Design and Construction Aspects of Berm Breakwaters

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ABSTRACT

Structural and functional aspects of berm breakwaters have been covered in earlier papers by the present authors and with geometrical design rules for berm breakwaters presented at ICCE 2014, this paper mainly focuses on design aspects related to armourstone, armourstone grading, quarrying for armourstone and construction aspects of berm breakwaters, especially where these aspects differ from conventional rubble mound structures.

INTRODUCTION

The *geometrical design rules* for berm breakwaters, presented in Van der Meer and Sigurdarson (2014) are based on cooperation between the two authors over a long period, both in the scientific as well as in the practical field, with a number of co-authored papers, see Sigurdarson and Van der Meer (2011, 2012, 2013).

Classification of berm breakwaters firstly distinguishes between mass armoured berm breakwaters, MA, and Icelandic-type berm breakwaters, IC. The mass armoured has a homogeneous berm of mainly one rather wide graded stone class while the Icelandic-type is constructed from several stone classes, usually more narrowly graded.

Secondly, the classification takes into account the structural behaviour of the berm breakwater. It describes the level of reshaping the berm breakwater will experience: a hardly, partly or fully reshaping berm breakwater. Stability numbers for a 100-year design wave height, H_{sD}, range from $H_{sD}/\Delta D_{n50} = 1.7 – 3.0$, where hardly reshaping structures are close to 1.7 and fully reshaping structures close to 3.0. Mass armoured types are mainly partly and fully reshaping (PR and FR), where the Icelandic types are mainly hardly or partly reshaping (HR or PR). Design stability numbers larger than 3 cannot be regarded as breakwaters, but if wide or voluminous enough, as dynamically stable structures.

Table 1 shows the classification for berm breakwaters, including indicative values for the stability number, $H_{sD}/\Delta D_{n50}$, the damage and the recession.

Table 1. Classification of berm breakwaters based on 100-year wave condition.

	Abbreviation	$H_{sD}/\Delta D_{n50}$	S_d	Rec/D_{n50}
Hardly reshaping Icelandic-type berm breakwater	HR-IC	1.7 - 2.0	2 - 8	0.5 - 2
Partly reshaping Icelandic-type berm breakwater	PR-IC	2.0 - 2.5	10 - 20	1 - 5
Partly reshaping mass armoured berm breakwater	PR-MA	2.0 - 2.5	10 - 20	1 - 5
Reshaping mass armoured berm breakwater	FR-MA	2.5 - 3.0	--	3 - 10

Design aspects of berm breakwaters are described by Van der Meer and Sigurdarson (2014) and can be summarised as follows. Prediction of *initial recession* can be calculated by a simple formula based on the stability number. But the final recession depends on design issues that may influence recession in a positive as well as negative way. Positive influences are:

- A gentle down slope (for berm breakwaters 1:1.5);
- A berm level at least 0.6 H_{sD} above design water level
- A relatively long berm (extra resiliency, but also less recession)
- A toe structure at a high level

Berm size (wanted resiliency, based on predicted recession) and crest level are the main parameters for design, but there are quite a number of other geometrical parameters to come to a good cross-section. These parameters are given in Figure 1 and have been described by Van der Meer and Sigurdarson, 2014.

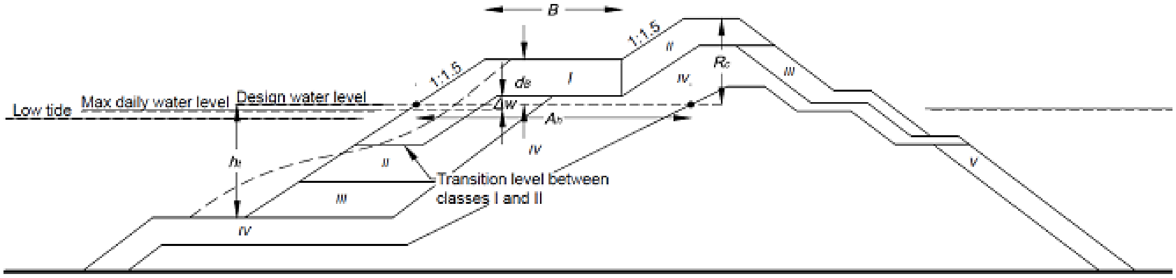

Figure 1. Principal cross-section of an Icelandic-type berm breakwater with the main geometrical design parameters.

