the breakwaters might develop an S-shape.

In the early eighties the berm breakwater was introduced. For the protection of a runway extension in Unalaska, Alaska, Hall et al (1983) proposed a wide berm of one rock class, where the armour system was designed so that essentially 100% of the quarry was utilised. The stability of the armour layer was to develop during early stages of wave attack. Model tests showed that with greater thickness of the armour layer, the smaller the stones needed to be.

Gradually the ideas of berm breakwaters developed more and more to a dynamic or reshaping breakwaters. Van der Meer and Pilarczyk (1986) grouped berm breakwaters or S-shape profiles as having a stability parameter, $H_s/\Delta D_{n50}$, between 3 and 6. It became the general idea that berm breakwaters were only applicable where large stones were of limited supply. These structures were built up of a homogeneous berm of relatively small stones with wide size gradation.

The natural dynamic structure

What can we learn from nature about dynamic movements of stones? First we will look at gravel or shingle beaches and then move to larger units in rock slopes or boulder beaches.

Gravel or shingle beaches are in some places built up of stones, which are all of similar size as a result of sorting by the sea. The fines have been sorted from the shingle and are found in less exposed areas of the beach. These beaches can have a stability parameter, $H_s/\Delta D_{n50}$, in the range of 50 to 200. As a result of a uniform particle size the gravel beaches have a high permeability. They form a dynamic profile often with a rather steep slope. What happens when we try to scale up the experience from these gravel beaches?

In some places around Iceland rock slopes or boulder beaches exist. The boulder reef at Rif, Figure 2, is an example of this. The height of the reef, which is in an area of 4 m tidal difference at spring tide, is about 5 to 6 m above low water level, with front slope of about 1:4.5 to 1:8. Seen from distance this reef looks like the ideal dynamic berm breakwater. Rounded boulders of several hundreds of kilos up to 1 or 2 tonnes form the surface of the reef. The stability parameter, $H_s/\Delta D_{n50}$, is in the range 3 to 6. This natural dynamic structure looks quite permeable. But looking in-between

the boulders on the surface, smaller stones appear, some tens of kilos in weight. When they are picked up it can be seen that voids are plugged by gravel and sand. Less than 1 m from the surface of the reef all voids are filled up with small particles. The reef is a wide structure with a flat slope over low water level. The natural armouring, which can be looked at as two layers of stones, is in a dynamic action during storms. The waves are breaking on the slope causing high uprush and overtopping. But the reef is by no means a porous structure that swallows up the wave energy.



Figure 2. The boulder reef at Rif is a natural dynamic structure.

The dynamic berm breakwaters

Similar trends can be seen in the reshaped berm breakwater at Bakkafjordur in north-east Iceland (Sigurdarson et al, 1998). The berm breakwater at Bakkafjordur was built in 1983 and 1984 from stones of rather poor quality quarried at the breakwater site. Deterioration of the stones has accelerated a dynamic development of the profile. In the winter 1992/93 the breakwater is believed to have experienced waves close to the design load. The berm was eroded up to the crest and an unstable S-profile had developed. Repair took place in 1993 and in spite of the poor quality of the rock it was decided to use the local quarry again. In the autumn of 1995, the structure was exposed to the design storm. Video recordings from the storm show breaking waves in front of and on the structure, resulting in heavy overtopping. Inspection of the reshaped profile showed that deterioration of the stones had caused filling and plugging of voids and the structure did not function as a berm breakwater any longer, Figure 3. The main conclusion that can be drawn from the Bakkafjordur breakwater is that in a dynamic structure stones will break and the voids will gradually be filled up with smaller stones. This will decrease the ability of the structure to dissipate wave energy. Inspection at the site led to the conclusion that the poor quality (highly altered tholeiite basalt) of the stones in the Bakkafjordur breakwater only accelerated a development that would occur over a longer time period if it was built of better quality stones.



Figure 3. The slope of the reshaped Bakkafjordur breakwater.

The rolling stones

The first concerns regarding rock quality came up at the same time as the berm breakwater was introduced in the early eighties (Poole et al, 1983). Those concerns were from the start a part of the development of the Icelandic berm breakwater. As stated before, no construction unit is as far from being standardised as the armour rock. Usually a large portion of natural stones used in breakwater construction has some fractures or other defects. When the stones start to move or roll up and down the slope and hit each other, high abrasion and splitting of stones will occur.

