LANDEYJAHÖFN
FERRY HARBOUR AT THE SOUTH COAST OF ICELAND
by
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1. INTRODUCTION

Vestmannaeyjar (Westmann Islands) is a group of islands 5 nautical miles from the south coast of Iceland. On the largest island, Heimaey, the Port of Vestmannaeyjar is located, a large fishing harbour and transportation port, benefiting from the fact that no other harbour exists on the entire 350 km long sandy south coast between Thorlakshofn and Hofn in Hornafjordur on the mainland. At present, the ro-ro passenger ferry Herjolfur makes the trip from Thorlakshofn to the Westmann Islands in 3 hours under normal weather conditions.

The main objective is to improve the frequency of transport to and from Westmann Islands and to shorten the voyage time for passengers, cars and cargo. Three alternative solutions have been discussed to fulfil this goal:

- **Replacing the existing ferry, Herjolfur:** The existing ferry is 3,354 GRT in size, 70.5 m long and with a beam of 16.0 m and a draft of 4.3 m with a regular service speed of 15 – 16 nautical miles per hour. The distance between Heimaey harbour and Thorlakshofn harbour is about 40 miles. The ferry has a capacity of 524 passengers and 62 private cars or 6 trucks and 35 private cars. The ferry Herjolfur is 19 years old and it is expected that she will be in service some additional years.

- **An undersea road tunnel from the mainland to Heimaey:** The proposed tunnel will be 18 km long and will reach down some 200 to 300 m below the seabed in the bedrock.

- **A new ferry harbour at the Bakkafjara coast, named Landeyjahöfn:** To improve the ferry connection between the Icelandic mainland and the Westmann Islands is to build a new ferry harbour at Bakkafjara. The sailing route will take 30 minutes instead of 3 hours and travelling route from Vestmanneyjabæ (Westmann Island Town) to Reykjavik (Capital of Iceland) will take 21/2 hours instead of 4 hours. There will also be more sailing trips per day and more capacity. The proposal means best economical solution and second best service.

In the year 2000 the Icelandic Maritime Administration (IMA) was assigned by Althingi (the Parliament of Iceland) to undertake a survey and feasibility study for a ferry and ferry port facility at Bakkafjara on the open south coast. This paper will highlight the proposed ferry harbour solution with issues related to wave climate, model testing, sediment transport and morphological evaluation. The paper will include important aspects and characteristics of the port at the south coast of Iceland.

![Figure 1: Westmann Islands and the south coast of Iceland from Thorlakshofn to Hofn](image-url)
2.0 INVESTIGATIONS FOR A FERRY HARBOUR AT BAKKAFJARA

2.1 Field measurements

Bakkafjara coast is located in the sheltered area behind the Westmann Islands immediately west of a river outflow, Markarfljót, Fig. 2. A breaker bar exists some 800-900 m off the shore which extent some 40 km further to west but along the coast to east of the river no bar has developed. The area at the proposed location of the ferry harbour at Bakkafjara is characterized by a deep trough up to 10 -12 m and depression in the bar of a water depth of around 6 m in front of the proposed location.

Wave measurements have been undertaken since 2003 some 2 km west of the location of the proposed harbour at Bakkafjara at 28 m water depth. Offshore wave data is available from the ECMWF both ERA 15 and ERA 40 from 1958 together with an offshore wave buoy located south of Westmann Islands at 120 m water depth. The offshore wave conditions are characterized by high waves that have been measured up to 16.7 m, Fig. 3. The long term wave height distribution at ECMWF 63°N, 21°W is $H_{s98\%} = 7.2$ m, $H_{s1\text{yr}} = 12.2$ m, $H_{s100\text{yr}} = 17.4$ m and at Bakkafjara sheltered by the Westmann Islands $H_{s98\%} = 4.3$ m, $H_{s1\text{yr}} = 6.7$ m and $H_{s100\text{yr}} = 8.4$ m.

![Figure 2: Examples of simulated wave fields in a regional wave model. Waves from SW are sheltered by the Westmann Islands.](image)

The tide is semidiurnal with a maximum range of 3 m. The sediments in the coastal zone and on the beach plane are medium sand with particle size $d_{50}$ between 0.10 and 0.50 mm. The evaluation of the location of the proposed harbour was based on measured bathymetries during the year 2002 to 2006 as shown in Fig. 4 and in studies of the historical coastline which shows that the coastline has been stable around this location whereas variability of up to 300 m is seen to the east of the location and 100 m to the west of the location.

