Armourstone for Berm Breakwaters

Sigurdur Sigurdarson, IceBreak Consulting Engineers ehf, Reykjavik, Iceland / Icelandic Road and Coastal Authority, Reykjavik, Iceland
Jentsje van der Meer, Van der Meer Consulting bv, Akkrum, The Netherlands / UNESCO-IHE, Delft, The Netherlands

Abstract
Armourstone are the most important construction material for berm breakwaters as well as for other rubble mound structures. The paper discusses several issues regarding the preparation for and design of armourstone projects. Firstly, what sizes of armourstone are available for the design? It is important to know what sizes can be quarried from nearby quarry or quarries and in what yield. Secondly, the choice of grading for an armourstone class, standard grading or non-standard, and the choice of median mass within the chosen grading. These factors can influence the cost of the structure greatly. Thirdly, quarrying for large armourstone is a discipline that not many quarry operators master. It is easy to blast the rock into small fragments but more difficult just to loosen up the rock to maximise the sizes of armourstone. Fourthly, placement of primary armour is important to achieve stable interlocked armour layer. The last issue addressed in this paper is the definition of rock surface and survey methods. Contracts based on volume need a definition of the rock surface.

Introduction
The design of modern berm breakwaters started in the early eighties in Canada with Baird and Hall being originators (Baird and Hall, 1983). The original design consisted of mass armoured berms that were reshaped to statically stable S-shaped slopes. The basic principle was to use locally available materials. The width of the berm was determined by the size of available armourstone, smaller stones required larger berms. The design was adopted in Iceland, developed through a number of breakwater projects and eventually led to a development with more stable structures by utilizing available rock sizes, large rock and more gradings. This more stable and only partly reshaping structure is called the Icelandic-type berm breakwater.

Real guidance on design and construction of berm breakwaters has been lacking, but the new book of both authors may be seen as an improvement on this, (Van der Meer and Sigurdarson, 2016). Aspects of this book have been presented at various conferences:

- New classification of berm breakwaters, (Sigurdarson and Van der Meer, 2012)
- Recession, wave overtopping and reflection, (Sigurdarson and Van der Meer, 2013)
- Geometrical design of the cross-section, (Van der Meer and Sigurdarson, 2014)
- Application of geometrical design rules, (Sigurdarson *et al.*, 2014)
- Quarries and rock grading, (Sigurdarson and Van der Meer, 2015)
- Designing berm breakwaters for different wave heights and different quarry yield, (Sigurdarson and Van der Meer, 2016)

The classification of berm breakwaters based on the stability number $H_s/\Delta D_{n50}$, takes into account the structural behaviour including the degree of reshaping. Applying the geometrical design rules makes it possible to compare different design options based on different stability parameters, sometimes the full range of stability parameters for berm breakwaters, $H_s/\Delta D_{n50}$=1.7-3.0, can be considered. For a fixed design wave height, different stability parameters mean different sizes of armourstone.

Recently the geometrical design rules for berm breakwaters (Van der Meer and Sigurdarson, 2016) were applied for a potential project in Greenland and used to make conceptual design options for a berm revetment (Sigurdarson and Van der Meer, 2016). With practically no information about available rock for quarrying various design options were considered with Class I armourstone ranging from 1-3 t

to 5-15 t for the initial design wave height of H_s = 4.4 m. This corresponds to designs with a stability parameter $H_s/\Delta D_{n50}$ of about 3.0 down to 1.7. Applying the geometrical design rules for armourstone classes with different stability parameters, it was possible to present different designs. For the small stones with high stability parameter the resulting design was more voluminous than for large stones with low stability parameter.

Yield prediction for armourstone

Rubble mound breakwaters and revetments can either be protected against waves by armourstone or artificial concrete units. If it is possible to quarry armourstone with a reasonable yield from an armourstone quarry and within a reasonable distance from the project site, it is often more economical to use armourstone to protect the structure instead of concrete units. An economic analysis is used for cost comparison. The main factors that affect the cost of using armourstone is the possible yield of armourstone from potential quarries, the distance and mode of transportation. A study on the two second terms will address possible roads, possible transport equipment, different sizes of trucks, trailers, off road trucks or trains and if sea transport is possible. This is a well-known procedure and needs no explanation. This is not true for evaluation of possible yield of armourstone from a quarry. Reliable methods for quarry yield prediction are not widely used. The yield is important as often the breakwater or revetment project has to pay the whole quarrying which can sometimes be several times the need of armourstone for the relevant project.

