Quarry and breakwater design studies for an Icelandic-type berm breakwater for the Oakajee Port development in Western Australia

Richard Mocke[1], Sigurdur Sigurdarson[2], Bill Carlton[3] and Omar B Smarason[4]
[1]JFA Consultants Pty Ltd., Suites 2-4, Addax house, 19 Wotan Street, Innaloo, Western Australia 6018,
[2]Icelandic Maritime Administration, Vesturvör 2, 200Kopavogur, Iceland.
[3]Oakajee Port & Rail, Level 3, 33 Richardson Street, West Perth, Western Australia 6005,
[4]Stapi Ltd, Ármula 19, 108 Reykjavik, Iceland

Abstract
The development of a new port facility at Oakajee has incorporated a great deal of historical planning, design and development. In early 2008, a fresh design approach was taken with the development of an alternative, Icelandic-type berm breakwater for the design of the breakwaters with the intention of utilising locally occurring rock materials within the design. The initial design stages were then followed up with the location and investigations of a new quarry location close to the proposed port location. Recent efforts have been concentrated on confirming the adequacy of the proposed quarry as well as the further development of the breakwater design to match the anticipated quarry yields.

1 Introduction

The state government of Western Australia has nominated Oakajee Port and Rail (OPR) as the successful proponent for the development of a new deep water port for the export of bulk iron ore at Oakajee, Western Australia. The project will comprise of: an initial phase of up to two cape class bulk ore loading berths; breakwater; dredged approach channel and manoeuvring area; and possible expansion, including a further cape class bulk berth and seven panamax class bulk / container berths.

JFA Consultants (JFA) Western Australia based specialist coastal, port and harbour engineers are managing the planning, investigations and design associated with the development of the breakwaters, dredging and reclamation aspects of the project. The Icelandic Maritime Administration (IMA) is assisting with the breakwater design aspects together with Stapi in regards to quarry investigations. HR Wallingford (HRW) are providing technical input into various aspects of the project (through JFA) including a detailed review of the breakwater selection process appropriate for the Oakajee location.

2 The Oakajee site

The Oakajee site is on a relatively open coast approximately 20 km north of Geraldon, which is located about 400 km north of Perth, Western Australia (see Figure 1). The site at Oakajee is exposed to swell and storm waves from SSW through W to NNW with the most direct exposure from around 240°N. The long period wave exposure causes considerable issues with mooring at the Geraldton Port. The tide range is small, as are tidal currents.

The outer part of the breakwater is expected to be on water depths exceeding 14 m with the breakwater head at a water depth of 24 m. Storms at 1:100 year return give Hs≈5m with Tp≈12-17 s in 20 m of water, so even the larger storm waves are unlikely to be depth-limited except at the inner sections of the breakwater. Cyclonic waves from around 290°N might exceed Hs≈ 5.5 m with Tp≈10–12 s, but these will be substantially oblique to the main breakwater, and direct cyclonic hits at this site will be rare.

Figure 1. Iron Ore Deposits and Oakajee Location Map, Western Australia

The seabed is generally rocky with limited sand pockets. Rock is available from quarries in the hinterland with the primary restrictions of rock type / density, durability, maximum armour size, and haul distance all varying with quarry source selected. Access to the site from land is relatively unrestricted, with no urban development or geographical features imposing any substantial difficulties, so new haul roads may be considered.

3 Initial development phase

The initial phase of the development for the proposed breakwaters at Oakajee involved a mass armoured-type breakwater design due to the aggressive wave climate precluding the use of a traditional two layer statically stable breakwater design. Further analysis supported by the Rock Manual (CIRIA, 2007), however, suggested that such breakwaters should preferably be non-reshaping statically stable. The non-reshaping statically stable breakwater (also known as the Icelandic-type berm breakwater) uses selected armourstone in the potentially mobile areas dimensioned to be statically stable.