NON-STANDARD GRADINGS FROM DEDICATED QUARRIES

Often breakwater projects involve the use of dedicated armourstone quarry for provision of material for the breakwater construction. Then the designer has more opportunities to define non-standard gradings for his design that fit both the quarry capabilities as well as demand for the structure. All size grades from the quarry should be used in the design, often the whole yield curve from the lightest up to the heaviest stones chosen for the project. In these projects the designer doesn't have to follow the well-known EN 13383 (2002) standard gradings and there can be considerable advantages and cost savings not to do so.

The standard gradings allow for up to 10% of the material to be lighter than the NLL and up to 5% lighter than the ELL, which weights roughly about 0.7*NLL. This is reasonable in the market where the standard gradings originate, but it is not necessary and makes projects more difficult to manage when stone classes are used, utilising the whole yield curve.

Stone classes from dedicated quarries should, if possible, cover the whole yield curve from about 0.3 or 1 t, depending on the project, and up to the largest piece of armourstone chosen for the project. Each armourstone class can be defined within minimum (M_{min}) and maximum (M_{max}) mass limits and depending on the project, either the mean or the median mass, M_{50}. The mean mass is defined as 50% by mass of pieces of armourstone passing and the median mass is defined as 50% by number of pieces of armourstone passing. To take account for small deviance in sorting it is practical to allow for 5% of the pieces of armourstone to be lighter than M_{min}, but limited to no piece of armourstone being lighter than 90% of M_{min}. These deviances could be due to breaking of stones, inaccuracy in the weighing or calibration of scales or weighing equipment. Generally it is permitted for pieces of armourstone to be larger than the upper limit providing that this does not affect the quality of the placement or achieving the filter criteria.

Standard gradings are produced according to the EN 13383 (2002) standard with considerable effort in documented sorting of the material, not only into the stone classes, but often each stone class has to be sorted into subclasses to ensure that the required median mass is met.

In projects with dedicated quarries there can be a great economical advantage in transporting the stone classes directly from the blasting pile to the breakwater, without stockpiling and placing each class into sub-classes. To facilitate this it is practical to define the required minimum median mass, M_{50min}, as easily achievable, within the natural grading from the quarry between M_{min} and M_{max}, as:

$$M_{50\,min} = M_{min} + 0.33 * (M_{max} - M_{min}) \quad \text{(by number passing)}$$

As the natural grading of armourstone from a quarry, within the M_{max} and M_{min} limits, results in a higher M_{50} than the M_{50min}, no extra measure is necessary to fulfil the M_{50min} requirement. This can be followed up by continuously weighing and recording individual stones. Designing by M_{50min} and defining the stone classes as above, results in a slightly conservative design as most quarries yield M_{50} higher than the minimum requirement. The advantage for the contractor, and that should reflect his price to the owner, is that it is often possible to place armourstone directly from blasting pile to the breakwater, without stockpiling and in case stockpiling is necessary, the costly management of sub-classes can be avoided.

ARMOURSTONE QUARRY YIELD PREDICTION

For the designer of a rubble mound structure, it is necessary to know what sizes of armourstone he can use for his design. In a moderate wave climate, where armourstone can be sourced from operating quarries producing the standard gradings, this is no problem. But things get more complicated when either the wave climate requires armourstone larger than the standard gradings or when there are no operating quarries nearby. Then it becomes necessary to predict a workable quarry yield for the project either of armourstone larger than usually produced from the operating quarry or from a rock mass available from a dedicated armourstone quarry.

The first step in predicting a workable quarry yield is to assess the in situ block size distribution. That is the distribution of the natural block sizes in the rock mass prior to quarrying. The in situ block size distribution is determined by the spacing between discontinuities cutting through the rock mass. These can be natural joints, bedding planes, other natural fracturing and weakness planes.

