engineering for man-made islands in the arctic

PORT AND WATERWAY ENGINEERS
Engineering for man-made islands in the arctic

- marine engineering
- coastal engineering
- nautical engineering
- port engineering
- project development
- project management

PORT AND WATERWAY ENGINEERS
HYDRONAMIC B.V. is one of the pioneers in the field of design and construction of artificial islands in the Arctic (and in other parts of the world as well).

The company provides consultancy services and is involved in turnkey projects in the fields of:
- river, coastal, offshore and nautical engineering
- construction techniques and equipment development
- feasibility and design studies
- project management

Our strong suit is that realistic consideration can be given to cost and execution aspects while operations are still in the feasibility and design phase.

This document presents a review of the many engineering aspects relating to the design and construction of structures in the Arctic. Examples from our own engineering practice are used in illustration, so that the reader may also gain an impression of our project capability and versatility.

The aim of this document is to present an overall impression of the many current aspects of coastal and offshore engineering in the Arctic regions and HYDRONAMIC's involvement therein. Numerous examples are drawn from HYDRONAMIC's own engineering experience.

We shall explain how complex mathematical models could be used. We also hope to show that not everything the engineer does is necessarily complicated. In many cases, if we want to compare concepts or if accurate data are lacking, a simple approach is both useful and justified. To this end we have developed straightforward calculation methods, so that we can give quick, to-the-point and practicable answers to our clients. Our practical, client orientated, approach is a logical consequence of our co-operation with sister companies, both in the field of engineering and the execution of hardware projects.
# TABLE OF CONTENTS

## FOREWORD

<table>
<thead>
<tr>
<th>1. GENERAL INTRODUCTION</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7</td>
</tr>
</tbody>
</table>

## 2. ISLAND CONCEPTS AND THEIR PRESENT STATE OF DEVELOPMENT

<table>
<thead>
<tr>
<th>2.1 General</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2 Shallow water: silt and gravel islands</td>
<td>10</td>
</tr>
<tr>
<td>2.3 Intermediate depth: sand and gravel islands</td>
<td>10</td>
</tr>
<tr>
<td>2.4 Islands beyond 30 m in depth</td>
<td>11</td>
</tr>
<tr>
<td>2.5 Summary of offshore islands</td>
<td>11</td>
</tr>
<tr>
<td>2.6 Islands in the Mackenzie River</td>
<td>11</td>
</tr>
</tbody>
</table>

## 3. ENVIRONMENTAL BOUNDARY CONDITIONS

<table>
<thead>
<tr>
<th>3.1 General</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2 Wind climate</td>
<td>15</td>
</tr>
<tr>
<td>3.3 Water depth</td>
<td>15</td>
</tr>
<tr>
<td>3.4 Waves</td>
<td>15</td>
</tr>
<tr>
<td>3.5 Sediment transport</td>
<td>15</td>
</tr>
<tr>
<td>3.6 Tide</td>
<td>18</td>
</tr>
<tr>
<td>3.7 Ice</td>
<td>18</td>
</tr>
<tr>
<td>3.8 Soil</td>
<td>20</td>
</tr>
<tr>
<td>3.9 River discharge</td>
<td>25</td>
</tr>
</tbody>
</table>

## 4. ISLAND DESIGN

<table>
<thead>
<tr>
<th>4.1 General design aspects</th>
<th>27</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2 Erosion by waves and currents</td>
<td>27</td>
</tr>
<tr>
<td>4.3 Slopes requiring protection against wave attack</td>
<td>29</td>
</tr>
<tr>
<td>4.4 Design of vertical walls</td>
<td>31</td>
</tr>
<tr>
<td>4.5 Ice forces</td>
<td>31</td>
</tr>
<tr>
<td>4.6 Soil mechanical aspects</td>
<td>34</td>
</tr>
<tr>
<td>4.7 Islands in a river</td>
<td>34</td>
</tr>
</tbody>
</table>

## 5. EXECUTION METHODS

<table>
<thead>
<tr>
<th>5.1 Introduction</th>
<th>37</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2 Dredge systems</td>
<td>37</td>
</tr>
<tr>
<td>5.3 Operational features</td>
<td>37</td>
</tr>
<tr>
<td>5.4 New concept</td>
<td>38</td>
</tr>
</tbody>
</table>
6. EXECUTION ASPECTS

6.1 General 41
6.2 Environmental aspects 41
6.3 Performance of dredges in ice 41
6.4 Accurate placement of fill material 46
6.5 Placement of caissons 46
6.6 Using a service harbour 46

7. ENGINEERING ASPECTS OF A WINTER HARBOUR, FIELD DEVELOPMENT BASE OR OFFSHORE TERMINAL

7.1 Introduction 49
7.2 Access channel 49
7.3 Harbour layout and protective structures 50
1. General introduction.

This document presents a review of the many engineering aspects of design and construction of structures in Arctic waters. Examples from HYDRONAMIC's own engineering practice are used in illustration. The objectives of the presentation are:

- to draw attention to specialist engineering aspects
- to show the interrelation between environmental boundary conditions, practicable execution methods, and possible design concepts
- to demonstrate HYDRONAMIC's practical project approach

For logical reasons, the references relate to island design and construction and to the necessary infrastructure such as a winter harbour with adjoining field development base or an offshore terminal.