4 Icelandic-type berm breakwaters

The Icelandic-type berm breakwater (IceBB) is a general modification of the original berm breakwater (see Figure 2). The structure is more stable and less voluminous than the original berm breakwater. It is built up of several narrower-size classes and an emphasis is put on utilizing the size gradation output of the armourstone quarry to its extreme to benefit the design.

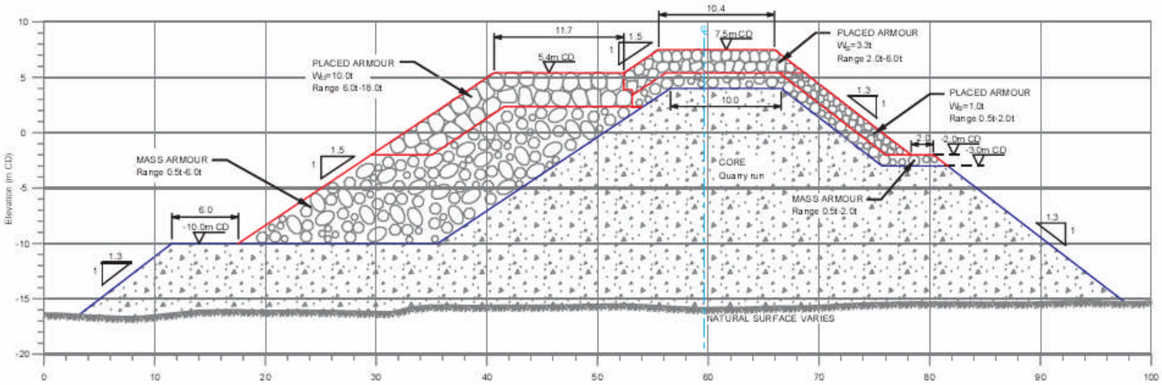

Figure 2. Typical cross section of the Icelandic-type berm breakwater

The design of the IceBB is flexible, which makes it relatively easy to adapt it to poorer quarry yields by thickening the rock filter layers between the main armour layers and the core. This increases the dissipation of wave energy through the filter layers before it reaches the core, which has a more reflective nature. Reduction or elimination of these filter layers, increases wave reflection and hence the size of armour rock required.

The IceBB concept has been in development over the past 25 years and nearly 40 such structures have been constructed worldwide over a wide range of wave climates, water depths and tidal conditions.

In Western Australia an IceBB has recently been included as part of the breakwater design for a new port expansion at an iron ore export facility in the Pilbara. This provided a particularly effective solution where quarry limitations prevented the production of large armour and the construction of a more conventional breakwater design.

5 Pre-feasibility design phase

5.1 Quarry Investigations

During the pre-feasibility design phase for Oakajee breakwaters in April 2008, information regarding the availability of large armourstone for the IceBB was based on a desk study. It concluded that there was a realistic possibility that large rock armour in the 10-20 tonne and 20-30 tonne stone classes could be obtained from granulite quarries within a reasonable distance from the Oakajee port site.

This was later confirmed with drilled rock cores from a potential quarry site (named GPP quarry) located approximately 16km from the port location. A quarry yield prediction assumed 30% of the quarried material heavier than 1 tonne and 10% heavier than 10 tonnes. The prediction was adjusted to a maximum stone size of 30 tonne.

During a subsequent site visit, a new site worth investigating was encountered (see Figure 3). This site has been called Site D and compared to the other (GPP) quarry site was much closer at about 6 km from the port location.

The first drilling phase at Site D took place in November 2008. A quarry yield prediction based on 7 out of the 9 boreholes predicted 35% of the quarry yield over 1 tonne and about 12% over 10 tonne

Figure 3. Surface geology at Site D showing granulite outcrops

The cores showed that the joint spacing becomes coarser with depth as well as rock competency (Figure 4) which means that the possibility to produce large armourstone increases with depth. Figure 5 shows a preliminary bench yield prediction for Quarry Site D based on the first drilling phase, different yield curves for the fresh rock above and below the elevation +50 m.