The bathymetrical measurements show years where a “spit” has developed from the delta towards west, see Fig. 4, and other years where the spit is non-existing. The spit develops after the growth of...
the delta during spring and summer followed by severe waves from south-easterly directions. It appears that the growth of the spit is dependent both on the supply of sand from the river and a long period of persistent south-easterly waves. The daily discharge at the river mouth from 1961 to 2001 has been calculated. The calculated sediment load depends on the river discharge, the grain size and the profile of the river cross-section. The annual discharge of sand based on the simulated periods is estimated to 150,000 m$^3$/yr.

Figure 4: Bathymetries measured between October 2002 and May 2006 during the research period of the project.
3.0 HYDRAULIC MODEL STUDIES

3.1 Introduction.

Experiences with the technique of hydraulic model studies were gained when model tests with remote controlled ship models were carried out for the navigational channels into Grindavik harbour. The tests were done during 1995-1996 and improvements were carried out during the years 1998 to 2002 by dredging the new entrance channel straight into the harbour and by constructing two Icelandic berm breakwaters to shelter the inner part of the entrance channel. The outer part of the new channel, Fig. 5 is 650 m long with 10 m water depth and 70 m wide and the inner part is 450 m long with 7 m water depth and 37 m wide. The Grindavik bay is about 1700 m long from its apex at the harbour entrance to the 30 m water contour. The bed in the innermost part of the bay consists mostly of lava with very irregular bottom contours. The old natural navigational channel into the harbour consists of three sections: the Approach Channel, the Reef Channel and the Entrance Channel.

![Figure 5: The layout showing the new straight navigational channel and the two Icelandic berm breakwaters into Grindavik harbour.](image)

The entrance is exposed to severe breaking waves, as the significant wave heights up to 16.7 m have been recorded offshore.

The criteria for safe navigation were established during the model tests of the Grindavik entrance as:

- Number of breaking waves in irregular sea with duration of 33 minutes.
- The navigational channel is open for fishing boats if less than 4 breaking waves are encountered in the channel.
- The navigational channel is closed for boats if 2 to 3 waves break after each other or 10 to 12 waves break which means less than 6% of the waves break during 33 minutes.
- Navigation with 49 m long remote controlled trawler confirms these criteria.

As a conclusion, navigation is regarded safe for fishing vessels up to 6% breaking waves according to the model tests and up to 10 % for larger fishing vessels according to the field experiences. Due to the success with a remote-controlled model ship, sailing through breaking waves, and later with the prototype experiences by the captains which confirm the tests into Grindavik harbour, Fig. 5, it was decided to use the same technique in the model for Bakkafjara ferry harbour, regarding the ship model, the generated waves in the model and the technique to evaluate the tests.

3.2 Navigational tests

Hydraulic model tests were carried out to investigate the wave disturbance in the Bakkafjara ferry harbour and to undertake navigational tests with a remote-controlled model ferry, sailing through the wave breaking zone into the harbour. The main emphasize was to establish criteria for safe navigation for the remote-controlled model ferry over the bar where intensive wave breaking occurs.
Figure 6: The upper figure to the left shows the location of the wave buoys (t3) and the navigational line (t1 to t2). The lower figure shows the depth along the navigational line. To the right is the layout of the physical model.

The model layout of the Bakkafjara ferry harbour with the deep trough at 10 – 12 m depth and the bar with the depth of 6 m at low tide is shown in Fig. 6. The model was built in the scale 1:60. Only two wave directions were tested from south-west/south-east and south together with three water levels at mean low tide 6.5 m, mean tide 7.4 m and mean high tide 8.3 m as the angle between wave direction from south-west/south-east to south is almost the same.

The proposed ferry was 49 m in length, with a beam of 12 m and a draft of 3.5 m and with intact stability of GM = 1.0 m. The ship model used was 50.1 m in length, with a beam of 10.8 m and a draft of 4.0 m and GM=1.0 m. The ship model was the same as used in previous model tests for Grindavik harbour.

Figure 7: Wave breaking at the bar in the prototype and in the model with the remote controlled model ferry.

