Design Considerations of Berm Breakwaters

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Abstract

The paper describes the ongoing development of design philosophy of stable berm breakwaters, which aims at minimum movement of armour rocks on the berm, taking into account the armour rock quality.

The general method for designing an Icelandic type berm breakwater is to tailor-make the structure around design wave load, possible quarry yield, available equipment and required functions. The present authors design many breakwaters each year and for low design wave height, Hs< 2.5 to 3 m, usually conventional design is chosen, but berm breakwaters for heigher wave heights. The availability of large rock is examined with the aim of finding a quarry giving over 15 to 20% of produced rock with stability parameter, Ho, below 3.0.

Berm Breakwaters

Various types of rubble mound breakwaters can be grouped as berm breakwaters. Some of the names that have been used to describe these structures include naturally armouring breakwaters, dynamically stable breakwaters, reshaping berm breakwaters, S-shape breakwaters, mass armoured breakwaters, statically stable berm breakwaters and multi layer berm breakwaters. Basically berm breakwaters have developed into two directions. On one hand are the dynamic structures built of few stone classes, usually only two, core material and berm stones. On the other hand are the more stable structures, some times referred to as Icelandic type berm breakwaters, built of several stone classes with the aim of optimising the yield of an armour stone quarry.

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In 1998 a PIANC Working Group was established with the aim of writing guidelines for the design of berm breakwaters. A part of this work has been to gather information on constructed berm breakwaters around the world, Table 1. Berm breakwaters may have many forerunners but in this list only structures built after the introduction of the berm concept, (Hall et al., 1983), are listed. The Icelandic berm breakwaters constitute 50% of constructed berm breakwaters in the world.

Table 1. A list of constructed berm breakwaters

Country	Number of constructed BB	Construction finished of the first BB
Iceland	27	1984
Canada	5	1984
USA	4	1984
Australia	4	1986
Brazil	2	1990
Norway	4	1991
Faeroe Islands	1	1992
Iran	5	1996
Madeira	1	1996
China	1	1999
Total number	54	

Design Philosophy

The aim of the design of a berm breakwater is to construct a berm with high wave energy absorption, to minimise wave reflection from the trunk and especially from the breakwater head for navigational reasons and to minimise wave overtopping during its live time. To fulfil these criteria the berm has to be stable. Therefore the berm of the Icelandic type berm breakwater is made of narrow graded stones in several classes with armour cover made of the largest possible stones available from the selected quarry. The void volume of the berm is large with porosity of up to 40%. The wave energy is dissipated in the berm and the bulk flow velocity and wave forces are lower. As the berm is statically stable the abrasion and breaking of the stones due to movements is minimised. Thus giving the structure a longer service live. This means that the idea of a dynamically stable structure is abandoned in favour of the stable Icelandic type berm breakwater (Sigurdarson et al. 1998a).

On the other hand Torum et al. (1999) have introduced new test method for evaluating the strength of the stones in relation to the impact energies a rolling stone on a dynamic berm may encounter. The purpose is to develop methods to estimate the suitability of specific quarries for dynamic berm breakwaters.

The Icelandic fishing harbours are small but they have to withstand one of the most severe wave environments in the world. As berths are often located just behind the breakwater it is necessary to minimise the wave penetration into the harbours and the wave overtopping. The berm concept has proven to be a successful solution for navigational safety for small entrances with heavy breaking waves due to little reflection and low overtopping compared with conventional breakwaters. A berm breakwater of the Icelandic type has been constructed on a weak soil foundation, consisting of more than 20 m of soft soil (Sigurdarson et al., 1999). In spite of a total settlement of close to 4 m in some areas, about 2 m more than predicted, it was easy to adopt the berm design to this changed situation during construction.

Valuable experience has been gathered through monitoring and inspection of berm breakwaters (Einarsson et al., 1999). Throughout the lifetime of the structure visual observation and recording is the most efficient and economical monitoring method. To evaluate the functional criteria of the structure, observation during storm situation is vitally important. Video recording by local harbour authorities are used to document this observation.

Damage Criterion, Design Parameters

The design criteria for rubble mound structures has developed considerably over the past 30 years, from being 5% damage for 25 to 50 year design return period, to the present of ca. 0 - 2% damage for 100 year design return period as a structural failure is no longer accepted. The increased demands to functional and technical criteria of the structures has led to much stricter criteria for the design of the berm thanks to the increased knowledge on design wave conditions, the strength and durability of rocks, possible quarry yields and the construction methods.