A review of the drilling results for the first stage of drilling determined that the rock at Site D would be classified as “Good” to “Excellent” in comparison to other quarry sites previously investigated and developed (see Table 1)

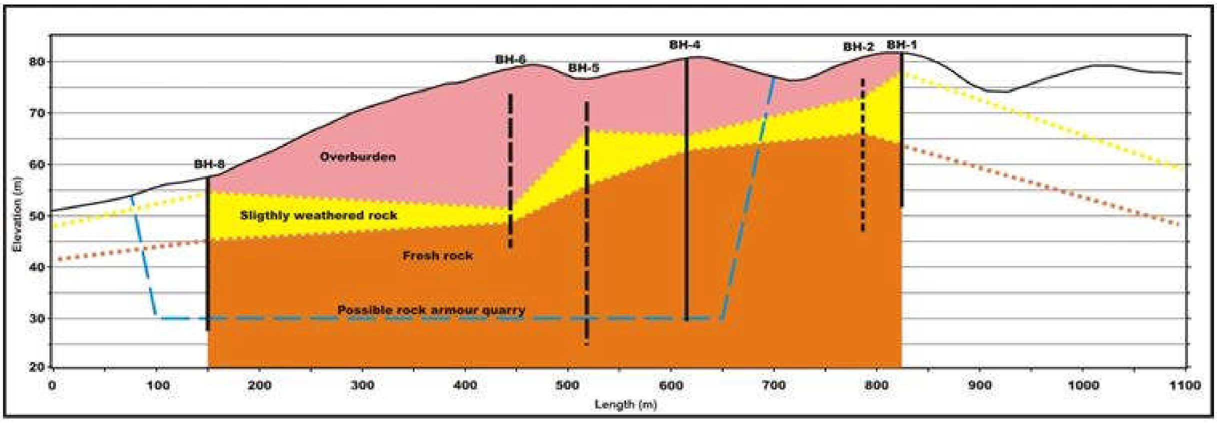

Figure 4. Geological profile at Site D – fresh rock (orange) overlain by moderately weathered rock (yellow) and overburden material (pink).

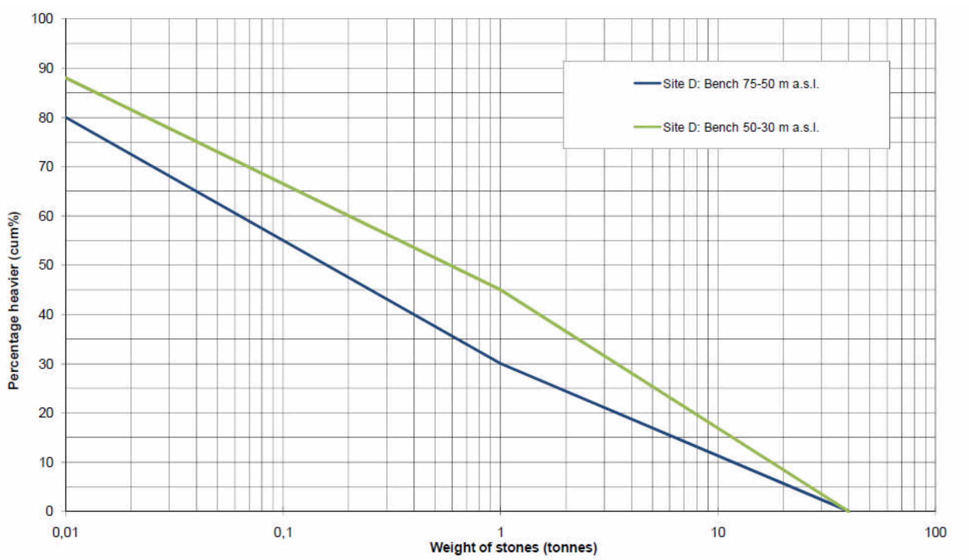

Figure 5. Preliminary bench yield prediction for Quarry Site D, based on the first drilling phase

Table 1. Guidelines for quality control of armourstone of igneous and metamorphic rocks (Modified from Smarason et al. 2000).