The presence of fines on the reshaped slope of a berm breakwater will result in plugging and filling up of voids, and an increase in the forces acting on each rock unit on the slope. This in turn will accelerate the dynamic movements of the stones and increase their breaking and splitting.

Rocking of stones in a berm breakwater can be accepted, but not rolling. The only rolling stones that last the rock 'n' roll are The Rolling Stones them selves.

Design Procedures

When designing the Icelandic type of berm breakwater the goal is that it shall be statically stable. Some deformation of the berm is allowed under design conditions, but reshaping into an S-shape is not allowed. It is recognised that the reshaping will increase during the lifetime of the structure, because of insufficient stone quality and repeated wave action. The design approach is not to fulfil certain prescribed stability parameters, $H_s/\Delta D_{n50}$, but to look at the correlation between the armour stone quarry, size distribution and quality; the design wave, height, period and direction; water depth; function of the breakwater, for what purpose is it built, is wave overtopping a

problem or not. In many cases we have been able to design berms with a high stability of the armouring layer without any extra cost.

Design parameters

Various parameters have been proposed to describe the berm profile, like the horizontal width of the berm or the cross-sectional area of the berm from surface to bottom. These parameters are not good to compare different design. Differences in upper and lower slope can change the width parameter significantly although the structure is almost the same. Deep water / shallow water or if the berm does not extend to the sea bottom influences the area parameter very much, although the structure may function the same. The width parameter has on the other hand no information on the location of the core relative to the inner edge of the berm, which is important, as the berm can extend under the upper slope and still function to swallow up the wave energy.

In order to be able to compare different berm structures with regard to stability and overtopping two parameters have been defined that describe the thickness and the volume of the berm, Figure 4. The first parameter is the horizontal thickness of the berm from surface into the core, B , measured at design water level. In the case that the core height is lower than the berm height, the parameter is measured to the extended core slope. The other parameter, A , is the cross-sectional area of rock under and over the aforementioned line from surface into core, one wave height down and one up (1.5 wave height down could also be considered). The area is measured into the centreline of the crest structure. Both parameters are made dimensionless with wave height, B/H_s and A/H_s^2 . Design guidelines for these parameters, dependent on the stability parameter, $H_s/\Delta D_{n50}$, are under development.

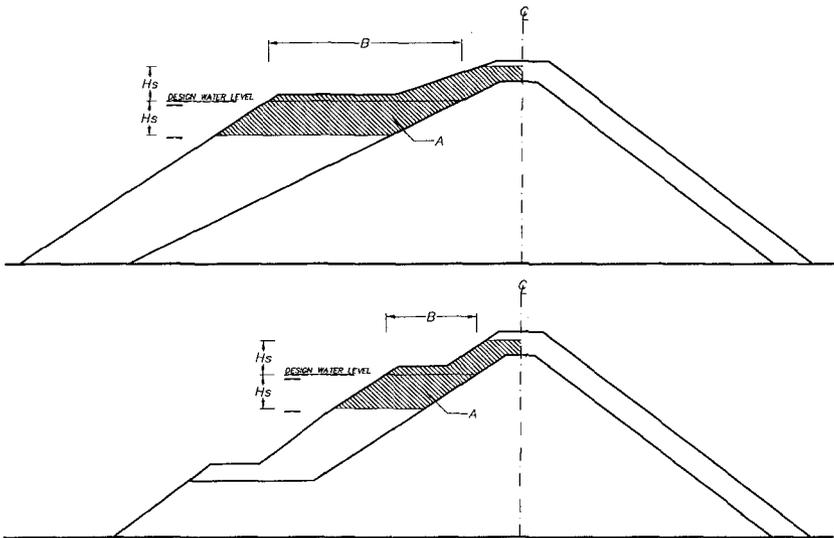


Figure 4. The parameters proposed for description of berm thickness.