The division of subject matter in this document is based on the simplified flow scheme for an island as drawn in fig. 1.

Chapter 2: Island concepts and general state of development. This chapter can be considered as a kind of historical review. Per island concept, we indicate the present state of development (pre-design, final design, construction, in use). The concepts are also discussed in relation to the environmental boundary conditions (blocks (1) and (2) of flow scheme).

Chapter 3: Environmental boundary conditions. The various boundary conditions are dealt with. It will

Fig. 1: Flow scheme for island design
be explained how these data can be gathered, interpreted and used (block (1)).

Chapter 4: Island design. In this chapter we go into some detail about the dimensioning of the various parts of the island, considering the forces exerted by the environment both during and after construction (block (4)).

Chapter 5: Execution methods. Examples are used to indicate which execution methods should be considered and how greatly their selection depends on the environmental boundary conditions (block (3)).

Chapter 6: Execution aspects. A rather arbitrary selection of specific execution aspects is made. The impact of the execution of works on the environment is also touched upon (block (5)).

Chapter 7: Engineering aspects of the design of a winter harbour, field development base or offshore terminal. Some specific coastal engineering and nautical aspects of the design of these facilities are dealt with.
2. Island concepts and their present state of development.

2.1. General

Nearly all the islands so far constructed in Arctic regions have been temporary exploration islands. The need for offshore production islands, especially in deeper waters, is still some years off. Conceptual designs are already being developed.

The basic difference with the temporary islands is that production islands have to be larger, while their constructional and operational integrity has to be safeguarded over a much longer period (‘temporary’ versus ‘permanent’).

The history of island construction in the Arctic seas runs parallel with the move from shallow to deep waters. We maintain the same order for our brief account of that history. The islands in the Mackenzie River are dealt with separately. Per range of water depth, we shall indicate the present state of development, distinguishing between the following phases:

- conceptual design and feasibility (phase I)
- detailed design and construction (phase II)
- exploration and/or production (phase III)

Some design features of the various island types will also be discussed.

Fig. 2: Construction of an island in shallow water
Fig. 3: Construction of an island in Mackenzie Bay

The depths mentioned for concept limits are merely indicative and may vary considerably depending on local conditions.

2.2. Shallow water: silt and gravel islands

The first islands constructed were silt and gravel islands in the Mackenzie Bay and Prudhoe Bay, at depths in the range of 3 to 5 m. Silt islands were constructed with floating grab cranes, while the material for the gravel islands was hauled, in the winter season, over the ice.

2.3. Intermediate depth: sand and gravel islands

Between 1975 and 1982 islands up to a depth of approx. 20 m were designed and constructed in the Mackenzie Delta. Most islands beyond the 10 m depth contour were constructed by using hydraulic dredges. To reduce on the quantity of fill material, various design concepts and construction methods employing steeper slopes are in the process of development. In Prudhoe Bay, island construction at this depth range has not yet been effected. In comparison with the Mackenzie Delta ice conditions are worse, resulting in a shorter ice-free working season. This problem is stimulating the development of improved, and even entirely new, techniques for island construction. In this respect thought is being given to ice-breaking dredges or to a dredge system working from the landfast ice.

2.4. Islands beyond 30 m in depth

For greater water depths other island concepts may well prove more...
feasible than the 'traditional' sand and gravel islands. Precise feasibility limits cannot be immediately established since these depend on too many factors, like availability of suitable borrow areas near the island site, availability of dredges capable of working at great depth, the duration of the working season, cost of methods to construct steep slopes, etc.

In the Canadian and Alaskan Beaufort Sea, caisson-retained islands are being developed. The first prototype was constructed in 1981 and more will follow. Other concepts use steel or filtercloth screens, or fibre boxes filled with sand and stacked stepwise.

Hybrid structures are also being designed. Possible collision with an ice island or an iceberg is considered to be a major design criterion for islands in deep water. For islands at a very great depth, as in the Labrador Sea or at the Grand Banks, the very bad environmental conditions to which the construction equipment and the structure themselves are exposed (storms accompanied by high waves) are an engineering problem of the first order.

2.5. Summary of offshore islands

In fig. 5 at the end of this chapter a summary of different design concepts for offshore islands, and the application of these islands, is presented. Some typical features with regard to the interaction between boundary conditions on the one hand and related design aspects (forces, strength, stability) and/or execution methods on the other are indicated in this summary.

2.6. Islands in the Mackenzie River

A design has been made for a number of production islands in the Mackenzie River. It was a major engineering task to prove their reliability in the event of a possible flood wave caused by the release of an upstream ice jam.