Test	**Excellent (A)**	**Good (B)**	Marginal (C)	Poor (D)	Comments
Rock Type	Gabbro, Granite, Porh. bas., **Quartzite Granulite**	Dolerite Ol.-tholeiite, Alkali basalt **Gneiss**	Tholeiite basalt, Andesite Dolomite, Limestone	Rhyolite, Dacite, Hyaloclatite, Ankarites	Guidelines for rock types without correlation to rock density.
Specific gravity (SSD) (t/m^3)	>2.9	2.65 – 2.9 **Site D**	2.5 – 2.65	<2.5	Density of rock is a good indicator of hydraulic stability in a breakwater.
Water absorption (%)	<0.5 **Site D**	0.5 – 1.0 **Site D**	1.0 – 2.0	>2.0	Important indicator of alteration and resistance to degradation, especially in cold climate
Point Load Index $I_{S(50)}$ (MPa)	>8.0 **Site D**	5.0 – 8.0 **Site D**	3.0 – 5.0	<3.0	Correlates with rock density and indicates resistance to breakage of blocks.
RQD_{50}	>70% **Site D**	50 – 70% **Site D**	30 – 50%	<30%	

5.2 Breakwater Stone Classes

Table 2 shows the proposed stone classes in the first design phase and Table 3 shows the matching of the required volumes and the supply of material from the quarry, based on the quarry yield prediction of the first drilling phase for Quarry Site D.

In these calculations it is assumed that 2.1 million m^3 of quarried material are needed for the breakwater, 1.5 million m^3 of core and 600,000 m^3 of rock in four different stone classes. The last column of Table 3 shows that this quarry yield prediction would actually result in an excess of large armour stone if suitably quarried.

Table 2. Proposed stone classes in the first design phase for the Oakajee breakwater.

Stone Class	W_{min} (t)	W_{max} (t)	W_{50} (t)	W_{max}/W_{min}	D_{max}/D_{min}	D_{50} (m)
I	18.0	30.0	22.0	1.7	1.19	2.01
II	6.0	18.0	10.0	3.0	1.44	1.55
III	2.0	6.0	3.3	3.0	1.44	1.07
IV	0.5	2.0	1.0	4.0	1.59	0.72

Table 3. Matching of required volumes from the first design phase and the quarry yield prediction of the first drilling phase in Quarry Site D.

Stone Class	W_{50} (t)	Volume in breakwater (m^3)	Quarry yield prediction %	Necessary quarrying (t)	Unused/required vol (m^3)
I	22.0	15,000	4.0%	84,000	69,000
II	10.0	80,000	8.0%	168,000	88,000
III	3.3	185,000	10.0%	210,000	25,000
IV	1.0	320,000	13.0%	273,000	-47,000
V	Quarry run	1,500,000	65.0%	1,365,000	-135,000
Total		2,100,000			

6 Planning (feasibility) design phase

The aim of this design phase was to review the pre-feasibility design of the breakwater with respect to any revised design wave conditions and to utilise the quarry yield predictions from Site D.

During the review of the design wave conditions at the site, the design wave heights at the trunk of the breakwater were increased about 10 – 15%, which required an increase in stone size. In the first design phase, stone Class I was only used for the breakwater head and Class II for the trunk. In the second design phase, stone Class I is used to protect both the trunk and head of the breakwater. the upper and lower limits of Class I have been widened to increase the volume of rock obtained in this class.

Table 4.presents the proposed stone classes for the Oakajee breakwater in the second design phase.