Navigational criteria established for the ferry over the bar into the ferry port were:

- The number of breaking waves
- Measure wave height at 18 m, 15 m, 10 m and 6 m in front of the bar, at the top of the bar and at 10 m depth landward of the bar and in front of the entrance of the ferry harbour.
- Sailing a remote-controlled model ferry,
• Evaluation of the total depth based on wave height, tidal elevation and the draft of the ferry.

The navigation is regarded safe for the ferry when up to 10% of waves break on the bar between 10 m and 6 m depth which stretches about 250 m along the navigational line.

The irregular wave generated in the model was measured along the navigation line over the bar into the harbour entrance and along the navigational channel inside the harbour to the ferry berth. The numbers of breaking waves were counted in front of the bar, at the top of the bar and behind the bar. The shippers that ran the remote-controlled ferry model had over 16 years experience as masters and chief mate on the existing ferry between Westmann Islands and Thorlakshofn harbour.

Each test consists of navigating the ferry from the berth through the navigational channel and over the bar out to the 15 m depth contour and then returning into the harbour. The speed of the ferry inside the entrance was 6 knots but 8 knots along the navigational line outside the harbour. The wave height was increased in steps for each run until critical navigational condition was achieved according to the master. The results are shown in Table 1 and 2.

<table>
<thead>
<tr>
<th>Wave direction \ water level</th>
<th>+2.3 m</th>
<th>+1.4 m</th>
<th>+0.5 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>South wave direction</td>
<td>4.5/4.1</td>
<td>4.2/4.6</td>
<td>3.9/4.1</td>
</tr>
<tr>
<td>(4.5 m at 10 m depth/4.1 m at the bar)</td>
<td>4.5/4.0</td>
<td>4.0/4.4</td>
<td>3.6/3.9</td>
</tr>
<tr>
<td>South-west / south-east wave directions</td>
<td>4.6/4.1</td>
<td>4.5/3.8</td>
<td>4.1/3.3</td>
</tr>
<tr>
<td>4.6 m at 10 m depth/4.1 m at the bar</td>
<td>4.4/3.9</td>
<td>4.4/3.8</td>
<td>4.2/3.4</td>
</tr>
</tbody>
</table>

Table 1: Critical wave heights at two location, 10 and 6 m depth over the bar for two different wave conditions. There are 180 m between the wave gauges.

<table>
<thead>
<tr>
<th>Wave direction \ water level</th>
<th>+2.3 m</th>
<th>+1.4 m</th>
<th>+0.5 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>South wave direction</td>
<td>7.6%</td>
<td>10.0%</td>
<td>11.1%</td>
</tr>
<tr>
<td></td>
<td>6.3%</td>
<td>9.9%</td>
<td>8.7%</td>
</tr>
<tr>
<td>South-west / south-east wave directions</td>
<td>3.0%</td>
<td>5.5%</td>
<td>7.2%</td>
</tr>
<tr>
<td></td>
<td>2.2%</td>
<td>7.2%</td>
<td>6.9%</td>
</tr>
</tbody>
</table>

Table 2: Number of breaking waves during critical wave conditions for two different waves.

The breaking criteria, where and how the waves break, are a function of the limiting wave steepness \( \left( \frac{H_b}{L_b} \right) \). Kamphuis (1991) proposed criteria for irregular waves which is based on extensive model testing and uses the definitive wave height at breaking:

\[
\frac{H_{sb}}{d_b} = 0.56 \ e^{3.5 \ m}
\]  

This expression includes the influence of the bar slope \( m \). Significant breaking wave height was determined as \( H_s \) were plotted against depth. The slope in front of the bar at Bakkafjara is \( m=1/50 \) and based on Rayleigh distribution:

\[
\begin{align*}
H_{02} / d_b & = 0.43 \ \text{equal to} \ 2\% \ \text{of the waves breaks} \\
H_{06} / d_b & = 0.51 \ \text{equal to} \ 6\% \ \text{of the waves breaks} \\
H_{10} / d_b & = 0.56 \ \text{equal to} \ 10\% \ \text{of the waves breaks}
\end{align*}
\]
The breaking characteristics of waves may now be determined by combining wave refraction calculation at the wave buoy location at Bakkafjara with the above wave breaking criteria and the results of the wave measurements in the model at critical conditions according to the master. As shown on figure 9.