Fig. 4: Production island in the Mackenzie river
<table>
<thead>
<tr>
<th>GROUP</th>
<th>DEVELOPMENT PHASE*</th>
<th>I DEPTH 0-5m</th>
<th>I DEPTH 0-5m</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISLAND CONCEPT</td>
<td>PHASE III</td>
<td>PHASE III</td>
<td></td>
</tr>
<tr>
<td>Silt island with sandbag retaining wall and core of sand to support drilling equipment</td>
<td>Gravel island with sandbag slope protection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AREA</td>
<td>CANADIAN / ALASKAN BEAUFORT SEA</td>
<td>CANADIAN / ALASKAN BEAUFORT SEA</td>
<td></td>
</tr>
<tr>
<td>ENVIRONMENTAL BOUNDARY CONDITIONS AND RELATED DESIGN ASPECTS</td>
<td>- Temperature → Freezing of surface so that bearing capacity increases</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Subsoil → Stabilty</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Waves and currents → Stability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EXECUTION ASPECTS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GROUP</td>
<td>DEVELOPMENT PHASE*</td>
<td>II DEPTH 5-20m</td>
<td>II DEPTH 5-20m</td>
</tr>
<tr>
<td>ISLAND CONCEPT</td>
<td>PHASE III</td>
<td>PHASE III</td>
<td></td>
</tr>
<tr>
<td>Sand or gravel island with beach slope protection of sandbags</td>
<td>Sand or gravel island with retaining bund slope protection and retaining bund of sandbags</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AREA</td>
<td>CANADIAN / ALASKAN BEAUFORT SEA</td>
<td>CANADIAN / ALASKAN BEAUFORT SEA</td>
<td></td>
</tr>
<tr>
<td>ENVIRONMENTAL BOUNDARY CONDITIONS AND RELATED DESIGN ASPECTS</td>
<td>- Waves and currents → Beach erosion during construction</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Beach erosion and stability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EXECUTION ASPECTS</td>
<td>- Workability and equipment spread</td>
<td>- Workability and equipment spread</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5: Review of offshore island concepts
<table>
<thead>
<tr>
<th>II DEPTH 5 - 20 m</th>
<th>III DEPTH 20 - 100 m</th>
<th>GROUP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PHASE I</strong></td>
<td><strong>PHASE II (PROTOTYPE)</strong></td>
<td><strong>DEVELOPMENT PHASE</strong>*</td>
</tr>
<tr>
<td>SAND OR GRAVEL WITH BEACH SAND MATTRESSES</td>
<td>CAISSON RETAINED SAND OR GRAVEL ISLAND MODERATE WAVE ATTACK</td>
<td>ISLAND CONCEPT</td>
</tr>
<tr>
<td>CANADIAN / ALASKAN BEAUFORT SEA</td>
<td>CANADIAN / ALASKAN BEAUFORT SEA</td>
<td>AREA</td>
</tr>
<tr>
<td>- WAVES AND CURRENTS → BEACH EROSION DURING CONSTRUCTION → STABILITY OF SAND MATTRESSES</td>
<td>- WAVES AND CURRENTS → EROSION DURING CONSTRUCTION → STABILITY OF ELEMENTS → STABILITY OF TOE CONSTRUCTION</td>
<td>ENVIRONMENTAL BOUNDARY CONDITIONS AND RELATED DESIGN ASPECTS</td>
</tr>
<tr>
<td>- WAVEABILITY AND EQUIPMENT SPREAD - PLACEMENT OF SAND MATTRESSES</td>
<td>- WAVEABILITY AND EQUIPMENT SPREAD - LEVELLING OF BERM AND ACCURATE PLACEMENT OF ELEMENTS</td>
<td>EXECUTION ASPECTS</td>
</tr>
<tr>
<td><strong>III DEPTH 50 - 200m</strong></td>
<td><strong>IV DEPTH 50 - 200m</strong></td>
<td><strong>GROUP</strong></td>
</tr>
<tr>
<td><strong>PHASE I</strong></td>
<td><strong>PHASE I</strong></td>
<td><strong>DEVELOPMENT PHASE</strong>*</td>
</tr>
<tr>
<td>TWO CONCEPTS OF ISLAND WITH HEAVY SLOPE PROTECTION</td>
<td>HYBRID STRUCTURE</td>
<td>ISLAND CONCEPT</td>
</tr>
<tr>
<td>LABRADOR SEA / GRAND BANKS</td>
<td>CANADIAN / ALASKAN BEAUFORT SEA LABRADOR SEA / GRAND BANKS</td>
<td>AREA</td>
</tr>
<tr>
<td>- WAVES AND CURRENTS → EROSION DURING CONSTRUCTION → STABILITY OF SLOPE AND BERM</td>
<td>- WAVES AND CURRENTS → STABILITY SUBMERGED PAD → STABILITY AND STRENGTH OF CONCRETE / STEEL STRUCTURE</td>
<td>ENVIRONMENTAL BOUNDARY CONDITIONS AND RELATED DESIGN ASPECTS</td>
</tr>
<tr>
<td>- ICE → ICE BERG PENETRATION</td>
<td>- ICE → ICE BERG PENETRATION INTO SUBMERGED PAD → COLLISION OF ICE ISLAND AGAINST CONCRETE / STEEL STRUCTURE</td>
<td>EXECUTION ASPECTS</td>
</tr>
<tr>
<td>- WORKABILITY } EQUIPMENT SPREAD - DREDGING DEPTH - CONSTRUCTION OF BERTHS - CONSTRUCTION OF SLOPE PROTECTION</td>
<td>- WORKABILITY } EQUIPMENT SPREAD - DREDGING DEPTH - PLACEMENT AND BALLASTING OF CONCRETE / STEEL STRUCTURE</td>
<td></td>
</tr>
</tbody>
</table>

* PHASE INDEX: I CONCEPTUAL DESIGN AND FEASIBILITY II DESIGN AND CONSTRUCTION III EXPLORATION AND OR PRODUCTION

13
3. Environmental boundary conditions.