Table 5 shows the various design parameters for the breakwaters. These are the design wave height and period, the type of cross section, either Icelandic-type berm breakwater or conventional 2 layer structure, and the stone class of the main armour. Figure 6 shows the location of the different structures including: the breakwater head, breakwater trunk, causeway, tug harbour and reclamation bund seawalls.

Table 4. Proposed stone classes for the Oakajee breakwater.

Stone Class	W_{min} (t)	W_{max} (t)	W_{50} (t)	W_{max}/W_{min}	D_{max}/D_{min}	D_{50} (m)
I	15.0	35.0	21.7	2.3	1.33	2.00
II	6.0	15.0	9.0	2.5	1.36	1.49
III	2.0	6.0	3.3	3.0	1.44	1.07
IV	0.5	2.0	1.0	4.0	1.59	0.72

Table 5. Design wave conditions

	Breakwater head	Breakwater trunk	Outer causeway	Outer causeway	Inner causeway
Design wave height (m)	5.1m / 5.5m	5.1m	3m<Hs<4.4	2m<Hs<3m	Hs<2m
Peak period	15.9s/10.7s	15.9s	15.9s	15.9s	15.9s
Type of cross section	IceBB	IceBB	IceBB	IceBB	Conv. b/w.
Main armour stone class	I	I	II	III	III

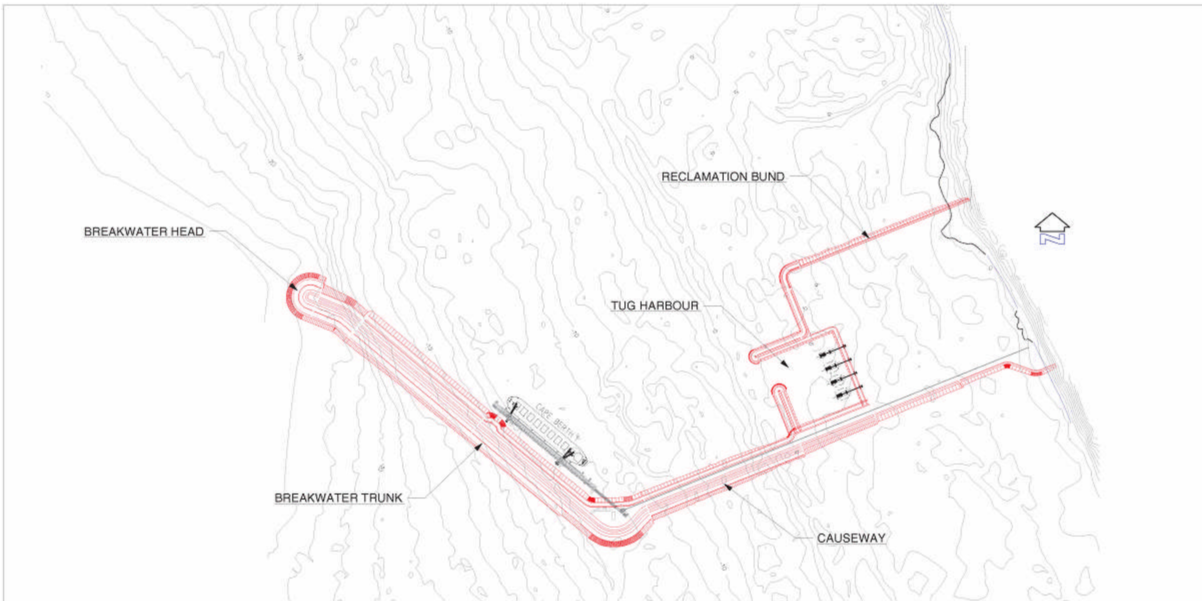

Figure 6. Oakajee port – design sections

PIANC (2003) classifies berm breakwaters in accordance with stability parameters as shown in Table 6, where the dimensionless stability parameters, H_o and T_{om} are defined as $H_o=H_s/\Delta D_{n50}$ and $T_{om}=T_m(g/D_{50})^{0.5}$.