The stability number of a conventional rubble mound breakwater is related to damage on the armour layer. Van der Meer (1988) defined the damage level, S, as the erosion area around still water level divided by the nominal diameter of the stones in second power, where S = 2-3 equals start of damage. Generally the actual number of stones eroded in a D_{n50} wide strip is equal to 0.7 to 1 times the damage S. This means that start of damage equals erosion of about 2 stones in a given cross-section.

The stability number for the stable, Icelandic type berm breakwater is related to the start of damage or recession of the stones at the edge of the berm. The recession, Re, is the erosion of the stones from the edge or the crest of the berm, it is often used to describe the reshaping of berm breakwaters. The stability criterion for the Icelandic type of berm breakwater is that after the design storm the recession of the berm shall not exceed two stone diameters, $Re/D_{n50}<2$. On the other hand stability criteria for dynamic berm breakwaters is often defined so that the recession shall not exceed the total width of the berm, (van der Meer and Koster, 1988), (Sayao, 1999).

The design criterion for the Icelandic type of berm breakwater has been developing over the past years. Three main parameters are recognised, the stability parameter of the edge of the berm, Ho, the width of the berm measured on design water level into the core of the structure, B, and the gradation of armourstone classes. The first two parameters are dependent, as higher stability needs less berm width than lower stability, (Sigurdarson et al., 1998b). The influence of the gradation of the armourstones on the berm width has been described by Hall and Kao (1991).

Good interlocking of carefully placed stones at the front and at the edge of the berm is prescribed in the technical specification, which is a part of the design of the Icelandic type berm breakwater. This is in contrast to the construction methods of dynamic berm breakwaters where armourstones are dumped but not placed. The importance of interlocking is well known from conventional breakwaters.

Quarry yield prediction as a tool in breakwater design

Quarry yield prediction has played an important role in the design phase of harbour breakwater projects in Iceland since the early 1980's, (Smarason et al., 2000). 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.

The importance of quarry yield prediction can best be described by a quotation to O.J. Jensen (1984). "In many projects, in which DHI has been involved in recent years, the lack of knowledge of available stone sizes in the quarry has turned out to be decisive for the breakwater profile at a very late stage, namely after initiation of the construction work. In some cases it has been necessary to modify the profile to fit the actual stone classes available." And later "It is for the above reasons extremely important for a breakwater project that information on the specific quarry is available at an early stage."

Often the owner/designer has to rely on the contractor for information on the maximum quarry yield. But dedicated armourstone production is not common and therefore there are not many contractors that 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. The present authors have been trying to change this situation and are gradually training contractors to work the quarries to requested specifications. Many contractors are now familiar with the quarry yields prediction and rely on the in their bids.

It has been demonstrated in many projects that although contractors complained at the beginning of the work that it would not be possible to obtain the predicted quarry yield, the yield prediction was, however, fulfilled in the end. This has often been achieved through small changes of the blasting design (i.e. tilt, burden and spacing of holes) and the amount of explosives used.

Furthermore, increased knowledge through quarry yield prediction and in the production of armourstone from various quarries has allowed the specification of large (10-20 tonnes) and extra large (20-30 tonnes) stones, typically to improve the stability of the edge of the berm. By increasing the size of the stones at the edge of the berm by a factor of two, the design wave height may increase by 25%. The percentage of large stones produced in the quarry can be as low as 2-5 % of the total quarried volume to allow for this 25% increase in design wave condition. Large hydraulic excavators and front loaders (75 to 110 tonnes) that can handle these large to extra large stones have become readily available. These large machines may raise the cost of the projects by 1-2%. Recent projects have utilised these large to extra large stones to the advantage of the stability and strength of the berm structures. A relatively low percentage of these largest stone classes can be of a great advantage for most breakwaters. This is not only valid for high to moderate wave conditions but also applies to lower wave load conditions where quarries with relatively low yield size distribution are used. For the same design wave condition and stability of the berm, the additional cost of the larger hydraulic excavator is compensated for by smaller berm width. Table 2 shows the results of a few quarry investigations where large and extra large stone have been required, (Smarason et al., 2000).

Table 2. Quarry yield prediction for some recent breakwater projects.