In armourstone quarrying the aim of the extraction process, which is usually blasting, is to loosen the rock mass by opening up the natural discontinuities and to produce a workable blast pile. Inevitably, the fracturing by the energy release from the explosives not only opens the natural discontinuities, but also opens new fractures. Some of the in situ natural blocks will be divided into smaller blocks. But while the in situ block size distribution is uncontrollable, the degree of fragmentation during blasting is controllable.

Figure 2. Coarse fracture pattern of the rock for the Sirevåg berm breakwater.

Several methods have been presented to predict the in situ and the blasted block size distributions. A summary of them is given in the Rock Manual (2007) and is not repeated here. Common to these methods is that they are mostly based on the *mean* spacing between discontinuities, joints and fractures, and consequently, they result in the *average* block volume or average block weight of the whole quarry.

But the designer is not interested in the average block weight. He is interested in the block sizes from the heavier end of the grading curve and often the small fraction of largest possible armourstone from the rock mass. In the Hammerfest project, with a design wave height of H_s=7.5 m, the largest stone class used in the design was 20-35 t and yielded 3% to 5%, see Sigurdarson et al. (2005). But the average yield from the quarry, 50% by mass or volume, was only about 0.1 to 0.2 t. Obviously, information on the average yield from the quarry would not have helped the designer very much.

The Icelandic quarry yield prediction (Icelandic QYP) is focused on the heavier end of the grading curve. It is based on logging discontinuity spacings from recovered solid cores and scan lines of open faces if accessible. The discontinuity spacings are described in terms of the RQD (rock quality designation value). Originally the analysis was based on scan lines on open surfaces of the rock source, but was later developed to be based on drilled borehole cores. The RQD value is defined as the proportion of the scan lines that consists of intact lengths of 0.1 m or longer. The Icelandic QYP uses not only RQD values based on 0.1 m, but also on other lengths and presents an in situ block size prediction based on these information.

The Icelandic quarry yield prediction is then determined by shifting the in situ block size distribution. The volume reduction, or degree of shifting, depends on various factors of the blast design, as well as several site and rock conditions. It is also different for different parts of the yield curve, the light and heavy parts of the grading curve and includes a compensation for further splitting due to handling of armourstone from the blasting pile to the breakwater.

The quarry yield prediction for a project in Hornafjördur, Iceland, Figure 3, is an example of a quarry yield prediction derived from in situ block size distribution, Smarason et al. (2000). Two quarry yield predictions are presented, A and B, where prediction B takes only the better parts of the quarry, while prediction A should be representative for a larger area, including poorer parts.

According to these predictions, the yield of armourstone heavier than 10 t would be 10 to 15% of the total quarried volume, while it is 21% in the unblasted rock, according to the joint space average. With a design wave height of H_s=3.8 m an Icelandic-type berm breakwater could have been designed with a maximum stone size of 5 t. But as larger stones were available from the quarry, these were used to increase the stability of the structure. It was decided that the two heaviest stone classes should be Class I 8-15 t and Class II 5-10 t. Figure 3 also shows a design curve and a curve called “Produced from quarry”, which is the achieved yield from the quarrying.

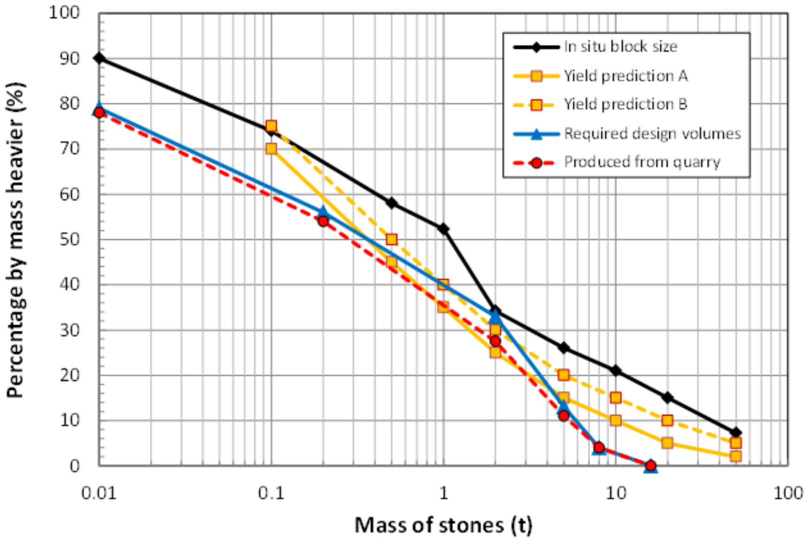

Figure 3. Quarry yield prediction, in situ block size distribution, design curve and production results. Breakwater project in Hornafjördur, Iceland, reproduced from Smarason et al. (2000).