Table 7 shows the stability parameters for different cross sections based on the primary stone class, and for the breakwater head, through consideration of both cyclonic and non-cyclonic waves.

The Icelandic-type berm breakwater should be designed for a low stability number, if possible H_o < 2.0. Optimum safety levels correspond to H_o of 1.8 and 2.0 and return periods of 25 and 50 years.

It can be seen that with reference to the stability parameter H_o the cross sections will in all cases be grouped as Statically stable non-reshaping berm breakwater based on the PIANC (2003) classification, but with reference to the stability parameter H_oT_{om} the cross sections enter the regime of Statically stable reshaped berm breakwater as the H_oT_{om} value exceeds the value of 40.

For the breakwater head with reference to the H_o stability parameter the cyclonic wave conditions are more critical, but with reference to the H_oT_{om} parameter the non-cyclonic conditions are more critical.

Table 6. PIANC (2003) classification of berm breakwaters

Type of breakwater	H_o	H_oT_{om}
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

Table 7. Stability parameters for the main armour on different parts of the breakwater

		H_s (m)	T_m (s)	Stone class	W_{50} (t)	D_{n50} (m)	H_o	T_{om}	H_o T_{om}
Breakwater head	Non-cyclonic	5.1	12.3	I	21.7	2.0	1.56	27.2	42
Breakwater head	Cyclonic	5.5	8.2	I	21.7	2.0	1.68	18.2	31
Breakwater trunk	Non-cyclonic	5.1	12.3	I	21.7	2.0	1.56	27.2	42
Causeway outer	Non cyclonic	4.4	12.2	II	9	1.5	1.80	31.3	57
Causeway inner	Non cyclonic	3.0	12.2	III	3.3	1.1	1.72	37.0	64

Table 8. Volumes needed for different structures and different stone classes.

Stone Class	Breakwater (m^3)	Reclamation Bund/Tug Groyne (m^3)	Land Fill Bund (m^3)	Quarry run from overburden (t)	Needed from quarry (m^3)
I	110,000				110,000
II	220,000				220,000
III	230,000	40,000			270,000
IV	350,000	60,000	20,000		430,000
V	1,790,000	200,000	80,000	-500,000	1,570,000
Total	2,700,000	300,000	100,000	-500,000	2,600,000

Table 9. Volumes in different stone classes from the upper benches and lower benches and matching of the total quarrying to the volumes needed for the breakwater.

Stone Class	QYP – above +50m (m^3)	Quarrying above +50m (m^3)	QYP – below +50m	Quarrying below +50m (m^3)	Unused/Required vol (+/-) (m^3)
I	7%	150,000	11%	50,000	90,000
II	9%	190,000	12%	60,000	30,000
III	8%	170,000	14%	70,000	-30,000
IV	13%	270,000	15%	80,000	-80,000
V	63%	1,320,000	48%	240,000	-10,000
Total		2,100,000		500,000	

The preliminary volumes needed for the different structures and different stone classes are presented in Table 9. Volumes in different stone classes from the upper benches and lower benches and matching of the total quarrying to the volumes needed for the breakwater.

In total, close to 2.7 million m^3 of rock is needed for the breakwater, 300,000 m^3 for the reclamation bund and tug groyne and 100,000 m^3 for the land fill bund. It is anticipated that over 500,000 m^3 of quarry run from the overburden, weathered rock, will be used for these structures. The result is that about 2.6 million m^3 of material in different stone classes are needed from the armourstone quarry.

It is assumed that about 2.1 million m3 will be quarried from benches above elevation +50 mAHD and 500,000 m^3 from benches below elevation +50 mAHD (see Figure 6). The quarry yield prediction for benches above and below elevation +50 mAHD presented in is now used to calculate the volumes in different stone classes. The last column in Table 9 shows the unused volumes in the different stone classes.

