Morphological modelling in the vicinity of groynes
an extended application in Delft3D-RAM including tidal impact

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Preface

This thesis is the result of the graduation project "Morphological modelling in the vicinity of groynes". The project aims to improve and extend an existing model application in Delft3D-RAM to take a next step towards a comprehensive tool describing the morphological processes around groynes. Ultimately such an application should provide a better understanding of the effects near groynes and form an instrument in the design and evaluation of sea defenses with groynes. The study was carried out from March 2002 to December 2002 at the Hydraulic Engineering section of the subfaculty of Civil Engineering, Delft University of Technology.

I would like to thank Jan van de Graaff for his help in finding a subject for my graduation project, his support during the past months and for commenting my thesis conscientiously. Furthermore I would like to thank Dano Roelvink for his help in finding my way in Delft3D, his helpfulness in the problems I met and his stimulating enthusiasm about coastal engineering and morphological modelling. I also thank Prof. Stive and Mr. Petit for their support and their his presence in the thesis committee.

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Delft, December 2002
Rob Visser
Summary

The shoreline develops on several time scales. At some places along the coast the amount of sand in a cross-section decreases continuously and the shoreline shifts landward. This phenomenon is called structural erosion and is often caused by an increasing longshore sediment transport along the coast. When it is necessary to protect the coast, e.g. because the sea defense function of the coast is threatened, groynes can be applied to reduce the longshore transport. The erosion is then prevented locally. Nevertheless past the protected area leeside erosion occurs due to the full presence of the original sediment transport. In order to make a proper design for a shore protection with groynes, insight in the effectiveness as well as the side-effects is essential. In a previous study a model application was set up for the simplified case of a coast subjected to a uniform and stationary wave field in absence of the tidal impact. However, the tide does influence the morphological development, e.g. due to the displacing beaker zone, the drying and flooding of the beach and the presence of tidal currents. In this study the application is extended with the tide and an improved representation of the groyne within the computational modules is proposed.

The applied computer model is Delft3D-RAM, a part of the Delft3D software-package, developed by WLDelft Hydraulics. The model is a process-based model that computes the 2-dimensional current, wave and sediment transport field and translates these into bed level changes. The computational time stays limited due to the “Rapid Assessment of Morphology” (RAM) procedure. In the RAM-procedure, it is assumed that the local current and wave field do not vary much as long as the bed level changes are small. Within a certain period, defined as the morphological time step, the current and wave field are not recomputed, and the transports are simply adapted for the changed bathymetry. The RAM-procedure also includes a method to account for the development of the dry beach resulting from the morphological changes in the wet area. This approach, the “uniform beach profile method”, redistributes bed level changes close to the waterline in such a way that the upper part of the beach profile shifts forward or backward while retaining its shape as initially predescribed.

The groyne is implemented in the numerical grid using the “thin dam” option in the flow module and the “sheet” option in the wave module. The combination of two thin dams perpendicular to the shore and one connecting the two tips not only blocks the currents and sediment transports completely, but also efficiently separates the morphological development at both sides of the groyne. A set of three sheets is required to block the waves and prevent interpolation effects from the numerical wave grid to the flow grid. The proposed modelling of the groyne leads to satisfactory results.

The model set up of the original application without tide is used as a starting point for the set up of an extended application including the tidal effects. Both the flow grid and the wave grid are refined around the groyne to obtain a more detailed representation of the local flow and wave field. In the extended application, the tide is implemented as a single sinusoid with a period of 12 hours. The propagation of the simulated tide corresponds more or less with the tide along the Dutch coast. The amplitude is taken higher than found in practice, namely 1.5 m. The application calculates the flow and waves iteratively to account for the interaction between the tide and the waves. The transports are then calculated throughout the tide and averaged over the tidal period. The bed level changes are computed from the averaged sediment transport field. Due to the computations over the full tidal period and an iterative calculation of currents and waves the application including tidal impact is computationally intensive.

To allow for larger morphological time steps and to prevent instabilities in the development of the bed the present RAM-procedure is extended with a mechanism smoothing out disturbances. It artificially redistributes sediment based on the gradient of the bed level change rate and a user-defined coefficient. Secondly it is proposed to reduce the tidal period to save computational time.
As long as the relative influence of the inertia on the tidal flow is small, the tide-averaged transport field is comparable for a tidal period of both 12 hours and 6 hours. A comparison of the two initial tide-averaged transport fields shows only minor differences.

The results of a stationary case, with only a wave-driven longshore current, and a tidal case, which also includes tidal effects, are compared. Both models show accretion upstream of the groyne and erosion at some distance downstream. At the leeside of the groyne a circular flow pattern is found, resulting from the spatially varying wave set-up. The circular flow transports sediment towards the groyne, where it is deposited. Directly downstream of the groyne thus some accretion is found.

When the tidal impact is included, the yearly undisturbed sediment transport is 10% less than when the tide is absent. It is observable that the tide spreads out the transports over a wider zone due to the changing water level. The tide-averaged transport field around the groyne predicted by the tidal model shows a more gradual change in the direction of the transports upstream of the groyne and less seaward pointing transports at the tip. The centre of the downstream circular flow pattern has slightly shifted towards the tip of the groyne, compared to the case without tide. After simulating 1 year with tidal impact, scour is found at the tip of the groyne. In general the morphological changes show a more gradual development in comparison to the stationary case, where some irregularities occurred downstream of the groyne.

The application of larger morphological time steps appears to result in disturbances in the coastal development. The application of a reduced tidal period does produce results comparable to a simulation over the full tidal period. In the present application, the Bijker/Bailard formula for sediment transport appears to be a robust formulation to simulate the morphological development. The Soulsby-Van Rijn formula leads in this case to highly disturbed results.

The extended application including the tidal impact on the morphological development leads, for the present simplified cases, to credible results. To improve the applicability for complex situations it is recommended to also include a non-stationary wave field and evaluate its influence on the morphology. Furthermore the results of the model should be compared to a practical case to obtain a reliable instrument for the design of groynes.
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1. Introduction

The coast is continuously subjected to the joint influence of wind, tide, waves and human interference, e.g. in the form of dredging or structures built into the sea. As a result of these processes the coastal zone changes constantly on different time scales. At some places along the coast the volume of sand stored within a certain area decreases continuously. The shoreline then regresses landward. This process is called structural erosion. Often, structural erosion is the result of an increasing sediment transport along the coast. It may cause economical damage, loss of functions within the coastal zone and may even threaten the possible sea defence function of the coastal zone. In these cases shore protection is necessary. The application of groynes might then be a solution.

The basic idea of the application of groynes is that one likes to interfere in the coastal processes. Groynes reduce or stop the sediment transport locally, so that structural erosion can be prevented. Outside the protected area, however, erosion will still occur or even increase. The erosion problem is often mainly displaced to the leeward side of the protected area. For this reason and because it is nowadays considered to be undesirable to intervene too much in the coastal processes, beach nourishments are commonly preferred to deal with structural erosion along the Dutch coast. Nevertheless, there are situations in which shore protection with groynes could work. To design and apply groynes successfully, it is necessary to be able to predict the effects of the measure. A process-based 2-dimensional (2D-) model application model be helpful to evaluate the morphological changes due to the construction of groynes, but is presently not yet available.

Jörissen (2001) investigated the possibilities of Delft3D-RAM, a computer model developed by WL|Delft Hydraulics, for the simulation of the morphological behaviour of the coast around groynes. For the simplified case of a straight coast with straight depth contours parallel to the coast, a uniform and stationary wave condition and the absence of the tide, his application appeared to be suitable to predict the morphological effects. This study aims to extend the existing application by including some additional effects. The project is concentrated on the implementation of the tide into the model, as well as the improvement of the modelling of the groyne. During the process it appeared that a number of additional adaptations were needed to make the existing application ready for further developments. Aspects that are involved are the resolution of the numerical grid, the reduction of the computational time, for example by adapting the time steps, and the introduction of a procedure smoothing out disturbances in the development of the bed. The results of the extended application are discussed for a case including tidal effects and a stationary case, which lacks the tidal influence. For reasons of simplicity the situation of a straight coast with straight depth contours parallel to the coast is again used as a starting point.

In Chapter 2 the theoretical backgrounds of this study are described, such as some relevant coastal processes, the causes of structural erosion and the possibility of shore protection with groynes. The problem definition and the objective of the study are also presented here. In Chapter 3 the concept of process-based morphological modelling is explained as well as the set-up of the applied modelling system. Chapter 4 deals with some particular aspects of the bed evolution model. It includes a description of the sub-model to handle the evolution of the dry beach, known as the uniform beach profile method. The implementation of groynes in the computational models is investigated extensively and described in Chapter 5. In Chapter 6 the stationary case is set up based on the application presented by Jörissen (2001). A number of aspects were adapted
to facilitate further developments of the application. Chapter 7 describes the changes in the stationary case to enable a morphological simulation of the coast around a groyne including the tidal impact. In this chapter also an adaptation of the bed evolution model is proposed to handle the considerable computational time. The results of the stationary case and the tidal case are discussed in Chapter 8. The study is concluded with conclusions and recommendations in Chapter 9.
2. Shore protection with groynes

2.1 Introduction
For a long time groynes have been used to stabilise the coast where erosion threatened the functions of the land-part of the coastal area. Presently groynes can also be used as a part of the sea defence, for example at Callantssoog, The Netherlands (see Figure 2-1). Abroad, groynes are sometimes also applied to obtain recreational beaches. To get insight in the functioning of groynes first some coastal processes are highlighted. Subsequently a number of possible causes of structural erosion are distinguished, followed by a description of the effect of groynes on the morphological development of the coast. The wish to quantify these effects leads to the problem definition and the objective of this study.

![Figure 2-1: Shore protection with groynes](image)

2.2 Some coastal processes

Coastal changes
Changes in the coastal zone are a direct result of occurring sediment transports, which in their turn are dependent on the influence of waves, currents and wind. The wind causes waves and wind-driven currents. Waves stir up material from the bed so that it can be transported and waves also induce wave-driven currents. The tide makes the water level change and introduces tide-driven currents. The resulting sediment transport in a certain point is defined as a quantity of material moving at a certain velocity:

\[ S = c \cdot u \]  

(2.1)

in which \( S \) is the sediment transport, \( c \) the concentration of sediment and \( u \) the velocity at which it travels. The effect of sediment transports on the coastal morphology becomes clear when the mass balance for a certain part of the coast is considered (see Figure 2-2 for a plan view). The area is enclosed at four sides, among which two rays (\( A \) and \( B \)) and the beach. For reasons of simplicity the sediment transport to/from the sea is now taken zero. When the inflow of sediment is larger than the outflow, the volume of sand in the area increases and accretion takes place. On the other hand, when more sand leaves the area than it enters, erosion occurs.
Mathematically, the mass balance for the 2-dimensional case is formulated as:

\[(1 - n) \frac{\partial V}{\partial t} + \frac{\partial S_x}{\partial x} + \frac{\partial S_y}{\partial y} = 0\] (2.2)

in which \(n\) accounts for the porosity of the settled sediment, \(V\) is the volume of sand stored, and \(S_x\) and \(S_y\) are the sediment transports in \(x\)- and \(y\)-direction.

**Sediment transport**

In coastal areas the sediment concentration \(c\) as well as the velocity \(u\) vary strongly as a function of time and elevation above the bed level. This is caused by the influence of the waves. Theoretically, the total sediment transport through a plane of unit width could be found by integrating \(c(z,t) \cdot u(z,t)\) over a certain time interval and the vertical. The current knowledge about the behaviour of \(c(z,t)\), however, is poor.

In the mean wave direction the time-average of \(u(z,t)\) is nearly zero, while the fluctuations of \(u(z,t)\) with time are large due to the orbital motion. In the direction perpendicular to the wave direction, \(u(z,t)\) is mainly determined by the presence of a (wave-driven) current. On wave period scale, it is often nearly independent of time.

The latter allows for the use of the time-averaged concentration \(\overline{c(z)}\) in the integral, which is better known than the concentration as a function of time. Furthermore, in practice the waves close to the shore approach the shore almost perpendicularly, so that the mean wave direction roughly coincides with the cross-shore direction, while the (wave driven) current acts in longshore direction. In longshore direction the sediment transport can now be determined by solving the integral:

\[S_x = \int_0^h c(z) \cdot u(z) \, dz\] (2.3)

in which \(S_x\) is the longshore transport in \(m^3/m/s\) (excluding pores), \(\overline{c(z)}\) is the time-averaged concentration in \(m^3/m^3\), \(h\) is the vertical distance between the bed and the waterlevel, \(u\) is the longshore component of the current and \(z\) is the elevation above the bed level. In cross-shore direction the sediment transport is mostly found with empirical models. Of course the distinction between longshore transport and cross-shore transport is merely theoretical, as the particles in reality move in a certain direction with a longshore and a cross-shore component.

A second distinction made, is the division of the total sediment transport into suspended load and bed load. The bed load consists of the material moving in the layer near the bottom by rolling and jumping. The suspended load is formed by particles moving in the layer above. In practise, there is no sharp transition between both kinds of transport, but in computational models it can be practical to make the distinction.
Waves
In the coastal zone waves are an important factor for the sediment transports. On shallow water they stir up material to make it available to be transported by currents. Waves may also induce currents themselves. In reality wave fields are very irregular and may vary in time and space. For modelling purposes, the waves are often schematised as regular waves with a sinusoidal shape. The characteristics of the full wave field are summarised in the properties of one single wave by means of statistics. The wave field is then (often) characterised by a significant wave height on deep water, a peak period and the direction of propagation. In combination with the water depth, the wavelength and the celerity can be determined.

When waves approach the coast, they change under influence of the decreasing water depth. The wave celerity and the wavelength decrease when the water becomes shallower. Apart from the changes in wavelength, the wave height also changes, so that the waves become even steeper. Ultimately either the wave will become too steep or the wave height will become too high compared to the water depth. In both cases the wave will break. The energy of the wave is then dissipated. The zone in which most waves break is called the breaker zone.

A second phenomenon related to the decreasing water depth is called refraction. Refraction is the change of the mean direction of wave propagation due to a changing water depth (or current) and is caused by the celerity being dependent on the water depth. Consider a coast with depth contours parallel to the waterline. When waves approach the coast under an angle, that part of the wave crest being already on shallower water will have a lower celerity than the part being on deeper water. The wave crest will therefore bend towards the shoreline, making the angle between these smaller.

Diffraction is the phenomenon of wave crests bending around an obstacle. Refraction and diffraction as found in practice is displayed in Figure 2-3.

![Figure 2-3: Refraction (left) at the shore and diffraction (right) around an offshore breakwater](image)

The presence of waves does contribute to the transfer of momentum in the water. This is known as radiation stress. As long as wave energy is conserved the radiation stress is constant. When energy is dissipated, for example in the breaker zone, the radiation stress decreases. Following from the balance of momentum, this results in a slope in the mean water level (pressure gradient) or the generation of a current. When waves approach the coast under an angle and start breaking, the decrease in radiation stress results in so-called wave set-up in cross-shore direction and a wave-driven current in longshore direction. The wave-driven current is counterbalanced by bed friction. The radiation stress, and thus the set-up and longshore current, are dependent on the wave height, the angle of approach and the water depth. The longshore current originating from the breaking waves forms an important mechanism for the transport of sediment.
On deep water the water particles under a passing wave make a circular motion, known as the orbital motion (see Figure 2-4). The deeper under the water surface, the smaller the radius of the circle gets. At a certain distance from the surface, the influence of the wave is not noticeable anymore. When a wave approaches the shore, the water depth decreases and the orbital motion is influenced by the bed. The circular motion changes into an elliptic motion with considerable horizontal velocities at the bottom. The continuously changing magnitude and direction of the velocities induce varying shear stresses on the surface of the bottom. Material is stirred up and becomes available for transportation by currents. Furthermore the friction, experienced by a possibly present current, is increased compared to the friction due to a current alone.

![Figure 2-4: Orbital motion for deep (left) and shallow (right) water](image)

**Tide**

The tidal motion consists of a vertical tide and a horizontal tide. The vertical tide is the periodical changing of the water level; the horizontal tide is a time-dependent current caused by the propagation of the tidal wave. Both influence the sediment transport processes along the coast.

The vertical tide results in a periodical displacement of the areas where waves affect the bed. Together with the wave height, the water depth is an important factor for the breaking of waves. The changing water level thus also influences the location of the breaker zone and the place where the longshore current is generated. Finally, the changing water level also causes the waterline to shift. At high water a larger part of the beach is affected by the waves than at low water, while at low water a larger part of the beach could be affected by the wind.

The horizontal tide is a current which direction and magnitude changes as a function of time. The tidal current mainly influences the sediment transport on deeper water. In the breaker zone, where a wave-driven current may be present, the effect of the tidal current on the sediment transport is usually less compared to the influence of a wave-driven current. Between these zones a transition zone is present where both the tidal current and the wave driven current affect the transport. Especially when the tidal flow in one direction is slightly stronger than in the other direction, the tide could cause a net transport.

### 2.3 Structural erosion and shore protection with groynes

The position of the coastline changes constantly on several time scales. An occasional heavy storm may cause the coastline to retreat temporarily and also the seasons following each other might influence the position of the coastline. Except for these short-term changes, at some places along the coast a gradual but structural decrease is found of the volume of sand stored. The beach will then become narrower and the dune gets affected. This phenomenon is called structural erosion. Structural erosion is often caused by an increasing longshore sediment transport along the coast (see Figure 2-2). It can be caused by several mechanisms, such an increasing wave-driven current along the coast (due to wave conditions varying from place to place), the shape of the coastal zone, or due to human interference, e.g. in the form of breakwaters constructed into the sea.
One of the measures that can be taken to deal with structural erosion, is the construction of groyne along the eroding coast. Groyne are relatively long and slender structures built into the sea, often perpendicularly to the coast. In The Netherlands groyne are often built up from rock, covered with asphalt penetrated rock or a revetment of placed blocks. An alternative form of the groyne is a row of piles built out into the water.

With its length and height relative to the sea bed, a groyne is able to affect the currents and sediment transports close to the shore. It can form a blockage for a wave-driven current and thus reduce the longshore sediment transport or it can keep away strong tidal currents from the vulnerable zone close to the beach.

In the “Basisboek Zandige Kust” (TAW, 1995) the following general cases for shore protection with groyne are considered:
1. A coastal area with waves approaching the coast at an angle with a dominating direction.
2. A coastal area with tidal currents and waves approaching at an angle.
3. A coastal area with a tidal channel close to the shore.

A coastal area with waves approaching the coast at an angle with a dominating direction
In situations where wave-driven currents dominate the erosion process, e.g. at a curved coast, groyne can be successfully applied to protect the coastal area. This is the case when the tidal amplitude is low and the waves originate from a dominant direction. The largest sediment transports are then found in the breaker zone, which can be (partially) blocked with groyne. Due to the reduced transport past the groyne, accretion might occur upstream of the groyne and in the coastline a characteristic saw-tooth pattern develops.

A coastal area with tidal currents and waves approaching at an angle
In a coastal area with tidal currents and waves approaching the shore at an angle, structural erosion may be caused by changing conditions along the coast, such as an increasing current, an increasing wave height, and/or a changing angle between the mean direction of wave propagation and the coast. Due to the influence of the tide the functioning of the groyne varies in time. During low water, the groyne form an absolute blockage for waves, currents and sediment transports. At high water, the groyne will be partially submerged and a reduced flow and sediment transport over the groyne will develop.

A coastal area with a tidal channel close to the shore
The presence of a tidal channel close to the shore may cause structural erosion. Groyne can then keep the tidal channel at a distance from the coast, so that the erosion is reduced.

