The Icelandic-type berm breakwater

Sigurdur Sigurdarson[1], Richard Mocke[2], Matt Primmer[2] and Sigurdur Gretarsson[1]
[1] IceBreak Consulting Engineers ehf, Reykjavik, Iceland; sigurdur.sig@simnet.is
[2] BMT JFA Consultants Pty Ltd, Perth, Australia

Abstract
This paper discusses the evolution of the design of the berm breakwater from the original dynamically reshaping berm and mass armoured breakwaters through to the development of the Icelandic-type berm breakwater. Experience with reshaped dynamic structures has demonstrated that the breaking and splitting of stones during the reshaping process causes voids to be filled up with smaller stones, which in turn reduces the ability of the structure to dissipate wave energy.

In contrast to dynamically reshaping berm and mass armoured breakwaters the Icelandic-type berm breakwater is designed to be statically stable with only limited reshaping. As it only allows limited stone movement on the reshaped profile it overcomes the problems of degradation and sorting of the armourstone and therefore maintains its stability and overtopping performance throughout its design life.

The Icelandic-type berm breakwater is normally designed with continuous armourstone classes, with the aim of utilising all size grades from predicted quarry yields. Armourstone classes are generally defined with stricter size grading than those presented in the Rock Manual. The key to the use of the Icelandic berm breakwater design is in its ability to match the predicted quarry yields of the potential quarries.

Keywords: berm breakwater, armourstone, quarry yield, surveying.

1. Introduction

The purpose of the paper is to introduce the Icelandic-type berm breakwater as an alternative in breakwater design. This design concept has been developed through a large number of projects where the designers have been involved at all stages, from early planning through to the ongoing monitoring of the performance of the constructed breakwaters.

The paper discusses the development of the dynamically reshaping berm and mass armoured breakwaters; from how degradation and sorting of the berm material has affected their performance to how this has been overcome in the design of the Icelandic-type berm breakwater. The paper provides a number of examples of berm breakwater projects including those of the Icelandic-type.

2. Development of Berm Breakwaters

The berm (or mass armoured) breakwater concept is not a new one but was not used extensively until the early 1980’s when it was “rediscovered” for projects with constrains on the size of local quarry materials. Since that time, many structures have been built worldwide, with nearly half of them in Iceland [13]. The primary advantage of the berm breakwater is that smaller armour stones can be used than needed for a conventional rubble mound breakwater and in many projects the full quarry yield can be utilised. Hence, the berm breakwater can be constructed with commonly available heavy construction equipment and from local quarry sites at a more economical cost.

In the late 1970’s and early 1980's many researchers and engineers were occupied with the idea of equilibrium slope and the importance of permeability [4]. Lessons were learned from the 19th century breakwaters, like the breakwaters in Plymouth, England, and Cherbourg, France, which were built by dumping all quarried material at the breakwater site. The breakwater at Mangalore, India, was also taken as an example. It was built without the benefit of heavy handling equipment using smaller size rock with a very wide berm. It was stated that when “maturing” these breakwaters might develop an S-shape. An alternative design was developed as for the Nome terminal in Alaska, where an S-profile was constructed to reduce stone size and crest height of the structure [5].

In Australia, the experience from the damage of the conventional rubble mound breakwater at Rosslyn Bay in 1976 introduced the idea of using commonly available rock sizes with the highest possible permeability. The concept of a mass armoured breakwater was defined as a rubble mound structure designed and built in an initially unstable form, but with sufficient material provided to allow natural forces to modify its shape to a stable profile [3].

In the early 1980’s the berm breakwater concept was introduced as part of a project to provide wave protection to a runway extension in Unalaska, Alaska. The proposed design used a wide berm of one stone class, essentially utilising 100% of the quarry yield [10]. The stability of the armour layer developed during early stages of wave attack. Model tests demonstrated that the required stone size could be reduced by increasing the thickness of the armour layer. The breakthrough for berm breakwaters was in 1983 when the design of the Helguvik breakwater was accepted for a NATO tanker terminal in Iceland [2]. The design, consisting of two stone classes, a wide layer of 1.7 to 7 tonnes stones and quarry run, was developed based on the expected quarry yield [1].

Gradually the research and design of berm breakwaters in many countries developed more and more towards dynamic or reshaping breakwaters. Berm breakwaters and S-shape profiles were classified as having a stability number, H_0, between 3 and 6 [19]. 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 a wide size gradation. In the mass armoured Southern breakwater at Mackay, Queensland, the gradation of the armour rock was even as wide as 30 kg to 30 tonnes [11].