Figure 9: Critical significant wave height along the navigational line for different water depth with waves from the south, south-west and south-east. Surface elevations: black: +2.3 m, green: +1.4 m and red: +0.5 m. Full drawn lines: numerical results and dots physical results.
The numerical wave model seems to capture the measured variation in wave height well, taking into consideration that the physical model is using uni-directional waves and that the wave model does not account for wave reflection.

### 3.3 Wave height criteria for the remote controlled model ferry

In Fig. 10 the critical wave heights at the wave buoy location at Bakkafjara is plotted against the different water levels for the three wave directions. The waves seem to vary linearly with the water elevation. Particularly, the variation of the “weighted wave heights” with 51.7% occurrence of south-westerly waves, 22.5% of southerly waves and 25.8% of south-easterly waves follows the approximation:

\[ H_s = 3.4 + 0.2 \times WL \quad (2) \]

where \( WL = \) water elevation.

![Figure 10: Critical wave heights at the wave buoy at Bakkafjara as a function of water levels for wave directions from south, south-west and south-east.](image)

The necessary depth for safe navigation is the draft (h) of the vessel in addition to 2/3 of the significant wave height defined by the breaking equation (1) for 10% wave breaking at mean low tide.

\[ d_{b10} = 2/3 \times 0.56 \times d_{b10} + h \quad d_{b10} = 1.60 \times h \]

The draft of the model was 4 m so the necessary depth is 6.4 m at mean low tide compared to 6.5 m in the model for 10% breaking waves.

### 3.4 Wave height criteria for the existing ferry

The existing ferry is 70.5 m long with a beam of 16.0 m and a draft of 4.3 m. Taking into account the experiences from Grindavik model tests and the size of the existing ferry together with the experience gained by the captains when sailing up to six times per day between Westmann Islands and Bakkafjara ferry harbour, the wave height criteria at the Bakkafjara wave buoy must be lowered by the difference in the draft of (4.0/4.3) at mean low tide for 10% critical wave conditions:

\[ H_s = 3.2 + 0.2 \times WL \]

### 3.5 Wave height criteria for the proposed new ferry

The size and the displacement of the proposed ferry was similar to the existing ferry but with much lesser draft of 3.3 m. As the ferry is no longer depth limited at low tide the safe navigation wave height criteria has been increased by 5% from the model tests.

Significant wave criteria for the proposed ferry are seen to vary linearly with the water level, WL:

\[ H_s = 3.6 + 0.2 \times WL \]
3.6 Down time evaluation

Based on wave buoy analysis for the years 2003 – 2006, the down time during an average year according to the significant wave criteria for the ferries are:

- **Significant wave criteria for the existing ferry** \( H_s = 3.2 + 0.2 \times WL \), down time 5.0 %
- **Significant wave criteria for the physical model** \( H_s = 3.4 + 0.2 \times WL \), down time 3.9 %
- **Significant wave criteria for the proposed ferry** \( H_s = 3.6 + 0.2 \times WL \), down time 2.8 %

4. SEDIMENT TRANSPORT AND MORPHOLOGY AT BAKKAFJARA

4.1 Introduction

The area of the proposed location is characterized by a deep trough up to 10 -12 m and depression in the bar at a water depth of around 6 m at low tide. The purposes of the comprehensive hydraulic studies were:

- To understand the physical processes, which determine the location of the depression in the bar
- To optimize the harbour layout to have minimum impact on the overall morphology and minimum sedimentation into the harbour.

The proposed location has been investigated by detailed analysis of waves, currents, sediments transport and morphological conditions in the coastal water at Bakkafjara in close cooperation with the DHI Denmark.

4.2 Evaluation of the sediment pattern along the coast

Wave refraction analysis from offshore to near shore has been undertaken intensively. These wave analyses show minimum wave height along the navigational line into the harbour for south-west offshore wave direction. The most common south-westerly waves lead to east going littoral drift along the entire stretch, but the east going transport capacity decreases from west to east into the zone sheltered by the Westmann Islands. These waves pass behind the Westmann Islands and push the net littoral drift on the outer bar to the west. During years of dominant waves from south-west the western part of the bar will grow toward east. During years of severe south-easterly waves the tip of the western breaker bar will be pushed back towards west.

The calculated average distributions of littoral drift are shown in Fig. 12 for three sections. To the west of the harbour the average littoral drift of 300,000 m³/yr, profile 2 is east going along the bar as well as along the inner profile. To the east of the river the average littoral drift of 400,000 m³/yr, profile 8 is east going along the inner part of the profile as a bar has not developed here. At the location of the harbour, profile 5, the net littoral drift is east going on the inner part of the profile and west going on the breaker bar. This sediment transport pattern is due to the sheltering effect on waves from the Westmann Islands.