Construction

A berm breakwater can be constructed using readily available land based methods and less specialised construction equipment compared to the construction of a conventional breakwater. Usual equipment comprises of a drilling rig, two or three backhoe excavators, sometimes a front loader, and some trucks, Figure 5. When the first berm breakwaters were built, bulldozers were used to push stones to the berm. That resulted in breakage of stones and too many fines that plugged the voids. Backhoe excavators with open buckets or prong, up to 75 tonnes, are used to place stones. The number of trucks depends largely on the transport distance. Tolerance for the placement of stones is greater than for the conventional breakwater design. Usually no underwater placement is necessary, as the front slope is steep. Placement of stones in a slope of 1:1.3 has been achieved down to 8 -10 m water depth.



Figure 5. From the construction of the Dalvik breakwater during the winter 1994-95.

Experience from Iceland shows that small local contractors can quickly adopt the necessary technique to construct berm breakwaters successfully (Sigurdarson et al 1997). The risk during construction is much lower and repairs are also much easier than for the conventional breakwaters. Each breakwater project is tendered out and there is competitive bidding for the works from up to 10 contractors. The lowest bid is usually accepted.

Good interlocking of carefully placed stones is advantageous at the front and the edge of the berm. Experience from many breakwater projects has shown that working with several stone classes and placement of stones only increases the construction cost insignificantly. The construction period of larger projects often extends over two years and experience has shown that partially completed berm breakwaters function well through winter storms. Repairs are much easier than for the conventional breakwaters.

Construction cost has been cut considerably in some recent projects by using dredged material, usually coarse sand and gravel, as a part of the inner core of the structure. Although the berm breakwater is constructed of several layers the advantage of using simple construction methods are still achieved. The advantage of sorting the stone mass into several stone classes to strengthen the structure is far greater than the relatively low additional cost.

Recent developments in berm breakwater design have aimed at using extra large stones (16-25 tonnes) in the more exposed parts of the structures with high wave load. The reason is twofold. Firstly, many of the better quarries are found to produce 10 to 20% of armourstones exceeding 10 tonnes in size. And secondly, heavier machines with greater capacity, like large backhoe excavators, have recently become more readily available from contractors. A relatively low percentage (1-3%) of the largest stone class can be an advantage for most breakwaters. This is not only true for these extra large stone classes but also applies to lower wave load conditions and where quarries with lower size distribution are used.

The Berm Breakwater Structure MAST Project

The design philosophy of the tailor-made size graded structure has proven to reduce deformation of the berm and at the same time lead to a less expensive structure. IMA has recently participated in a European MAST project Berm Breakwater Structure (Sigurdarson et al, 1998) and (Juhl et al, 1998). A series of model tests were carried out in a wave flume at the Danish Hydraulic Institute. The difference in reshaping of a berm breakwater constructed of two stone classes was compared with armoured Icelandic type structure. One of the conclusions of the MAST project was that the Icelandic type structures showed a reduction in erosion volume and recession of the berm compared to the original berm breakwaters. The Icelandic design with armouring on top of and at the front of the berm, allows a significant reduction in the berm width, which varies with a range of parameters as for example wave steepness, stone gradation and breakwater geometry.

Comparative Cost Analysis

Conventional rubble mound versus dynamic berm breakwater

Several studies have been published comparing conventional rubble mound breakwater to dynamic stable berm breakwater. Ligteringen et al (1992) has published a comparative evaluation of various breakwater structures for a site between the islands of Lamma and Cheung Chau in Hong Kong. The water depth ranges between 10 and 18 m. The seabed consists of 15 to 25 m thick, soft marine deposits overlying alluvium. The site is exposed to typhoon generated waves with significant wave height of about 6.0 m. A comprehensive range of breakwater and geotechnical solution has been taken into consideration. In the second stage evaluation construction cost is given for a dynamic berm and a conventional rubble mound breakwater for three breakwater layouts. The cost for the berm type ranges between 67% and 86% of the cost for the conventional rubble mound.

Hauer et al (1995) has made a detailed comparison between a conventional statically stable breakwater and a dynamically stable berm breakwater. Two types of

quarry yield curves are used, a wide curve and a steep curve. According to this study the differences depend strongly on the way the quarry yield is subdivided into different stone classes for both types of breakwaters. Overproduction of the lighter stone classes is necessary to satisfy the demand for the heaviest armour stone classes. And it is stated that the extent of this overproduction has decisive influence in the comparison of the total cost. This is in very good agreement with experience from Iceland.