3.1. General

The natural environment imposes a great number of boundary conditions for the selection of the design concept. Directly, through the forces which are exerted on the island body and its parts, and their influence on the island stability. Indirectly, because the environment largely determines the equipment and building methods which can be used.

The following boundary conditions are dealt with in this chapter (the last one relates to island construction in a river):
- wind climate
- water depth
- wave climate
- tide
- ice conditions
- soil conditions
- river discharge

We give some examples to show how data already available can be interpreted and used for engineering purposes. In many cases site surveys have to be carried out to gather more data. Data on waves and currents can sometimes be obtained from hindcast calculations.

3.2. Wind climate

Wind is the driving force for the generation of (wind) waves and wind driven currents. Even in remote areas some representative wind data are usually available. The relevant engineering task is to gather these data and arrange the common and extreme wind speeds statistically.

3.3. Water depth

At offshore locations the water depth is the most fixed boundary condition. For many engineering calculations the depth contours in the project area have to be defined in a depth matrix. This matrix may be used, for example, to calculate the wave and current pattern and the sediment transport (erosion, sedimentation).

3.4. Waves

General information on waves, such as significant wave heights and their occurrence, is usually obtainable from handbooks. If there are no sufficient or relevant data for the project area, they can be calculated in the wind wave prediction model. The model takes following phenomena into account:
- fetch limited wave growth
- variability of wind wave direction
- effects of water body geometry
- bottom friction and bottom percolation
- wave breaking

3.5. Sediment transport

The driving forces for sediment transport are the (tidal) currents and the waves. The mathematical morphological model enables the sediment transport in a certain area to be calculated, using the calculations of the two dimensional tidal model, the wave penetration model and a calibrated sediment transport formula. In this respect calibration means that a formula with a sound theoretical background is used, the coefficients of which have been determined on the
Fig. 6: Computed wave heights in an estuary
basis of actual reference measurements.

After calibration, the morphological model can be used to predict the sediment transport in a newly created situation, for example after the construction of an island (chapter 4) or the dredging of an access channel (chapter 7).

The propagation of waves through an area can be calculated with the refraction programme (REFDIF), taking into account the effects of shoaling, refraction, diffraction, friction and percolation, the latter two in most cases being negligible.

Fig. 7: HYDRONOMIC's sediment-transport meter

Fig. 8: Calibration of a sediment formula

<table>
<thead>
<tr>
<th>BIJKER FORMULA</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEDIMENT CALCULATED WITH BIJKER</td>
</tr>
<tr>
<td>B = 4.00000</td>
</tr>
<tr>
<td>D50 = 1500000E-04</td>
</tr>
<tr>
<td>D90 = 1000000E-03</td>
</tr>
<tr>
<td>RIPPLE = 0.20000</td>
</tr>
<tr>
<td>CORRELATION = 0.783449</td>
</tr>
</tbody>
</table>

CALCULATED TRANSPORT (KG/SEC)
3.6. Tide

For many engineering projects the propagation of the tide into an estuary or an area sheltered by islands or reefs or into the mouth of a river has to be known. For an area of complex bottom geometry the two dimensional flow model can be used. To calculate the tidal movement in a river mouth, with or without branches, the one dimensional model (EXPLICIT) is suitable.

3.7. Ice

Ice can occur in different forms. To explain some of the engineering aspects of ice, we consider two different sea areas, viz. the Beaufort Sea and the Labrador Sea.

**Beaufort Sea**

Ice data which have to be known are:
- ice coverage
- ice strength and thickness
- distribution of new ice and multi-year ice
Fig. 11: Presentation of the occurrence of different conditions of ice coverage at different depths

Fig. 12: The diving bell used for soil investigations

- distribution and size of ridges
- seasonal aspects

It is the task of the engineer to gather these data and elaborate them, so that they can be used to design an island, resistant to the forces caused by the ice, and to plan the execution (working season, equipment spread, equipment development).

**Labrador Sea**

The ice conditions in the area are mainly of importance for determining the ice free period and for calculating the effect of iceberg collision. With regard to the latter aspect, shape, size, strength, occurrence and sailing speed of icebergs have to be known.

3.8. Soil

No structure, onshore or offshore, can be designed in detail, let alone constructed, before a good knowledge and understanding of the soil conditions has been obtained.
Fig. 13: Prediction of a flow pattern in the area where islands have to be constructed, after an ice-jam release
Fig. 14: Schematisation of a river system for the one dimensional flow model
Fig. 15: Deformation of the water-level profile after an instantaneous release of an ice-jam

Fig. 16: Branch velocities after instantaneous release of an ice-jam
Soil data should be available in order to:
- design a stable structure
- find a suitable borrow area for building material

There are several different methods of carrying out offshore borings:
- within the zone of landfast ice (Beaufort Sea within 40-60 ft depth contour):
  - ice free season: using floating equipment
  - winter season: using equipment standing on the ice
- in deep water where icebergs are frequent a flexible system has to be adopted, enabling equipment to be moved out of the path of an iceberg at short notice (within two or three hours).