The morphology of the river mouth and the delta vary strongly from year to year. Waves from south-east push the river mouth to the west whereas waves from south-west push the mouth to the east. The delta grows during smelting periods of the glacier. The river outflow where smelting of a glacier during spring and summer supplies about 1 mill. m³/yr fines and about 150,000 m³/yr of sand to the coastal zone. A guiding wall will be established east of the harbour along the river to avoid migration of sand from the estuary to the west of the harbour.
Figure 12: Average littoral drift and the distribution along the coastal profiles at locations west of, at and east of the planned harbour. Note different scales for sedimentation transport.

Analysis of littoral drift capacity during the period 1959-2006 has shown that no continuous event, or series of storms, has led to west going transport at the location of the delta of more than 500,000 m$^3$, which correspond to a few hundred metres of spit formation. The east going littoral drift is more common and many events are registered where the littoral drift on the outer bar east of the harbour exceeded 150,000 m$^3$.

Figure 13: Average offshore wave energy direction and wave energy, 1959 – 2006. East going littoral drift at Bakkafjara for directions > 195° and west going for directions < 180°.
As shown in Fig. 4 the outer bar has almost closed off the depression of the bar during the last few years. However, analysis of a long time series for average wave energy and direction of the average offshore wave energy, see Fig. 16, clearly indicates that this is not the most common situation.

In the past years there have been a series of years with high energy from south-westerly directions which has led to lengthening of the bar from west towards east. Fig. 14 shows the details of the variations of the two determining parameters wave energy and average wave direction during the period of measurements. Fig. 4 and Fig. 14 can be compared and it appears that the dynamic behaviour of the depression can be explained. The risk of having to dredge the depression through the outer bar has been evaluated and found acceptable for the project. It is noted that the required navigational depth is 6 m.

![Figure 14: Average offshore wave energy direction and wave energy, 2000 – 2006. East going littoral drift at Bakkafjara for directions > 195° and west going for directions < 180°.](image)

The magnitude of the rip current is controlled by the gradient in the surface elevation. In Fig.15 the surface elevation for conditions with waves from south-west and south is depicted. The figure clearly shows the variation in water level along the coastline with south-westerly waves changing from 1.4 m at approximately 4 km west of Bakkafjara to around 1.15 m in the sheltered area near Bakkafjara. The difference in surface elevation is approximately 25 cm which is of a magnitude fully capable of driving a relatively strong current. For the southerly waves the gradient increases even further with a change in surface elevation 30 cm over 800 m.

![Figure 15: Surface elevation under south-western (upper) and southern (lower) storm conditions. Colours: surface elevation. Isolines: bathymetry](image)
The rip current will maintain a depression in the outer bar where the waves are at minimum; however, the dimensions of the depression are a function of the wave height and wave direction. The dimensions are determined by the continuous “battle” between the scouring effect of the rip current and the infill of sediment transported by the long-shore current along the outer bar on the up-drift side and erosion on the down-drift side. The long-shore current is strongest when the wave angle is 45 degrees to the coastline and weakest when waves attack perpendicularly, thus dominant rip scouring may be expected when the waves approach from SSW (or SSE).

4.3 Dredging through the depression of the outer bar.

To understand the physical processes involved, excavation down to 7 m at low tide through the bar over a distance of 150 m was investigated. In Fig. 16 the model bathymetry with the described modifications in the morphology is shown where the white rectangle indicates the model output area.

![Model bathymetry for morphology with excavation of bar](image)

**Figure 16:** Model bathymetry for morphology with excavation of bar

The simulated bed levels were extracted along a line across the excavation, shown as a black dashed line before and after the storm, Fig. 14. The morphological changes are presented in Fig. 18 after running a mature south-westerly storm event from February 1989. It is seen that the excavation is displaced in the eastward direction by approximately 70 m (the 6 m contour line). The water depth in the central part of the excavation is increased by 10-20 cm over the period. This case shows exactly the two mechanisms at play. The resulting level of the bar is a continuous battle between the rip current induced erosion and the deposition of sand caused by the long shore current. The present storm is seen to displace the depression eastward and although the water depth over the depression is increased the depth at the navigation line is decreased.