They conclude that for the specific harbour layout and the specific wave conditions considered in this study the construction of the berm breakwater instead of a conventional rubble mound breakwater resulted in considerable savings. Up to 64% savings of the total cost could be achieved for transport distances from quarry to construction site of 0 to 25 km. For extremely long transport distances, 250 km, 30% savings could still be achieved

Icelandic type berm breakwater versus conventional rubble mound breakwater

First a comparative cost analysis will be presented between the Icelandic berm breakwater and the conventional rubble mound breakwater. Then the difference between the Icelandic and the dynamic approach will be discussed.

The following cost comparison is influenced by a breakwater being designed in a moderate wave climate in Iceland. The structure stands on an 11 m water depth, where the mean spring tidal difference is about 4 m. The design wave height is H_s 3.0 m with mean period of T_z 9.2 s, the mean high water spring tide is +4.0 m and the design water level is +4.7 m. A conventional cross section is designed with a front

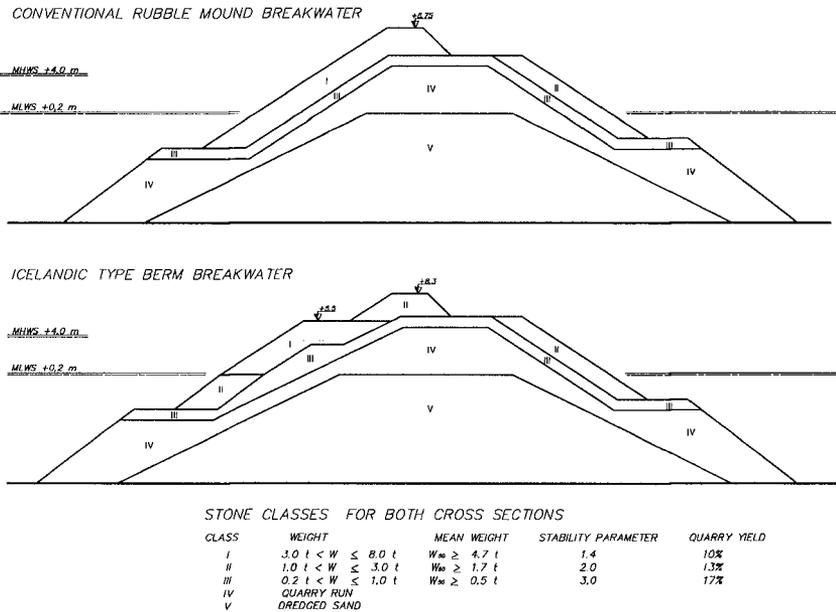


Figure 6. Cross-sections for the comparison between the conventional rubble mound breakwater and the Icelandic type berm breakwater.

slope of 1:1.5, a crest elevation of +8.75 and a toe structure at the front at -3.5 m, Figure 6. The required average mass of stone is determined according to the methods of van der Meer (1988 and 1993). Designing for damage factor $S = 2.1$, practically start of damage, storm duration of 3 hours, the mass density of the basaltic rock 2.85 tonne/m^3 , the required average mass of stone, M_{50} , is 4.7 tonne. Armour stone classes are class I, 3 to 8 tonne. The harbour side is protected by class II, 1 to 3 tonne stones and class III, 0.3 to 1, tonne stones are used as filter layer on both sides. The available armour stone quarry is expected to give about 10% in class I, 13% in class II and 17% in class III.

To make the comparison not to favourable for the berm design, the same stone size is used on top of and at front of the berm as for the armour layer on the conventional breakwater, meaning an unusually high stability for a berm breakwater, Figure 6. The harbour side of the two cross-sections is completely the same, as is the toe structure on the front side, the only difference being the front of the structures from crest down to toe.

The cost estimate is very dependent upon the distance to the quarry. In general, quarries for production of armour stones and core material are within a distance of 10 to 15 km from the construction site. If the distance to a suitable armour stone quarry is more than that, another quarry closer to the structure is usually used for production of the core material. In the calculated example, the distance from the quarry to the breakwater site is about 10 km.

It is also common to use dredged material in the inner part of the core for economical reasons. The price difference of using dredged material instead of trucking the available quarried material in the case of the conventional breakwater is about 20% per m^3 in this case. Table 1 sums up key parameters in the cost comparison.