Breakwater site	Predicted Quarry Yield				Volume
	>20 t	>10 t	>5 t	>1 t	(m^3)
Bolungarvik	2	5	11	34	265,000
Blonduos	4	9	14	32	100,000
Hornafjördur, S-Barrier	2-5	5-10	15-20	40-45	60,000
Hornafjördur, E-Barrier	5-10	10-15	15-20	35-40	100,000
Husavik	3-4	7-10	12-16	24-32	300,000
Sirevåg, Norway	15-17	22-25	30-33	47-54	640,000
Vopnafjördur	10-20	20-30	30-40	50-60	40,000

Blast design is the most important factor for a successful breakwater project. It is the deciding factor in securing that the desired fragmentation of the rock is obtained. It is absolutely vital that the blasting engineer is prepared to adjust his blasting pattern to suite each particular quarry and he may have to adjust his pattern several times within the same quarry to maximise his results. We usually find that a drill pattern with a 3” drillbit close to 3-4 m burden (b) and 2-2.5 m spacing (s) for a bench height of 9-12 m gives the best results in sound porphyritic basalt lavas. The ratio s/b should for best results lie between 0.6 and 0.7.

A new blasthole row should not be drilled until after the clearing of the bench face and quarry floor is completed. Only then can the blasting engineer decide on his drill pattern and tilt of holes. It is important that the holes be drilled parallel with a dip of 70-80°, for best results and minimum damage to the blasted rock. This causes minimum throw of the blasted rock as only the bottom part of the bench is thrown out and the upper part falls into the blasted pile. A low specific charge should be used, generally 200 g (+/-50 g) per cubic metre of solid rock, depending on rock soundness and desired block size. Contrary to CIRIA/CUR (1991) we maintain that explosives with a high shock energy and lower gas content give better results. We also prefer explosives with higher detonation velocities, close to the sound velocities of the rock mass. Otherwise the sound wave may be reflected from the quarry face back to the blasted wall before the explosive have opened up the blast line, causing unnecessary additional damage to the blasted armourstone.

Production of large and extra large armourstone requires a coarse drill pattern than generally used in armourstone production. For optimum results it may be necessary to produce a significant amount of blocks that may be two to three times the largest desired armourstone for the project. These oversized block will have to be split afterwards using a single 2” to 3” hole or a row of narrower hand drilled holes for more accurate splitting into two pieces. A single hole cannot be recommended unless the quarry yield is somewhat better than the design requires. A steel ball of 6-7 tonnes is sometimes used but it can only be recommended in quarries exceeding the demand of the design. It should be emphasised here that the size reduction of the largest block is the area where the contractor can make his biggest earnings on a breakwater project. Unprofessional approach to this part of the work can lead to considerable overproduction in the quarry, which should by no means be rewarded.

Contractors may in the past have been able to claim on quarries where limited preparation was carried out, as the owner had not got the means to prove that excess production could have been caused by mishandling of the quarry. Thorough quarry investigation and quality assurance programme, (Smarason et al., 2000), have freed the owners from compensation to the contractors in this area. If, however, the quarry investigation is not carried out in accordance to the recommendations, unforeseen defects have appeared in some quarries, which has led to overproduction as some of the substandard armourstones have been rejected and those quarries have dissected unforeseen fracture zones.

The quality assurance programme presented by Smarason et al. (2000) aims at finding out the weaknesses of the quarried rock at an early stage. It is important to know the material and its properties, i.e. rock type, discontinuity spacing for quarry yield prediction, density and absorption, strength (point load index), freeze/thaw resistance (in cold climates), and resistance to abrasion in abrasive conditions. No test, however, can replace the personal visual inspection of the experienced engineer or geologist.

Sirevåg berm breakwater

In 1998 the Icelandic Maritime Administration (IMA) and Stapi Ltd. Consulting Geologists were commissioned by the Norwegian Coastal Administration to investigate quarries and design a berm breakwater in Sirevåg, which is located at the west coast of southern Norway. The breakwater, Figure 1, should be designed as a stable Icelandic type berm breakwater for a wave height with a 100 years return period. It should also withstand a wave height with 1000 year return period, which is referred to as the worst case scenario, without total damage.