![Morphological changes during February 1989.](image)

**Figure 17:** Morphological changes during February 1989.
Figure 18: Simulated bed levels along the excavation before and after the February 1989 storm.

In the case of excavating part of the outer bar the bar is more stable implying that the excavated area with water depth of 7 m is closer to being in equilibrium with the forcing conditions of the selected period. This investigation shows that the depression in the outer bar is a persisting feature in the morphology and that the reason for the depression is the transport induced by alongshore variation in the wave set-up.

The depression in the bar can be explained. The depression in the outer bar will decrease during years of unfavourable wave conditions from SSW, however, will increase and be re-established during years of SE storms and SW storms

Unfortunate combinations of storms may remove the depression in the bar. Historically, other combinations of storms will re-establish the depression. The deep trough off Bakkaljara is stable. The port can be designed to almost always have sufficient depth off the entrance.

4.5 The lay-out of the harbour.

The distance between the breakwaters at shore was originated 900 m and the breakwaters extend approx. 700 m from the shore line out to the present 8 m depth contour located at the deep through. The entrance width was originated 70 m with a 40° angle layout between breakwaters. During the final design of the harbour lay-out, the distance between the breakwaters was decreased to 600 m and the entrance width was increased to 90 m together with an increase of the angle layout to 65°angle between the breakwaters. When it was realized that the existing ferry will be used the next years, the width of the entrance was increased in accordance to the beam of the ferry from 70 m to 90 m as the beam of the existing ferry is 16 m compared to 10.8 m for the model ferry. The channel width is determined in accordance to the Approach Channel a Guide for Design (PIANC/IAPH) “Approach Channels, Preliminary Guidelines” (1997) taking into account the presence of the cross current (rib current) at the harbour entrance. The critical water depth of 5.5 m has been defined for the entrance area. The requirement on entrance area water depths is defined to ensure that the ferry will be able to navigate safely through the entrance. The entrance is made of rubble mound berm heads supplemented with fender dolphins along the entrance to provide protection to the ferry during approach. It is noted that the required navigational depth at the bar is 6 m. The methodology is in accordance with accepted standards for the actual planning level.

4.6 The equilibrium depth in front of the harbour.

Due to the streamline shape and the narrow entrance the majority of the sand will bypass the harbour and it appears that the impact on the adjacent coastline is very small. The bathymetry will adjust to a depth in front of the harbour which allows the sand migrating in the inner part of the coastal profile from the west towards the harbour to bypass. Erosion on the updrift side of the harbour will occur both on the western and the eastern breakwaters due to the accelerations of the current speed along the breakwaters following the contraction of the field towards the entrance of the breakwaters. The erosion at the base of the western and eastern breakwaters is found to be in the order of 3 m with respect to initial bathymetry. It should be noted that once the equilibrium depth in front of the entrance is reached, sediment will bypass on the bar and reduce the erosion.

Examples of results are presented in Fig. 19 for rough south-west wave height of 3.7 m to the left and rough south-east wave height of 6.9 m at the Bakkaljara wave buoy to the right. The upper panels show the bathymetry measured May 2006 and the harbour layout. The second panels show the
modelled bathymetry after 200 days with constant severe waves from south-west and from south-east directions. The third panel in Fig. 19 shows a close-up around the entrance.

Figure 19: Upper panels: initial bathymetry, second panels: modelled bathymetry of constant wave action of 3.7 m at the wave buoy from south-west to the left and to the right south-eastern wave of 6.9 m, third panels: close-up around the harbour entrance with morphological changes at three points off the harbour.

The presence of the harbour is seen to have an immediate impact on the morphology in the vicinity of the harbour. The most prominent development in the morphology is found on the up-drift side of the harbour along the breakwaters. Here a bar is building up to accommodate the bypass of sediment. The bar is seen to migrate towards the entrance, however, only to a certain point. The build-up of the bar comes to an end as the equilibrium between the sediment transport capacity and the water depth is attained. This happens when the sediment transport capacity becomes constant along the streamlines. As the flow is concentrated in the area in front of the entrance the depth must increase until the sediment transport capacity becomes constant.

For the rough south-easterly conditions the littoral sediment is transported to the west and near the harbour the sediment is seen to bypass along two main sediment routes; one close to the eastern breakwater and one along the existing outer bar. Along the eastern breakwater sediment is seen to form a bar in a way similar to the bypass bar formed during rough south-westerly conditions.