	Conventional rubble mound breakwater	Icelandic type berm breakwater
Total volume of breakwater	801 m^3/m	846 m^3/m
Total volume of materials from quarry	398 m^3/m	414 m^3/m
Total volume of dredged sand	403 m^3/m	432 m^3/m
Total volume of rocks larger than 3 t	61 m^3/m	33 m^3/m
Total quarried material needed for production of rock	610 m^3/m	420 m^3/m
Excess quarried material	200 m^3/m	
Extra cost due to excess production	25%	
Extra cost due to larger total volume		10%
Machine needed for placing large stones	Crane 60 t	Excavator 45 t
Armour stone placing rate	30 stones/hour	60 stones/hour
Relative cost of machine per hour	2	1
Relative cost of placing armour stone	4	1
Extra cost due to placing of armour stones	10%	
Number of capable contractors	2	10
Extra cost due to limited competition	5 - 20%	
Relative total cost	130% - 150%	100%

Table 1. Comparative cost analysis between the Icelandic type berm breakwater and the conventional rubble mound breakwater.

In total there is a 15% difference in cost in producing and transporting stones and core material, 10% difference in placing the material and 5 to 20% difference in limited competition. This adds up to 30 to 50% higher cost for the conventional breakwater. Even in a moderate wave climate, the difference is this high and with higher design wave height the difference will increase. Also, a poorer quarry yield will increase this difference. Although a better quarry yield lowers the difference, the difference in placing and limited competition will still remain. This should answer the question, why we retain the berm concept, even though the structure aims at static stability with a number of different rock gradings.

Icelandic type berm breakwater versus dynamic berm breakwater

In the example above, a dynamic structure would need to be of the order of 10% more voluminous than the Icelandic berm breakwater and the dynamic berm would need at least 25% more volume of stones than the Icelandic type berm. The cost of this far exceeds the cost for sorting and placing several stone classes. The largest waste in the two-stone class berm breakwaters is twofold. Firstly, large stones are used or are lost into places where they are not needed, at large water depth or inside the structure close to the core. And secondly, the contractor is not asked to produce close to the maximum yield from the quarry.

The cost comparisons with the Icelandic type berm breakwater are not comparable with the aforementioned studies, Ligteringen et al (1992) and Hauer et al (1995), since they may rely on different assumptions.

Recent examples

The Dalvik breakwater

The Dalvik breakwater, which was constructed in 1994 and 1995, is 320 m long and has a volume of 104,000 m³. The available quarry was of good quality with predicted quarry yield of 46 to 54% over 0.3 tonne. As the wave load was moderate, the design anticipated the use of dredged material in the inner part of the core, coarse sand or gravel, up to 30% of the total volume of the structure. The dredged mound experienced a winter storm before protected with material from land, but only minor

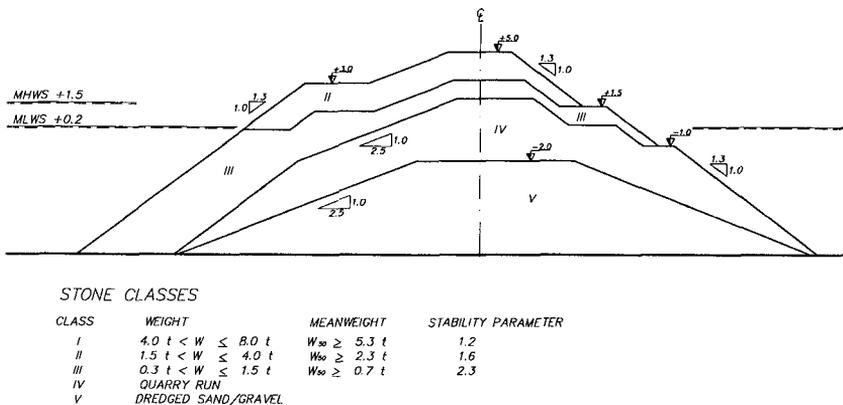


Figure 7. Cross-section of the Dalvik breakwater

deformation of the mound was measured. Figure 7 shows a cross-section of a trunk section. Class II rock, 1.5 to 4.0 tonne rock with stability parameter 1.6, covers the berm in two layers from low water level up to the crest and in one layer on the rear side. Class III rock is used between class II and the core material. The reason for class III extending down to sea bottom was that the design anticipated that all quarried material was placed with land based equipment. In order to increase the thickness of the berm around design water level a flat slope, 1:2.5, of the core is chosen. Class I rock, ≥ 4 tonne, is used on top of the berm at the breakwater head. The design fully utilises all stones over 0.3 tonne with an overproduction in both classes I and II. A 100% utilisation of all quarried material was achieved in spite of the use of dredged material.