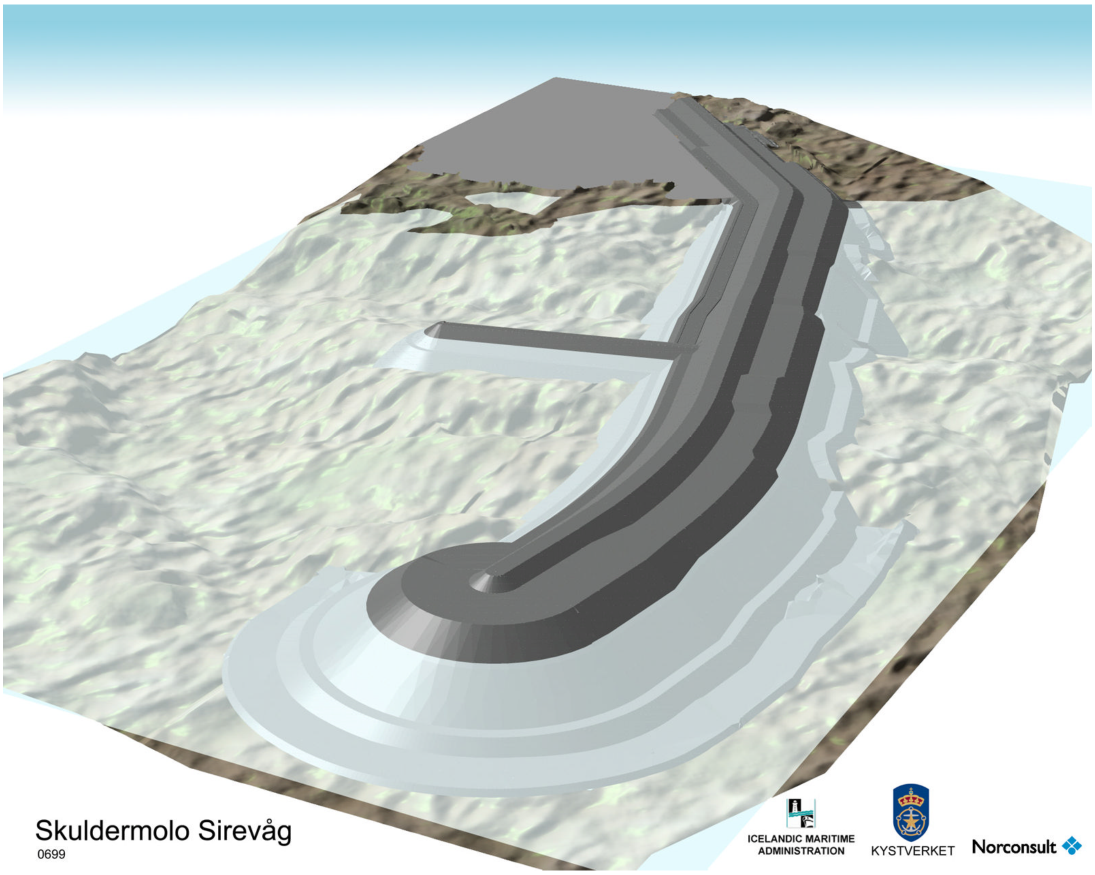

Figure 1. The Sirevåg berm breakwater

Sirevåg is exposed to heavy waves from the North Sea. The design wave with 100 years return period for the outer part of the breakwater was established by SINTEF as Hs = 7.0 m with Tp = 14.2 s (SINTEF, 1999). Wave measurements were started in the beginning of December 1998 at the location of the breakwater head at 17 m water depth. Measurements are taken every half-hour. Two large storms with waves close to the design storm were recorded during the winter 1998 to 1999, on December 27^{th} with Hs = 7.0 m and Tp = 14 s and on February 4^{th} with Hs = 6.7 m and Tp = 15 s.

To establish a design wave height along the breakwater IMA has performed wave refraction analysis from offshore into the location of the Sirevåg breakwater (IMA, 1999). The HISWA wave model was used for this purpose. The breakwater will partly be constructed on rocky bottom and partly on fine quartz sand. The depth of the rocky bottom is very variable from 3 m to 22 m with steep slopes. Under the outermost 150 m is a flat sand bottom. The breakwater is in all about 500 m long and extends about 400 m into the sea. The equivalent head-on wave height for stability calculations is estimated by the incoming wave height, 50 m or half wave length outside the berm, multiplied with a cosine of the wave obliquity in a power of 0.4 (Lamberti and Tomasicchio, 1997), Table 3.