Several combinations of wave directions and height have been modelled with both cases of wide and narrow harbour configuration and with the angle between the two main breakwaters of 40° and 65° to support the design of the harbour with special emphasizes on the required navigational depth of 5.5 m. These morphological simulations show that the wider configuration has lower bypass depth than the narrow one and that there are only small differences in bypass depth between angle 40° and 65° and low wave conditions from south-west direction are the critical in terms of fulfilling the navigational depth requirement of 5.5 m. In conclusion, the differences between the three layouts are considered small.

Typical examples of results are presented in Fig. 20 for an angle between the breakwaters of 40° where the water depth in front of the harbour is seen to stabilise at around 5.5 m after several months.
Figure 20: Typical examples of results for an angle between the breakwaters of 40° where the water depth in front of the harbour is seen to stabilise at around 5.5 m after several months.

Further, the sedimentation of sand in the fore-harbour due to eddy exchange has been estimated as well as the sedimentation of fines during the periods where the adjacent river discharges large amounts of fine sediments.

4.7 Sedimentation of sand into the harbour.

The sedimentation of sand into the harbour has been estimated as well as sedimentation of fines during the periods where the adjacent river discharges large amounts of fine sediments. For the entrance width of 90 m the initial rate after construction is estimated to sediment ca 5,600 m³/yr and after approximately 10 years and beyond the mean sedimentation rate is increased to 30,000 m³/yr. The annual sediment rate will, however, change significantly due to the unusual much variability in the wave climate as shown in Fig. 13 and 14. During calmer years the sedimentation rate will be approximately half of the average rate whereas during rough years it will be several times the average.

4.8 Accumulation of Fine Suspended Sediments

The volume of the water that enters the harbour each day is approximately 500m x 600m x 2 m = 600,000 m³. This means that each month a volume of ca. 600,000 x 30 x 2 = 36 mill m³ enters the harbour basin. Assuming the significant concentration for 2 months per year and assuming that this concentration is 100 ml/l the sedimentation inside the harbour is 2,700 m³ per year. The sedimentation will accumulate evenly in the entire harbour basin and will lead to annual sedimentation thickness height of about 1 cm.

5.0 CONSTRUCTION OF THE BERM BREAKWATERS

5.1 The Icelandic Berm Breakwater.

Berm breakwaters were introduced in the early 1980’s as an alternative to traditional rubble mound breakwaters, Fig. 21. The fundamental principles of the berm design philosophy are that not only is the expected wave load taken into account but also the potential yield from the available armour stone quarry, available construction equipment and the pursued function of the breakwater.
Berm breakwaters have proved themselves successful in the subarctic climate of Iceland where violent storms and surge are not uncommon in wintertime. After intensive model tests in 3D hydraulic physical models at IMA and prototype experiences the engineers at the Icelandic Maritime Administration have developed a certain distinctive type of the berm breakwater, the stable berm breakwater or the Icelandic-type Berm Breakwater characterized by several stone classes arranged in a stable structure. The main advantage of the Icelandic-type Berm Breakwater is its endurance to strain as was proven in Sirevåg Norway, where a berm breakwater of this category designed by the engineers of the IMA withstood a design storm without any notable damage. In addition to its suitability under difficult weather conditions the Icelandic-type Berm Breakwater has proven to be economically advantageous and manageable to build even with limited resources.

5.2 Landeyjahöfn Ferry Harbour – Estimate of material and cost

According to the time schedule, the construction of the ferry harbour commenced in August 2008 and will be completed in July 2010. The existing ferry will start service in the summer 2010.

The Landeyjahöfn harbour project consists of two 700 m long Icelandic Type Berm Breakwaters, 4.8 km of revetments, dredging, a quay and access road. The proposed entrance width is 90 m and the initial water depth at the entrance is approximately 8 m. The navigational channels in the harbour will be dredged down to -7 m in the outer part of the channel and down to -5.5 m in the inner part and in the manoeuvring area.
Figure 23: Construction of the breakwaters at Landeyjahöfn Port.