The Husavik breakwater

The Husavik harbour located on the north east coast of Iceland is exposed to waves and swells from north-west to north-east. The outer breakwater, a concrete pier, was widened and protected from overtopping in 1989 to 1990 by a berm structure (Sigurdarson et al, 1995). Still the pier did not shelter the harbour sufficiently well and in the summer of 1997 a contractor was hired to construct a 100 m long breakwater, as an extension to the pier. Figure 8 shows a cross-section of an outer trunk section. One of the features of this design is that the front slope of the berm is more flat than usual, 1:1.5 over elevation -1.0 . This is done to increase the stability of the berm. Another feature is the location of the core in relation to the crest or the inner edge of the berm. This location aims at minimising the total volume of the structure. On the breakwater head and outer most 20 m class I rock covers the front and top of the berm, but class II rock on the rest of the structure. The upper slope, crest and back slope are on the other hand covered by class III rock, as is the front slope under -1.0 m in elevation. The inner part of the structure is built up of class IV rock. The design aims at fully utilising all rocks from the quarry over 0.5 tonne, given that the contractor produces close to the maximum quarry yield, which is 35%.

In the autumn of 1997 sudden changes in the use of the harbour became evident. This development made an alteration in the location of the breakwater

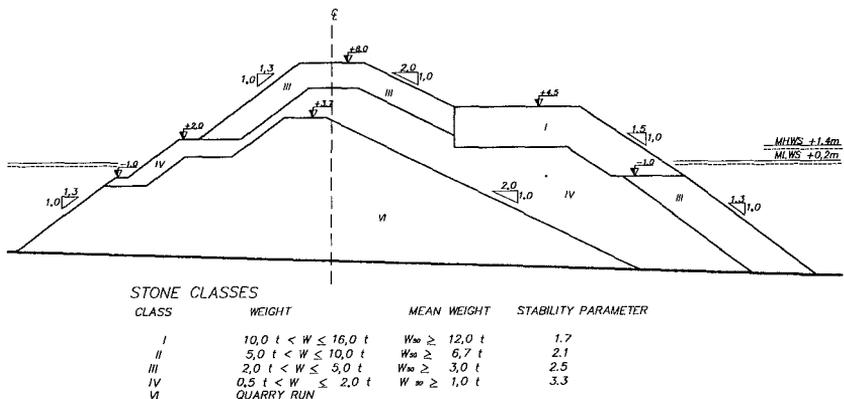


Figure 8. Cross-section of the Husavik breakwater

necessary. The new location is in a more exposed area. Since funds were not available for a full construction the contract was renegotiated so that rocks were produced and stored near the new location.

Conclusion

Instead of a dynamic approach to berm breakwater the Icelandic type aims at a more stable structure. The use of larger stones more narrowly graded on top and at the front of the berm increases the permeability and the ability of the structure to swallow the wave more rapidly.

Although the Icelandic berm requires larger stones than the dynamic type it aims at maximising the utilisation of all quarried material. And often only a small fragment of the quarried material is used to reinforce the structure. It has been proven in many projects that the Icelandic berm lowers the construction cost significantly. Large, voluminous, dynamic structures may be attractive in some special cases. It is, however, believed that the narrower, stable Icelandic berm has a much wider usage. In the dynamic approach an uncontrolled movements of stones will occur which can not be accepted, especially in the breakwater head.

Cost comparison between the Icelandic type berm breakwater versus conventional rubble mound breakwater show significant reduction in the construction cost. The Icelandic berm breakwaters have proved to withstand design or near to design wave condition with only minor profile changes, Figure 9.



Figure 9. The Bolungarvik breakwater in 1996 after having experienced the design storm lasting for at least two days in January 1995.

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