A large number of the dynamic reshaping berm or mass armoured breakwaters have not performed so well. In many cases the dynamic development of the profile has both resulted in degradation of the rock armour as well as sorting of material where the larger rocks are displaced to the toe of the profile while smaller rock remain on the flat part of the slope. The degradation and sorting of material has resulted in decreased permeability, increased runup and (in some cases) unacceptable reshaping of the profile.

The Bakkafjordur berm breakwater in Iceland built in 1983-1984 is an example of a reshaping breakwater [8]. Stones of rather poor quality quarried at the breakwater site were used for the construction. Deterioration of stones on the berm accelerated the dynamic development of the profile. After a storm in 1992 the breakwater was heavily reshaped and repaired the year after by stones from the same quarry site. In 1995 the breakwater was exposed to wave conditions close to the design wave height. The berm was eroded up the crest and an unstable S-profile had developed. Video recordings show waves breaking in front of and on the breakwater. Inspection of the reshaped profile showed that deterioration of the stones had caused plugging of the voids and the structure did not function as a berm breakwater, resulting in higher forces on the slope and high wave overtopping. The year after the breakwater was repaired with two layers of large stones.

The Racine Harbour North Breakwater on Lake Michigan, Canada, constructed in 1986 is another example of a reshaping structure [12]. During the first five years after construction the breakwater was frequently exposed to severe wave action resulting in excessive reshaping of the berm profile [17]. After a series of model tests the stability of the breakwater was improved by placing large armourstones on top of the reshaped profile.

The Mackay Southern breakwater (previously mentioned) is also an example of a mass armoured breakwater that has suffered excessive reshaping during the last two years.

Experience with reshaped dynamic structures has demonstrated that when stones start to roll up and down the slope and collide, breaking and splitting of stones will occur, followed by abrasion. Voids will be filled up with smaller stones and the ability of the structure to dissipate wave energy will decrease. The degradation and the resulting filling of voids is, however, not taken into account in the hydraulic model testing.

It is interesting that although the originators of the berm concept are Canadian and some of the first structures of this kind were constructed there, the experience with reshaping berm breakwaters has halted the development and construction of berm breakwaters in Canada.

3. The Icelandic-type Berm Breakwater

Parallel to the development and research on reshaping berm breakwaters a more stable design was developed in Iceland in close cooperation between all parties involved; designers, geologists, supervisors, contractors and local governments. The designers were directly involved in establishing environmental design conditions, hydraulic model studies, writing of tender documents, managing contracts and supervision of the construction of the breakwaters. In these early berm structures the berm was built up of several stone classes, each with narrow size gradation. Interlocking was specified on top of and at the front of the berm. In contrast to the classifications referred to above, the largest stone class usually has a stability number, H_0, close to 2.0 or less. Instead of looking at the berm as a mass of stones, the design focuses more on each unit as an element of a structure.

In contrast to dynamically reshaping berm and mass armoured breakwaters the Icelandic-type berm breakwater mostly holds its form. As it only allows limited stone movement on the reshaped profile it overcomes the problem of degradation of the armour stone and filling of voids. Therefore it maintains its stability and overtopping performance throughout its design life.

The Icelandic-type berm breakwater concept has been in development over the past 27 years with nearly 40 structures being constructed worldwide for a wide range of wave climates, water depths and tidal conditions. Since the year 2000, several projects have made use of extra large armourstone, with the largest armourstone class being more than 15 to 20 tonnes, Table 1.

Table 1 Recently constructed Icelandic-type berm breakwater [16].

Project Location	Construction period	H_s	Class I	Total vol.
Sirevåg, Norway	2000–2001	7.0m	20-30t	620 Km^3
Húsavík, Iceland	2001–2002	6.8m	16-30t	270 Km^3
Grindavík, Iceland	2001–2002	5.1m	15-30t	170 Km^3
Hammerfest, Norway	2002–2003	7.5m	20-35t	3.000 Km^3
Vopnafjördur, Iceland	2003–2004	5.0m	8-28t	140 Km^3
Thorlákshöfn, Iceland	2004–2005	5.5m	8-25t	230 Km^3
Landeyjarhöfn Iceland	2008–2010	6.1m	12-30t	600 Km^3
Helguvík, extension Icel.	2008–2010	5.0m	15-25t	350 Km^3

Figure 1 Class I stones, 20-35t on top of the Icelandic-type berm of the breakwater protecting the Hammerfest LNG plant, Norway.