An estimated 650,000 m$^3$ of rock are needed to build the two breakwaters, another 50,000 m$^3$ of rock and 200,000 m$^3$ of gravel to build the revetments. The estimated total required dredging is 250,000 m$^3$. The quay for the Westmann Islands ferry will be 100 m (70 m + 2x15 m) long with a water depth of 5.5 m. A 250 m$^2$ service house is planned for e.g. ticket sale, waiting lounge for passengers and a walking bridge for boarding the ferry. Parking facilities are estimated to hold 200 cars with an overall area of 4 hectares.

Figure 24: Arial view of Landeyjahöfn Port in August 2009.

The access road, including a bridge, to and from Landeyjahöfn will be 11.8 km long and is connected to Highway 1, as well as a connection with the nearby located airfield. It is expected that the sandy coast will be covered with grass in the year 2010 and there are also plans to build manes around the ferry area to protect the area from wind driven sand.

The estimate cost for this project is as follows:

- Breakwater, revetments and dredging: 2,400 million ISK
- Harbour quay and service house: 600 million ISK
- Access road and bridge: 780 million ISK
- Other construction costs: 400 million ISK
The total estimated cost for the Landeyjahöfn Port project amounts to 4,180 million ISK. This amount is related to the price index from May 2009 and includes all costs for preparation, design, construction and supervision. The total estimated cost as of April 2006 (price 2009) was 4,435 millj. ISK in March 2007 5,200 millj.ISK.

The Landeyjahöfn ferry harbour will be operated by the Icelandic Maritime Administration and the ferry will be operated by shipping company Eimskip under the supervision of the Road Administration.

A suitable quarry was found some 500 metres over sea level in a nearby mountain 19 km from the construction site. The quality of the Ankaramit Basalt rock is good and the expected size distribution is some 6.5 % between 12 – 30 tonnes, 13 % between 5 – 12 tonnes and some 45 % between 0.2 – 5 tonnes.

Construction of the berm breakwaters began on 16 May 2009 when the first quarry load was dumped by the contractor Sudurverk in the sea at Bakkafjara. In the middle of August the quarry core mound was completed and the placement of the rocks commenced. Work on the berm breakwaters was completed in October except the breakwater heads as 5 m thick layers of the final large rock-placement along the heads is expected to be completed in February 2010.

5.4 Preliminary results of the morphological changes during construction of the berm breakwaters

During the construction period the waves have been easterly and south-westerly as shown in Fig, 25 where the wave roses for the construction period so far can be compared with the average wave roses for the last 50 years.

![Wave Roses](image_url)

**Figure 25: Wave Roses offshore at 63°N, 21°W, 1958 – 2002 ECMWF ERA 40 and for the construction period from May to end of December 2009.**

A bathymetric survey was undertaken on 21 May 2009 before the construction commenced. Since then, bathymetric surveys were carried out on 13 August, on 1 October, and to some extend on 16 November 2009. The results presented in this paper are preliminary results and the final results will be presented during the PIANC Congress in May 2010.
Figure 25: Differential plan for bathymetry from 16 May to 1 October to the right and 1 October to 16 November 2009 to the left.

As shown in Fig. 26 the depth of the bar has increased from 6 m to some 6.7 m and the depth some 50 m in front of the entrance has decreased from 8.3 m to some 5.9 m during the constructions of the breakwaters from May to middle of November. Minor changes have occurred at the bar 200 m west and east of the navigational line. The depth has decreased 200 m west of the line due to a south–westerly storm in December 2009.
6. CONCLUSIONS

At the present time the new ferry harbour is under construction and will be open for service in the middle of July 2010. The paper presents the experience gained by the IMA staff by investigating the harbour structures on the exposed south coast of Iceland. The ferry project has been investigated by detailed analysis of waves, currents, sediment transport and morphological conditions in the coastal waters at Bakkafjara in close cooperation with the staff of DHI, Denmark. The paper deals with the combination of analysis of the navigation through breaking waves in the coastal environment, quantification of littoral drift in order to understand the overall processes and the detailed analysis of the processes around the new harbour for optimising the layout with regard to impact and sedimentation. So far, the whole project has been according to the investigation carried out.

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The author has drawn on experience from various studies undertaken by the staff of IMA in Iceland and abroad over the past 40 years. The studies have been investigated by detailed analysis of waves, currents, sediment transport and morphological conditions in the coastal waters at Bakkafjara in close cooperation with DHI, Denmark by using the Danish software and expertise under supervision of Ida Brøker head, Coastal & Estuarine Dynamics.

8. REFERENCES