Predicting a quarry yield from the in situ block size distribution of a rock mass can be done with various degrees of achievability. Easily achievable quarry yield predictions assume that not only will all discontinuities open during the fragmentation process, but in excess to that most of the larger natural blocks will break up into several smaller blocks. But with knowledgeable blasting techniques and handling of armourstone, it is often possible to achieve a higher yield of large armourstone. Challenging the quarry management and operation is to make a quarry yield prediction close to the upper limit of the achievable quarry yield. This requires a yield prediction based on a careful analysis of the discontinuities and an understanding of the process. Through experience in a number of armourstone projects over a period of more than 30 years, the Icelandic quarry yield prediction has been developed, mostly in Icelandic projects of igneous rock, as well as in projects worldwide with rock of various origin, including sedimentary and metamorphic rocks.

Test blasting or trial blasts to determine the quarry yield are not recommended. The quarry yield prediction based on analysis of drilled cores from the rock mass with a reasonable grid, is far more reliable than test blasting. Test blasting is limited to a small part of the rock mass to be quarried and there can be considerable variability in the rock mass.

QUARRY PLANNING

Armourstone quarries have to be planned on basis of the rock source to be exploited. Some rock sources are homogeneous, others are inhomogeneous, both in vertical and in horizontal directions. A thorough quarry investigation identifying the best suitable rock source, is therefore necessary. Depending on the volume of material needed for the construction of the breakwater and the time available for quarrying, a production capacity can be chosen to balance the quarry output to the construction requirements. With multiple operating locations it is possible to achieve a blast and output cycle to meet the required production capacity. This can be done with multiple faces, a single long face or multiple benches.

Often pairs of excavators and wheel loaders are used to work on the blasting pile for sorting armourstone in different stone classes and to load the material on trucks for transport, Figure 4. In smaller projects some contractors choose to use only excavators to work on the blasting pile and load on trucks, instead of excavators and wheel loaders.

Figure 4. Sorting of material from the blasting pile with excavators and front loaders, loading of truck from the stock pile. The Hammerfest project.

Quarry management and breakwater construction has to be planned together. All handling of material, like loading on trucks, hauling or sorting of material, does cost money. Therefore, it is important to minimise the need for stockpiling or sorting operations into sub-classes.

In general, all quarry run used as core material should be hauled directly to the breakwater and put in place. With a proper planning of the breakwater construction, it is often also possible to place a part of the armourstone classes directly to the breakwater, especially the lighter classes. Usually the heavy armourstone classes must be stockpiled as these will be used in the final stages of construction.

To be able to sort material directly to an armourstone class and not into sub-classes, depends very much on the definition of the armourstone class, mainly on the criterion of the median weight, M_{50}. With a relaxed median weight criterion, it is possible to skip additional sorting operations and enable direct placement of armourstone from the blasting pile to the breakwater. If the median weight is defined close to the natural gradation between M_{max} and M_{min}, then it is often necessary to stockpile all armourstone classes, often in sub-classes, and to adopt additional sorting operations to fulfil the median weight criterion.

Planning of the quarrying and construction of the Sirevåg berm breakwater in Norway was a challenging task. A new quarry was to be opened in a hilly area with very limited area for stockpiling of material. At the start of quarrying, there was actually no space. The area was at a small bay opposite to the breakwater construction site. All material had to be transported by sea and the contractor chose to use a split barge for the task. Figure 5 shows the initial construction phases of the Sirevåg berm breakwater. Instead of starting to dump quarry run along the centre line of the cross-section, the contractor chose to start dumping material at the toe. By doing this he was gradually able to dump most stone classes directly to the breakwater instead having to stock pile them. In the first phase it was soon possible to dump Class IV 1 -4 t, on top of Class V, the quarry run. Then in the second phase Class III 4-10 t followed and at last in the third phase Class II 10-20 t. At this stage, it was only necessary to stockpile Class I 20-30 t.