A new and quickly recoverable system, which has already proved its efficiency, is the diving bell for soil investigations. The diving bell is lowered to the place on the seabed where a boring has to be made. The borings are executed from inside the diving bell.

**3.9. River discharge**

Together with soil conditions, the river regime is the main environmental boundary condition for the design of islands in a river. In the Mackenzie River floods may occur at the end of the winter season, due to the release of ice jams. Computer calculations were carried out in the one dimensional flow model (EXPLICIT) to predict the discharge, current and water level curves along the river, which could result from this. Both instantaneous and stepwise releases of ice jams can be simulated in the computer model.

In the area where the island has to be constructed, the detailed flow pattern around the islands can be calculated, using the two dimensional flow model. This model requires the water level data to be given at the open boundaries.

A next step would be to make a detailed model (smaller grid size) around one island.

Fig. 17: Flow pattern around one island after an ice-jam release
4. Island design.

4.1. General design aspects

Once the island location has been determined, the possible design variations relate to the type of fill material, the steepness of the slope and the slope protection.

**Fill material**

In most cases there will not be much choice of fill material. Material with an average grain size of less than 150-200 micron is not suitable for island construction purposes.

**Steepness of slopes**

The properties of the fill material and the method of placement determine the in situ inclination of the slope. There are a number of concepts which can be used to construct steeper slopes; for example:

- special dump techniques
- retaining caissons of steel or concrete
- fabric filter cloth or steel screens
- retaining berms made up of sandbags, gravel or reinforced soil

**Slope protection**

In many cases slopes of sand and gravel or slopes retained in filter cloth need protection against erosion by waves and currents. The same applies to berms at the toe of a caisson. These are very critical parts of the design.

For islands in deep water the danger of icebergs penetrating the slope is a serious problem.

Materials which can be used to armour slopes are sandbags, quarry stones and blocks and concrete armour elements. A new material, which can be quickly applied, is the sand mattress.

In the following sections some typical engineering aspects are dealt with. Reference will be made to actual examples to explain how the effect of some environmental boundary conditions can be calculated, and how the parts of the island can be designed to withstand these design forces.

4.2. Erosion by waves and currents

Waves and currents are the significant parameters in the process of erosion and sedimentation.

**Submerged pad or island under construction**

The two dimensional flow model and the refraction model could be used to calculate, respectively, the current and wave pattern in the area of a submerged berm. Next the results of these two calculations could be used to calculate the sediment transport in one or more consecutive storms. Thus a prediction can be made as to how much fill material will be lost during construction. This is a relevant aspect worth taking into consideration when planning the execution and calculating the capacities of the equipment. It could also indicate the feasibility of temporary protective measures.

**Island extending above the waterline**

For a sand or gravel island with an unprotected slope it is possible to
predict the order of magnitude of erosion and sedimentation in a single storm or during the lifetime of the island. The island can then be re-dimensioned accordingly to allow for this erosion. The calculation could also be used to assess the repair(s) which will have to be carried out during the island's lifetime.

A straightforward calculation would first calculate the refraction of waves at the island slope. The breaker height and breaker angle, determined per island section, would then be used to calculate the longshore sediment transport. This calculation could be repeated for a number of storms, coming from different directions. If the statistical distribution of storms is also allowed for, the order of magnitude of the resulting erosion or sedimentation per section can be calculated.
4.3. Slopes requiring protection against wave attack

In this section some design methods and a new slope protection concept are discussed.

Design methods

The design of slope protection for an island body exposed to wave attack bears many similarities to breakwater design, but is still an engineering problem of the first order.

Many calculation methods have been developed to design the armour layer(s). In most cases laboratory investigations have also to be carried out, especially for heavily exposed structures or structures with a critical stability. The whole wave spectrum needs to be considered (irregular wave generation).

Armour computations alone would suffice only for pre- or conceptional design studies or the design of structures under moderate wave attack. The most straightforward calculation method (Hudson) only considers the significant wave height in a storm. Once the exceedance frequency of significant wave heights and the repair cost (if damage has already occurred) are known, the design can be optimized, taking into account the lifetime of the structure.

The effect of the wave period can also be considered, using a modified formula in which the so-called Irribarren number is included. This would make it possible to calculate the damage which might occur to the armour layer(s) for the full wave spectrum.

New slope protection concept

A new slope protection material has been developed to protect river embankments against erosion. It is the so-called sand mattress, built-up of two layers of filter cloth sewn together in longitudinal sections and filled pneumatically with dry or moist sand at the site. The material possesses good mechanical and u.v. radiation resistance. A special tool has been constructed to pull the sand mattress below water.

As the material can be applied quickly and is relatively cheap, it may be a good proposition to use it to protect islands in the Arctic. It is recommended that a laboratory test and a full-scale test to be carried out to prove its capability in withstanding wave attack and to indicate how the system could be optimized for this new application.