Table 3. Design Wave Height and the Worst Case Scenario.

Station number along the breakwater (m)	Design wave height 100 year return period	Worst case scenario 1000 year return period
	Hs (m)	Hs (m)
0 to 70	4.8	5.3
75 to 125	3.5	3.9
145 to 210	6.2	6.8
215 to 240	6.4	7.3
245 to 275	6.2	6.8
280 to 400	6.7	7.4
Breakwater head	7.0	7.7

During the preparation phase for the Sirevåg project various model tests were performed at SINTEF. An interesting study was made to compare wave damping for different configuration of berm breakwaters to a conventional rubble mound breakwater (Jacobsen et al., 1999). The analysis shows that berm breakwaters reduce the wave energy penetrating around the breakwater head and into the harbour more efficiently than a conventional rubble mound breakwater of equal length.

In the preliminary design three sets of stone classed were considered. Based on the overall utilisation of all quarried material according to a preliminary quarry yield prediction and fulfilment of stability criteria for all sections of the breakwater, one set was chosen, Table 4.

Table 4. Stone Classes and Quarry Yield.

Stone class	w_{min}-w_{max}	w_{mean}	w_{max}/ w_{min}	d_{max}/ d_{min}	Expected quarry yield
I	20.0 – 30.0	23.3	1.5	1.14	5.6%
II	10.0 – 20.0	13.3	2.0	1.26	9.9%
III	4.0 – 10.0	6.0	2.5	1.36	13.7%
IV	1.0 – 4.0	2.0	4.0	1.59	19.3%

The geological investigation and quarry yield prediction included drilling of 25 cored drill holes and surface scan-lines. Three possible quarries (A, B and C) were assessed for the Sirevag breakwater. A quarry yield prediction was carried out for the three quarries for a 640,000 m^3 breakwater (Stapi Consulting Geologists, 1999). The armourstone material is gabbroic anorthosite rock of good quality, Figure 2. The quarry yield prediction, Figure 3, for a carefully worked quarry is about 50% over 1 tonne, about 30% over 3 tonne and about 15% over 10 tonne. This will result in about 6% in stone class I, 20 to 30 tonne, 10% in stone class II, 10 to 20 tonne, 14% in class III, 4 to 10 tonne, and 19% in class IV, 1 to 4 tonne, Table 4.

Figure 2. The rock in quarry A for the Sirevåg berm breakwater.