When designing rubble mound structures, it is necessary to know what sizes of armourstone can be used for the 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 potential dedicated armourstone quarry.

The first step in predicting a workable quarry yield is to assess the in-situ block size distribution of the rock mass. That is the distribution of the natural block sizes in the rock mass prior to quarrying. Depending on the type of rock in-situ block size distribution can be uniform over a large area or highly variable, in which case it is necessary to define the rock mass for quarrying carefully. 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 of the rock mass, 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 and depends on the blasting design.

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 rock mass to be quarried.

Figure 1: Coarse fracture pattern of the rock for the Sirevåg berm breakwater to left. Drilled cores that have been analysed for quarry yield prediction for a breakwater project in Husavik.

This is of little use as 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 for example, with a design wave height of H_s=7.5 m, the largest stone class used in the design was 20-35 t and its quarry yield prediction was 3% to 5%, see Sigurdarson et al. (2005). On the other hand, 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 quarry yield prediction developed through a number of projects in Iceland by Omar Bjarki Smarason is focused on the heavier end of the grading curve Smarason et al. (2000). The method is based on logging discontinuity spacings from recovered solid cores and scan lines of open faces if accessible, see Figure 1 for an example. The discontinuity spacings are described in terms of the RQD value (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 quarry yield prediction used in Iceland is not only based on RQD values based on 0.1 m, but also on other lengths and presents an in-situ block size prediction based on this information.

The 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.

There can be two scenarios as mentioned above. Firstly, the case of tendering out a project including opening of a new quarry. In order to get the benefits from the quarry yield prediction the contractor has to believe that the prediction can be realised. If he doesn't he might add cost to his unit prices for overproduction in the quarry to meet the requirements of armourstone. In the case of an operative quarry that has not been focusing on large armourstone an emphasis may have to be made to convince the quarry operator that the yield of armourstone can be increased. The equipment in the quarry is not aimed at large armourstone and neither are the logistics nor the blasting procedures and all this must be changed. That has a cost and this cost must be included in the unit prices. There can be many hurdles before the scepticism is overcome.

The quarry yield prediction for a project in Hornafjördur, Iceland, Figure 2, 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 10-15% of the total quarried volume, while the in-situ yield of the unblasted rock is 21%, 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 2 also shows a curve for required design volumes and a curve called "Produced from quarry", which is the achieved yield from the quarrying.