The application of groyne as shore protection measure is illustrated using the sketch in Figure 2-5. The upper sketch shows a coastal area in plan view. The graph below shows the development of the longshore sediment transport along the coast. The original sediment transport distribution is indicated by line (1). The inflow of sediment ($S_0$) is less than the outflow of sediment ($S_h$), so structural erosion occurs. With the construction of groyne, it is attempted to influence the sediment transport to such an extent that the situation represented by line (3) is achieved. The sediment transport, being constant within the area under consideration, will cause no coastal changes in the protected area, as the inflow and the outflow of sediment are then equal. When situation (2) is achieved, the sediment transport is not reduced enough to prevent erosion completely. On the other hand, when situation (4) occurs the original erosion is replaced by accretion, as the outflow of sediment in the area to be protected is higher than the inflow.
At the right hand side of the protected area the original sediment transport has not changed, as the processes causing the increasing sediment transport along the coast are not changed. Outside the protected area erosion will therefore still occur. Directly downstream of ray $B$, the sediment transport even increases suddenly. As a result, intensified erosion occurs at the lee side of the last groyne. The more the sediment transport is reduced within the protected area, the more severe the leeside erosion will be. In fact, the erosion problem of the original area is now moved to the area right of $B$. In order to make a proper design for the shore protection it is desirable to obtain a clear insight into the effects of the measure, so that situation (2) and (4) can be prevented and the impact on the area right of $B$ can be judged.

The effect of a groyne on the morphological development of a coast is now considered for the simplified case of a coast with a constant wave-driven longshore sediment transport. In fact, in this example no structural erosion would occur at all if the groyne were absent, and the construction of groynes would not be necessary as shore protection measure. When a single groyne is constructed extending into the breaker zone, the longshore current will be partially blocked and the sediment transport past the groyne will be reduced. Upstream of the groyne accretion will occur. Downstream, erosion will take place due to the reduced inflow of sediment and the presence of the undisturbed sediment transport further downstream. Around the groyne a characteristic accretion/erosion pattern will develop, as indicated in Figure 2-6.
The effectiveness of the reduction of the sediment transport at the groyne is determined by several parameters, such as the length of the groyne, its height, the cross-shore distribution of the transport and -in the case of multiple groynes- the number of groynes and their mutual spacing. As a result of the waterline shifting seaward, the reduction of the transport at the groyne will decrease as a function of time. Upstream, the shoreline will rotate slightly so that the angle between the wave crests and the shoreline decreases.

Downstream of the groyne an interesting phenomenon occurs due to the impact of the groyne on the local wave field. As the waves approach the groyne at an angle, at the lee side a sheltered zone is present where the waves are lower than further downstream where the shore is exposed to the full wave field. In the sheltered zone thus less wave energy is dissipated as the waves break. This locally results in a smaller decrease of the radiation stress and less wave set-up than further downstream. The difference in water level initiates a current towards the groyne close to the water line. A circular flow pattern subsequently develops, transporting sediment towards the groyne. There it is deposited, so that directly downstream some accretion can be observed.

2.4 Modelling of the morphological development

Once it is decided to protect a coastal area with groynes, the sediment transport can -theoretically- be reduced to any desired degree between no transport at all and the original transport. Important parameters involved in the design are the length, the height and the number of groynes and their mutual distance. Presently, the time-dependent reduction of the transport, as well as the morphological development of the coast in the vicinity of the groynes is hard to predict. For a proper design of the protection works, more insight in the long-term behaviour of the measure is desirable, not only to assure an effective solution for the area to be protected, but also to evaluate the impact on the downstream area.

With the increasing computational capacity of computers 2- and 3-dimensional computer models have become available to model coastal processes. These so-called process-based morphological models are able to compute the morphological development within a coastal area based on the occurring wave fields, currents, sediment transports, bed level changes and their interactions. The computations are based on the primary physical processes, such as conservation of mass, momentum and energy. These are expressed as partial differential equations and can be solved numerically by a computer for a grid representing the model area. In 2D-models, depth-averaged equations are applied, while 3D-models also account for depth effects. Delft3D is a software package developed by WL|Delft Hydraulics to simulate the morphological behaviour of coastal zones and rivers with a 2D- or 3D approach.

The advantage of the 2D- and 3D- morphological models compared to the existing 1D single line models is their ability to describe the actual coastal processes. The models give a better insight into the phenomena involved and can be applied for more complicated situations. A disadvantage of the new models is the large computational effort required for a simulation. Depending on the size of the model area and the simulation period a morphological simulation may take hours to days. It is expected, however, that the increasing capacity of computers will improve the applicability of the 2D- and 3D- models.

In spite of the existence of process-based morphological models, they were not yet applied for the case of a shore protected with groynes. Jörissen (2001) investigated the applicability of Delft3D-RAM, a part of the Delft3D package, to simulate the morphological behaviour of a coastal area with groynes. He developed a method to incorporate the dry beach within the computation, known as the uniform beach profile method, and he implemented a method to represent the groynes within the model area. The model was tested for the simplified case of a shore with straight depth contours parallel to an initially straight coast and the presence of a single groyne. Along the coast a uniform wave-driven current was present due to an imposed wave field with waves approaching the coast at an angle.
The results of this case were compared to the results of the existing 1D single line model UNIBEST-CL. The conclusions of that study were (among others):

- The morphological simulations carried out with the Delft3D-RAM model show a reasonable representation of the morphological development.
- The uniform beach profile method is a robust method to compute bed level changes in the cross-shore profile.
- The applied method to represent the groyne in the model does not always lead to realistic results.
- In comparison to UNIBEST-CL the model with Delft3D-RAM predicts a considerably lower reduction of the sediment transport at the groyne. The displacement of the waterline upstream and downstream of the groyne is therefore also less than predicted with UNIBEST-CL.

Although Jørissen showed that Delft3D-RAM can be applied successfully for the modelling of the morphological behaviour around groynes, the application can not yet be used for realistic predictions in practical situations. First the application should be extended to represent more complex situations, the modelling of the groyne should be improved and the model should be tested against a situation in practice.

### 2.5 Problem definition and objective

**Problem definition**

In the previous sections an overview is given of the causes of structural erosion, the application of groynes as shore protection measure and the interest in a tool that can predict the morphological behaviour of the coastal area in the vicinity of groynes. The model application of Jørissen forms a suitable starting point for the set-up of a 2D process-based tool. His application could be extended to account for more complex situations. Some points of interest are:

- Influence of the horizontal and vertical tide
- Influence of a non-stationary wave condition
- Review implementation groynes in the model
- More realistic representation of groynes in the model
- More complex geometry of the coastal area under consideration
- Validation of the model based on a practical situation

In this study, two elements are selected to be discussed more in detail. The other elements could be treated in a following stage to finally arrive at a useful tool for the simulation of complex situations. The influence of the tide and the modelling of the groyne are further clarified.

In the study of Jørissen the influence of the tide was left out of consideration. Still, the horizontal tide as well as the vertical tide are important coastal processes, which certainly affect the morphological development of the coast. The changing water level dictates from which point sediment is stirred up by the waves, over which zone the waterline is displaced and where the waves start breaking. These three factors obviously affect the near shore sediment transports. Furthermore, the morphology outside the breaker zone is influenced by the presence of tidal currents. A model application for the coastal morphology around groynes should contain the influence of the tide in order to include more relevant processes.

Jørissen implemented the groynes as impermeable and high enough to protrude out of the water under all circumstances. The modelled groyne thus forms a complete blockage for all waves, currents and sediment transports. In practice, however, groynes often are submerged during high water and some transport over the groyne will always occur. When including the tide in the model, attention should be paid to the modelling of groynes. Furthermore, Jørissen concluded that the applied method to represent groynes in the computational modules not always led to realistic results.
Objective
In this study an extended 2D-model application will be set up to simulate the morphological development of the coast in the vicinity of groynes. The application by Jörissen will be used as a starting point and will be adapted to include the influence of the horizontal and vertical tide. The modelling of the groyne will be reviewed and improved if necessary. The results of the extended application will be evaluated based on the situation of an initially straight coast with depth contours parallel to the shoreline and the presence of a single groyne.
The test case is a highly simplified case in which, in absence of the groyne, no structural erosion would occur at all. For practical applications, the case is therefore less relevant. In this study, however, it clarifies the impact of the tide compared to a situation without tide and excludes possible additional difficulties involving more complex situations.
3. Description of the modelling system

3.1 Introduction

The morphological development of the coast is governed by the complex interaction of currents, waves, sediment transport and bed level variations. Furthermore almost every coastal area is subject to human interference in the form of structures, dredging or nourishments. In order to be able to simulate these processes and their interactions and to predict morphological developments, so-called process-based morphodynamic models have been developed during the past decades. The essence of these models is the simulation of the physical processes based on primary physical principles, such as conservation of mass, momentum and energy. Wave action, flow and sediment transport are represented by 2-dimensional depth-averaged differential equations, which are solved for a certain model area. Delft3D-MOR is a process-based morphodynamic model developed by WL Delft Hydraulics and is a subset of the Delft3D-software package. Delft3D-RAM, which is used in this study, is an adapted version of Delft3D-MOR.

This chapter will start with a short introduction on process-based morphodynamic modelling. Next, Delft3D-MOR will be described as it shares its main principles with Delft3D-RAM. The subsequent section will deal with Delft3D-RAM, after which the flow, wave and sediment transport models are described. The bed evolution model of Delft3D-RAM will be discussed separately in Chapter 4.

3.2 Process-based morphodynamic modelling

The basic concept of a process-based morphodynamic simulation is the coupling of a number of 2D computational models for the physical processes (i.e. waves, currents, sediment transport) via a bed evolution model. Distinction is made between "initial sedimentation/erosion models", "medium-term morphodynamic" (MTM) models and "long-term morphological" (LTM) models (de Vriend et al., 1993). Starting with a bed topography, successively a wave field, a current field and a sediment transport field is computed. Bed level changes are found using the sediment transports and the assumption of sediment conservation. The updated bed topography is then fed back into hydrodynamic and sediment transport computations. This procedure is outlined in Figure 3-1.

![Figure 3-1: Concept of morphological models](image_url)
The looped system is able to describe the dynamic time evolution of the bed properly. However, in general the flow module is a time consuming module. For long-term simulations it is therefore desirable to reduce the computational efforts using a so-called parametric model. With this model the difference in time scale between the hydrodynamic and bed response processes is exploited. Both Delft3D-MOR and Delft3D-RAM are based on this principle.

3.3 Delft3D-MOR

Delft3D-MOR integrates the effects of wave action, currents and sediment transport on morphological developments. The modelling system consists of computational modules for each of the four principal processes and a steering module to control the execution of these modules. In Figure 3-2 an overview is given of the components of the Delft3D-MOR system and the associated Delft3D-programs.

![Diagram showing the components of Delft3D-MOR](image)

Figure 3-2: Overview of the components of Delft3D-MOR

The five modules are:

- The steering module MORSYS calls the computational modules in any prescribed order, arranges the time progress of each module and allows iterations between the modules.
- The Delft3D-FLOW program is used as current module. Delft3D-FLOW solves the non-steady, 2D-averaged or 3D shallow water equations. In the present application it is applied in the 2D depth averaged mode.
- The Wave module is formed by Delft3D-WAVE. Delft3D-WAVE can be used to compute the evolution of random wind-generated waves based on the energy balance equation.
- The sediment transport module Delft3D-TRAN calculates the transports using a user-defined sediment transport relation. Distinction can be made between bed load and suspended load transport. For the latter a quasi-3D advection-diffusion equation is used.
- The bottom module Delft3D-BOTT determines the bed level changes based on the spatial gradients of the computed sediment transport.
- In Section 3.5, 3.6 and 3.7 of this chapter more details will be given on the flow, wave and transport modules.

Delft3D-MOR is able to reduce the number of hydrodynamic computations by making use of the difference in time scale between the hydrodynamic and bed response processes. It is assumed that, during a certain interval, the bed level variations are so small that the wave and current field do not change significantly and do not have to be completely re-computed. The morphological process is now split up into full morphological time steps and intermediate time steps. This is outlined in Figure 3-3. The length of a full morphological time step is typically days to months, the length of an intermediate time step hours to days.

At the beginning of the morphological time step a full hydrodynamic simulation of the wave-current interaction is made over, for example, one tidal cycle. For a number of characteristic time points (e.g. at high, low and mean water level for the wave field and more often for the flow field) the velocity and wave fields are stored. Subsequently the simulation process continues within the full morphological time step using intermediate time steps, in which the transport fields and the bed level changes are computed. Within each intermediate time step, the velocities
and the orbital velocities at the characteristic time points of the tidal cycle are adjusted for the changed depth and, based on the associated transport fields, an adjusted tidal averaged transport field is computed. With this averaged sediment transport field, the bed level changes over an intermediate time step are computed. When the bed level has changed so much that a completely new hydrodynamic wave-current simulation based on the new bathymetry is required, the next morphological time step begins. This approach is called "continuity correction" (De Vriend et al., 1993).

![Diagram of the simulation process in Delft3D-MOR](image)

**Figure 3-3: Simulation process in Delft3D-MOR**

### 3.4 Delft3D-RAM

Delft3D-RAM is an extended version of Delft3D-MOR and makes use of the same computational and steering modules as described in Section 3.3. Both models share the basic principle that small bed level variations are supposed not to affect the overall flow and wave patterns. Just like in the MOR-model, distinction is made between morphological time steps with a full hydrodynamic wave-flow simulation and intermediate time steps with a sediment transport field that is only adjusted for the changing water depth. Nevertheless, Delft3D-RAM (RAM = Rapid Assessment of Morphology) has some advantages compared to the MOR-model. (Roelvink et al., 1998 and Roelvink et al., 2001).

The first difference between the MOR and RAM-model concerns the adjustment of the tide-averaged sediment transport field. During the intermediate time steps, the MOR-model first adjusts the velocities and orbital velocities for the changed water depth at all characteristic time points. Then a sediment transport simulation over a tidal cycle is carried out and finally the tide-averaged sediment transport is determined. The RAM-model skips the adjustment of the velocities and the transport simulation over a tidal period. Instead, it directly adapts the tide-averaged sediment transport field by assuming a simple power relation between the sediment transport and the local water depth. This approach is computationally more efficient than the continuity correction and requires very little computational effort.
Figure 3-4: Simulation process in Delft3D-RAM

Figure 3-5: Model structure of Delft3D-RAM

Figure 3-6: The staggered grid of Delft3D-FLOW
The adjustment of the tide-averaged transport field creates a second advantage. In case of the MOR-model, the wave-current simulation is carried out for only one condition (e.g. one wave height, direction and period, one tidal amplitude), which is supposed to be representative for the conditions over the period of at least one morphological time step. With the RAM-method it is possible to carry out a full simulation of the hydrodynamics and the sediment transport for a number of conditions. With the results a weighted tide-averaged sediment transport is determined. This representative averaged transport field then forms the input for a new cycle of intermediate time steps. The procedure is outlined in Figure 3-4. An important point is that the computations for the several conditions can be carried out simultaneously, using different processors, which reduces the computational time considerably. An additional advantage of the use of the transport field averaged over several conditions is that a more gradual transport field is produced with less sharp transitions. This leads to a more gradual evolution of the bed level, so that the chance of instabilities is reduced.

The model structure of a separate hydrodynamic/sediment transport computation and a RAM-update computation recurs in the modules that are used within Delft3D-RAM. The main components are:
- The steering module RAMMOR, which controls the execution of the other modules and transfers the depth and sediment transport information between these modules.
- The combined hydrodynamic/sediment transport module MORSYS, which in fact consists of a Delft3D-MOR model including the current module Delft3D-FLOW, the wave module Delft3D-WAVE and the transport module Delft3D-TRAN. The bed level variation module Delft3D-BOTT is absent, as the RAM-bed evolution model “RAMBCH” arranges the evolution of the bed.
- The module ADDW which computes a representative (averaged) sediment transport field out of the data from MORSYS
- The RAM-bed evolution module RAMBCH, which carries out the updating of sediment transports and computes the bed level variations.

The model structure and exchange of data is described in Figure 3-5.

3.5 Flow model

Delft3D-FLOW is a hydrodynamic computer model that is intended for the simulation of non-steady flow and transport phenomena. The model can be used for both 2-dimensional (depth-averaged) and 3-dimensional calculations on coastal, river and estuarine areas where the horizontal length and time scales are significantly larger than the vertical scales. Typical applications of Delft3D-FLOW are the simulation of tide and wind-driven currents, wave driven currents, stratified and density driven currents, river flow, transport of dissolved material and pollutants.

Delft3D-FLOW takes into account the following physical phenomena:
- Tide generating forces
- Density driven flows
- Shear-stress at the bottom
- Wind shear-stress on the water surface
- Wave induced stresses (radiation stress) and mass fluxes
- Influence of waves on the bed shear stress
- Turbulence induced mass and momentum fluxes
- The effect of the rotation of the earth (Coriolis)
- Drying and flooding

In this study Delft3D-FLOW is applied in the 2D depth averaged mode.

Delft3D-FLOW solves the unsteady shallow water equations which are derived from the 3-dimensional Navier-Stokes equations for incompressible free surface flow. As a result of the shallow water assumption, vertical accelerations are assumed to be small compared to the gravitational acceleration, so that the vertical momentum equation is reduced to the hydrostatic
pressure relation. The system of partial differential equations for conservation of mass and momentum is solved with a finite differences method on a rectangular, orthogonal curvilinear or spherical grid. On the horizontal grid, the principal variables water level and velocity are arranged in a special way that is known as a staggered grid. The staggered grid is displayed in Figure 3-6. The water level points (pressure points) are defined in the centre of a continuity cell. The velocity components are located on the borders of the cell. The water depths are defined at the corners of the grid cells.

To solve the shallow water equations Delft3D-FLOW uses the Alternating Direction Implicit (ADI) method. In contrast to explicit time integration methods, in which the time step is strictly bounded by the Courant condition, the ADI-method couples an efficient computational procedure with unconditional stability. The ADI-method splits each time step into two stages of half a time step. During the first stage the equations in x-direction are solved implicitly in time, while the equations in y-direction are solved explicitly. The next stage the procedure is applied the other way around. The accuracy of the results is determined by the grid size, time step and local water depth, expressed in the Courant number.

An extensive description of Delft3D-FLOW and its numerical aspects can be found in the user manual (WL|Delft Hydraulics, 2001) and Stelling (1984).

3.6 Wave model

The Delft3D-WAVE module can be used to simulate the evolution of random wind-generated short-crested waves in coastal areas. At present two different wave models are available within Delft3D. These are the second-generation HISWA wave model and the third-generation SWAN model. The HISWA model is the standard option within Delft3D and is used in this study. HISWA is a numerical model that calculates the evolution of waves for a given bottom topography, water level and stationary wind and current field in deep, intermediate and shallow water according to the linear wave theory. The model includes the following physical phenomena:
- shoaling and refraction over a bottom of variable depth
- shoaling and refraction due to a varying current field
- wave generation due to wind
- energy dissipation due to breaking
- energy dissipation due to bottom friction
- non-linear wave-wave interactions
The effect of diffraction is not modelled in HISWA.

In HISWA the propagation and evolution of the waves is based on the spectral action balance equation. The spectrum is discrete in the directions, while the distribution of energy over the frequencies is parametric. Thus, in each spectral direction a mean frequency and a frequency-integrated energy density are propagated at the group velocity of the mean frequency. The energy balance equations are formulated as partial differential equations with the two horizontal coordinates and the spectral wave direction as independent variables and the mean frequency and the frequency-integrated energy density as dependent variables. The differential equations are solved on a rectangular grid using a so-called forward marching technique. This implies that the numerical equations are solved row by row over a rectangular grid, beginning at the incident wave boundary where the wave characteristics are imposed. The effects of wind, current and bottom are integrated locally. For the propagation in x-y space an implicit numerical scheme is used, so that the grid size must fulfill certain conditions to obtain numerical stability.