About 90,000 m^3 of Class I stones have not been used in the design and about 30,000 m^3 in Class II. In these calculations it is assumed that the excess material in the heavier stone classes can be used for lighter classes. This means that about 120,000 m^3 of excess material in Classes I and II can be used to fulfil the need for material in Classes III and IV.

7 Planning of the breakwater construction

There are four main challenges in the breakwater construction:

- Production of large armourstone in the quarry;
- Quarry production maintained to meet breakwater construction schedule;
- Building of the breakwater in the constant swell conditions; and
- Limited construction time.

7.1 Production of armourstone

Preliminary quarry yield predictions suggest that it will be possible to get the necessary size and volume of armourstone. It should be noted however that this will only be possible through the use of correct blasting techniques such as using a wide drilling pattern and limiting the amount of explosives. Through the production period it will be important to register the result of each blast to be able to monitor the percentage of each stone class. If the volume of armourstone achieved from the blasting does not follow the quarry yield curve then changes in the blasting pattern will need to be considered.

Table 10 presents a list of some of the more recent IceBB projects in Iceland and Norway. This includes information relating to the construction period, design wave height for the most exposed section of the breakwater, largest rocks used, total volume and bottom depth at the deepest section of the breakwater.

7.2 Conceptual quarry plan

It is recognised that the quarry output is an important consideration in achieving the construction timeframe. Initially a construction period of 2 years was considered, including a 6 months period of mobilisation, which leaves 18 months for the quarrying and breakwater construction. The approach of balancing quarry output to construction requirements requires a production capacity of 6 to 7,000 m^3 of material each day. This is achieved through developing a quarry with multiple operating locations and needs 300 to 400 m of working face to achieve the blast and outload cycle to meet the above demand. This can be carried out on multiple faces, a single long face or multiple benches.

7.3 Breakwater construction methodology

The breakwater is of the IceBB type and many of these have been built before under different conditions. Some of these breakwaters are exposed to higher design wave conditions, but what distinguishes the Oakajee site from the others is the constant swell, that will be present during the construction period.

The method that is being proposed is a combination of building the breakwater from land with conventional methods and from sea with a split barge, when the swell is not too high.

Analysing the constructability of the IceBB breakwater included drawing up phase plans for the construction of the breakwater. In the beginning it focused on land based construction methods. This included using a 120 tonne excavator to place armourstones above a level of -2 m and introducing a 300 tonnes crane for the placement of quarry run and various stone classes to the core, subsea berms and lower parts of the bulk placed stone classes. The crane would use rock skips to place material. All armourstones on the surface of the breakwater are assumed to be placed with an excavator to secure interlocking between the individual stones.

Table 10. Recently constructed Icelandic-type berm breakwater.

Project/Location	Construction year	H_s	Largest rocks	Total volume	Deepest section
Sirevåg (Norway)	2000 – 2001	7.0m	20.0t <w< 30.0t	620,000m^3	-18m
Húsavík (Iceland)	2001 – 2002	6.8m	16.0t <w< 30.0t	270,000m^3	-12m
Grindavík (Iceland)	2001 – 2002	5.1m	15.0t <w< 30.0t	170,000m^3	-5m
Hammerfest (Norway)	2002 – 2003	7.5m	20.0t <w< 35.0t	3,000,000m^3	-35m
Vopnafjörður (Iceland)	2003 – 2004	5.0m	8.0t <w< 28.0t	140,000m^3	-9m
Thorlákshöfn (Iceland)	2004 – 2005	5.5m	8.0t <w< 25.0t	230,000m^3	-5m
Landeyjarhöfn (Iceland)[1]	2008 – 2009	6.1m	12.0t <w< 30.0t	600,000m^3	-9m
Sirevåg (Norway)[1,2]	2000 – 2001	7.0m	20.0t <w< 30.0t	620,000m^3	-18m

1 Landeyjahöfn and Helguvík are under construction

2 Helguvík, extension of existing breakwater.

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