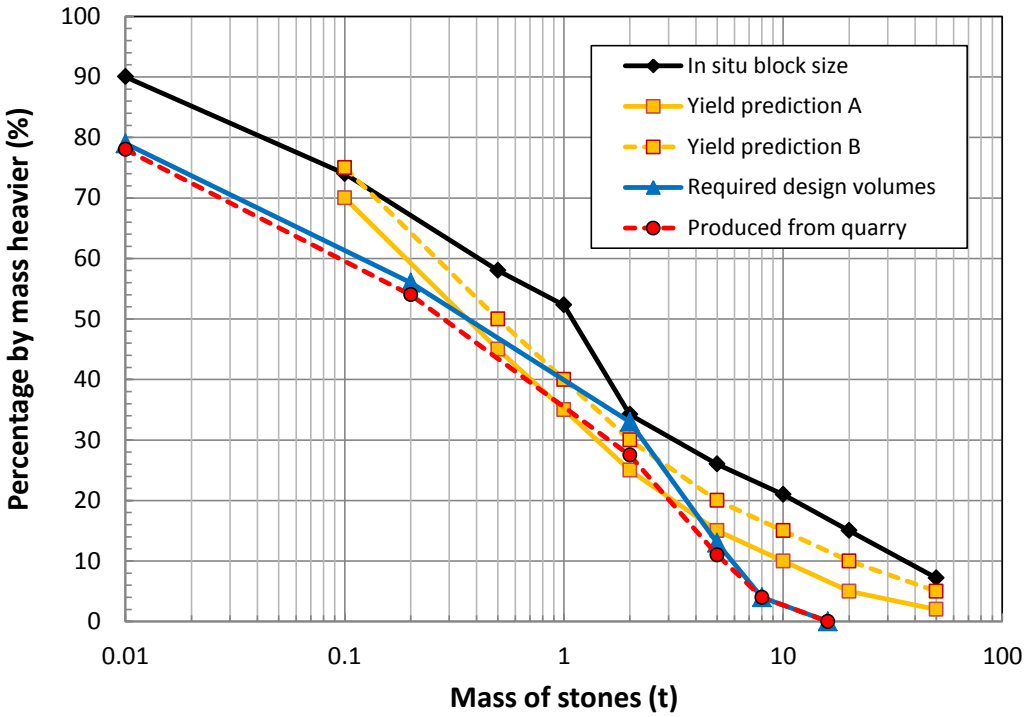

Figure 2: Quarry yield prediction, in-situ block size distribution, required design volumes curve and production results. Breakwater project in Hornafjördur, Iceland, reproduced from Smarason et al. (2000).

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 quarrying process.

In opening a new quarry, test blasting or trial blasts to determine the quarry yield are not recommended for various reasons. Firstly, test blasting is limited to a small part of the rock mass to be quarried and there can be considerable spatial variability in the rock mass. Secondly, often the rock mass that is likely to yield the largest armourstone is not at the surface but more likely deeper into the rock. Thirdly, in the case of large armourstone it is hardly unlikely that very heavy equipment will be brought to sort armourstone from the blasting pile of the test blasting and in that case the blasting engineer has the tendency to avoid large stones that cannot be handled by the equipment brought to the site. 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. On the other hand, test blasting can be performed in an operating quarry if large enough equipment is brought to the site.

Armourstone gradings

Armourstone gradings for breakwater projects can either be chosen as the standard gradings advocated by the Rock Manual (2007) and the European standard for armourstone, EN 13383 (2002) or non-standard gradings can be chosen.

When working in areas where there is an active market with armourstone there can be economical advantages sticking to the standard gradings in the design. This can be the EN 13383 standard grading used in the region around the North Sea or other standard grading not complying with EN 13383 in other regions. The reason for this can be that the quarries in the area produce armourstone as a by-product of for example production of gravel for road construction and sort them in standard gradings on stockpile, which can then be delivered to projects often by short notice. On the other hand, when working with dedicated quarries there are usually much more economical advantages in using non-standard gradings in the design. This could for example be when the demand for a rock class slightly exceeds the effective mean mass of a certain standard grading class and the designer then has to use the next heavier class, although that class is considerably heavier than needed. More economical is to adjust the armourstone class to fit the demand. Usually the heavier armourstone classes are priced higher and their layer thickness is larger, meaning that more volume of this larger rock would be needed when jumping up one standard class compared to slightly change the classes to meet the demand. In that case, it is an advantage to work with non-standard gradings and slightly adjust the limits of the class to fulfil the requirements.

Another factor that the designer can play on is the width of the armourstone class. If there is a need for large volumes in one class, it can be chosen wider and similarly, if less volumes are needed, a narrow class can be chosen. This is based on the fact that the size grading of armourstone sorted from a blasting pile follows a certain grading curve. Depending on the rock mass the yield curve can be high or low and steep or gentle, but generally the rock masses will yield into all size grades. For example, the yield into the 1-3 t class will often be about double that into the 3-6 t class.

As stated earlier the Rock Manual (2007) and EN 13383 (2002) give a lot of information on standard gradings, which derive from the countries along the North Sea. The standard gradings have been proposed by the armourstone industry, producers and transporters.

The development in Iceland derives from working with a dedicated quarry for a project. Stone gradings can then be chosen according to the need of armourstone sizes, considering the complete breakwater and not only one separate section. Moreover, a very fast and reliable method has been developed to come to correct stone classes in the quarry that can be transported directly to the breakwater. This method is based on weighing each stone directly in the quarry when it is handled and counting the grading on number instead weight, including a safety factor to assure a correct M_{50}.

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 (Nominal Lower Limit) and up to 5% lighter than the ELL (Extreme Lower Limit), 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.

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}. A practical definition is:

$$M_{50\ min} = M_{min} + 0.33*(M_{max} - M_{min}) \qquad \text{(by number passing)} \qquad (1)$$

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.

Quarrying for large armourstone

The general believe worldwide is often that very large rock, say larger than 10-15 t, cannot be produced in enough quantity. In many projects, worldwide the authors have experienced that quarry operators claim that their quarry only yields up to 6, 8 or 10 t. The experience in many berm breakwater projects involving dedicated quarries have proven differently. Berm breakwaters have been designed and constructed with the heaviest grading reaching 35 t stones where it was believed that a maximum workable stone class could only reach 15 t.