Delft3D-WAVE can be used in combination with Delft3D-FLOW and Delft3D-TRAN to account for wave driven currents, wave set-up, enhanced bed shear stress and the effect of stirring by waves on the sediment transports. To facilitate the interaction with the other modules of Delft3D, HISWA makes use of several grids. The calculations are carried out on the
computational grid, in which other grids may be nested. The bottom and current input for the calculation is provided on the input grid, which preferably has the same resolution as the computational grid in the areas of interest. Data from a flow simulation of Delft3D-FLOW can be transferred to the computational grid through the input grid. The output of the wave computation can subsequently be provided on both the computational grid and any other grid, such as the grid of Delft3D-FLOW. HISWA handles the time variation in a quasi stationary manner. The (stationary) computations are carried out at specified intermediate time levels corresponding to certain (time dependent) circumstances in the Delft3D-FLOW model.

More details about Delft3D-WAVE and HISWA can be found in the user manual of Delft3D-WAVE (WL|Delft Hydraulics 2000) and in Holthuijsen et al. (1989).

### 3.7 Sediment transport model

Delft3D-TRAN is the sediment transport module of Delft3D. The model calculates the 2-dimensional sediment transport field based on a time-dependent bottom and current field from a Delft3D-FLOW simulation and wave data from a Delft3D-WAVE computation. The sediment transport is calculated on the grid that is applied in Delft3D-FLOW and is to be determined according to a selected sediment transport relation. Delft3D-TRAN offers a number of sediment transport formulas, each with its own area of interest, such as:

- Engelund-Hansen
- Meyer-Peter-Müller
- Bijker with waves
- Van Rijn
- Ribberink-Van Rijn
- Soulsby-Van Rijn

The transport of sediment can be in the form of bed load and suspended load. Although in natural conditions there is no strict division between suspended load transport and bed load transport, some transport relations do make this distinction.

Delft3D-TRAN is capable of calculating the time-dependent sediment transports as well as the (tide-) averaged sediment transport field. In combination with the bed level change module Delft3D-BOTT, the model can also be applied in a continuity correction approach. This option is however not used in this study.

Delft3D-TRAN can be used in several modes, among which the “total mode” and the “suspended mode”. In the total mode, both the bed load and the suspended load are calculated with an algebraic transport formula. The suspended transport is assumed to be the equilibrium transport, calculated as the instantaneous equilibrium concentration, multiplied with the instantaneous velocity. The total transport is the summation of the bed load and the equilibrium suspended load. The total mode does not take into account adaptation effects or diffusive transport.

In the suspended mode, a (depth averaged) equilibrium sediment concentration is derived for the suspended transport using an algebraic transport formula. The actual suspended sediment concentration is found from the equilibrium concentration in combination with an advection-diffusion equation. This approach enables the simulation of adaptation effects and diffusive transport in two directions. The bed load transport is calculated directly with an algebraic formula. The sediment transport in the so-called suspended mode is the summation of the actual suspended transport, in which the adaptation effects and diffusion effects are included, and the bed load.

For more information about Delft3D-TRAN, the reader is referred to the manual of Delft3D-MOR (WL|Delft Hydraulics, 2001).
4. Description of the RAM bed evolution model

4.1 Introduction

The RAM-model is a parametric model used to improve the computational speed as well as some practical aspects of morphological modelling. The main principles of the RAM-method are explained in Chapter 3. The present chapter will focus on the details. The RAM-method uses a tide-averaged and/or condition-averaged sediment transport field as input and provides an adapted bathymetry for the situation after a certain morphological time step. The input sediment transport field is computed from a full hydrodynamic simulation of flow and waves. Within the RAM-procedure the transports are simply updated and the bed level is accordingly adapted. The RAM-procedure can be maintained until the bed has changed so much that a new full hydrodynamic simulation is required.

In the zone around the waterline, some specific problems occur when erosion and accretion is modelled. A method, known as the “uniform beach profile method”, is implemented in the RAM-model to deal with the development of the beach.

The RAM-method is implemented in the program “RAMBCH”. For more information about the RAM-method the reader is referred to Roelvink et al. (1998) and Roelvink et al. (2001).

4.2 Updating of the sediment transports

The sediment transport field is dependent on the wave and the current field, and is generally expressed as a function of the velocity \( \vec{u} \) and the orbital velocity \( u_{orb} \):

\[
\vec{S} = f(\vec{u}, u_{orb})
\]

It is assumed that small changes in the bed level do not cause the overall flow and wave pattern to change. The sediment transport field is then only a function of the flow and wave field and the local water depth. The flow and wave field are assumed to be constant during a morphological time step, while the water depth may vary within this time step. In that case, the sediment transports are only dependent on the local water depth.

The sediment transports are initially calculated by a sophisticated model, based on the actual hydrodynamic circumstances. Subsequently they are corrected for the changing water depth until the bottom has changed so much that a new hydrodynamic calculation is necessary. The period over which the updating of the transports takes place is called the morphological time step.

The correction of the sediment transport for the changed bed level is expressed as:

\[
\vec{S}_{corr} = \frac{S_{t=0}}{S_{t=0}} \cdot f(z_b)
\]

In which \( \vec{S}_{corr} \) is the corrected transport, \( S_{t=0} \) is the sediment transport based on the hydrodynamics at the beginning of a time step and \( f(z_b) \) is a function of the water depth \( z_b \).

The function \( f(z_b) \) can be formed considering that the sediment transport \( \vec{S} \) usually is proportional to the velocity \( u \) to some power \( b \):

\[
[S] \propto \left| \vec{u} \right|^b \propto \left( \frac{1}{h} \right)^b \propto \left( \frac{1}{q} \right)^b \cdot h^{-b}
\]
where \( \vec{v} \) is the velocity, \( \vec{q} \) is the discharge per unit of width and \( h \) is the water depth. A similar relationship can be assumed between the sediment transport and the orbital velocity. Since the hydrodynamic parameters are taken constant, the sediment transport can now be described with:

\[
\mathbf{S} = A(x, y) \cdot h^{-b}
\]  \hspace{1cm} (4.4)

The power \( b \) is simply assumed to be constant throughout the model area, while the value of the parameter \( A \) may vary from place to place. As sediment transports are generally proportional to the third to fifth power of the velocity, \( b \) should be between 3 and 5. For each grid cell on the grid \( A \) can be determined from the initial sediment transport field and the initial local water depth:

\[
A(x, y) = \frac{|\mathbf{S}_{i=0}|}{h^{-b}}
\]  \hspace{1cm} (4.5)

Next, the transports are updated using the found values of \( A \):

\[
|\mathbf{S}_{corr}| = A(x, y) \cdot h^{-b}
\]  \hspace{1cm} (4.6)

### 4.3 Computation of the bed level changes

The change of the bed level is a result from gradients in the sediment transport and can be expressed following the mass balance principle:

\[
(1 - n) \frac{\partial z_h}{\partial t} - \frac{\partial S_x}{\partial x} - \frac{\partial S_y}{\partial y} = 0
\]  \hspace{1cm} (4.7)

where \( n \) is the porosity, \( S_x \) the sediment transport in x-direction and \( S_y \) the transport in y-direction (excluding pores). The sediment transport is calculated in \([m^3/s/m]\). The bottom change is solved numerically on the grid of Delft3D-FLOW with a FTCS discretisation (see Figure 4-1). The bed level changes are computed in the depth points of the grid while the calculated sediment transports are located on the water level points:

\[
(1 - n) \frac{z_{h_{i+1,j}}^{n+1} - z_{h_{i,j}}^{n}}{\Delta t} = \frac{\left( S_{x_{i+1,j}}^{n+1} - S_{x_{i,j}}^{n} \right)}{2 \cdot \Delta x} + \frac{\left( S_{y_{i,j+1}}^{n+1} - S_{y_{i,j}}^{n} \right)}{2 \cdot \Delta y}
\]  \hspace{1cm} (4.8)

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure4-1}
\caption{Computation of the bed level change from transports}
\end{figure}
The FCTS scheme is extended to a LAX-type scheme, which introduces negative diffusion, to guarantee numerical stability. The sediment transports are corrected with a compensating diffusion term using an artificial bed slope effect \( \alpha \frac{\partial z_b}{\partial s} \):

\[
S_x = S_{x_{\text{original}}} \left( 1 + \alpha \frac{\partial z_b}{\partial x} \right) \tag{4.9}
\]

\[
S_y = S_{y_{\text{original}}} \left( 1 + \alpha \frac{\partial z_b}{\partial y} \right) \tag{4.10}
\]

where \( S_x \) and \( S_y \) are the corrected transports, and \( S_{x_{\text{original}}} \) and \( S_{y_{\text{original}}} \) are the transports following from Equation (4.6), and \( \alpha \) is a diffusion coefficient.

The LAX-scheme for the computation of the bed level change is an explicit scheme. This implies that the stability of the solution is bounded by the Courant-criterion. The Courant number should not exceed 1. On the other hand, the accuracy of the results decreases with a lower Courant number due to numerical diffusion. To obtain stability in combination with an accurate solution a variable time step is applied. The time step is automatically determined and dependent on a maximum Courant number, to be specified by the user, the grid spacing and the bed level change rate:

\[
\Delta t = \frac{Cr \cdot \Delta x}{c_b} \tag{4.11}
\]

where \( \Delta t \) [s] is the time step, \( \Delta x \) [m] is the grid spacing, \( Cr \) [-] is the Courant number and \( c_b \) [m/s] is the bed celerity, which is a function of the sediment transport and the local water depth.

At the boundaries of the model area disturbances in the bed level might occur because the imposed sediment transport will not fully match the local circumstances. Gradients in the transports in the zone near these boundaries could lead to unwanted ongoing erosion. This is prevented by suppressing the bed level changes in the first two rows of grid cells next to a boundary.

### 4.4 Uniform beach profile method

In process-based morphological models all sediment transports are assumed to be generated by the interaction of currents and waves. In the computational model these quantities are defined on a grid and logically only present in the grid cells in which the bottom is under water. The change of the bottom level in a certain grid cell is calculated from the surrounding sediment transports based on the principle of conservation of mass. Consequently, bottom level changes can only be found in the wet grid cells. This approach makes it difficult to model the effect of an eroding coast properly because the bottom level of a dry grid cell adjacent to the waterline will never decrease and the cell will stay dry. Continuous erosion might result in an ever increasing water depth in the wet cell adjacent to the waterline, resulting in a steep gradient in the bottom level at the waterline.

In practice, the interaction between the dry and wet part of the beach does exist. Possible mechanisms redistributing the sediment over the beach profile are the transport of sediment by the wind, bottom instabilities, a dynamically varying waterline due to the tide and the run-up and rush-down of waves. These mechanisms are not directly included in the morphological models because they are not related to the motion of water or occur on a scale too small to be represented on the computational grid.
Besides the interest in a formulation for the exchange of sediment between the dry part and the wet part of the beach, there is another wish for a formulation redistributing the sediment around the waterline. The calculated currents, waves and sediment transports near the waterline tend to cause some unphysical irregularities. In practice, these would be levelled out by small-scaled wave-induced processes redistributing the sediment. The numerical grid is usually too coarse to cover these processes, but the model could be extended with some redistribution mechanism representing these sub-grid processes to avoid unphysical effects.

The problems as have been mentioned can be overcome by the use of the so-called “uniform beach profile method”. This method makes use of the fact that in practice the beach profile at a coast, exposed to a certain wave climate, is found to develop towards an equilibrium profile. The upper part of the beach profile responds rapidly to disturbances from the equilibrium state and retains its shape almost constantly. Morphological changes as erosion or accretion thus result in a displacement of the waterline and beach profile, while the shape of the profile itself remains unchanged. This is shown in Figure 4-2. With the uniform beach profile method this principle is implemented in the computational module for the bed level changes. That part of the beach profile which will retain its shape during a morphological simulation is called the uniform beach profile. The uniform beach profile is located between two user defined bottom levels. The lower and thus wet boundary is called the uniform profile depth and the upper and dry boundary is called the top of the dune.

![Figure 4-2: Concept of the uniform beach profile method](image)

The computational procedure is split up into two stages. During the first stage for all wet grid cells the bottom level change rate \(\frac{\partial z}{\partial t}\) is calculated conventionally, applying the mass-balance principle for each individual grid cell in combination with the calculated sediment transports. In the dry grid cells of course no bottom changes are found. An arbitrary result of such a computation is displayed in the upper part of Figure 4-3.

The second stage is gone through only by the grid cells situated within the uniform profile zone and takes place row by row perpendicular to the waterline. For each row the artificial total inflow of sediment \(S_{in}\) is determined by adding the volume changes of the individual grid cells:

\[
S_{in} = \frac{\partial V_{tot}}{\partial t} = \sum_{j=1}^{N} A_j \frac{\partial z_j}{\partial t}
\]  

(4.12)

in which \(A_j\) is the area of cell \(j\), and \(\partial V_{tot}/\partial t\) is the volume change per unit of time (see also the lower part of Figure 4-3). Of course the bottom change rates of the dry grid cells do not contribute to the total, as these are zero.
The total inflow $S_{in}$ is now redistributed over the total wet and dry part of the uniform profile zone. It is assumed that the inflow enters the uniform profile zone from the deepest point of the beach profile and decreases linearly to zero at the top of the dune. The sediment transport through a cell is proportional to the depth relative to the uniform profile depth:

$$S_j = S_{in} \frac{z_{dune} - z_i}{z_{dune} - z_{profiledepth}}$$

in which $S_j$ is the transport through cell $j$, $z_{dune}$ is the level of the top of the dune, $z_i$ is the depth of cell $j$ and $z_{profiledepth}$ is the uniform profile depth. The volume balance for each grid cell is now:

$$\frac{\partial V_j}{\partial t} = -\Delta S_j = +S_{in} \frac{\Delta z_j}{z_{dune} - z_{profiledepth}}$$

The new bed level change rate for each grid cell follows:

$$\frac{\partial z_i}{\partial t} = \frac{1}{A_j} \frac{\partial V_j}{\partial t}$$

Now the new bed level can be determined for the whole uniform profile zone, resulting in a backwards or forward moving beach profile.

### 4.5 Application of the uniform beach profile method

The uniform beach profile method has appeared to be a suitable solution for an actual simulation of the morphological development around the waterline, as shown by Jörissen (2001). When the method is applied in a model the following points of interest should be considered:

- Top of the dune
- Uniform profile depth
- Resolution numerical grid

and in the case of a model concerning groynes:

- Length of the groyne
Top of the dune
The upper boundary of the uniform profile corresponds with the highest level of the dry beach that is directly influenced by the morphological processes around the waterline. Although the name “top of the dune” suggests that the whole dune is included in the uniform profile, the actual uniform profile is in the present application assumed to extend only to the dune foot. One of the reasons for this is that the exchange of sediment between the beach and the dune takes place on a rather large time scale. Morphological changes around the waterline are assumed not to result directly in a change of the position or sand volume of the dune. From the upper boundary the uniform profile is modelled with a horizontal beach plain, as is shown in Figure 4-4.

![Figure 4-4: Upper boundary of the uniform profile zone](image)

In a situation with accretion the supply of sand results in the beach profile shifting seaward. The beach is extended more than that the dune grows or is displaced, as shown in Figure 4-4. This process can also be observed in reality, for example at the southern side of the breakwaters of IJmuiden, The Netherlands.

The situation of erosion is more complicated. Initially, the erosion will result in a landward shifting beach profile and a decreasing beach. In spite of the distance between the waterline and the dune foot, changes in the position of the waterline will soon affect the dune foot. After some time, the volume of the dune will thus decrease. This effect is not included in the present model application. It is assumed that on a small time scale the sand volume of the dune will remain unchanged. For a long-term simulation, however, the approach does not correspond with reality. The regression of the waterline will be over-predicted, as the dune will function as a sand buffer supplying more sand than the assumed beach plain.

In connection with the highly simplified case presented in this study, the approach is certainly acceptable. For future (design-) applications it is recommended to include the effects on the development of the dune as a whole.

In the study of Jörissen the upper boundary of the uniform profile zone was located at MSL +2.00 m for both the accreting and the eroding area. This value is also used in this study.

Uniform profile depth
The uniform profile depth must be chosen in proportion to the upper boundary. When the wet part of the uniform profile is too small compared to the dry part, relatively much sediment is exchanged with the dry zone of the profile. In the case of accretion, little sediment stays behind in the wet zone, causing a rather small bottom change compared to the deeper part of the profile where the sediment is not redistributed. A considerable discontinuity may then develop at the transition from the uniform profile zone to the deeper zone. Jörissen successfully applied a uniform profile depth of 3.75 m, which is also used in this study.
In addition to the required depth, also the number of wet grid cells must be sufficient. When the uniform profile zone covers too few grid cells, the impact of a possible deviant bed level change in one cell might become too high, again causing irregularities at the lower boundary. Jörissen found that at least four to five wet grid cells are needed to prevent an unstable development of the bed level.

Resolution grid
The uniform profile method enables the waterline to move forward and backward. Due to the use of a numerical grid, the waterline shifts with discrete steps of at least the width of one grid cell. When the grid spacing cross-shore is rather large, the angular shape of the waterline will cause a distorted flow pattern resulting in a distorted sediment transport field. Furthermore a too coarse grid in the uniform profile zone introduces numerical diffusion in the uniform profile method. This must be prevented by applying sufficiently small grid sizes. In this study the grid size around the waterline is 15 m.

Length of the groyne
Depending on the length of the groyne and the chosen uniform profile depth, the tip may be situated within the uniform profile zone. When this is the case, the bottom changes seaward of the tip of the groyne are also redistributed over the beach profile. Generally the velocities in the vicinity of the tip are rather high due to flow contraction, resulting in higher sediment transports and the possible occurrence of scour. At the upstream side of the groyne, the accretion close to the beach may be counterbalanced by the erosive trend at deeper water, so that the waterline stays constant or even recedes. While in practice the beach profile could get steeper, this is not assumed to occur within the uniform profile zone. The results of such a simulation should therefore be treated with care. Jörissen applied a minimum groyne length of 165 m to prevent this problem. As a matter of fact, also long groynes experience the problem after some time, as the accretion upstream makes the uniform profile depth approach the tip of the groyne.
4. Description of the RAM bed evolution model
5. Modelling of a groyne

5.1 Introduction

The length of a groyne is large in comparison with its width. In order to predict the morphological development of the coast in the vicinity of a groyne, especially the length of the groyne is important, as it determines the local flow pattern and the sediment transport field. The width of a groyne is relatively small, so that its impact on the morphology can be neglected. Just like in reality, the modelled groyne needs to block currents, waves and sediment transports. In this study it is assumed that the groyne forms a complete obstruction at all possible water levels, in spite of the fact that many groynes are actually flooded during high water or are sometimes permeable. Modelling these effects however is presently too complicated because small-scale processes are involved which are not represented by a medium-scale model of the coastal area. Moreover, vertical accelerations may occur in the case of flow over a flooded groyne. This effect cannot be described by the present flow-model because a hydrostatic pressure distribution over the depth is assumed. Applying some overall factor for a reduction of the sediment transport through and over the groyne might be possible, but insight in this matter is still lacking.

The implementation of the groyne into the computational grids of the model is still an important item for a reliable representation. The slender shape of the groyne in combination with the specific properties of the numerical grids requires close attention to the way the groyne should be implemented. In this chapter the possibilities will be described to implement the groyne into Delft3D-FLOW and Delft3D-WAVE. Delft3D-TRAN and the bed level variation computation make use of the same computational grid as Delft3D-FLOW and will be treated together with this module. The chapter will conclude with an example of the proposed modelling of the groyne in the different modules and some results of a test case.

5.2 Implementation in Delft3D-FLOW

In Delft3D-FLOW a staggered grid is applied. A staggered grid implies that the quantities that are used in the computation are specified at different positions on the numerical grid. Distinction is made between depth points, water level points and velocity points. In the depth points the water depth is defined as the vertical distance between a reference level, usually Mean Sea Level, and the bottom. The depth is positive when the bed level is below the water level. The water level is defined as the distance between the reference level and the wet surface. A water level above the reference level is positive. The velocities in x- and y-direction are, among other things, computed from the water levels and located between them. The concept of the staggered grid is illustrated in Figure 5-1.