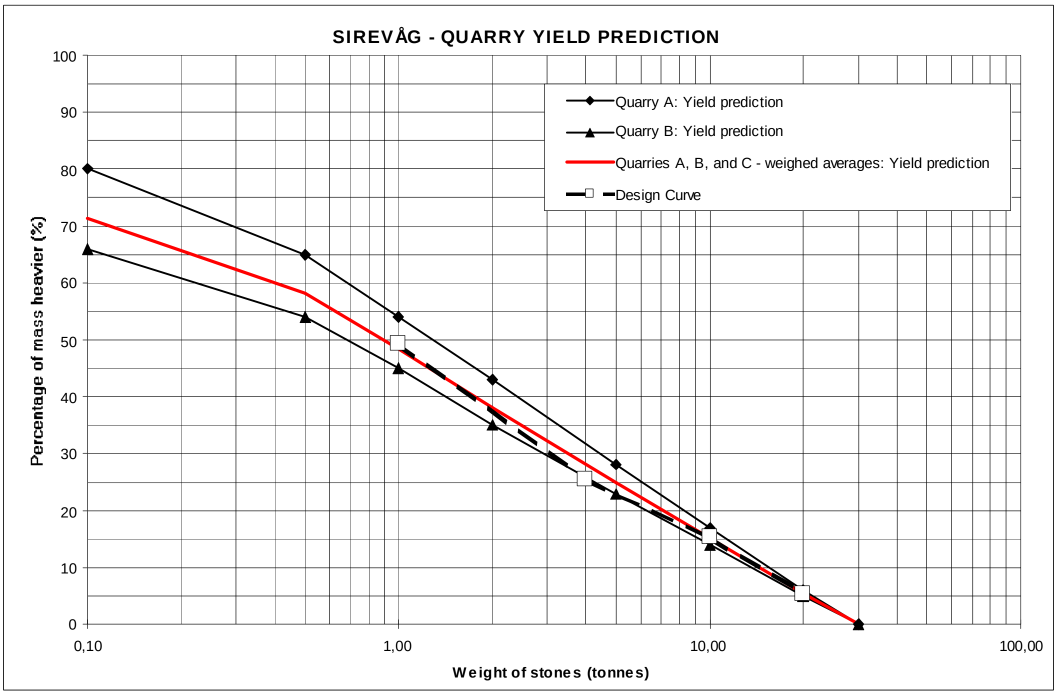

Figure 3. Quarry yield prediction for and design curve for the Sirevåg breakwater.

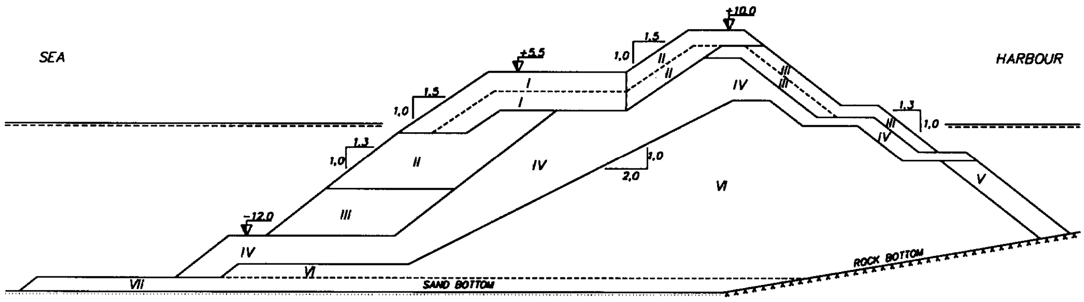

Figure 4. Sirevåg berm breakwater, cross section for the outer part.

Cross section of the outer part of the breakwater is shown in Figure 4. The design fully utilises all quarried stones over 1 tonne and a 100% utilisation of all quarried material is expected for the project.

Six contractors were pre-qualified to bid on the project.   The lowest bidder was E. Pihl & Søn of Denmark.   They draw on experience gained by their subsidiary company Istak of Iceland, which has experience in construction of berm breakwaters.

Figure 5.   Loading of the split barge from quarry B on the northern side of Sirevåg.

The equipment park used by the contractor consists of 4 backhoe excavators 110, 75, 50 and 25 tonnes, 3 front loaders 75 and two 45 tonnes, 3 dumpers, a split barge of 250 m^3 capacity and 3 drilling rigs. In the preparation phase the contractor considered the possibility of using a 200 tonnes crane for placing the largest stones on the breakwater. He, however, decided to use large excavator both in sorting the largest stones and placing them on the breakwater.

It has become apparent that in a project of this size larger excavators and wheel loaders are most important in handling the largest stones. It may, however, be equally important to have smaller machines for the sorting and handling of the smaller stone classes, as they are equally critical in the production. The lack of smaller excavators in sorting of smaller stones may lead to the loss of too high percentages of these stones into the quarry run.

The contractor started production in quarry B in March 2000, Figure 5, but from July 2000 he has been quarrying both in quarry A and B. Quarry B is expected to give about 400,000 m^3 and quarry A about 220,000 m^3. About 65% of the total volume had been quarried at the end of August 2000. The yield from the quarry has been more or less as predicted, classes I and II have been as predicted, where as classes III and IV are slightly under the predicted yield. The blasting technique the contractor has chosen coupled with the lack of small excavators may have contributed to the lack of stones in the lighter classes.

Conclusions

The aim of the design of a berm breakwater is to construct a berm with high wave energy absorption to minimise wave reflection from the trunk and especially from the breakwater head for navigational reason and to minimise wave overtopping. The Icelandic type berm breakwater has proved to be a successful solution for navigational safety in harbour entrances with heavy breaking waves.

The design and construction of rubble mound breakwaters is filled with uncertainties. Definite criteria to be fulfilled in the design of berm breakwaters will not be set up. However, from available sources the structures will be designed as stable as possible. It is the design methods that should be dynamic not the structures.

Acknowledgements

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Keywords for the following paper

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Quarry yield prediction
Stone gradation
Stone classes
Prototype experience
Sirevag breakwater

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