Quarrying for large armourstone is a discipline that not many contractors master. Large rocks will not be available after blasting, unless it is properly planned and the contractor is executing blasting and other production activities appropriately. This is typically done with the technical assistance of the design and/or supervision team and others with experience in producing large armourstone.

Production of armourstone is important for berm breakwaters. In Iceland, the technique to produce “large” armourstone from the bedrock has developed from one project to another and from one contractor to another. With increased experience from a number of projects and production of large armourstone, the blasting methods have developed. The main terms used in bench blasting design are given in Figure 3.

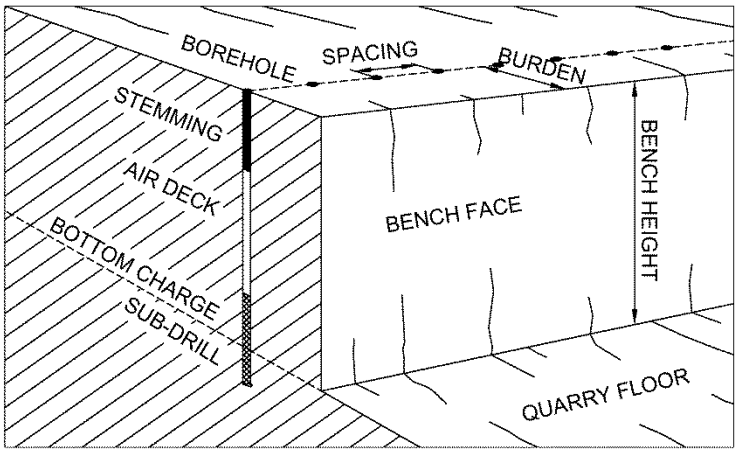

Figure 3: The main terms of bench blasting design

A good guideline for blasting for armourstone is given in the Van der Meer and Sigurdarson (2016). This has been learned and developed through a number of projects where the supervision team has brought experience learned from a contractor in one project to another contractor in another project. The guideline includes a number of measures for improving the yield of large armourstone, where the most important are:

- One row blasting instead of multi rows;
- Decreased specific charge;
- Changing the distribution of charge within the blasting hole;
- Optimise the utilisation of the bench;
- Emphasize on secondary breakage of oversized rock.

In the Hambantota Port Development project in Sri Lanka (Sigurdarson et al. 2014) a berm type revetment was designed to protect an artificial island. The berm was reinforced with a double layer of 5-10 t armourstone, Figure 4. 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.

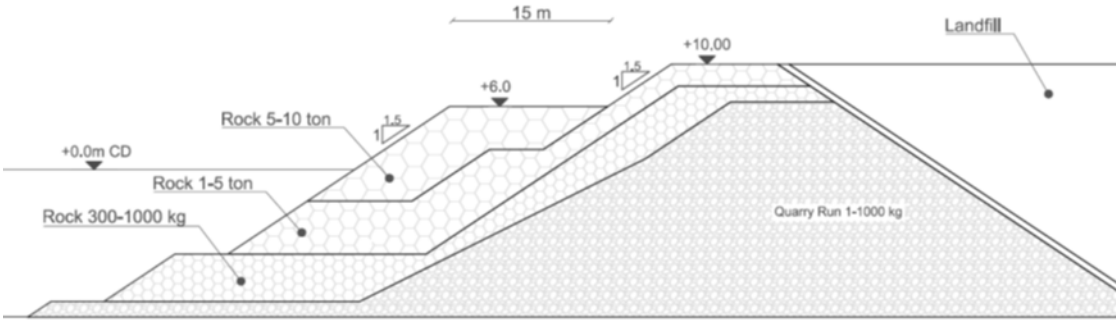

Figure 4: Hambantota Port Development project. Final design of the Icelandic-type Berm Breakwater optimized during physical model testing, from Sigurdarson et al. 2014.

Due to lack of experience in the production of large armourstone, the yield of the 5-10 t class from the excavation of the harbour basin area was considerably lower than predicted during the first months of construction, only between 2 and 3%. 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, see Figure 4. Correct quarrying for the required rock sizes is very important for the viability of the project.

Figure 5: Hambantota Port Development project, the contractor's team examining the blasting pile after test blasting in the harbour basin area.

Armourstone placement

As other rubble mound structures 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 of construction equipment, 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 detailed in Van der Meer and Sigurdarson (2016).