![Figure 5-1: The staggered grid of Delft3D-FLOW](image-url)
In Delft3D-TRAN the sediment transports are determined for the water level points of the flow grid. The transports are computed using the four surrounding velocities. The bed level variations are computed from the surrounding sediment transports by RAMBCCH and are defined at the depth points. In addition to the location of these quantities on the grid, also the impact of the groyne on the computational results must be considered. For the implementation of the groyne three possible options are considered:

1. Modelling the groyne with a single row of negative water depths, as suggested by Jörissen [2001]. A negative water depth implies that the points lie above MSL.
2. Modelling the groyne using the “dry points” option of Delft3D-Flow
3. Modelling the groyne using the “thin dams” option of Delft3D-Flow

The options will be discussed successively.

**Row of negative water depths**

Jörissen modelled a stationary situation without tidal influences. He assigned a value of one metre above Mean Sea Level to the depth points at the location of the groyne. This is illustrated in Figure 5-2. The blocking effect of this approach is based on the following principle. The water depths $d_{m,n}$ and $d_{m,n+1}$ both are above MSL. The water depth at the x-velocity point $u_{m,n}$ is in fact not defined directly, but is required for the flow computation. Delft3D-FLOW determines this water depth by taking the average depths of the two neighbouring water depth points. The water depth at the velocity point $u_{m,n}$ is thus set above MSL and consequently the velocity $u_{m,n}$ must be zero. The groyne now forms an obstacle for the longshore current. An unwanted side effect of this approach is that the water depth at the y-velocity point $v_{m,n}$ is the average of the neighbouring depth points $d_{m-1,n}$ and $d_{m,n}$. The influence of the negative depth of $d_{m,n}$ results in a decreased depth at the velocity point and an affected velocity $v_{m,n}$. The velocity is now dependent on the arbitrary chosen height (negative depth) of the groyne. This applies for all v-points on both sides of the groyne.

Next the sediment transports are computed using the surrounding velocity points. For example, the sediment transports $x_{m,n}$ and $y_{m,n}$ are found with $u_{m,n}$, $u_{m,n}$, $u_{m,n}$ and $v_{m,n}$. The fact that $u_{m,n}$ is zero should not lead to problems. Finally, the bed level variations are computed, also based on the information of surrounding points. The bed level variation at $d_{m,n-1}$, for instance, is found using the sediment transports at the water level points $(m,n-1)$, $(m,n)$, $(m+1,n-1)$ and $(m+1,n)$. Now a serious problem does arise. The depth points at the groyne are influenced by the sediment transports of the left side as well as the right side of the groyne. Because of the presence of the transports, the (negative) depth of the groyne will change, and even worse, this will affect the averaged depth at the adjoining v-velocity points. The morphological development on one side of the groyne is thus able to influence the development of the other side. Jörissen indeed found implausible transports directly next to the groyne. He avoided this problem by setting the transports around the groyne to zero in the program code. However, in some test cases this led to the development of a deep scour hole at the lee side of the groyne.

![Figure 5-2: Groyne as row of water depths above MSL](image-url)
Dry points option within Delft3D-FLOW

The dry points of Delft3D-FLOW are grid cells around a water level point that are always dry during a computation, irrespective of the local water depth and water level. In fact, these dry cells are excluded from the computation. The groyne can be modelled as a row of dry points perpendicular to the waterline. This is illustrated in Figure 5-3. The difference with the concept of negative depth points is that the groyne now is centred on the water level points instead of on the depth points.

During a hydrodynamic simulation, the velocities perpendicular to the boundary of a dry cell must be zero because there cannot be any exchange of water between a wet cell and a dry cell. For example, the x-velocities \( u_{m-1,n} \), \( u_{m,n} \), \( u_{m+1,n} \) and \( u_{m,n+1} \) will be zero as well as the y-velocity \( v_{m,n} \). A row of dry points thus forms an obstacle for the flow. In the following sediment transport computation all transports around the dry points can be computed properly from the surrounding velocities. The sediment transport at the water level point \( (m+1,n) \), for example, will be based on the velocities \( u_{m,n} \), \( v_{m-1,n} \), \( u_{m+1,n} \) and \( v_{m,n+1} \), of which \( u_{m,n} \) is zero. The dry points enforce a clear division between the morphological changes on both sides of the groyne.

The sediment transports at the water level points of the dry cells are not defined, as there is no water in the cell. Delft3D-TRAN sets the values of the coordinates of these points to 9999999 and the sediment transports to 999,999 to exclude them from the computation. Although RAMBCH recognises the transports as undefined and sets them to zero, it does not change the values of the coordinates. Still these points are included in the computation. When subsequently the bed level variation at depth point \( d_{m+1,n} \) is computed, a mass balance is applied for the area \( \Delta x \times \Delta y \) and the inflow and outflow of sediment through the planes \( \Delta x \) and \( \Delta y \) is evaluated. The wrong coordinates of the point \( (m,n) \) cause an error in the computation of \( \Delta x \) and \( \Delta y \) and therefore an error in the bed level computation.

![Figure 5-3: Groyne as a row of dry points](image)

![Figure 5-4: Groyne as a set of thin dams](image)

Thin dams option within Delft3D-FLOW

A thin dam is an infinite thin object that is defined over the velocity points of the grid. It runs from depth point to depth point (see Figure 5-4). A thin dam prevents the exchange of water between neighbouring grid cells. The depth at the depth points on the thin dam holds for both sides of the dam. A single thin dam is thus not effective for the case of the groyne. After all a completely different water depth can be expected at both sides of the groyne. In Figure 5-4 the groyne is therefore modelled with a set of three thin dams. The first thin dam starts at the beach plain, extends in cross-shore direction to the depth point \( d_{m+1,0} \) and blocks the flow in longshore
direction. The second thin dam runs parallel to the first dam at a distance of one grid cell. The third thin dam connects the depth points \( d_{w_{1},0} \) and \( d_{w_{n},n} \). It seals an elongated area which will form the groyne. In this way the joint thin dams function just as the dry points with respect to the blocking effect on flow and sediment transport. An important difference, however, is that water is still present within the enclosed area. In the absence of flow, the sediment transports will there be zero. The bed level variations at one particular side of the groyne are thus only influenced by the sediment transports at that side.

The use of three thin dams in the flow module is expected to represent the groyne well (under the assumptions presented in Section 5.1). The thin dams will block the currents and sediment transports and clearly divide the development of the bed on both sides.

### 5.3 Implementation in Delft3D-WAVE

Up till now no attention was paid to the modelling of a groyne with respect to the presence of waves. Nevertheless, also within the wave computation a blocking object is needed to represent the influence of the groyne. First the treatment of flow, bottom and wave information in Delft3D-WAVE is considered.

In Delft3D-WAVE several grids are used. The computational grid is a rectangular grid on which the program solves the balance equations and computes the wave properties. The wave properties are defined at the corners of the grid cells. The bottom grid is a secondary grid, on which the input for the actual computation is provided. The necessary data for the computation, such as water depths and velocities, is taken from the bottom grid and transferred to the computational grid by interpolation. When data from Delft3D-FLOW is to be used, the bottom grid serves as an intermediate grid. First the information from the flow grid is interpolated to the bottom grid, and subsequently from the bottom grid to the computational grid. When the wave computation is completed, the results are in their turn exported to the grid of the flow module where they are located at the water level points. Again interpolation is used when the two grids do not match exactly. So, besides the implementation of the groyne in the computational grid, the minimising of interpolation errors must also be kept in mind.

![Diagram showing grids used in Delft3D-WAVE](image)

**Figure 5-5: Grids used in Delft3D-WAVE**

Delft3D-WAVE offers the possibility to set an obstacle for the waves. The obstacle can have the form of a sheet or a dam. In both cases a transmission coefficient can be applied. In this study, the transmission coefficient is set to zero, assuming that the groyne forms a complete blockage for flow and waves. The two options that are investigated are:
1. A single sheet
2. A set of three sheets
The use of the different terms “sheet” and “thin dam” for the blocking element may be confusing. Although Delft3D-FLOW and Delft3D-WAVE use a different terminology, in both cases an infinite thin object is meant which blocks the flow or wave energy. The positioning of both elements on the grid does differ. The location of thin dams in Delft3D-FLOW is bounded by the position of the depth points. A thin dam always connects a series of depth points and runs over velocity points. The sheet in Delft3D-WAVE can be placed independently from the computational grid using x- and y-coordinates. It may begin and end at any arbitrary location in the model area.

**Single sheet**

When the groyne is modelled by means of a single sheet, the transmission of wave energy through this sheet will be blocked. This is illustrated in the left-hand side of Figure 5-6. The sheet can be placed either over the wave height points (I), or between the wave height points (II). In the first case the wave heights at the sheet are normally defined and do not differ much from the surrounding wave heights. From the results it is not clear whether these wave heights are influenced by the left side, the right side or both sides of the sheet. This way of modelling the groyne is therefore not suitable. Next, the sheet is placed between the wave height points. It can be observed that the wave field differs on both sides of the sheet. A sheet located between the wave height points clearly blocks the wave energy.

The location of the sheet will then logically agree with the centre of the area of the flow grid which is enclosed by the thin dams. This means that the sheet, projected on the flow grid, lies over the water level points, as is clarified in Figure 5-6. Yet a problem occurs when the wave height at these points is determined. For example, the wave height at water level point A of the flow grid is found by interpolation between the neighbouring wave height points (B, C, D and E) of the computational grid of the wave module. However, these points are located on different sides of the sheet, resulting in an incorrect wave height. As long as only the wave heights within the enclosed area are affected by wave impact from both sides, the problem is not relevant. When the cells of the computational grid of the wave module are wider than two times the width of a flow cell, also the points next to the groyne are affected. This should be avoided.

*Figure 5-6: Groyne as single sheet over (I) and between (II) the wave height points*
Set of three sheets
When the groyne is modelled using a single sheet, the wave heights within the enclosed area of the flow grid are non-zero. Although this doesn’t affect the flow and wave pattern around the groyne, still some cross-shore flow may develop within the enclosed area, resulting in small sediment transports. The influence of these unphysical transports on the evaluation of the surrounding depth points must be avoided. Therefore it is better to model the groyne in such a way that the wave heights within the enclosed area are zero. This can be achieved by the application of a set of three sheets, as illustrated in Figure 5-7. The joint sheets assure that no wave energy can reach a row of wave height points of the computational grid of the wave module. When x-coordinates of these points do exactly match with those of the water level points of the flow grid, an absolute distinction is made between the wave impact from both sides. Moreover, when the grid cell spacing of the flow grid and the computational grid is taken equal in x-direction, no interpolation errors will occur at all. If the x-coordinates and/or the grid spacing of the wave grid and the flow grid do not correspond, interpolation errors can be expected.

![Computational grid DelF3D-WAVE vs Grid DelF3D-FLOW](image)

Figure 5-7: Groyne as a set of three sheets

Jörissen [2001] also models the groyne in the wave module with a set of three sheets. The width of his set of sheets however is equal to two cells of the computational grid. His obstacle surrounds two rows of wave height points. This is illustrated on the left-hand side of Figure 5-8. This method fits well to the way he implemented the groyne in the flow module (see Figure 5-2). In combination with the thin dams, the method is less suitable. The wave height points of the wave module should now coincide with the water depth points of the flow grid, as shown in Figure 5-8. Although the wave height at the water level points within the enclosed area become zero by interpolation between two zeros, the wave heights directly beside the groyne will be the average of a certain wave height and zero. This artificial reduction of the wave height should be avoided.

A set of three sheets around one row of wave height points on the wave grid is a suitable method to represent the effect of a groyne in the wave module. The method can be combined well with the proposed method to implement the groyne in the flow module. When the x-position of the water level points on the flow grid and the wave height points on the wave grid correspond, and the grid spacing of both grids is chosen equal, the interpolation effects are minimised.

In the following section, an example is given of the proposed representation of the groyne.
5.4 Example with results

Set-up test case

In a test case, the groyne is modelled with three thin dams in the flow model and with a set of three sheets in the wave model, as described in the previous sections. The test case corresponds completely with the stationary case as discussed extensively in Chapter 6. The case describes the evolution of an initially straight coast with a single groyne under the influence of a constant and uniform wave-driven current. The tide is left out of consideration. The imposed wave condition consists of a uniform and stationary wave field with a significant wave height of 1.65 m at deep water and a peak period of 6.0 s. At deep water the angle between the wave crests and the shoreline is 20°. The directional spread of the waves amounts 25°.

It is expected that the modelled groyne effectively blocks currents, waves and sediment transports. In the results, it should be visible that the groyne forms and obstruction for the wave-driven current and causes the flow and the sediment transport to bend around the structure. At the leeside of the groyne, the wave height should be lower than upstream of the groyne, where the coast is exposed to the full wave climate. In the depth points within the thin dams the flow velocities, sediment transports and wave heights should be zero, as the enclosed area should be completely separated from external impact. Obviously, the absence of these quantities within the thin dams indicates that the blockage functions well. In the depth points coinciding with the location of the thin dams, the computed bed level changes should directly follow from the mass balance of the surrounding transports. Before the results are considered, first the implementation of the groyne is discussed more in detail.

In Figure 5-9 an overview is given of the applied flow and wave grid, as well as the implemented thin dams and sheets. In the vicinity of the groyne the grid cell spacing in longshore direction of both the flow and the wave grid is taken 25 m so that the resolution around the groyne is suitable to represent the local flow and wave field. In cross-shore direction the grid cell spacing of the wave grid must be constant, while the grid cell spacing of the flow grid may vary. The cross-shore grid spacing of the wave grid is 12.5 m, for the flow grid this is 15 m at the waterline and over 100 m at 2 km from the beach. The computational wave grid and the bottom grid are set up identically, so that errors in the interpolation of input data to the computational grid are prevented. Because the data to be transferred to and from the flow grid is defined on the water level points of the flow grid, these points must match as much as possible with the wave height points of the wave grid. Therefore, at the intended location of the groyne the longshore (x)-
position of a row of water level points coincides with the x-position of a row of wave height points on the wave grid. In Figure 5-9 this is indicated with an arrow. In cross-shore direction the correspondence of the positions cannot be achieved. However, at the groyne the wave field varies more from one side to the other side than in cross-shore direction, so this is no real problem. Furthermore the cross-shore grid spacing of 12.5 m is so small that the interpolation errors in this direction will be limited due to the small changes from point to point.

![Wave grid and flow grid](image)

*Figure 5-9: Example implementation of the groyne in flow and wave grid*

Now that the grids are set up, first the groyne is implemented in the flow grid. The centreline of the groyne coincides with the previously mentioned row of water level points. Two thin dams are defined over the depth points on both sides, extending from a depth point at the landward boundary of the model area to the intended location of the tip of the groyne. The third thin dam connects the tips of the two thin dams so that an enclosed area is formed. The enclosed area can be regarded as the groyne. The location of the tip of the groyne must correspond to a depth point. Possible locations are indicated in Figure 5-9 with a, b, c, etc. In case the desired location of the tip does not correspond to a depth point the grid must be adapted. In the example the groyne length is 417 m. The thin dams defined from (12500, 0) to (12500, 417); from (12525, 0) to (12525, 417) and from (12500, 417) to (12525, 417). The water level points within the enclosed area are at x-location 12512.5 m.

The final step is the implementation of the sheets in the wave grid. The placement of the sheets is not limited to grid locations, but can be defined with (x,y)-coordinates. The row of wave height points corresponding to the centre of the groyne is located at 12512.5 m. On both sides of this row sheets are defined coinciding with the thin dams. These start at the landward boundary and extend to the tip of the groyne. The third sheet is placed between the tips of the two other sheets. The sheets are now also defined from (12500, 0) to (12500, 417), from (12525, 0) to (12525, 417) and from (12500, 417) to (12525, 417). All wave height points within the thin dams are now isolated from the wave energy at the sea, so that also in the wave model a groyne is constructed.
Results
The results of the test case are discussed considering the initial hydrodynamics and sediment transports. Figure 5-10 shows the velocity field around the groyne. The location of the thin dams coincides with the groyne drawn. The x- and y-velocities are plotted as a vector in the water level points of the flow grid. It is clearly visible that the velocities in the points “within” the groyne are zero. The flow field is influenced by the presence of the groyne and bends around the tip. At the lee side of the groyne a circulation pattern has developed due to a difference in wave set up along the waterline.

In Figure 5-11 the wave field around the groyne is represented by wave vectors at the water level points of the flow grid. The wave vectors point in the direction of wave propagation while their length indicates the local (RMS-)wave height. “Within” the groyne the wave height is zero, indicating that the wave energy is blocked. In the area close to the groyne the wave directions turn towards the groyne. The reason for this phenomenon is the directional spreading the wave model accounts for. Due to the presence of the groyne the wave energy from certain directions is blocked, causing the average direction to change.

![Figure 5-10: Velocity field around the groyne](image1)

![Figure 5-11: Wave field around the groyne](image2)

The (RMS-)wave height is also plotted. (see Figure 5-12). At the lee side of the groyne the wave height is less due to the sheltering influence of the groyne.
In Figure 5-13 the sediment transport field is shown. It includes bed load as well as suspended load transport. Just like the flow field, the sediment transport field is blocked by the presence of the groyne. Upstream, the sediment transports bend away from the water line and turn around the tip of the groyne. The sediment transports “within” the groyne are zero, indicating that the groyne blocks the sediment transports completely.

Computations by hand on the bed level changes in the vicinity of the groyne have shown that the bed evolution model computes these properly from the surrounding sediment transports. Mass is conserved and bed level changes on one side of the groyne are not influenced by sediment transports on the other side of the groyne.

Based on the results presented in this section, it is concluded that the proposed method to implement the groyne in the flow and wave module leads to reliable results. The method will be used to implement the groyne in the cases discussed in the following chapters.
Figure 5.12: Wave height around the groyne

Figure 5.13: Sediment transport field around the groyne
6. Model set up for the stationary case

6.1 Introduction

The stationary case describes the idealised situation of an initially straight coast with parallel depth contours. The model area measures almost 20 km in longshore direction and 3 km cross-shore. At deep water a stationary and uniform wave field is present. The waves, approaching the shoreline under an angle, cause a longshore current within the surf zone. The influence of the horizontal and vertical tide is not taken into account by assuming a constant water level at Mean Sea Level (MSL). Originally, the coastal area is in equilibrium state due to the uniform and constant longshore sediment transports. At the start of a simulation, however, the area will be confronted with the presence of a groyne perpendicular to the shoreline. As a result of the interruption of the longshore sediment transports, accretion and erosion will take place and the interaction between the coast and the groyne can be studied.

This chapter will describe the general model set up for the stationary case. It discusses the model structure and the use of the flow model, wave model, sediment transport model and RAM-model. The representation of the groyne in the models is described in Chapter 5. In Chapter 8 the results of simulations of the stationary case are discussed.

As starting point the model set up by Jörissen (Jörissen, 2001) is used. It is desirable to adapt some aspects of that set up to improve the results and the computational effort. The major differences between the present application and the application set up by Jörissen are of computational nature and involve:

- Implementation of the groyne using “thin dams” in the flow module and “sheets” in the wave module instead of depth points with a value above MSL. This is discussed extensively in Chapter 5. For more information the reader is referred to that chapter.
- A finer resolution of the numerical flow and wave grid in the vicinity of the groyne in order to achieve a better description of the hydrodynamic and morphological behaviour in that area.
- An increased time step to improve the computational time of the Flow-module.

6.2 Model structure

In the stationary case, the flow-, wave- and sediment transport fields are not directly time-dependent due to the absence of the tide and the stationary wave condition. Although the bathymetry changes as a function of time, the time scale of this process is rather long. A straightforward model structure can therefore be applied. The simulation is split up into morphological time steps and intermediate time steps, as explained in Section 3.4. During the intermediate time steps, the sediment transport field is quickly updated according to the RAM-scheme, assuming that the changes in the flow and wave field are negligible. After a number of intermediate time steps the bathymetry has changed in such a way that a full flow, wave and sediment transport computation is required. This computation forms the beginning of a new full morphological time step. Due to the stationary conditions no averaging over different conditions is necessary, but the spin up time of the flow- and sediment transport model must still be taken into account. The model structure is outlined in Figure 6-1, after which a number of steps are described more in detail.
At the beginning of the morphological time step the following procedure is applied:
1. Initial flow computation of one time step, excluding wave effects, to initialise the water depth for the wave computation.
2. Wave computation based on the output of the initial flow computation. Local wave conditions are determined for the entire model area and are stored on the flow grid.
3. Full flow computation, including wave-current interaction, until spin up effects have dampened out sufficiently and stationary water levels and flow velocities are acquired. Only these stationary results are used in the sediment transport computation.
4. Sediment transport computation based on the stationary results of the flow and wave computation. The stationary sediment transport field at the end of the computation is stored to be used in the RAM-module.