The Icelandic-type berm breakwater is built up of several narrowly graded armour classes with the larger armour classes placed at the most exposed locations within the breakwater cross section. These narrowly graded armour classes have a higher porosity than wider graded armour classes and therefore higher permeability, which increases the stability of the structure and decreases both the overtopping and reflection from the structure.

The low overtopping potential of the structure has been demonstrated both in hydraulic model tests as well as in prototype. The necessity to minimise wave overtopping in Icelandic fishing harbours is high as the berths are often located just behind the breakwater. Several breakwaters with berth structures on their inner side and suffering large wave overtopping have been protected by the Icelandic-type berm structures, which have proven to be very effective in reducing overtopping. Physical model tests have confirmed the advantages of the Icelandic berm breakwater compared to the conventional rubble mound structures [18].

An Icelandic-type berm breakwater structure was chosen to protect the Hammerfest LNG plant in northern Norway partly due to low overtopping requirements. The plant is located in sub-polar region where icing from accumulation of frozen sea spray may represent significant difficulties for the plant structures. Wave overtopping was therefore an important factor in the choice of a wave protecting structure, [15].

The berm concept has been proven to successfully increase navigational safety for narrow entrances with heavy breaking waves due to decreased reflection, compared to conventional breakwaters.

Figure 2 The Icelandic-type berm structure protecting the Hammerfest LNG plant, Norway. The porous high berm protects the rather vulnerable plant against overtopping and sea spray icing in arctic environment.

4. PIANC classification of berm breakwaters

PIANC (2003) classifies berm breakwaters in three categories based on the stability parameters $H_0=H_s/\Delta D_{n50}$ and $H_0T_{0m}=T_m(g/D_{50})^{0.5}$, see Table 2. In the first category, only few stones are allowed to move similar to a conventional rubble-mound breakwater. In the second category the profile is allowed to reshape into a profile, which is stable and where the individual stones are also stable. In the third category the profile reshapes into a stable profile, but the individual stones may move up and down the slope.

The Icelandic-type berm breakwater falls into either of the categories *Statically stable non-reshaped berm breakwater* or *Statically stable reshaped berm breakwater*.

Table 2 Classification of berm breakwaters based on the stability parameters H_0 and H_0T_{0m} according to [13].

Type of breakwater	H_0	H_0T_{0m}
Statically stable non-reshaped berm breakwater	< 1.5-2	< 20-40
Statically stable reshaped berm breakwater	1.5-2.7	40-70
Dynamically stable reshaped berm breakwater	>2.7	>70

5. Availability of large armourstone

Quarry yield prediction has played an important role in the design phase of harbour breakwater projects in Iceland since the early 1980's. The prediction is based on analysing drilled cores from the potential rock mass. It has proven to be a valuable part of the design process in preparation for successful breakwater projects. Preliminary designs are based on initial size distribution estimates from potential quarries, and the final design is tailored to fit the selected quarry. Quarry selection is a process which aims to provide rocks best suited to the wave conditions of the construction site and at the same time to minimise transport costs and environmental disturbance.

Often the owner/designer has to rely on the contractor or quarry operator for information on the maximum quarry yield or the size of the largest stones obtainable from the quarry. These estimates are very often biased by the size of equipment the contractor/quarry operator has available.

Dedicated armourstone production is not common and therefore there are not many contractors who have much experience in this field. Guidelines for blasting for armour stones are insufficient and only a few contractors have much experience in drilling and blasting for breakwater construction. It is therefore important that the supervision team has the expertise to supervise the quarry management.

The availability of armourstone is a very important aspect in the planning and design of breakwater projects. This is particularly true for the design of the Icelandic-type berm breakwater where the information on the availability of large armourstone is regarded as equally important as the information on the wave loads the structure will be exposed to.

In many countries rock armour quarries only yield up to 6 to 8 tonnes armourstone and rarely 20 tonnes armourstone.

Recent guidance and literature, [6] [7], has highlighted that variable yield results from armourstone quarrying can be improved by a number of important measures. Recent cases, [15], illustrate that unlike blasting associated with aggregates and mining operations, optimisation of the extraction process has to have a focus on the potential for production of large blocks for armourstone right from the outset of the quarry development.

Large armour stones will not be available from the blasting pile unless it is properly planned and the contractor is executing blasting and other production activities appropriately, typically with the technical assistance of the design/supervision team and others with experience in producing large armourstone.