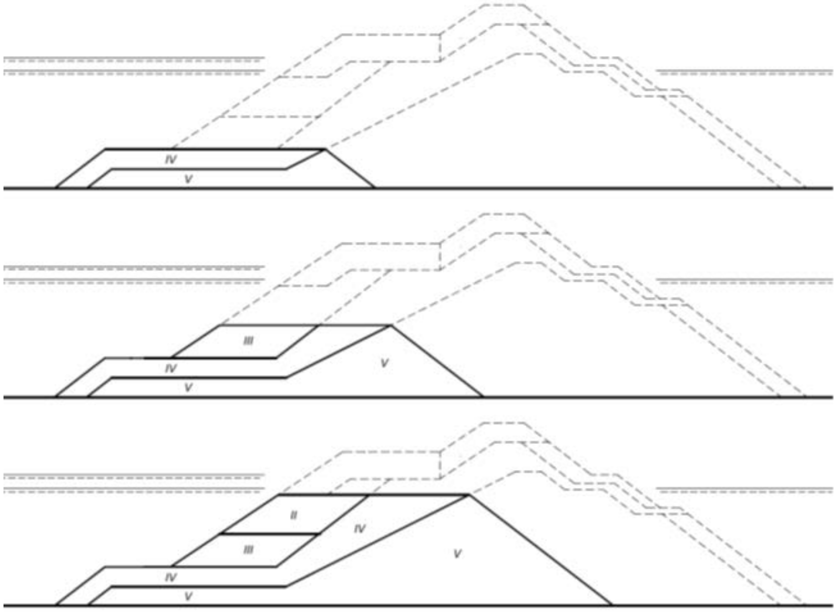

Figure 5. The initial construction phases of the Sirevåg breakwater for material dumped by a split barge. Class V is quarry run, Class IV is 1-4 t, Class III is 4-10 t and Class II is 10-20 t.

ARMOURSTONE QUARRY IN THE CONTRACT

When a breakwater project is planned in an area where there is not an active market of armourstone, then it is in the owner’s interest to locate a possible quarry, or quarries, for armourstone and core material. This can either be an already open quarry or opening of a new quarry. In that case the process involves an agreement with landowners, acquiring an environmental approval and planning permission for the quarry. This is a lengthy process and cannot be left to the contractor to arrange.

A part of the quarry investigations is a quarry yield prediction, a prediction of what sizes of armourstone can be produced from the rock mass to be quarried and in what yield. Often the quarry yield prediction is the basis for the design of the berm breakwater and regarded as equally important as the wave load. It is in the owner’s interest to provide the contractor with information about the quarry and possible yield of armourstone. This involves a risk that the contractor is not able to fulfil the expected yield, either that he has not the knowledge how to work the quarry with regard to armourstone production, or that he lacks the will to do so in the particular time of the project. It is therefore important that the quarry yield prediction has suitable safety margins. It is also necessary that the owner’s supervision team is familiar with armourstone production. If the achieved yield lies below the predicted yield, then the team must be able to suggest improvements early on, how the contractor can work the quarry to improve the yield.

If it is on the other hand proven that the quarry is not yielding as expected, then the geometrical design guidelines for berm breakwaters provide an excellent tool to act on that and possibly change the design.

When the quarrying of armourstone, the transport of material from the quarry to the breakwater and the construction of the breakwater, is all on one hand and the responsibility of the contractor, then it involves less risk for the owner to base the contract on volume instead of weight. The volume is less disputable than the weight of material needed to fill that volume. When contracts are in weight, factors such as packing density and layer porosity have large influence on the bill. But these factors can be difficult to determine. The volume on the other hand can easily be calculated from cross-sections, but it requires a definition of the constructed surface of the rock structure. A contract in weight is more in the favour of the transporter or the supplier of rock to the breakwater as it reduces their risk, but leaves the owner with higher risk of what he has to pay at the end of the project.