The sand mattresses could also prove to be an effective means of stabilizing berms on which fill retaining caissons or steel screens are placed.
Fig. 19: Deep-water breakwater

Fig. 20: Testing an island-slope protection
4.4. Design of vertical walls

Vertical fill retaining structures must remain stable under wave impact.

The soil mechanical stability of the sub-base should also be considered (there is a possibility of liquefaction and failure along a sliding plane due to the dynamic loading of the caisson).

In addition, the toe of the caisson or other retaining structure must be stabilized to prevent erosion. Quarry stones or concrete blocks could be used, but for this application the sand mattresses might also be an attractive alternative.

4.5. Ice forces

The design of islands at shallow and intermediate water depths must be checked in relation to the effect of massive ice pile-up. Various sliding planes have to be considered.
Fig. 23: Sand-mattress slope protection

Fig. 24: Equipment for placing sand mattresses
Program: WavePressure

Calculation according to Nagai

Waveheight = 3.00 meters

Enter width of caisson (meters): 9

Rho caisson, $\mu = 0.32, 0.38, 0.44, 0.50$

Width of caisson: .32, .38, .44, .50

Waveheight = 3.00 meters

Period = 7.00 seconds

Depth in front of wall = 6.50 meters

Height of construction = 9.50 meters

Depth of parapet = 2.00 meters

Slope of wall = 90 degrees

Reflection coefficient = 1.0

Wavelength = 71.99 meters

Wave pressure in KN/m2

When the parameter is > 1.0, the caisson will not fail.

However, this value is without any safety-factor.

<table>
<thead>
<tr>
<th>Level</th>
<th>Pressure (KN/m2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.60</td>
<td>5.20</td>
</tr>
<tr>
<td>1.95</td>
<td>2.30</td>
</tr>
<tr>
<td>1.30</td>
<td>0.90</td>
</tr>
<tr>
<td>0.65</td>
<td>0.95</td>
</tr>
<tr>
<td>0.00</td>
<td>0.90</td>
</tr>
<tr>
<td>-0.65</td>
<td>0.50</td>
</tr>
<tr>
<td>-1.30</td>
<td>-13.00</td>
</tr>
<tr>
<td>-1.95</td>
<td>-19.00</td>
</tr>
<tr>
<td>-2.60</td>
<td>-26.00</td>
</tr>
<tr>
<td>-3.25</td>
<td>-31.00</td>
</tr>
<tr>
<td>-3.90</td>
<td>-36.00</td>
</tr>
<tr>
<td>-4.55</td>
<td>-41.00</td>
</tr>
<tr>
<td>-5.20</td>
<td>-46.00</td>
</tr>
<tr>
<td>-5.85</td>
<td>-51.00</td>
</tr>
<tr>
<td>-6.50</td>
<td>-56.00</td>
</tr>
</tbody>
</table>

Total pressure: 264.26 KN/m2

Moment is: 1927.96 KN.m

Arm is: 7.30 m

Total tension: -135.78 KN/m

Moment is: -759.22 KN.m

Arm is: 5.59 m

Data measured from bottom.

Fig. 25: Wave impact on a vertical wall
In deep water there is a possibility that an iceberg may collide with the artificial island. Penetration of icebergs into the island body has to be calculated, in order to evaluate the influence of this type of loading on the island integrity. In the mathematical model penetration is simulated with a short time step, including non-linear aspects such as soil failure and ice failure. The forces exerted by environmental influences, like currents, wind, pack ice, are also taken into account. Both centric and excentric impacts can be simulated.

For the design of some parts of the island the crushing strength of ice has to be considered. For example, in order to dimension fill retaining elements and to check local stability aspects.

4.6. Soil mechanical aspects

Aspects of soil mechanical stability under certain ice conditions have already been dealt with in section 4.5. Other soil mechanical aspects are:

- sliding stability of slopes, also under seismic conditions
- liquefaction of parts subject to dynamic loading (for example by wave attack)
- bearing capacity and settlements of soil

**Fig. 26: Various sliding planes**

**Fig. 27: Different stages of iceberg penetration**

4.7. Islands in a river

For the Mackenzie River some specific hydraulic engineering computations were carried out concerning the reliability of the man-made island concept with high surge velocities after an ice jam release.

First the surge velocities for discharge and release conditions with different probability were calculated (section 3.8). Next these data were used to predict damage to the slope protection and to predict local scour at the toe of the island.
Propriétés des matériaux

<table>
<thead>
<tr>
<th></th>
<th>1 [t/m³]</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>l</td>
<td>1,78</td>
<td>1,64</td>
<td>1,27</td>
<td>1,51</td>
</tr>
<tr>
<td>l_s [t/m³]</td>
<td>0,96</td>
<td>0,86</td>
<td>0,72</td>
<td>0,86</td>
</tr>
<tr>
<td>q [°]</td>
<td>35</td>
<td>40</td>
<td>45</td>
<td>40</td>
</tr>
<tr>
<td>c [N/m²]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Stabilité:

a. Condition normale : F ≥ 1,47

b. Condition sismique (avec coeff. sismique horizontale 0,1 g) : F ≥ 0,98

Poids du couronnement (section interne)

91 KN/m²
5. Execution methods.

5.1. Introduction
In this chapter three different dredge systems and their operational features are briefly discussed, to indicate that the selection of equipment and the equipment spread are determined by a number of factors which can only be judged by specialist expertise.