As a result, and in line with the recognised guidelines [7], it is recommend that a range of measures be adopted in addition to standard practice to ensure that the risk of lower than expected yield is managed, including:

- experienced blast designers with demonstrated and suitable armourstone production techniques;
- well-trained inspectors familiar with blasting procedures, stone quality, and stone inspection techniques employed on site;
- qualified personnel with armourstone production experience, including a geologist who should monitor and modify blast planning to maintain yield predictions; and
- Client Superintendent's team should also include qualified personnel with large armourstone production experience.

Measures such as the above and the use of contractors experienced in large armour production and construction of large rubble mound breakwaters during the procurement and construction phases, will minimise the risks associated with armour size reduction during quarrying and handling.

6. Rock armour specifications

For practical reasons, rock armour specifications used for the construction of Icelandic-type berm breakwaters are different from those used for conventional rubble mound structures. This section discusses the reasons for these differences.

6.1. Projects in volume not mass

Projects involving the Icelandic-type berm breakwater differ in two main ways from many rubble mound breakwater projects. Firstly, they are usually based on volume of different armourstone classes rather than mass. This has consequences on the quantification. Secondly, the definition of the armourstone classes is different than advocated by [6] and [9].

The Icelandic-type berm breakwater has developed through projects with a dedicated armourstone quarry usually operated by the contractor constructing the breakwater. The projects are typically based on volume rather than mass and generally require the use of survey methods to define the rock surface. This is in contrast to [6] where the main focus is on defining layer thicknesses and bulk mass densities as the projects are usually based on mass.

A common definition of the theoretical surface in North Atlantic: "The rock surface shall be defined as the plane through which armour stones protrude by one third of the surface area".

Figure 3 Narrowly graded stones on the Husavik berm breakwater, Iceland. Classes I and II, 16-30 and 10-16 tonnes. The photo clearly demonstrates the need to have a clear definition of the rock surface.

Figure 4 The Sirevåg berm breakwater, Norway, final inspection of the 20-30 tonnes Class I on berm.

6.2. Survey methods for rock armour

Several survey methods exist for rubble-mound structures, like the highest points method, spherical foot staff and conventional staff placed at recommended regular intervals.

In recent Icelandic-type berm breakwater projects some with armourstone classes in the order of 15 to 35 tonnes, the profile measurement has been performed with a GPS staff measuring on the top of the armour stones. The theoretical rock surface is then defined as a factor times the nominal diameter below the measured surface. This factor is determined at the start of placement on test panels.

Figure 5 Surveying with a GPS staff of the Class I stones, 16 to 30 tonnes, of the berm at trunk and head sections before building the crest structure of the Husavik berm breakwater, Iceland.

Figure 6 The Hammerfest breakwater, Norway, inspection survey with a GPS staff of the 20 -35 tonnes Class I stone of the unfinished berm.

6.3. Continuous armourstone classes

The Icelandic-type berm breakwater is normally designed with continuous armourstone classes, with the aim of utilising all size grades from predicted quarry yields. Armourstone classes are generally defined with stricter size grading than those presented in [6] [9]. The key to the use of the Icelandic berm breakwater design is in its ability to match the predicted quarry yields of the potential quarries. Full utilisation of all size grades from 0.5 or 1.0 tonne up to 25, 30 or 35 tonnes, has been achieved in many projects, both small and large. This has been possible through reliable quarry yield prediction.

7. Performance of the Icelandic-type berm breakwater

As stated earlier, the design of the Icelandic-type berm breakwater has been in development over the past 27 years. Of the nearly 40 structures, except for a few of the earliest structures, all have performed very well. Many of the structures have experienced wave loads close to or even exceeding the design wave conditions. After two design storms the profile reshaping of the Sirevåg breakwater is within the design criteria [14], [16].

Recently the latest development of an Icelandic-type berm breakwater involved a particularly tough testing programme including multiple 100 year return period wave conditions with profile reshaping fulfilling strict design criteria. The breakwater also survived a number of overload conditions without being reshaped to an extent that would threaten the stability of the structure.

Figure 7 Excavator placing Class I 16-30 tonnes stones on the head of the Husavik berm breakwater, Iceland.

8. Summary

The Icelandic-type berm breakwater concept has been in development over the past 27 years through research and prototype experience. Nearly 40 structures have been constructed worldwide in a wide range of wave climates, water depths and tidal conditions In recent laboratory studies the design of the front face has been further optimised to provide increased stability.

The availability of armourstone is a very important aspect in the planning and design and quarry yield prediction is an integrated part of the design process for the Icelandic-type berm breakwater. This has enabled the use of extra large armourstone, with the largest armourstone class being more than 20 tonnes. The use of the Icelandic-type berm breakwater has proven to be an economically feasible solution in many projects.