CONSTRUCTION EQUIPMENT

Nowadays, equipment can be rented for a specific project or bought with a guaranteed selling price at the end of the project. This means that the contractor has not to own the equipment park needed for the project when giving his tender and he can acquire the best suitable equipment for a specific project. The project will benefit from a thorough study of construction procedures to determine the best suitable construction equipment.

As for other rubble mound breakwaters, berm breakwaters are constructed both with land-based as well as with waterborne construction equipment. On land, trucks bring material on to the breakwater, quarry run or armourstone. For short distances, front loaders can transport armourstone and dump at locations where long reach is not required. Placing of different layers of armourstone with land-based construction equipment is usually done with excavators, but sometimes cranes are used, especially if there is need for long reach.

Excavators that have been used for placing of armourstone, range in size from about 20 t to about 120 t. To allow for heavier lifting capacity to place armourstone in long reaches, the excavator is factory altered by increasing working pressure of the hydraulics and increasing its counterweight. It is assumed that the excavator uses its tipping capacity to its full extent. As a rule of thumb the excavators can place armourstone to full reach of a normal boom with a weight of up to one-third of its total weight. For example a 110 t Liebherr R984 excavator with a 7.8 m long gooseneck boom and a 4.5 m long stick can place a 35 t stone in a 12 m distance from its centre point, utilising the buoyancy of the submerged stone, see Figure 6.

Figure 6. A 110 t excavator with a rock prong, Sirevåg breakwater.

The most common waterborne construction equipment are split barges, but other types of barges like side dumpers can also be used. Split barges are usually self-propelled with two shuttles and two engines. The size varies from about 300 m^3 to 800 m^3, 40 to 60 m long. Split barges have not only been used to place quarry run and smaller stone classes, but also larger pieces of armourstone, up to about 20 t. In that case only one row of large stones is placed at the bottom of the barge.

ARMOURSTONE PLACEMENT

Berm breakwaters are constructed of both “bulk-placed” armourstone and core and for the Icelandic-type also “placed primary armour”. Bulk placement can be done in many ways, by end-tipping with trucks, with wheel loaders and excavators, with cranes by using rock trays or skips, as well as with floating barges. Each method has its advantages and disadvantages with regard to reach, placement rate, vulnerability to wave and wind conditions, as well as cost. End-tipping with trucks and wheel loaders have shortest reach, cranes have the longest reach, while barges have unlimited reach but are restricted by water depth.

The term “placed primary armour” is defined as individually placed pieces of armourstone, located within the first two layers on the exposed side of the breakwater: the berm front slope above an elevation just below low water, the top of the berm and on the crest.

Placing of primary armourstone to increase stability of the berm, has to comply with several requirements. It is recommended that the level of the armourstone is built up progressively and follows a placement sequence similar to that detailed in Figure 7

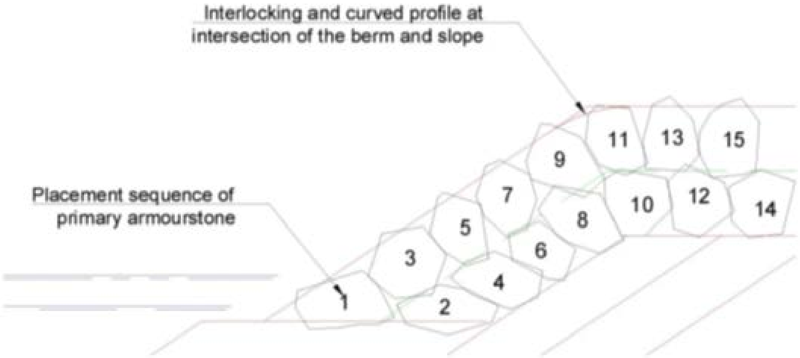

Figure 7. Recommended placement sequence of primary armourstone

DEFINITION OF ROCK SURFACE AND SURVEY METHOD

When contracts for breakwater construction are based on volume, the definition of the rock surface becomes an important issue. Figure 8 from the Hammerfest berm breakwater, using extra-large armourstone with rough placement, clearly demonstrates the need to have a clear definition of the rock surface.

Figure 8. Class I stones, 20-35 t on the berm of the Hammerfest breakwater.