The working season for conventional equipment is short. This is leading to the development of improved equipment and even to new dredging concepts.

5.2. Dredge systems
The main selection criteria for the dredge system to be used are workability in the area (waves, currents, ice), the characteristics and location of the borrow area, and the order of magnitude of the required production capacity.

In principle there are three systems with which large production rates are possible:
- trailing suction hopper dredge (hopper dredge)
- cutter suction dredge (cutter dredge)
- plain suction dredge

Their fields of application are completely different.

The hopper dredge trails one or two suction pipes over the seabed, while sailing, thereby dredging the surface layer over a wide area. This dredge can handle a great variety of soils.

With a cutter dredge accurate profiles can be dredged, both in shallow and in deep waters. The material to be dredged is cut loose with the cutter head mounted on the suction pipe.

The bow, with the ladder and cutter head, moves from side to side around a spud astern, thus creating a flat bottom. This operation is effected by tightening and slackening the wires of the bow anchors.

The plain suction dredge is a stationary dredge system which needs deep borrow pits of loose, granular material. A small overburden of clay can be penetrated with water jets mounted on the suction pipe. The dredge is anchored to keep it in position.

The various procedures for transport and placement of fill material speak for themselves. Some hopper dredges can also be used as a stationary dredge and/or are equipped with a pump-ashore unit.

The dredge method used, especially the fill placement technique, may influence the overall island design.

5.3. Operational features

Operation in waves

A large, modern hopper dredge can work in waves up to 3 m height, as the suction pipe(s) are swell compensated.

The cutter dredge can operate in waves of 1-1.5 m height. A plain suction dredge equipped with a flexible pipe and swell compensators can operate in waves of 2.5-3 m height.

Operation in ice

Existing hopper dredges can be made more ice resistant so that they can continue their work when freeze-up begins. The hulls of the other two
types of dredges can also be ice strengthened. The most vulnerable parts, however, are the anchor wires, the suction pipe (and cutter head) and the floating pipeline. Sufficient dredge and equipment development experience is available to improve these dredge systems and in this respect we may think of improved anchor handling systems, use of D.P. systems, adaptations to the hull, submerged pipelines, etc.

5.4. New concept

In the foregoing section it was discussed how the output of floating dredge equipment could be increased, by prolonging or improving operation after freeze-up. New concepts are also being investigated. Over the last few years a design for a stationary dredge system operating from the landfast ice has been developed in concept.

Its general feasibility cannot yet be assessed as it still has to be related to specific sites and projects. The attraction is that the period, during which operations are possible from landfast ice, is longer and more predictable than the ice-free season.
Fig. 30: Ice-strengthened hopper dredge
Fig. 31: Dredge system standing on ice
6. Execution aspects.

6.1. General
This chapter starts with a brief review of the impacts on the environment made by different dredging methods. These impacts have to be considered before the method to be used is selected. Next, we go into some detail about various execution aspects. We do this with reference to three examples:
- calculation of production rates of floating dredge equipment under various conditions of ice coverage; this in relation to the development of ice breaking dredges and dredges operating from the landfast ice
- accurate placing of fill material for berms at great depth
- placement of caissons on submerged pads

These examples will show that not only the design of the island but also the preparation and planning of its execution require specialist engineering. This may be in the field of work methods, equipment spread and/or development of equipment.

6.2. Environmental aspects
Dredging has an impact on the environment. Physical impacts occur both on the sea floor and in the water column.

Sea floor
Depending on the dredge method used, either the surface layer over a wide area is removed or very deep borrow pits are created locally. Both methods exert a certain influence on the bottom fauna and possibly the total number of fish in the area.

Water column
The overflow, when the hopper of the dredge or dump barge is being filled, will cause higher sediment concentrations in the water column downstream of the dredge. With the soil characteristics and the environmental conditions (waves, currents) known, the turbidity in the downstream area of the dredge can be calculated. Similar calculations could be carried out in the area where the material is dumped or discharged from the pipeline.

6.3. Performance of dredges in ice
Conventional, but ice strengthened, dredge equipment can operate for two to three months in the Canadian Beaufort Sea. In the Alaskan Beaufort Sea the ice conditions are worse. The average duration of the working season (operational criterion is that the ice coverage is less than two oktas (or 25 %)) is considerably shorter: viz. 45-50 days at a depth of 40 ft, 40-45 days at a depth of 60 ft and only 25-30 days beyond a depth of 100 ft.

Feasibility studies have indicated that ice strengthened or ice breaking dredge equipment, purpose developed for operation in this area, may be economically attractive, as their working season would be longer.

No practical experience has yet been obtained in the performance of dredges, when there is more than one to two oktas ice coverage. So far as was practicable, assumptions were made about the possible sailing
Fig. 32: Performance of a hopper dredge in a typical season
speeds of hopper dredges or barges under various conditions of ice coverage. Thus the cycle times (determining the production rate) could be estimated.