The duration of the morphological time step is imposed by the rate at which the bed changes take place. When the bed level varies rapidly, a frequent updating of the full flow-, wave and sediment transport field is required, while for long-term changes a considerable larger time interval can be applied. In case of the construction of a groyne, the initial impact on the development of the bed will be large. However, after a number of years the coast will almost have adapted itself to the new situation and the bed level change rate will be substantially less. To optimise the computational effort, the number of full flow computations can be reduced by applying a time dependent morphological time step. Nevertheless, in the present application a constant time step of 2 days is used for reasons of simplicity.

6.3 Flow model

Numerical grid
The model area of 19 km longshore (x-direction) and 3 km cross-shore (y-direction) is covered with a rectangular grid. The grid consists of 128 x 89 computational grid cells. To save computational time the grid is refined in the areas of special interest and wider where no detailed information is needed. At the lateral borders of the model area the grid spacing in longshore direction is 500 m. At the seaward border the grid spacing in cross-shore direction is 120 m. In the vicinity of the groyne the grid spacing is 25 m in longshore direction. Around the tip, the grid spacing in cross-shore direction is 30 m. Jörissen found that in the vicinity of the waterline, a grid spacing of 15 m in cross-shore-direction is required in order to simulate the coastal development properly, using the uniform beach profile method. He combined this with a morphological time step of two days. The model area is displayed in Figure 6-2.
In the present model set up, the applied grid spacing around the groyne is 25 m. This is half of the grid spacing applied in the model set up of Jörissen. In tests it appears that around the groyne the flow field and sediment transport field varies considerably from place to place. (See for example Figure 5-10 and Figure 5-13). When the grid is too coarse, the flow and transport field is represented by too few “measuring” points and the overall pattern cannot be represented well. This might result in distortions in the development of the bed. To prevent this effect, a smaller grid spacing is applied in the present model set up.

![Diagram of the model area](image)

**Figure 6-2: Sketch of the model area**

**Bed Topography**

The bed topography that is used in the present stationary case is the same as Jörissen used for his application. The bed profile is derived from four 5-yearly measurements of cross-section 115.60 of the Dutch JARKUS system and is characteristic for the coastal area of Delfland, The Netherlands. Jörissen calibrated the parameters of the Bialard formula for cross-shore transport in such a way that the beach profile remains stable over a period of one year for the imposed wave climate. As a result, all morphological changes in the model area can be attributed to the influence of the groyne.

At the seaward boundary of the model area the water depth is MSL -10.00 m. It is assumed that the processes that take place between the MSL -8.00 m and MSL -10.00 m depth contour do not directly influence the morphological development of the coast. The bed profile is assumed to extend to MSL +2.00 m, behind which a beach plain is situated. The cross-shore profile is indicated in Figure 6-3.

![Cross-shore profile](image)

**Figure 6-3: Cross-shore profile**
**Boundary conditions**

The flow grid contains three open boundaries and one closed boundary. The closed boundary is formed by the coast, the open boundaries are located on both sides of the model area and at the seaward end. At the open boundaries, boundary conditions are required to represent the influence of the outer world. At the seaward side of the model a water level is prescribed with a constant water elevation at MSL +0.00 m. To make this boundary less reflective to disturbances with the eigen frequency of the model area, a reflection coefficient α is specified. In the stationary model a value α =230 [-] is used.

At the lateral boundaries a so-called Neumann boundary condition is applied. This kind of boundary condition is a non-standard feature of Delft3D-FLOW and can only be applied with an adapted version of the program. In case the Neumann boundary is not available, the best solution is to apply a water elevation at MSL. With the Neumann condition water level gradients perpendicular to the boundary are set to zero:

\[
\frac{\partial \eta}{\partial x} = 0
\]  

(6.1)

where \( \eta \) is the instantaneous water level relative to MSL. As the gradient of the water level at the boundary is set to zero, the water level at the boundary is determined by the water level in the inner part of the model area. This enables a situation in which the computed wave set-up is also present at the lateral boundaries. Former simulations have shown that when the Neumann boundary condition is applied, the smoothing time must be set to zero to prevent numerical problems.

**Initial condition and simulation time**

At the start of the simulation the water level is at MSL throughout the model area and the velocities are zero. Obviously, this situation does not match with the imposed boundary conditions and wave action. Due to this difference spin up effects appear at the start of the simulation. Tests have shown that after 50 minutes the spin up effects have dampened out sufficiently, so that a situation with stationary water levels and flow velocities is reached. This stationary flow field can subsequently be used in the following step of the computational procedure.

**Time step**

The duration of a morphological simulation is highly dependent on the flow computation. Although the computational time of the stationary simulation is acceptable, it is foreseen that the simulation over a full tidal cycle will require an extensive flow computation. To reduce the computational effort the time step of the flow computation is enlarged compared to the model of Jörissen. The maximum time step of a numerical solution method is generally bounded for reasons of stability and accuracy. Due to the ADI-time integration method of Delft3D-FLOW (see also Section 3.5) the solution is unconditionally stable. The accuracy of the solution is dependent on the Courant number (Cr):

\[
Cr = \frac{\Delta t \sqrt{gh}}{\{\Delta x, \Delta y\}}
\]  

(6.2)

where \( \Delta t \) is the time step, \( g \) is the gravitational acceleration, \( h \) is a representative water depth and \( \{\Delta x, \Delta y\} \) is a characteristic value for the grid spacing in either x- or y-direction. For situations with flow around irregular (staircase) closed boundaries the ADI-method is known to be inaccurate for Courant numbers larger than 4\( \sqrt{2} \). An extreme example of such a geometry is a narrow channel that makes an angle of 45 degrees with the numerical grid. Generally the Courant
number should not exceed a value of 10, but for problems with rather small variations in time and place substantially higher values can be accepted. The manual of Delft3D-FLOW thus advises to carry out sensitivity tests to determine the largest possible time step for accurate results. For more information, the reader is referred to the user manual (WL|Delft Hydraulics, 2001) and Stelling (1984).

The influence of four different time steps is evaluated. It is expected that the results of the flow computation might become inaccurate especially in the area close to the groyne and in the vicinity of the waterline because of the large variations of the velocity from place to place. A comparison is made between a simulation with a time step of 15 s (model Jörissen), 60 s, 120 s and 240 s. The characteristic depth for the area around the groyne is taken 4 m and the typical grid size 25 m. For the situation along the waterline the typical depth and grid size are assumed to be 1 m and 15 m respectively. The related Courant numbers are shown in Table 6-1. The Courant numbers associated with the time step of 15 s are rather low, while those associated with the time steps of 120 s and 240 s are large. Although the time step of 60 s shows a somewhat higher Courant number than the recommended value of 10, this seems a promising option.

<table>
<thead>
<tr>
<th>Δt (s)</th>
<th>Cr (-) around groyne</th>
<th>Cr (-) along waterline</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>3.8</td>
<td>3.2</td>
</tr>
<tr>
<td>60</td>
<td>15.2</td>
<td>12.6</td>
</tr>
<tr>
<td>120</td>
<td>30.4</td>
<td>25.3</td>
</tr>
<tr>
<td>240</td>
<td>60.7</td>
<td>50.1</td>
</tr>
</tbody>
</table>

*Table 6-1: Comparison several time steps*

A sensitivity test was carried out with the mentioned time steps simulating the initial flow field around a groyne. The results can be found in Appendix A. It is obvious that a time step of 240 s leads to inaccurate results. The zone along the waterline turns out to be the most vulnerable to this so-called ADI-effect. At the first sight, the results of the other three simulations seem identical. However, while the differences between the 15 s time step and the 60 s time step are negligible, a small deviation in the order of centimetres per second is found between the 120 s time step and the 60 s time step. The velocities predicted with the 60 s time step are generally slightly higher. Again, in the zone close to the waterline the largest deviations are found, especially at the re-attachment point at the right side of the groyne. Considering the non-stationary location of the waterline and the vulnerability of the ADI-method for irregular (staircase) closed boundaries, it seems unwise to apply the time step of 120 s. A time step of 60 s will lead to reliable results in combination with an improved computational effort compared to a simulation with the original time step of 15 s.

*Bottom friction model*

The bottom friction is dependent on the joint influence of currents and waves. For the computation of the actual bottom friction distinction is made between the friction due to currents alone and the friction due to waves alone. The friction due to the currents is related to the depth-averaged velocity, while the friction due to the waves is related to the orbital velocity near the bottom. In this study, following Jörissen, the formulation of Bijker is used to describe the effect of combined current and wave action. In addition to the Bijker approach also the friction model of Fredsøe is taken into account in the results (Chapter 8). For more information about both friction models the reader is referred to the user manual of Delft3D-FLOW (WL|Delft Hydraulics, 2001, p.9-53/9-56; see also Appendix T) and Soulsby et al. (1993). The bottom roughness is defined with a Manning coefficient of 0.028 s/m$^{1/3}$.

An overview of the input data of Delft3D-FLOW can be found in Appendix B.
6.4 Wave model

**Computational and bottom grid**
The numerical grid of the wave model is adapted in comparison with the original model set up by Jörissen. A finer grid is applied to obtain a more detailed representation of the wave field in the vicinity of the waterline and around the groyne. In the present application of Delft3D-Wave two grids are applied to compute the wave conditions in the model area. A coarse grid is used to cover the entire model area and a finer grid is used for the area around the groyne (see Figure 6-4). Both the resolution of the coarse grid and the finer grid are higher than in the application of Jörissen.

![Diagram](image.png)

*Figure 6-4: Model area with flow and wave grid*

The coarse grid computation is carried out first. Subsequently, the results are used to determine the boundary conditions for the finer grid computation. This approach combines a reduction of the computational time with accuracy in the area where it is needed. For reasons of simplicity, the main wave grid is shown within the conventional x-y-axis system of the flow model. In fact Delft3D-WAVE uses an own coordinate system. The origin is located at deep water (in the point [1450,3025]) with the x-axis pointing in the mean wave direction, in this case towards the shore. For more information about the coordinate system of Delft3D-WAVE, the reader is referred to the user manual (WL|Delft Hydraulics, 2000).

The coarse wave grid is taken wider than the flow grid because along each lateral side of the grid a region exists where the wave field is disturbed. The line dividing the disturbed area from the undisturbed area starts at the up-wave corner points and makes an angle of approximately 30° with the border. The coarse grid has a typical grid spacing of 25 m cross-shore and 50 m in longshore direction. In the set up of the application of Jörissen, the grid spacing was 50 m cross-shore and 100 m in longshore direction.

The grid size of the refined grid is 12.5 m cross-shore and 25 m longshore. The finer grid measures 500 by 1500 m and is centred on the groyne. Both computational grids are linked to an identical bottom grid on which the input for the Wave-computation is provided. Because the information from the Flow-module is used as input, the bottom grids only serve as an intermediate grid onto which the information is interpolated.

**Boundaries**
At the boundaries of the coarse computational grid the incident wave conditions are prescribed. The finer computational grid obtains its boundary information from the coarse grid. In the stationary model the wave conditions at deep water are assumed to be uniformly present and stationary in time. The same wave condition is therefore applied both at the lateral boundaries of the model area and the seaward boundary. Along both lateral sides of the grid the wave field is disturbed by an import of zero energy. By taking the computational grid larger than the model area, these effects do not influence the model area and a uniform wave condition is achieved.
The mean wave condition applied in the stationary model is based on the analysis of field measurements at Noordwijk by Jörissen and is assumed to be representative for the wave climate at the location where the coast profile was taken. The wave condition is characterised by:

- Significant wave height \( (H_{\text{sw}}) \): 1.65 m
- Spectral peak period \( (T_p) \): 6.0 s
- Angle between wave crests and shoreline \( (\alpha) \): 20°

An overview of the input data of Delft3D-WAVE can be found in Appendix B.

### 6.5 Sediment transport model

**Sediment transport formulas**

Delft3D-TRAN is used in the “suspended” mode. In the suspended mode, distinction is made between the calculation of the bed load and the suspended transport. The bed load is directly determined with an algebraic formula. The actual suspended transport is computed in two steps. First, for the suspended sediment an equilibrium concentration is determined using an algebraic formula. Then, the actual sediment concentration is determined from the equilibrium concentration in combination with an advection-diffusion equation. This approach enables the simulation of adaptation effects and diffusive transport.

In this study different formulas are applied for the sediment transport in longshore and cross-shore direction because these transports are dominated by different processes. In the longshore direction the wave driven current plays an important role. Sediment is stirred up by the waves and subsequently transported by the longshore current. The Bijker formula is often used for this situation. The cross-shore sediment transport is caused by other processes, such as wave asymmetry, bed slope effects and undertow. This is accounted for by the Bailard approach. The total sediment transport is the sum of the transport in longshore and cross-shore direction.

**Calibration coefficients Bailard model**

The coastal area under consideration in the stationary model is assumed to be in equilibrium state when the groyne is absent. The equilibrium shore profile is dependent on the local wave climate in combination with the applied cross-shore sediment transport formula. The Bailard formula, implemented by Nipius (1998), contains two parameters to adjust the magnitude and the direction of the transport. Jörissen calibrated these parameters, \( facA \) and \( epsl \), by simulating the morphological development of the model area during one year. He found out that the bed level changes after one year were less than 0.10 m with (Jörissen, 2001):

- \( facA \): 0.30
- \( epsl \): 0.18

These values are also applied in this study.

**Time frame**

In Delft3D-TRAN the time step of the transport model cannot be taken less than twice the time step of the flow model. Therefore a time step of 120 s is used. Tests have shown that after five time steps adaptation effects have been established and a stationary sediment transport field is found. The simulation time of the transport model is thus 10 minutes.

**Dispersion coefficient**

The suspended sediment transport is modelled with an advection-diffusion equation. The advection term describes the sediment transport due to the prevailing current. The diffusion term accounts for the sediment transport caused by the turbulent exchange of sediment between areas with a higher concentration and areas with a lower concentration. Diffusive transport may occur in two directions. The turbulence is expressed with a dispersion coefficient. Jörissen used a dispersion coefficient with a value of 0.10 m²/s instead of the default value of 1.0 m²/s. This
approach reduces the sediment transport from the breaker zone (high concentration) to the deeper part of the model area (low concentration). The value of 0.10 m$^3$/s is also used in this study.

An overview of the input data of Delft3D-TRAN can be found in Appendix B.

### 6.6 RAM-model

**Parameters uniform beach profile method**

In the input of Delft3D-RAM the upper and lower limit of the uniform beach profile method is defined. In Section 4.5 it is described which considerations should be kept in mind when determining these limits. In this study the values used by Jörissen are also applied, because of the satisfactory results in his study. The top of the dune is defined at MSL +2.0 m, the uniform profile depth at MSL -3.75 m.

**Time steps**

The morphological time step to be applied is dependent on the rate at which morphological changes will take place. In case the bed develops rapidly, the flow and wave field will have to be recomputed often, as the simple updating of the sediment transports within the RAM-module will not be able to deal with the highly changed bathymetry. On the other hand, when the bed evolves slowly, a larger morphological time step can be applied. It is expected that in the case of the groyne, initially considerable changes will occur within a limited period. After some time, the development will approach an equilibrium state, so that the bed level varies only slowly. The desired morphological time step could therefore increase with the simulation time. However, it is quite arbitrary under which circumstances the morphological time step could be increased and at what moment during the simulation this would occur. Following Jörissen thus a constant morphological time step of 2 days is applied.

Within the morphological time step the bed level changes are calculated with intermediate time steps. The RAM-module itself determines the optimal time step based on a user-specified maximum Courant number (see Section 4.3). The Courant number should not exceed 1 [-] to obtain a stable solution, while the accuracy of the solution decreases with a lower Courant number due to numerical diffusion. In this study a Courant number of 0.9 [-] is applied.

**Inactive zone**

Along the boundaries of the model area disturbances in the flow field and/or the sediment transport field may occur due to the imposed boundary conditions. Gradients in the sediment transport may subsequently cause areas with erosion. As this erosion increases, the disturbances could propagate through the model area and causes unwanted effects on the morphological development. Along the borders of the model area therefore an inactive zone is defined in which no bed level changes are allowed. The width of this zone measures two grid cells.

**Power in transport relation**

The power $b$ used in the relation for the updating of sediment transports (see Equation (4.4)) is taken 4 [-], which is a common value.

An overview of the input data of the RAM-model can be found in Appendix B.
7. Implementation of tidal effects

7.1 Introduction

The stationary case describes the idealised situation of a coast that is attacked by a uniform and stationary wave condition. The influence of the tide is ignored by assuming a stationary water level at MSL. However, the horizontal tide as well as the vertical tide will affect the morphological development of the coast. The water level determines the location of the breaker zone and thus, in case the waves are approaching the coast under an angle, where the longshore current is generated. Furthermore, the water level determines where the waves will start stirring up material from the bed, so that it can be transported by the longshore current. Finally, the location of the waterline also depends on the water level. These three effects will influence the average sediment transport field resulting from a varying water level. Generally, the tide-averaged sediment transport in the presence of the tide will be spread out over a wider zone than in a model with a constant water level. The sediment transport within the breaker zone is often dominated by the presence of waves, while the sediment transport in the outer zone is often dominated by tidal flow. In between an area with a mixed influence can be distinguished. The presence of a residual tidal flow will certainly affect the morphological development to some extent. A case including tidal effects is set up to investigate the influence of the tide on the morphological behaviour of the coast in the vicinity of a groyne.

This chapter will describe the model set up for the case including tidal effects. The set up of the stationary case, as described extensively in Chapter 6, serves a starting point. In the present chapter only the changes and additions in relation to the set up of the stationary case are presented. Apart from these items, both cases are equal.

For information about the modelling of the groyne, the reader is referred to Chapter 5. The results of simulations with the case including tidal effects are discussed in Chapter 8.

In relation to the model set up of the stationary case two kinds of changes and additions can be distinguished. A number of adaptations is directly related to the implementation of the tide in the model, such as:

- Different boundary conditions in the flow module to represent the tide
- An iterative computation of the waves and currents
- Items related to the exchange of results between the different computational modules

Other adaptations are necessary to improve the computational performance of simulations including tidal effects. These involve:

- An increased full morphological time step to improve the simulation time
- An extended version of the RAMBCH module to be able to simulate with an increased morphological time step without the occurrence of unstable developments in the bed
- Alternative boundary conditions in the flow module to represent a tide with a shorter period than usual. This "reduced" tide could be applied to reduce the computational effort of a simulation compared to a simulation with the full tide.

7.2 Model structure

The tidal case needs a more extensive simulation of the interaction between the flow and waves due to the varying water level and the presence of tidal flow. The simulation over a full tidal cycle also requires much more computational time than a stationary simulation over just the spin-up time. In the tidal case balance must be found between sufficient accuracy and a satisfying computational time. Because the wave and flow computation are carried out consecutively, these computations must be repeated for a number of times to find the actual flow and wave field in an
iterative way. According to the manual of Delft3D-MOR (WL/Delft Hydraulics, 2001) executing the wave and flow model twice often provides a solution that differs less than 5% from solutions achieved after many more iterations. In this study, these recommendations are followed and the flow and wave model are run twice. Executing both models three times would lead to an uneconomical computational time and would hardly improve the results.