In the North Atlantic, the rock surface of rubble mound structures has for many years been defined as the plane through which armourstone protrude by one third of the surface area. This is an easy definition to place in the Specifications, but more difficult to control. In some projects the constructed surface was checked with a detailed survey but often this was done with the survey rod, not placed on the highest points of the stones, but reasonably low for a subjective evaluation of the rock surface definition. In other projects it was agreed-upon by the contractor and supervisor to base the definition of the constructed profile or surface on a highest point survey, lowered by either a fixed distance or a distance calculated as a factor times the nominal diameter of the armourstone class. Here it is recommended to develop the last mentioned method and to use the modern GPS staff survey equipment.

The Rock Manual (2007) advocates that rock surfaces should be surveyed with a spherical foot staff with a diameter of $0.5*D_{n50}$, also called a survey ball. The idea behind this survey method is that the staff is neither placed on top of stones nor at low levels or between stones and it results in a surface that is not far from the definition used in the North Atlantic. But the operation, measuring with the spherical foot staff, is both expensive, time consuming, takes up valuable space on the breakwater, usually requiring a crane and involving several persons. Therefore, it is proposed to use the more modern GPS rod survey instead where applicable.

It is recommended that when above water, the constructed profile shall be determined by measuring the highest point of any piece of armourstone with a GPS rod. The constructed profile shall be defined as a factor times the nominal stone diameter, D_{n50}, beneath the measurements. This factor will depend on the armourstone shape and type of placement, and may be determined from a test panel.

THE HAMBANTOTA ARTIFICIAL ISLAND REVETMENT

The Hambantota Port Development project is a major industrial and service port on the southeast coast of Sri Lanka. Phase 2 of this project included excavation of a large basin into the land in dry conditions and an artificial island built out of the excavated material. Sigurdarson et al. (2014) describe the development of a berm breakwater revetment design for protection of the artificial island. As large volumes of rock would become available from the excavation, efforts were made in a Value Engineering Study to come up with an optimized design using this rock as efficiently as possible. The maximum rock size for design was limited by the available equipment for rock handling and was set to 10 tonnes. After preliminary designs indicated that a wide berm revetment would be feasible, a more comprehensive study was performed for further design. The geometrical design rules of Icelandic-type berm breakwaters, developed by Van der Meer and Sigurdarson (2014), were applied.

The preliminary design was optimized in a hydraulic physical model study, with several refinements of the design adding to the stability. The results of the hydraulic model study showed higher stability than expected from the design formulae of Sigurdarson and Van der Meer (2013). Analysis showed that this was due to several design improvements. By applying the geometrical design rules it was possible to achieve higher stability and less reshaping.

Of about 20 million m^3 of soil and rock to be excavated from the harbour basin of the Hambantota port, there were about 5 million m^3 of slightly weathered rock. The design phase included an assessment of the possible yield of large armourstone from the slightly weathered rock. Based on rather limited information, a quarry yield prediction was presented, predicting that it would be possible to quarry about 8 to 12% into an armourstone class of 5-10 t.

Most contractors lack the experience in quarrying for large armourstone and during the first months of excavation, the yield of the 5-10 t class was considerably lower than predicted. During a site visit of the design team, several measures were recommended, changing the blasting technique and quarry procedures. This resulted in more than tripling the yield of 5-10 t and reaching the predicted quarry yield. Correct quarrying for the required rock sizes is very important for the viability of the project.

Figure 9. Examining the blasting pile after successfully improving blasting design.

CONCLUSIONS

Several papers have been presented by the present authors, covering most aspects of structural and functional behaviour of berm breakwaters. The present paper focuses on practical design issues that can lead to considerable cost savings. As an example, with a proper definition of the minimum median mass of an armourstone class, sorting, handling and stockpiling of armourstone can be simplified considerably. By analysing the rock mass to be quarried and focusing a quarry yield prediction on the heavier end of the grading curve, the design can make advantage of large armourstone. Experience has shown that the yield of large armourstone can be increased by improving the blasting design. The cooperative work of the authors will soon be presented in a book “Design and Construction of Berm Breakwaters” published by World Scientific Publishing Company.

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