9. References

[1] Baird, W.F and Hall, K.R. (1984). The Design of Breakwaters using Quarried Stones, in *Proc 19th Intern. Conference on Coastal Engineering*, pp 2580-2591.

[2] Baird, W.F. and Woodrow, K. (1987). The Development of a Design for a Breakwater at Keflavik, Iceland in Willis, Baird and Magoon (Eds), *Berm Breakwaters: Unconv. Rubble-Mound Brkw.* pp 138-146.

[3] Bremner, W., Harper B.A. and Foster, D.N. (1987). The Design and Construction of a Mass Armoured Breakwater at Hay Point, Australia. In: Willis, Baird and Magoon (Eds), *Berm Breakwaters: Unconventional Rubble-Mound Breakwaters.* pp 147-218.

[4] Bruun, P. and Johannesson, P. (1976). Parameters Affecting the Stability of Rubble Mounds. *J. Waterways, Port, Coastal and Ocean Eng*, 102(2), pp 141-164.

[5] Bruun, P. (1985). *Design and Construction of Mounds for Breakwaters and Coastal Protection* Elsevier.

[6] CIRIA, CUR, CETMEF, (2007). *The Rock Manual. – The use of rock hydraulic engineering*. CIRIA C683.

[7] Coastal Engineering Research Centre (2006). *Coastal Engineering Manual*, Report No. EM 1110-2-1100, USACE

[8] Einarsson, S., Sigurdarson, S., Viggósson, G., Smárason, O.B., and Arnorsson J. (2002) Berm Breakwaters – Design Construction and Monitoring. In: *Breakwaters'99. Int. Symp. on Monitoring Breakwaters.*

[9] EN 13383: (2002). Armourstone – Part 1: Specification, Part 2: Test methods

[10] Hall, K.R., Baird, W.F. and Rauw, C.I. (1983). Development of a wave protection scheme for a proposed offshore runway extension, *Proceedings of Coastal Structures 83*, ASCE, pp 157-170.

[11] Johnson, R.A; McIntyre, P.T and Hooper, G. (1999). Mackay Small Craft Harbour Breakwater a Case Study in Reshaping Berm Breakwaters In: *Coasts & Ports '99: Proc. 14th Australasian Coastal and Ocean Engineering. Conference*, p.298-303

[12] Montgomery, R.J., Hofmeister, G.J. and Baird, W.F. (1987) Implementation and performance of berm breakwater design at Racine, WI. In: *Berm Breakwaters: Unconventional Rubble-Mound Breakwaters*. Ed. D.H. Willis, W.F. Baird and O.T. Magoon. ASCE, pp 230-249.

[13] PIANC (2003). State-of-the-Art of Designing and Constructing Berm Breakwaters. WG40.

[14] Sigurdarson, S., Jacobsen, Smarason, Bjordal, Viggosson, Urrang and Torum, (2003) Sirevåg Berm Breakwater, design, construction and experience after design storm. In: *Proc. Coastal Structures 2003*, ASCE.

[15] Sigurdarson, S., Loftsson, A., Lothe, A.E., Bjertness, E. and Smarason, O.B. (2005) Berm Breakwater Protection for the Hammerfest LNG Plant in Norway - Design and Construction. *Proc. of Coastlines, Structures and Breakwaters 2005*, ed. N.W.H. Allsop, Thomas Telford, ICE, London, pp.349-362.

[16] Sigurdarson, S., Mocke, R., Smarason, O, Carlton, B. and Allsop, W., (2009). Development of an Icelandic-type berm breakwater for the Oakajee port project in Western Australia, In: *Coasts, Marine Structures and Breakwaters 2009*, Edinburgh, ICE.

[17] Sigurdarson, S., Viggosson, G. and Smarason, O.B. (2005). Berm Breakwaters. Appendix 2 to Advances in the Design and Construction of Coastal Structures by I. J. Losada. In P Bruun, ed. *Port and Coastal Engineering – Developments in Science and Technology*, Journal of Coastal Research Special Issue No. 46.

[18] Sigurdarson, S., Viggosson G. Benediktsson, S. and Smarason O.B. (1996). Berm Breakwaters, Tailor-Made Size Graded Structure. In: Proc. *11th Harbour Congress, Antwerpen*.

[19] Van der Meer, J.W. and Pilarczyk, K.W. (1986). Dynamic stability of rock slopes and gravel beaches. *Proc. 20th ICCE*, Taipei.