The exchange of data, e.g. water level, wave height and flow velocity, between the different computational modules is enabled by the use of the so-called communication file. Although the flow computation requires wave data on every time step, it is not economical to compute wave fields for all these time steps. Instead, wave fields are computed for some characteristic moments during the tidal cycle and stored in the communication file. The flow module then interpolates the wave data fields available on the communication file. Subsequently the results of the flow computation are also stored in this file at certain storage intervals. The sediment transport module uses the flow and wave data, available on the communication file to determine the sediment transports. The model structure is outlined in Figure 7-1, after which a number of steps are described in more detail.

![Figure 7-1: Model structure tidal model](image)

At the beginning of the morphological time step the following procedure is applied:

1. Initial flow simulation excluding wave effects, to initialise the water depth for the wave computation. The computation lasts for 10 minutes, which is the storage interval on the communication file.

2. Wave simulation based on the output of the initial flow computation. The wave conditions are determined for a number of times during the tidal period. As no varying water level is computed yet, the wave computation is carried out for a stationary water level.

3. Flow simulation over 14 hours including the previously computed (stationary) wave effects. The first two hours precede the actual 12-hours tidal simulation to deal with spin-up effects.

4. Wave simulation for a number of times during the tidal period using the water depth, varying water level and current field from the flow simulation.

5. Final flow simulation over 14 hours with realistic wave conditions and wave driven current.

6. Sediment transport computation based on the results of the last flow and wave simulation. Spin-up effects have dampened out after a simulation of 10 minutes. Only the results of the last 12 hours are taken into account for the determination of the tide-averaged sediment transport field.
7.3 Flow model

Boundary conditions
The tide is modelled as a single sinusoid with a period of 12 hours. The propagation of the tidal wave was derived from the situation along the Dutch coast. The distance between IJmuiden and Hoek van Holland is approximately 60 km and the tidal wave travels in approximately one hour from Hoek van Holland to IJmuiden. The celerity of the tide in the model is therefore taken as 60 km/h, or 16.67 m/s. The applied tidal amplitude is 1.5 m, which is substantially higher than found in practice. This higher amplitude was chosen in order to cause a larger displacement of the waterline and breaker zone to emphasise the effects. Furthermore, when this tide is represented well by the model, a tide with a lower amplitude would be no problem. The tide is now characterised by:

- wave period \( (T) \): \( 12 \text{ hr} \)
- wave frequency \( (\omega) \): \( \frac{1}{6} \pi \text{ rad/hr} \)
- wave length \( (L) \): \( 720 \cdot 10^4 \text{ m} \)
- wave number \( (k) \): \( 8.73 \cdot 10^6 \text{ rad/m} \)
- amplitude \( (A) \): \( 1.5 \text{ m} \)

Along the seaward boundary of the model area, a water level boundary condition is applied. In general the water level \( \eta \) is described with:

\[
\eta = A \cos(\omega t - kx) \tag{7.1}
\]

In Delft3D-FLOW the sine and cosine are computed in degrees instead of radians. The terms between the brackets are therefore given in degrees. The variable \( t \) has the unit [hr]. At the sea boundary upstream of the groyne, \( x \) is zero, so that the water level is described with:

\[
\eta = 1.5 \cos(30 \cdot t) \tag{7.2}
\]

At the sea boundary at the downstream side of the groyne, where \( x \) is 19 km, the water level is described with:

\[
\eta = 1.5 \cos(30 \cdot t - \varphi) \tag{7.3}
\]

in which \( \varphi \) is equal to \( k \cdot x \). Between these points the phase varies linearly with the \( x \)-position, so that the shape of the tidal wave is undisturbed.

At the lateral sides of the model area, a Neumann boundary condition is applied. The water level gradient is obtained by taking the derivative of \( \eta(x,t) \), described with:

\[
\frac{\partial \eta}{\partial x} = Ak \sin(\omega t - kx) = Ak \cos(\omega t - kx - 90) \tag{7.4}
\]

To suit the boundary condition to Delft3D input, the sine is rewritten to a cosine. In the Delft3D-FLOW input the parameter \( k \) must be treated with care. In the term between the brackets \( k \) is given in degrees per metre, while \( k \) in the term before the cosine is given in rad/m. At the upstream boundary where \( x \) is 0, the boundary condition is:

\[
\frac{\partial \eta}{\partial x} = 1.31 \cdot 10^{-5} \cos(30 \cdot t - 90) \tag{7.5}
\]
At the downstream boundary, the water level gradient is:

\[
\frac{\partial \eta}{\partial x} = 1.31 \cdot 10^{-2} \cos(30 \cdot t - 90 - \phi)
\]  (7.6)

in which \( \phi \) is equal to \( k \cdot x \).

**Initial condition and drying/flooding of grid cells**

In the numerical model the process of drying and flooding of parts of the beach is represented by removing grid points from the flow domain that become "dry" when the water level decreases and by adding grid points that become "wet" when the water level rises. Drying and flooding causes a discontinuous movement of the closed boundary and generates small oscillations in the water level and velocities. The small grid cell spacing cross-shore required by the uniform beach profile method is favourable to prevent these oscillations. Generally the flooding of grid cells results in higher oscillations than the drying. For numerical reasons the disturbances caused by flooding are less when the grid cells have already been wet. Therefore the manual of Delft3D-FLOW advises to start the simulation at high water in case drying and flooding of grid cells occur. This advice is followed, as can be seen in the imposed boundary condition at the sea side boundary. As initial condition a uniform water level of MSL + 1.5 m is applied. After a simulation time of two hours spin-up effects have dampened out.

### 7.4 Wave model

**Number of computed wave fields**

The flow and sediment transport modules require wave data on every time step. Since computing wave fields for every time step would lead to too high a computational effort, these modules interpolate the available wave data to the time points on which the data is needed. This is an acceptable approach because the wave field slowly changes under the varying circumstances. Generally, wave fields are only computed at high, low and mean water level. However, especially in the zone close to the shoreline where drying and flooding of grid cells occurs, the interpolation of wave data introduces errors. The larger the tidal range, the more severe these errors will be. In this study the wave conditions are therefore also computed on intermediate times between high, low and mean water level. The times on which the wave field is computed are shown Figure 7-2.

![Figure 7-2: time points computed wave fields](image)

In a sensitivity test a case with the proposed number of wave fields was compared to a case with wave fields at high, low and mean water level only and a case with wave fields at intervals of 30 minutes. It was assumed that an inaccuracy in the wave computation would ultimately express itself in the computed sediment transports and that the differences between the models could be evaluated considering the initial and undisturbed tide-averaged longshore sediment transport. The
results of this test are displayed in Appendix C. It appears that the case with the proposed number of wave fields and the case with wave fields at every 30 minutes predict an almost identical sediment transport distribution over a cross-section perpendicular to the coast. The yearly sediment transport for both cases differs only 0.1%. The transport distribution of the case with wave fields at high, low and mean water level is close to the waterline somewhat lower, resulting in a yearly transport which is 5% less than that of the other two cases. The proposed number of computed wave fields is thus appropriate for a proper sediment transport computation.

Data used from flow computation
In the input file of Delft3D-WAVE it must be specified which information from the flow computation should be taken into account in the wave computation. Delft3D-WAVE enables the inclusion of the bottom level, the water level and the currents. The bottom information is imported to obtain the water depths which have been adjusted during the previous morphological time step. The water level is taken over from the flow model at each time point on which a wave field is computed to take into account the influence of the vertical tide. The accompanying current fields are imported to compute the influence of the current on the wave propagation. However, tests have shown that, in case the wave-current interaction is computed with only two iterations, including the effect of the current field on the wave propagation leads to some errors in the wave and current field around the groynes. These errors result in the development of some unphysical circular flow patterns and a disturbed tide-averaged sediment transport field (see Appendix D). Excluding the influence of the current field on the wave propagation or repeating the flow and wave computation three times instead of two times considerably reduces the errors. Probably when waves are low and velocities are small an accurate computation of the wave-current interaction is difficult and the solution converges oscillating to the actual wave-current interaction. Therefore, the influence of the currents on the waves is neglected and the current fields are not taken over from the flow computation.

7.5 Sediment transport model

Interval flow/wave data
In the previous section it was concluded that wave data on high, low and mean water level and one time point between these characteristic moments are sufficient to obtain a reliable sediment transport field. In this section the influence of the time interval of the flow fields on the sediment transport is discussed. In general the flow conditions vary on a much smaller time scale than the wave conditions and therefore the flow data are required on more time points than the wave data. A comparison is made of transports calculations based on data intervals of five, ten and twenty minutes. The results can be found in Appendix E. When the undisturbed tide-averaged longshore transport distribution is considered, the results of the computations with an interval of five and ten minutes are almost identical. The yearly transport differs only 0.5 %. The model with a data interval of twenty minutes shows disturbances in the zone where drying and flooding occurs. The yearly sediment transport differs 4.5 % from the two other computations. For the tidal case therefore a data interval of ten minutes is applied.

7.6 RAM-model

Extended bed evolution model
The fact that the hydrodynamic and sediment transport computation of the tidal case takes much more time than the computations of the stationary case, makes the tidal case hard to deploy for a long term morphological simulation. When the morphological time step of two days, as applied in the stationary case, is also applied in the tidal case, a simulation over a rather short period of just one year takes, depending on the computer used, a whole week. Although some parts of the model, e.g. the size of the model area and the number of grid cells, might be optimised, this case would be unsuitable for practical applications. Increasing the morphological time step to six or even ten days would reduce the number of flow computations considerably and improve the
applicability. However, this measure implies that the updating of the sediment transport field takes place less often and errors might be introduced which could get out of hand due to the absence of a correcting flow field. The errors appear particularly around the lower boundary of the uniform profile zone.

A solution for the problem of the occurring instable bed level changes is found in a more recent version of the bed level change model "RAMBCH", namely "RAMBCH-CLAY". This extended version of the model offers a number of new possibilities, among which an algorithm with a smoothing influence on bottom changes. The principle of the smoothing is based on averaging the bottom changes of neighbouring grid cells in an iterative way, so that exceptional bed level changes are limited. At the end of each output interval the cumulative bed level change $dz_{i,j}$ is calculated for all grid cells. Next, the cumulative bottom changes of all grid cells are averaged with a user defined smoothing factor $f$, which indicates the relative influence of the original bed level change. The new bottom change of a grid cell is:

$$dz_{i,j} = (1 - f)dz_{i,j} + \frac{f}{4} (dz_{i+1,j} + dz_{i-1,j} + dz_{i,j+1} + dz_{i,j-1})$$

(7.7)

The newly computed bottom change is not applied until all other new bottom changes are determined, so that the averaging procedure is not partly based on adapted values and partly on the original values. Within a morphological time step the averaging procedure can be repeated a (user defined) number of times so that a stronger reduction of extreme bed level changes is gained.

![Figure 7-3: Averaging of bed level changes](image)

Although the concept of smoothing is useful, some remarks can be made concerning the functioning of the original smoothing procedure.

At first, the averaged bottom changes are directly added to the water depth to obtain the new water depth. This implies that, when the grid cells do not have the same size, mass is not necessarily conserved. This is clarified with an example (see also Figure 7-3). If the bottom change in point $(i, j)$ would be 1.0 m and the bottom change in all other cells would be 0.0 m and $f$ is 0.5, then the corrected bottom change in point $(i, j)$ is 0.5 m and in the points $(i+1, j), (i, j+1), (i, j+1)$ and $(i, j-1)$ 0.125 m after one iteration step. Suppose the grid cell $(i+1, j)$ has an area twice that of the other cells mentioned, then sediment is created in cell $(i+1, j)$, as the area of the cell is not taken into account. It would therefore be better to model the smoothing procedure with transports from one cell to another, so that the conservation of mass can be guaranteed.

A secondary point of interest is the moment the smoothing procedure is carried out. The smoothing is applied only on time points when the newly calculated bed level is to be stored in a file. In this way, the smoothing is dependent on the number of output intervals. The more often output is generated, the more smoothing is applied. If the smoothing is considered to represent some sort of physical process, it would be more realistic if it was time dependent.
Finally, the smoothing procedure does not take into account the influence of the grid spacing. Consider the example mentioned above. After one iteration step the bottom change in point \((i,j)\) is 0.5 m. In the surrounding grid points \((i+1,j)\), \((i-1,j)\), \((i,j+1)\) and \((i,j-1)\) the bottom change is 0.125 m. The redistribution of sediment appears to be independent of the grid spacing. This implies that whether the grid spacing is, for example, 10 m or 100 m, the smoothing effect is equal. However, if the smoothing is assumed to represent some physical process, it is imaginable that the redistribution of sediment would decrease with the distance between two points. Because of these observations an improved smoothing procedure is proposed.

**New smoothing procedure**

As starting point for the new procedure, it is assumed that the smoothing mechanism to be implemented in the model represents some physical process that prevents the occurrence of large irregularities in the bed topography. In reality this process will arise out of the interaction between waves, currents and the bed level. In the model however, this adaptation process can not be reproduced directly because its time scale as well as its length scale is smaller than that imposed by the numerical grid and time step. The process is now implemented on a higher scale as a redistribution process, where the degree of redistribution of sediment is determined by a smoothing coefficient and the gradient of the bed level change rate. In contrast to the original procedure the redistribution of sediment will be based on actual transports, so that mass should be conserved. The use of the gradient of the bed level change rates includes the influence of the distance between grid points. After all, when the difference in bed level change rate between two points is supposed constant and the distance between these points is supposed to increase, the gradient of the bed level change rate will decrease.

Without smoothing the bed level change rate is given by:

\[
(1-n) \cdot \frac{\partial z_{\text{orig}}}{\partial t} - \frac{\partial Sx}{\partial x} - \frac{\partial Sy}{\partial y} = 0 \tag{7.8}
\]

in which \(\frac{\partial z_{\text{orig}}}{\partial t}\) is the bed level change rate in m/s and \(Sx\) and \(Sy\) are the sediment transports in x- and y-direction in \(m^3/s/m\). Due to the smoothing procedure a correcting bed level change rate is added to the original bed level change rate:

\[
\frac{\partial z}{\partial t} = \frac{\partial z_{\text{orig}}}{\partial t} + \frac{\partial z_{\text{corr}}}{\partial t} \tag{7.9}
\]

For reasons of simplicity the bed level change rate \(\frac{\partial z_{\text{orig}}}{\partial t}\) is now called \(w_{\text{orig}}\). The correcting change rate is the result of correcting transports in x- and y-direction \((Sx_{\text{corr}}\) and \(Sy_{\text{corr}}\). The correcting transports are assumed to be dependent on a smoothing factor \(\varepsilon\) and the gradient in bed level change rate:

\[
Sx_{\text{corr}} = \varepsilon \cdot \frac{\partial w_{\text{orig}}}{\partial x} \tag{7.10}
\]

\[
Sy_{\text{corr}} = \varepsilon \cdot \frac{\partial w_{\text{orig}}}{\partial y} \tag{7.11}
\]

so that:

\[
(1-n) \cdot \frac{\partial z_{\text{corr}}}{\partial t} - \frac{\partial Sx_{\text{corr}}}{\partial x} - \frac{\partial Sy_{\text{corr}}}{\partial y} = (1-n) \cdot \frac{\partial z_{\text{corr}}}{\partial t} - \varepsilon \cdot \left( \frac{\partial^2 w_{\text{orig}}}{\partial x^2} + \frac{\partial^2 w_{\text{orig}}}{\partial y^2} \right) = 0 \tag{7.12}
\]
The form of this equation corresponds to the equation of diffusive transports. The bed level change rate is redistributed over a certain area in a diffusive manner. The smoothing factor \( \varepsilon \) has the dimension \( [m^2] \) and is related to the area over which an irregularity is assumed to be redistributed. Within the RAM-model the proposed procedure can be repeated a user-defined number of times so that irregularities will be stronger reduced.

Results
The new smoothing method was first tested for the stationary case to obtain results within a reasonable computational time. Tests were carried out with morphological time steps of two, six and ten days over a simulation period of one year. The applied smoothing factors were 0 m\(^2\) (no smoothing), 10 m\(^2\) and 50 m\(^2\). First the results are evaluated for a morphological time step of two days. Although no instabilities occur when a smoothing factor of 0 m\(^2\) is applied and smoothing is in fact not necessary, the influence of the smoothing on the results can easily be considered. It appears that the results with a smoothing factor of 0 m\(^2\) and 10 m\(^2\) are identical after one year.

The results of the simulation with a factor of 50 m\(^2\) differ slightly within the uniform profile zone, as shown in Appendix F. The differences in bottom level occur around the waterline and measure 0.10 m at maximum. The uniform beach profile turns out to get somewhat steeper. According to the "uniform beach profile" method the shape of the profile should not change. However, the smoothing is also applied within this zone and causes small changes in the profile. The small grid spacing, which is generally present in this zone, enlarges the effect. As long as the effect stays limited to a few centimetres per year and the simulation time is limited to a number of years no problem arises. With higher smoothing factors the development of the beach profile should be watched carefully. It is then up to the user of the model to decide whether the reduced computational time or the constant beach profile is preferred.

A second cause of possible inaccuracies introduced by the smoothing procedure is the fact that no special measures are included yet to prevent the exchange of sediment through the groyne due to smoothing. Apparently these transports are very small, as the influence on the morphological development around the groyne is at least not visible in the plot.

With the tests involving a morphological time step of two days it is demonstrated that the application of smoothing factors up to 50 m\(^2\) leads to reliable results. Next a comparison is made between the results with several time steps and a smoothing factor of 50 m\(^2\) (see Appendix F). A simulation, with a time step of six days without smoothing, shows that already after two months instable bottom changes occur at the foot of the uniform profile zone, directly upstream of the groyne. When smoothing is applied with a factor of 50 m\(^2\) the bottom instability is suppressed and the morphological development of the beach is simulated over a whole year without any trouble. Even with a time step of ten days no irregularities occur at all.

When the results of time steps of two, six and ten days are compared, it appears that the morphological time step does have an effect on the erosion and accretion rate. The model with a time step of two days predicts a slower morphological development with less erosion downstream of the groyne and less accretion upstream. The mutual differences between the results of the six day and ten day time step are significantly less. The higher accretion and erosion rate with a larger morphological time step can be understood when it is considered that with the RAM-method only the magnitude of the sediment transports is corrected for the changed bed level. However, close to the groyne also the direction of the sediment transports changes considerably with a changing bed level. With the relatively small time step of 2 days the directions of the sediment transport are adapted more often, resulting in a slightly less pronounced morphological development.
7.7 Alternative Flow model

In addition to the adapted smoothing procedure allowing larger morphological time steps, a second proposition is made to deal with the large computational time of the tidal model. A very pragmatic approach is chosen to deal with the duration of the flow computation. The concept is based on the fact that the morphological development, i.e. the bed level change, is computed from a tide-averaged sediment transport field. The averaged sediment transport field originates from a flow, wave and transport calculation over the full tidal cycle, usually equal to 12 hours, and possibly some extra time to deal with spin-up effects. If a similar calculation would be made with a slightly shorter tidal period, the tide-averaged transport would not differ much from the original result.

As long as the influence of the inertia on the flow is small compared to the influence of the driving force and the friction, the approach is viable. In general, this is the case when the flow changes only slowly as a function of time. It is expected that, although the influence of the inertia should not be ignored completely, the results will give a quite accurate indication of how the results of a full simulation over 12 hours would be. A simulation with the reduced tidal period can be used in a preliminary stage to obtain a quick insight in the results that can be expected. Ultimately a simulation with a full tidal period can then be carried out for a more reliable forecast. In the following a model set-up is presented in which the tidal period is reduced to 6 hours instead of the actual period of 12 hours.

The tidal period is reduced with 50%. As a result the wave frequency, wave length and wave number do also change. The celerity does not change, as well as the amplitude, which is needed to retain the driving force.

The reduced tide is characterised by:

- wave period ($T$): 6 hr
- wave frequency ($\omega$): $\frac{1}{3}\pi \, \text{s/hr}$
- wave length ($L$): $360 \cdot 10^3 \, \text{m}$
- wave number ($k$): $1.75 \cdot 10^{-5} \, \text{rad/m}$
- amplitude ($A$): 1.5 m

Due to the different characteristics of the tide, the boundary conditions are adapted. In Delft3D-FLOW the sine and cosine are computed in degrees instead of radians. The terms between the brackets are therefore given in degrees. The variable $t$ has the unit [hr].