A numeric model, in which the ice conditions and the manoeuvring characteristics of ships 1) are simulated, could be used to optimize the selection of the type of equipment and the equipment spread needed, or for the development of new equipment. Aspects, like penetration through new ice and the extent to which ice information is available to the navigating officer, could be included in the model. In that way the feasibility of using or developing ice information systems, to improve the dredge performance, can also be evaluated.

The performance of a stationary dredge, working in an ice field, can also be simulated. In particular the workability of a dynamically positioned (D.P.) plain suction dredge could be compared with a plain suction dredge kept in position only by anchors. A D.P. plain suction dredge would be a new combination of known techniques.

In the simulation the dredge's capability to avoid collisions with large ice floes, while still maintaining an acceptable production rate, has to be investigated for both concepts.

1) The ship manoeuvring model is described in chapter 7.
Fig. 34: Seaway Sandpiper

a new dimension to pipeline covering....
6.4. Accurate placement of fill material

There are many cases where fill material has to be very accurately placed at great depth:
- toe protection of offshore gravity structures
- construction of gravel berms to retain finer grained fill material
- covering of trenched pipelines

The Seaway Sandpiper is a vessel which has already proved its efficiency with regard to accurate placement of material at a great depth (up to 1000 ft).

6.5. Placement of caissons

The allowable tolerance when sinking caissons or tunnel elements as fill retaining structures for island construction is small. As it is a critical operation the placement procedure has to be simulated in advance. This can also be done with the ship manoeuvring simulator.

Much experience has been obtained in similar operations, for example the sinking of tunnel elements in a river with currents and the sinking of caissons to seal off river arms from the sea (the Dutch Delta scheme).

6.6. Using a service harbour

For projects of which the construction phase takes some years, a service annex winter harbour is needed. After finishing the work such a harbour, depending on its location and layout, could be used as a supply and maintenance base for the operations on the field, with the possibility to establish also some other field development facilities, such as an LNG plant, an oil and gas separation plant or a loading terminal. These facilities will otherwise have to be provided by an offshore terminal.
Fig. 36: Service harbour
7. Engineering aspects of a winter harbour, field development base or offshore terminal.

7.1. Introduction

The basic design criteria are established by the operational requirements. Some specific coastal engineering aspects (after the basic site selection has been made or if alternative locations have to be compared) are:

- access channel
- harbour layout and protective structures (breakwaters)

7.2. Access channel

In many cases the site is situated in an area with insufficient water depth. An access channel has then to be dredged. There are two aspects to be considered with regard to the alignment and the dimensions of the access channel:

- safe navigation
- minimization of capital and maintenance dredging cost

**Safe navigation**

With the ship manoeuvring simulator various channel alignments and dimensions can be compared.

The ship in the simulator behaves like an actual ship: the pilot can give rudder and engine commands, thus influencing the course and speed of the ship. The behaviour of the ship is also influenced by waves, currents, wind and shallow water effects.

After sufficient manoeuvres have been made, they are analysed statistically in order to calculate the channel width. The limits of the channel are expressed in the probability that they are exceeded for a specified number of ship passings. For example, if during the period considered 1000 ship passings
are expected, a chance of 0.1% means that on average one of these ships would come beyond this limit.

Dredging cost

In a deepened navigation channel siltation is nearly always to be expected. With the morphological model a prediction of the annual siltation (and in some sections erosion) can be made. Thus the annual maintenance cost can be estimated. This can be done for different channel alignments. Keeping in mind the criteria of safe navigation, the capital dredging cost and the maintenance dredging cost, the optimum channel alignment and dimensions can thus be selected.

In many cases insufficient data are available to justify such a detailed sedimentation programme. A quick method has been developed to arrive at a first estimate siltation of channels crossed by tidal currents.

7.3. Harbour layout and protective structures

The ship manoeuvring simulator can also be used to determine the harbour layout. Allowance can be made in the model for tug assistance. With the hydraulic models described earlier, the hydraulic aspects of harbour design, like currents, wave penetration and sediment transport, can be calculated. Some engineering aspects of breakwater design have already been discussed in chapter 4.

Fig. 38: Schematic of HYDRONAMIC's ship manoeuvring simulator
Fig. 39: Pilot training himself at the manoeuvring simulator

Fig. 40: Extreme limits of sailing together with the 1% and 0.01% exceedance frequency in a navigation channel
Fig. 41a: Result of an entry manœuvre with tug assistance (vector plot of used tug forces)
Fig. 41b: Result of an entry manoeuvre with tug assistance (ship plot)
SEDIMENTATION WITHOUT CHANNEL

scale 1 : 50000

* erosion of 100 cm or more
* erosion of 50 cm
* sedimentation of 100 cm or more
* sedimentation of 50 cm

Fig. 48a: Sedimentation and erosion calculated in the morphological model (without channel)
SEDIMENTATION WITH 14M CHANNEL

scale 1 : 50000
* erosion of 100 cm or more
* erosion of 50 cm
* sedimentation of 100 cm or more
* sedimentation of 50 cm

Fig. 42b: Sedimentation and erosion calculated in the morphological model (with channel)