When placing armourstone in a double layer, whether it is on a conventional rubble mound breakwater or on the front slope of a berm breakwater, it is important that the constructed surface reaches the cross-sectional design lines of the structures. This has sometimes been a problem as stones are very irregular and can be placed differently. Unless the excavator or crane operator placing the armourstone knows exactly where the cross-sectional design lines are located on the real structure, it is likely that the constructed surface will not match the design surface exactly. In that case, it will not be a stable armour layer if a part of a layer is added on top of what has been constructed, if the constructed layer is too thin or if the highest stones are stripped off in the case it is too thick. Therefore, the placement sequence similar to that detailed in Figure 5 is recommended building the armour layer up progressively placing the outmost stone on each level first. This placement sequence was adopted by operators of excavators placing rock in Iceland.

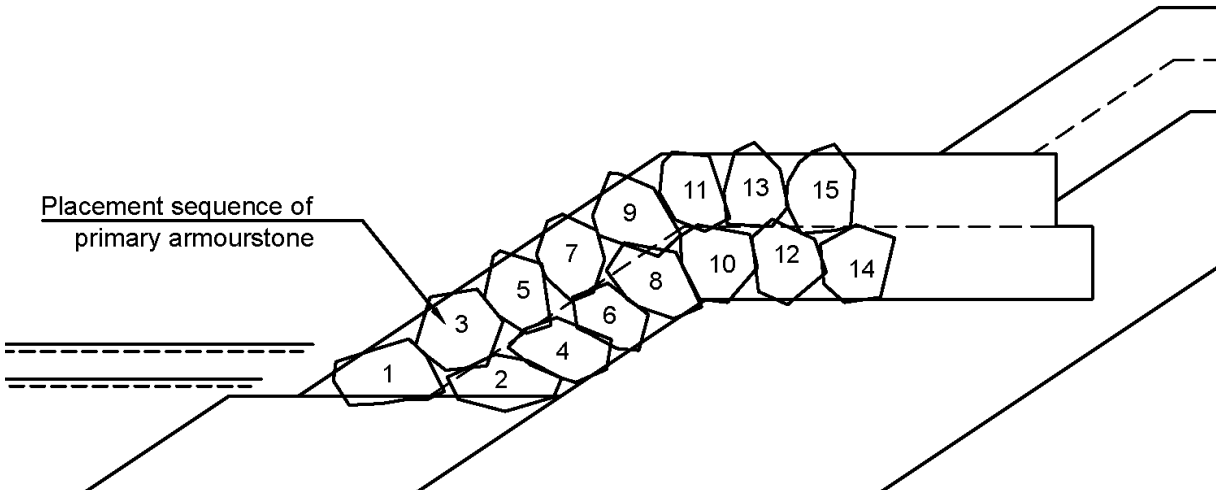

Figure 6: Recommended placement sequence of primary armourstone

Definition of rock surface and survey methods

When contracts for breakwater construction are based on volume, the definition of the rock surface becomes an important issue. Figure 7 from the Hammerfest and the Husavik berm breakwaters, using extra-large armourstone of 20-35 t and 16-30 t respectively with rough placement, clearly demonstrates the need to have a clear definition of the rock surface.

Figure 7: Class I stones, 20-35 t on the berm of the Hammerfest breakwater to left, and 16-30 t on the berm of the Husavik breakwater to right

In the North Atlantic region, 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.

Figure 7: Surveying the Class I stones 16-30 t with a GPS staff on top of the berm of the Husavik berm breakwater, Iceland

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 region mentioned above. 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, see Figure 7.

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.

Conclusions

Geometrical design rules for berm breakwaters have been developed and presented in Van der Meer and Sigurdarson (2016). An example of their application is given where different design options were considered for a potential project in Greenland.

Armourstone is the most important construction material for berm breakwaters as well as for other rubble mound structures. In the planning phase and design of berm breakwaters as well as of other rubble mound there are many design issues that influence the economy of the breakwater or revetment project. Some of these issues do not look important at first sight but can have considerable cost effect. It is important to choose an armourstone grading that best fits the rock source and the design load on all sections of the structure. Even the choice of median mass within the chosen armourstone grading can influence the cost of the structure greatly.

Berm breakwater projects are usually based on volume of the different armourstone classes rather than their weight. This calls for a firm definition of the rock surface and practical survey methods using modern survey equipment.

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