At the sea boundary upstream of the groyne the water level is described with:

$$\eta = 1.5 \cos(60 \cdot t) \quad (7.13)$$

At the sea boundary at the downstream side of the groyne the water level is described with:

$$\eta = 1.5 \cos(60 \cdot t - \varphi) \quad (7.14)$$

in which $\varphi$ is equal to $k \cdot x$. At the lateral boundary upstream of the groyne, the water level gradient is:

$$\frac{\partial \eta}{\partial x} = 2.62 \cdot 10^{-5} \cos(60 \cdot t - 90) \quad (7.15)$$

At the lateral boundary downstream of the groyne, the water level gradient is:
\frac{\partial \eta}{\partial x} = 2.62 \cdot 10^{-5} \cos(60 \cdot t - 90 - \varphi) \quad (7.16)

The simulation time of the flow model is set to 8 hours, consisting of the reduced tidal period preceded by 2 hours to deal with spin-up effects. Except for these changes in the flow model, also new time points must be set in the wave model on which the wave computations are carried out. Just like in the original tidal model the wave fields are computed on time points with high water, low water and mean sea level, as well as on one time point between those characteristic moments.

Because the tidal period is reduced with a factor 0.5 and the celerity of the tidal wave is maintained at 16.67 m/s, the wave number \( k \) is multiplied with a factor 2:

\[ k = \frac{2\pi}{c \cdot T} \quad (7.17) \]

in which \( c \) is the celerity and \( T \) is the tidal period. This implies that the phase difference \( \varphi = k \cdot x \) over the model area is twice as large compared to the situation with a full tidal period. The difference in water level over the model area is therefore larger and higher velocities can be expected. Except for the water level gradient, the velocities are also influenced by, e.g. bed friction and inertia effects. Therefore the tidal current was simulated for a case with a tidal period of 6 hours and a case with a tidal period of 12 hours. Figure 7-4 shows the resulting velocities as a function of time for a point at relatively deep water (MSL -9.0 m). The maximum velocities in the simulation with the full tidal period are 0.48 m/s during flood and 0.46 m/s during ebb. At maximum flood as well as maximum ebb, the velocities in the simulation with a period of 6 hours are 0.15 m/s higher. For practical cases, the results found with the reduced tidal period should be calibrated, so that the actual situation is represented well. In this study no corrections will be applied to the results.

![Graph showing velocities tidal current for tidal period of 6 hrs and 12 hrs](image)

*Figure 7-4: Velocities tidal current for tidal period of 6 hrs and 12 hrs*

The effect of the higher tidal velocities on the sediment transport is evaluated considering the initial tide-averaged sediment transport field around the groyne. Appendix G shows the results of a simulation with a tidal period of 12 hours and a simulation with a tidal period of 6 hours. It appears that the differences between both transport fields are very small. The case with the reduced tidal period could therefore be used as a substitution for the case with the full tidal period.
8. Results

8.1 Introduction

This chapter describes the results of simulations of the morphological development of the coast in the vicinity of a groyne. It discusses the results of a “stationary” case including a stationary wave condition and a “tidal” case including tidal effects in combination with a stationary wave condition. Furthermore the results are described of a number of variations in the model set up.

The general model set up for the stationary case is presented in Chapter 6. The model set up of the case including tidal effects is presented in Chapter 7. The latter is described based on the changes and additions in relation to the set up of the stationary case. The representation of the groyne in the computational modules is discussed in Chapter 5. The explanations are accompanied by the most relevant results presented in plots.

In Section 8.2 and 8.3 first the situation of an initially straight coast with depth contours parallel to the shoreline is considered for the undisturbed case where no groyne is present. Section 8.2 describes a simulation of the stationary case, Section 8.3 a simulation of the tidal case. The simulations give insight in the undisturbed currents, wave fields and sediment transports and show how the (small) autonomous morphological changes throughout the model area.

In Section 8.4 the results of two versions of the stationary case are discussed based on a simulation of the coastal development around a single groyne with a length of 260 m. The (only) difference between the two versions concerns the bottom friction model for the combined influence of currents and waves. In this section it is verified if the stationary case is able to generally represent the phenomena observed in practice.

In Section 8.5 the results of the tidal case are compared with those of the stationary case. A single groyne is applied, with a length of 260 m.

Section 8.6 and 8.7 treat the possibility to reduce the considerable computational time of the tidal case. Section 8.6 describes the consequences of increasing the morphological time step from 2 days to 5 or 10 days, while in Section 8.7 a method is tested to reduce the computational time of the flow computation by applying a reduced tidal period.

In Section 8.8 the tidal case is tested with a negligible impact of the waves to evaluate the autonomous morphological development around the groyne due to the tide only. Finally the sensitivity of the tidal case for the applied sediment transport formula is evaluated in Section 8.9 based on a test with the relation of Soulsby-Van Rijn instead of the previously applied Bijker formula.

The simulations carried out are summarised in Table 8-1. Particular changes in the model set up are displayed in italic. The appendices in which additional results can be found are mentioned in the last column.

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<th>tide included</th>
<th>waves included</th>
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*Table 8-1: Simulations carried out*
The results of the morphological simulations are visualised based on:

- Morphological development after 1 year
- Relative reduction of the sediment transport at the groyne
- Total volume change in a reference area upstream of the groyne
- Volume change per metre along the original shoreline

The morphological development of the coastal area is shown based on a plot of the water depths relative to Mean Sea Level after 1 year. The depth contours are displayed increasing with steps of 1 metre starting at MSL.

The relative reduction of the sediment transport at the groyne is measured every month, starting at the start of the simulation. The relative transport reduction $r$ is found (see also Figure 8-1) by:

$$ r = \left(1 - \frac{S_{\text{reduced}}}{S_{\text{undisturbed}}} \right) \cdot 100 \% $$  \hspace{1cm} (8.1)

in which $S_{\text{reduced}}$ is the integrated transport past the groyne and $S_{\text{undisturbed}}$ the integrated transport through a plane perpendicularly to the original shoreline.

*Figure 8-1: Measuring points for the sediment transports and volume changes*

The total volume change in the reference area upstream of the groyne is found by integrating all bed level changes over the area under consideration. The volume change is displayed monthly. The reference area is displayed in Figure 8-1. The volume change per metre along the original shoreline is determined over the same reference area, as well as an equivalent area downstream of the groyne. The volume change per metre is shown after 3, 6, 9 and 12 months.
8.2 Stationary case with undisturbed transport

To evaluate the hydrodynamics and the sediment transports of the stationary case a simulation was carried out for a situation without a groyne. Due to the uniform wave condition and the absence of the groyne, no gradients in the sediment transport should occur and the bed profile should remain unchanged. Furthermore, the application should produce the same results as found by Jörissen (Jörissen, 2001, p.7-2/7-4). The results of an initial computation of the hydrodynamics and the sediment transports are shown in Figure 8-2.

The graph shows a significant wave height of 1.65 m at deep water that diminishes with the decreasing water depth due to bed friction, breaking and refraction. The breaking of the waves results in an increasing water level in cross-shore direction, which is known as wave set-up, and the generation of a longshore current due to the approach of the waves at an angle of 20°. The maximum wave set-up is 0.16 m at the waterline, while the water level at deep water is at MSL. The maximum longshore velocity of 0.18 m/s is found 30 m from the waterline. The peak in the velocity distribution cross-shore corresponds with the zone where relatively much wave energy is dissipated due to breaking. The longshore current decreases in seaward direction until it becomes zero at a distance of approximately 500 m from the waterline. Although the driving force for the longshore current is not present in this outer zone, the influence of the near-shore current is still noticeable because of the turbulent diffusion of momentum.

When these results are compared to the results described by Jörissen some considerable differences appear. The maximum longshore current found by Jörissen is 0.30 m/s at 50 m from the waterline. From this point the velocity decreases to 0.10 m/s at 600 m from the waterline and then to 0.08 m/s at 1800 m from the waterline. These relatively high and unexpected velocities at deep water were attributed to either a high turbulent diffusion coefficient in the model or a rather high dissipation of wave energy on deep water due to bottom friction. However, the results cannot be reproduced by the adapted model set up in this study, although the same coefficients were applied. The absence of a longshore current on deep water does seem more realistic. Apart from this effect, the wave set-up and maximum velocity found by Jörissen are higher than the values found in this study. This can be explained by the adaptation of the computational grid of the wave module. In this study a more detailed grid is applied with a resolution of 25 m in cross-shore direction instead of the former 50 m. Due to the larger grid spacing in the application of Jörissen, the dissipation of wave energy from one grid cell to another is rather abrupt causing also an abrupt forcing for the longshore current and a higher peak velocity. Some examples of this effect are included in Appendix H.
The results of the stationary case seem reasonable, although it is felt that the wave driven current is fairly low compared to realistic situations. The reason for this might be the bottom friction. In the model set up the Manning coefficient for bottom friction due to currents alone is somewhat high compared to other applications. Furthermore, the enhancement of the bed shear stress due to the influence of waves is modelled by an approach of Bijker, which provides a rather high value compared to, for example, the approach of Fredsøe (User Manual Delft3D-FLOW p.9-53/56, WL|Delft Hydraulics, 2001, see also Appendix T, and Soulsby et al., 1993). The approach of Fredsøe is commonly applied in morphological models. A comparison between the longshore current predicted by both friction models and a case with a lower Manning coefficient can be found in Appendix I. In the following also the friction model of Fredsøe will be applied. It is emphasised that the sediment transports are computed independently of the bed friction model with the Bijker formula for sediment transport.

The distribution of the longshore sediment transport is shown in Figure 8-3 for both friction models. The accompanying longshore currents are also displayed. The higher longshore current of the Fredsøe model results in a much higher sediment transport. The maximum total transport with Bijker friction is $0.54\times10^4$ m$^3$/m/s and is located 150 m from the waterline, the maximum according to Fredsøe is $1.63\times10^4$ m$^3$/m/s and is located 170 m from the waterline. The total sediment transport on yearly basis through a plane perpendicular to the coastline is 440,000 m$^3$/y for the Bijker friction model and 1,500,000 m$^3$/y for the Fredsøe model. Jörissen found a yearly sediment transport of 1,960,000 m$^3$/y, which is substantially higher. This difference is not only caused by the higher velocity of the longshore current in the breaker zone, but also by his rather high velocities on deeper water, which result in considerable transports.

After a simulation of one year with the friction model of Bijker, the occurring bed level changes are limited to a few centimetres throughout the model area. Around the lateral boundaries of the nested computational wave grid small disturbances appear. However, these are not more than 0.15 m, which is certainly acceptable.

### 8.3 Tidal case with undisturbed transport

The tidal case, as described in Chapter 7, was tested for a situation without a groyne to be compared to the results of the stationary case. Distinction was made between the computation of the initial hydrodynamics and sediment transports and the morphological simulation over one
year. The initial computation was run with the full model set up including a tidal period of 12 hours, to be entirely able to compare the results with the former simulations. The simulation over one year was calculated with a morphological time step of four days and a reduced tidal period of six hours in order to reduce the computational time. The smoothing factor \( \varepsilon \) (see Section 7.6) was set to zero. This approach was considered acceptable, as the expected morphological changes were expected to be so small that no irregularities should occur.

First the water level and tidal current over the tidal period are considered. Both were monitored at a point located in the middle of the model area where the water depth is 9 m and the influence of the wave driven current can be ignored. As expected from the boundary conditions high water occurs at \( t=0 \) hrs and \( t=12 \) hrs and low water at \( t=6 \) hrs. The magnitude as well as the development of the tidal current appears to be highly dependent on the chosen bottom friction model, as can be seen in Figure 8-4. When the friction approach of Bijker is followed, slack water occurs at \( t=6:20 \) hrs and 12:40 hrs, while following the friction according to Fredsøe this is one hour later, viz. at \( t=7:20 \) hrs and \( t=13:30 \). The maximum ebb and flood current also differ considerably. The maximum tidal current with the Bijker model is 0.25 m/s, compared to 0.50 m/s according to the Fredsøe model. The latter is by far more reasonable, taking into account the tidal currents observed in practice.

![Figure 8-4: Water level and tidal current as a function of time](image)

Because the longshore current is an important factor for the magnitude of the longshore sediment transport, the velocity distribution cross-shore is evaluated for some characteristic moments of the tidal cycle. In Appendix J maximum flood, ebb and slack water are considered for the case with the bottom friction according to Fredsøe. In the graph it is clear that the wave driven current in the breaker zone is increased by the flood current and decreased by the ebb current. The wave driven current varies between 0.20 m/s and 0.35 m/s. The breaker zone obviously is displaced by the varying water level. During maximum ebb and maximum flood the tidal current is higher at deeper water and lower closer to the waterline. This effect is caused by the increasing bottom friction when the depth decreases.

The distribution cross-shore of the tide averaged longshore transports is shown in Figure 8-5 for a bottom friction according to both Bijker and Fredsøe. The transport includes the suspended load and the bed load. The results of the stationary case are also presented in the graph. Clearly, the sediment transports of the tidal cases are more spread out over the zone close to the waterline due to the time-dependent water level and location of the breaker zone. Farther than 800 m from the waterline no transports are found. The yearly longshore sediment transports integrated over the cross-section is 490,000 m³/y for the case with the Bijker approach and 1,420,000 m³/y for the case with the Fredsøe approach. The difference with the yearly transports of the stationary case is 11% and 5% respectively.
After a simulation of 1 year without groyne throughout the model area bed level changes of circa 0.15 m occur. Within the uniform profile zone accretion takes place, so that the beach profile shifts seaward over 6 m. Outside the uniform profile zone erosion is found, indicating a net cross-shore transport towards the coast (see Appendix K). Apparently the coefficients of the Bailard approach for the cross-shore transport, as described in Section 6.5, do not match completely with the situation of a stable coast when the tide is included. Some additional bed level changes occur around the boundaries of the nested wave grid. The maximum bed level change is 0.40 m at the upstream boundary of the nested grid.

### 8.4 Stationary case with groyne

Two tests were carried out with the stationary case. In the first test ("Bk", for short) the model was set up with the bottom friction according to Bijker, in the second test ("Fr") the friction according to Fredsøe was applied. As already became clear in Section 8.2 the undisturbed yearly sediment transport of the two cases differs approximately a factor 3. Except for the bottom friction both cases were identical and set up following the description in Chapter 6. The chosen length of the groyne was 260 m. The RAM model with the improved smoothing procedure according to Section 7.6 was applied with a smoothing factor $c$ of 50 m².

In Figure 8-6 and Figure 8-7 the morphological development of the area around the groyne is shown, as it is found after a simulation of 1 year. Additional results of the simulation can be found in Appendix L.

The presence of the groyne partly blocks the sediment transport along the coast. As a result of the local reduction, upstream of the groyne more sediment is supplied than is transported to the downstream side and accretion occurs. Both cases show this accretion at the upstream side of the groyne. As could be expected from the higher yearly sediment transport, most accretion is found in the case Fr. The waterline directly upstream of the groyne moves over 85 m, while this is only 60 m in the case Bk. The accretion predicted by case Fr stretches out over a zone of approximately 2 km and decreases in upstream direction.

At the other side of the groyne erosion takes place because at the groyne less sediment is let through than it is transported farther downstream. The maximum regression of the waterline in case Fr is found at approximately 250 m from the groyne and measures 45 m. The erosion zone stretches out up to 2.5 km downstream of the groyne.
8. Results

Figure 8.6: Morphological development of the stationary case with Bijker friction

Figure 8.7: Morphological development of the stationary case with Fredsøe friction

Directly downstream of the groyne some accretion takes place due to the presence of a circular flow pattern displacing sediment towards the groyne. This phenomenon is explained by the presence of lower waves in the sheltered area of the groyne than where the coast is fully exposed. The resulting difference in wave set-up causes a current towards the groyne in the breaker zone.

Apart from the accreted and eroded volumes, the morphology around the groyne develops differently for both cases. In case Bk a very gradual development is found. The depth contours shift almost parallel and no irregularities are found. The coastal development of case Fr shows some irregularities in the depth contours, especially at deeper water downstream of the groyne. The depth contours bend rather sharply around the groyne consecutively followed by a zone with more erosion and less erosion on deeper water. This reveals itself in curved depth contours. This pattern is already visible after a simulation of 1 month and grows with the increasing simulation time. An additional simulation of case Fr carried out with a decreased morphological time step of 1 day instead of 2 days showed a similar morphological development. The exact cause of the irregularities is not known. A possible cause is a large angle between the wave crests and the shoreline directly downstream of the groyne. An angle close to 45° might introduce instabilities. Secondly, the irregularities could be caused by adaptation effects in the sediment transport.

The initial reduction of the sediment transport at the groyne is 55% for case Bk and 49% for case Fr. This corresponds to an initially passing transport equivalent to 205,000 m³/y for case Bk and to 785,000 m³/y for case Fr. These quantities correspond rather well to the proportion between
the undisturbed transports. After 1 year the reduction of the sediment transport has decreased to 38% for case Bk and 27% for the case Fr. See also Appendix L.

The fact that the transport in case Bk is more reduced can be explained by the fact that in this case the undisturbed transport is mostly concentrated in the shallow zone within the reach of the groyne, while in case Fr a considerable part of the undisturbed transport takes place on deeper water, past the tip of the groyne (see Figure 8-3). This sediment can pass the groyne more easily.

### 8.5 Tidal case with groyne vs. stationary case

To evaluate the influence of the tide on the morphological development around a groyne a comparison was made between the stationary case and the tidal case. The cases were set up according to the description in Chapter 6 and 7 respectively. The bottom friction model of Fredsøe was applied. The transports were computed with the Bijk formula for sediment transport. The morphological time step applied in both cases was 2 days and the groyne length was 260 m. The tidal computation was carried out with the full tidal period of 12 hours. The undisturbed yearly transport of the stationary case was found to be 1,530,000 m³/y, while the undisturbed yearly transport of the tidal case was only 1,390,000 m³/y. This differs approximately 10%. The "undisturbed" transports are measured 4.5 km upstream of the groyne. Still, these undisturbed transports differ slightly from the transports found in a simulation without groyne (see Section 8.2 and Section 8.3)

The (tide-averaged) sediment transport field of the case with tidal effects as well as the transport field of the case without tidal effects is displayed in Figure 8-8 (see also Appendix M). It is obvious that the undisturbed sediment transport, which enters the figure at the left side, is more concentrated in the stationary case. In the tidal case it is more spread out. The maximum sediment transports are higher in the stationary case. This is a direct result of the displacing waterline and breaker zone, and is also observed in Figure 8-5.

In the tidal case, the direction of the (averaged) sediment transport directly upstream of the groyne varies more gradually from place to place than in the stationary case, where it changes rather abruptly within some grid cells. As a result the sediment transports along the groyne towards the tip are higher.

Downstream of the groyne the circular flow pattern does also differ. In the tidal case the centre is predicted to be located somewhat closer to the tip of the groyne, both in longshore and in cross-shore direction. The sediment transports in the circular pattern are also smaller.

In the tidal case the sediment transports on deeper water, seaward of the groyne, have a direction more or less parallel to the shore. In the stationary case, the transports make an angle with the shoreline.

The resulting morphological development after 1 year predicted for the tidal case is shown in Figure 8-9. The results are compared to the results of the stationary case, displayed in Figure 8-7. Additional results of both cases can be found in Appendix N.

For the stationary case some irregularities were found in the morphological development of the coast. These irregularities occurred on deeper water and were particularly found downstream of the groyne. In the results of the tidal case the irregularities are absent. The waterline as well as the depth contours on deeper water vary smoothly from place to place. Seaward of the tip of the groyne, the tidal case shows depth contours becoming closer to each other, indicating a steeper gradient in the bottom slope and the origination of a scour hole. Past the tip of the groyne the depth contours first bend towards the shore and then become parallel to the shore.

In the tidal case bed level changes occur on deeper water than in the stationary case. In the tidal case the -8 m depth contour upstream of the groyne is displaced in seaward direction and downstream it is displaced towards the shore. In the stationary case the position of the -8 m contour is almost stable.
8. Results

Figure 8-8: Stationary (left) and tide-averaged (right) sediment transport field at start of simulation

Figure 8-9: Morphological development tidal case

The initial reduction of the sediment transport at the groyne is comparable for both cases. The initial reduction for the stationary case is 49%, for the tidal case this is 47%. From a certain moment shortly after the start of the simulation, the reduction of the sediment transport passing the groyne is higher for the tidal case than for the stationary case (see Appendix N). This is surprising, because the tide spreads out the undisturbed sediment transport over a wider zone, as shown in Figure 8-5. A substantial part of the transport occurs farther from the shore in comparison to the situation without tide. It could therefore be expected that in the stationary case more sediment would be trapped by the groyne and the transport would be more reduced. Apparently, the tide influences the flow field and sediment transport field around the groyne to such an extent that this rough approach can not be applied.

In the case including tidal effects, the upstream accretion is 723,000 m$^3$. In the stationary case less accretion is predicted, namely 629,000 m$^3$. From the volume change per metre it can be seen that in the tidal case more sand is deposited within the first kilometre upstream than in the stationary case. Farther upstream this is the other way around. Although the sediment transport past the groyne is relatively stronger reduced in the simulation including the tide, the absolute difference between the undisturbed transport and the reduced transport is more or less equal for both cases. It could therefore be expected that the degree of accretion predicted for both cases would correspond. However, while the accretion in the simulation with tidal effects agrees rather well with the difference between undisturbed and reduced transport, this is not the case in the simulation without the tide.
This effect is attributed to the way the data are presented. The change of sand volume is measured over a certain reference area, as described in Section 8.1. The location of the upstream boundary of this area does not correspond with the location of the plane through which the undisturbed transport is measured (see also Figure 8-1). Furthermore, the transport reduction at the groyne as well as the undisturbed transport is calculated from the transports integrated over the full wet cross-section of the model area, while the volume changes are determined over a smaller zone. Possible additional transports through the sea boundary are also not taken into account. In conclusion, the measured reduction of the transports at the groyne can not directly be translated to the change of sand volume within the reference area. The time dependency of the transports makes it hard to undeniably prove the correctness of the mass balance of the reference area. On the other hand, the conservation of mass is checked within the RAM-bed evolution module and shows no shortage of sediment.

8.6 Tidal case with increased morphological time step

Three cases with different morphological time steps were compared to investigate the possibility to reduce the computational time of the application. As starting point the tidal case of the previous section was taken. This case had a morphological time step of 2 days. In two additional cases morphological time steps of 5 days and 10 days were applied. Apart from the time step, the model set up for all three cases corresponds to the description in Chapter 7. The tides were imposed with a tidal period of 12 hours and the bottom friction was modelled according to the Fredsøe model. The length of the groyne was 260 m. The smoothing coefficient $c$ was 50 m$^2$.

The results of a simulation over 1 year with the increased morphological time steps are shown in Figure 8-10 and Figure 8-11. These are compared to the results of the case with a time step of 2 days, as shown in Figure 8-9. The computational time of a simulation over 1 year was 17 hours for the time step of 10 days, 36 hours for the time step of 5 days and 110 hours for the time step of 2 days. Additional results of the simulations can be found in Appendix O.

The most striking difference between the results are the instabilities that occur in the position of the depth contours. While the depth contours vary smoothly in longshore direction for the time step of 2 days, the position of the coastline is distorted at the upstream side as well as the downstream side of the groyne for larger time steps. After one year the affected area as well as the magnitude of the instabilities is larger as the morphological time step increases. Downstream of the groyne the length scale of the irregularities appears to be larger than upstream. The instabilities occur mainly in the zone in which the depth is within the reach of the uniform beach profile. Outside this zone, where the water depth is over 4 metres, the evolution of the bed is quite similar for all three cases.

The instabilities are probably caused by the higher morphological activity within uniform profile zone, rather than by the uniform beach profile method itself. Apparently the hydrodynamic conditions vary considerably within a morphological time step larger than 2 days and the local changes in the flow and wave field cannot be ignored. This can be illustrated by the results after 1 month, as shown in Appendix P. In the case with a time step of 10 days relatively much sand is deposited directly upstream of the groyne, while this sand is distributed more evenly over a longer distance following the 2 days-case. In the 10 days-case the direction of the sediment transports directly upstream is not adapted soon enough to the changed bed, so that the sand is deposited too concentrated in a certain area.

The resulting irregular form of the depth contours causes the development of a locally distorted flow and wave field in the following hydrodynamic computation, so that the next RAM-procedure starts with a distorted transport field. The error obviously enlarges itself and propagates through the model area. This effect might be related to adaptation effects in the sediment transports.

Initially the transport at the groyne is reduced equally in all cases and amounts 47% of the undisturbed transport. Due to the different morphological development around the groyne the
transport reduction evolves differently for the three time steps. The cases with the increased time step show a higher reduction of the transport at the groyne (see Appendix O).

Figure 8-10: Morphological development tidal case, time step 5 days

Figure 8-11: Morphological development tidal case, time step 10 days

While the inflow of sediment upstream is roughly equal, it could be expected that the volume of sand stored upstream would be larger compared to the results of the case with a time step of 2 days. However Appendix O shows that most accretion occurs in the case of a time step of 2 days, namely 723,000 m$^3$. The accretion found in the cases with time steps of 5 days and 10 days is significantly less, 645,000 m$^3$ and 606,000 m$^3$ respectively. In addition to the explanation given in Section 8.5 a second possible cause is mentioned.

From tests concerning the improved smoothing procedure (see Section 7.6) it was concluded that, although smoothing transports through the groyne are possible, these would be small and that the effect on the morphological development around the groyne would be negligible. Possibly, this conclusion is not always valid. In that case the sediment transport through the groyne should be added to the reduced transport past the groyne, in order to understand the mass balance. Adding up the all transports through the borders of the reference around should then correspond to the volume change measured.

A possible cause for the different magnitude of the smoothing transports through the groyne for the cases with the various time steps could be the difference between the concentrated accretion directly upstream of the groyne found in the cases with the increased time step and the gradual accretion, found with the time step of 2 days.

The smoothing procedure should be improved to prevent the occurrence of smoothing transports through a groyne.
8.7 Tidal case with reduced tidal period

In Section 7.7 a method was proposed to reduce the computational time of the tidal case by imposing a tidal period of 6 hours instead of the actual 12 hours. When the influence of the inertia on the flow field is small compared to the influence of the driving force and the friction, the tide-averaged sediment transport field will differ only slightly for both cases if the same tidal amplitude is applied. A simulation with a tidal period of 6 hours was carried out over a period of 1 year and compared to the results of the tidal case with the original tidal period of 12 hours. The boundary conditions of the case with the reduced tidal period can be found in Section 7.7, the boundary conditions of the full tidal period can be found in Section 7.3. Except for the tidal period, the model set up was identical for both cases. The morphological time step was 2 days, the groyne length was 260 m and the bottom friction model of Fredsoe was applied. The undisturbed yearly transport was 1,390,000 m³/y with the full tide and 1,410,000 m³/y with the reduced tide, which differs only 2%.

![Figure 8-12: Morphological development tidal case reduced tidal period](image)

The results after a simulation of 1 year with the reduced tidal period are shown in Figure 8-12. More results can be found in Appendix Q.

The morphological development after 1 year is very similar to the results for the case with the full tidal period (Figure 8-9). While the full computation over 1 year took 110 hours, the computation with the reduced tidal period took only 41 hours. Upstream of the groyne, the development of the zone with a depth less than 5 m is almost identical for both cases. With the full tidal period more accretion is found on deeper water. While the -7 m depth contour is hardly displaced with the reduced tidal period, the -8 m depth contour has moved seaward over 30 m with the full tidal period. In the cross-section where the groyne is located, the depth contours on deeper water have equally moved towards the tip of the groyne, indicating the same degree of scour. In the case with the full tidal period the depth contours bend rather sharply around the groyne. In the case with the reduced tide a more gradual curve is found due to the larger relative influence of the inertia. This results in some more accretion directly downstream of the groyne.

Initially the sediment transport for the case of the tidal period of 6 hours is reduced with 43% at the groyne. The reduction of the transport with the full tidal period is 47%. During the simulation the transport reduction decreases gradually for both cases (see Appendix Q). After 1 year, the difference in the relative reduction of the transports for the two cases is still more or less equal. The higher transport past the groyne in the case with the reduced tidal period is related to the larger impact of the inertia on the flow and the smaller curvature around the groyne.

The case with the full tidal period predicts more accretion than the case with the reduced tidal period. With a tidal period of 12 hours 723,000 m³ accretion is found, with a tidal period of 6 hours 661,000 m³. This difference can be directly related to the different reduction of the sediment transport at the groyne.
8.8 Tidal case with alternative sediment transport formula

A test with an alternative sediment transport relation was carried out to get insight into the sensitivity of the results for the chosen sediment transport formula. The applied alternative formula is the formula of Soulsby-Van Rijn. This formula incorporates the influence of currents and waves on the sediment transport and is operational within Delft3D-TRAN. WL Delft Hydraulics has the experience that morphological changes computed with the Soulsby-Van Rijn formula are more pronounced, while the Bijker formula has a tendency to flatten out the morphological changes.

Within Delft3D-TRAN the Soulsby-Van Rijn formula is implemented with only two input parameters, viz. the ratio D90/D50 and a calibration coefficient. In this case the values of 1.5 [-] and 1.0 [-] were respectively used. Except for the sediment transport relation both cases were set up identically. The morphological time step was 2 days.

The undisturbed yearly sediment transport with the Soulsby-Van Rijn formula was 700,000 m³/y.

![Figure 8-13: Morphological development tidal case, Soulsby-Van Rijn formula used](image)

The morphological development after 6 months of a case with the Soulsby-Van Rijn transports is displayed in Figure 8-13. The upstream as well as the downstream development is highly disturbed. This process is already initiated within the first month of the simulation. Although the tendency of accretion upstream of the groyne and erosion downstream of the groyne is noticeable, the simulation is distorted to such an extent that the typical behaviour of a shore in the vicinity of a groyne can hardly be recognised. The phenomenon of the instable development in the shallow water within the -4 m depth contour makes one think of the instabilities observed in the results of the cases with the increased morphological time step.

To discover the possible cause of the instabilities, the simulation with the Soulsby-Van Rijn formula was repeated for the stationary case because of its limited computational time. The results of this case show similar instabilities in the morphological development, although these are now also found on deeper water and mainly occur at the downstream side of the groyne (see Appendix R). A strange phenomenon is the receding coastline directly upstream of the groyne. A reduction of the morphological time step from 2 days to 1 day does not cause any changes and nor does the exclusion of the smoothing procedure. Finally it was investigated if the disturbances were caused by the transition from the coarse computational wave grid to the refined grid. The refined grid was removed and the whole coarse grid was refined to the degree of the original refined grid. This resulted in a more gradual development of the depth contours upstream (see Appendix R). However, downstream the disturbed pattern remained almost unchanged and the recession of the waterline directly upstream of the groyne was not prevented.
8.9 Tidal case without wave-driven current

To evaluate the autonomous influence of the tide on the morphological development around the groyne a simulation was carried out from which the wave impact was excluded. The case including tidal impact was therefore slightly adapted by imposing a wave height of only 0.05 m at deep water. To reduce the computational time the unnecessary computation of the wave-current interaction was limited to 1 iteration step instead of 2 steps (see Section 7.2). The tidal amplitude was increased to 1.85 m, as with the original amplitude of 1.5 m hardly any bed level changes were found around the tip of the groyne.

The morphological development after 9 months shows the occurrence of scour around the tip of the groyne (see Figure 8-14, and also Appendix S). The erosion starts at the left side of the groyne and bends around the tip to the right. The flood current appears to be dominant over the ebb current. At the tip of the groyne, the maximum bed level change measures 1.45 m. The influence of the scour is noticeable up to the -8 depth contour.

Figure 8-14: Morphological development tidal case, no waves present
9. Conclusions

9.1 Introduction

In this study an extended application was set up in Delft3D-RAM for the simulation of the morphological development of the coast in the vicinity of groynes. As starting point an earlier application was used in which the influence of the tide on the morphological changes was not included yet. In the present application the tidal impact is taken into account and the representation of a groyne in the computational modules has been improved. During the study it appeared that also a number of improvements and additions could be made to the existing model set up. Some of these were directly related to a proper implementation of the tide, others had a more general purpose. The adaptations are, among other things, a higher resolution of the numerical grids around the groyne, the possibility to reduce the computational time and the inclusion of a computational procedure smoothing out disturbances in the development of the bed.

The extended application was tested for the simplified case of an initially straight coast with straight depth contours parallel to the coast. In the coastal area a single groyne with a length of 260 m was applied to evaluate its effect on the morphological development. Simulations were carried out for a “stationary” case, in which the coast was only subjected to a uniform and stationary wave condition and a “tidal” case, in which also tidal effects were included. The results of both cases were compared and the differences were discussed. A number of additional tests was carried out to investigate the possibility to reduce the computational time of the model and to judge the sensitivity of the results to the applied sediment transport formula. Finally also a test was carried to evaluate the results of a simulation including the tidal effects, but excluding waves.

In this chapter the conclusions of the study are drawn and some recommendations are given for the further development of the application.

9.2 Conclusions

Implementation tidal effects

The extended application presented in this study accounts for the influence of the tide on the morphological development of the coast in the vicinity of groynes. With the extended application a different morphological development of a coast is found in comparison to the application without tidal impact. The computational time of the extended application is 10 to 30 times the computational time of the application without tidal impact. A simulation over a period of 1 year is feasible, but the present applicability for simulations over a longer period is limited.

The results of a simulation including tidal effects differ from the results of a simulation without tide. The main differences are:

- The undisturbed sediment transport with tide is spread out over a wider zone due to the varying water level and shows a lower maximum transport. The yearly undisturbed transport with tide is 1,390,000m³/y. Without tide it is 10 % more, viz. 1,530,000 m³/y.
- The relative reduction of the sediment transport at the groyne is higher in a simulation including tidal effects. The yearly averaged reduction is comparable for both cases.
- Around the groyne the tide-averaged sediment transport differs locally in magnitude and direction from the transport without tide.
- The morphological behaviour of the case including the tidal influence develops more gradually in time than when the tide is excluded. Disturbances found in the results of the stationary case do not appear in the results of the tidal case.
At the tip of the groyne scour occurs as a result of the tidal flow passing the groyne. The impact of the groyne is also noticeable on deeper water. Both phenomena seem plausible. The autonomous morphological development without groyne shows a net transport of sand from deeper water to the coast indicating that the equilibrium beach profile is steeper when the tidal influence is present.

Modelling of a groyne
In the extended application the representation of a groyne in the computational modules has been improved with the use of “thin dams” in the flow module and the use of “sheets” in the wave module. The present approach prevents the artificial correction of sediment transports, as applied in the former application. With the proposed method the currents, waves and sediment transports are blocked efficiently and the bed develops without irregularities. The evolution of the bed at one particular side of the groyne is not influenced by developments on the other side of the groyne. The method to model the groyne also guarantees conservation of mass.

Reduction of the computational time
The application including tidal effects is computationally demanding due to the flow, wave and sediment transport computation through the full tidal cycle and the iterative calculation of currents and waves. Two methods have been investigated to reduce the computational time.
- Increasing the morphological time step from 2 days to 5 or 10 days leads to increasing irregularities propagating through the model area. This approach seems therefore not suitable.
- Reducing the tidal period does appear to be possible to obtain a quick indication of the morphological behaviour around the groyne. Although the predicted development of the geometry around the groyne differs locally and the sediment transport past the groyne is reduced somewhat less, the accreted volume upstream of the groyne differs within a margin of 10%. The time-dependent behaviour is represented well.

Smoothing procedure
To allow for the application of larger morphological time steps, a computational procedure was included preventing the occurrence of unstable bed developments. The procedure forms a part of the RAM bed evolution model and smoothes out disturbances by redistributing sediment. The extent of redistribution is dependent on the gradient of the bed level change rate. The method is especially effective at the transition from the uniform beach profile to deeper water. Although the method prevents actual instabilities, disturbances in the morphological development might still occur.
- When the morphological changes occur on a rather long time scale, as in the stationary case with the Bijkerv friction model, larger morphological time steps can be applied successfully.
- When the morphological change rate becomes higher due to larger sediment transports, as in the tidal case with the Fredsøe friction model, disturbances occur with an increasing time step. These disturbances are a result of updating the flow and wave field too scarcely. A sensitivity study should always be carried out when increasing the morphological time step.

Sensitivity of the application
With regard to the calculation of currents, waves and sediment transports, the following conclusions are drawn:
- The Bijkerv formula for sediment transport is a robust formulation to predict the morphological changes around groynes. The Soulsby-Van Rijn formula appears to be too sensitive in areas where the flow and wave field varies considerably from place to place. In the present application it introduces major distortions compared to the results achieved with the Bijkerv formula.
- The occurring velocities and sediment transports are highly dependent on the bottom friction coefficient and the bottom friction model for the joint influence of current and waves. Close to the shoreline, the position and spacing of the computational wave grid greatly determines the results.
9. Conclusions

Irregularities
For a number of cases disturbances were found in the development of the depth contours. Two possible explanations are suggested:

- A large angle between the wave crests and the depth contours may cause instabilities. When the angle is larger than 45° the effect of the waves is different from waves with an angle smaller than 45°.
- The disturbances might be caused by adaptation effects in the sediment transport. When the length scale of the disturbances is approximately the same as the adaptation length, the disturbances might grow and propagate through the model area.

The present extended application shows, for a simplified case, a credible representation of the coastal processes and the morphological development in the vicinity of a groyne. During the study it appeared that, in addition to the inclusion of tidal effects, a number of changes and additions had to be made to the existing application. Because of the limited time for this project, the case including tidal effects is not fully exploited yet. Still, with the set up of this extended application in Delft3D-RAM, a next step has been taken towards a comprehensive tool that is able to simulate complex situations.

9.3 Recommendations
To arrive at an application that is suitable for the design of groynes and the prediction of the morphological development of the coast in practical cases, more research has to be carried out. Therefore the following recommendations are given:

- With the present application simulations were carried out for a case with a highly schematised coast and one particular tidal wave. It is recommended to test the application for a model area with a more complex geometry and other tidal characteristics.
- To improve the application further it would be interesting to include a non-stationary wave condition. The presence of several wave conditions instead of just one stationary wave field may cause a different development of the coastal morphology. Furthermore, a non-stationary wave condition might prevent the occurrence of disturbances in the results.
- As shown in the present study the velocities and the sediment transports are highly dependent on the applied bottom friction coefficient and the friction model. It would be desirable to compare the results found by the model with field data from a practical case and to bring these in accordance.
- It would be desirable to obtain more insight in the occurrence and development of the disturbances as observed in this study.
- The proposed smoothing procedure within the RAM bed evolution model should be further improved by preventing the occurrence of smoothing transports through the groyne.
- For a succeeding version of the application, it should be considered to use the wave model SWAN instead of HISWA, which was used in this study. SWAN offers the possibility to carry out the computations on the numerical grid of the flow model. This would simplify the implementation of the groyne and reduce the interpolation errors. The computational time of SWAN is generally higher, but on the other hand the number of grid cells (and thus computations) will be reduced due to the possible use of a varying grid spacing.
- The substantial computational time of the application including tidal effects makes it hard to deploy for practical situations. The computational time should therefore be reduced.
10. References


TAW, 1995, Basisboek Zandige Kust, behorende bij de leidraad zandige kust.


Appendices:

Appendix A: Sensitivity test hydrodynamic time step
Appendix B: Input data
Appendix C: Number of wave fields
Appendix D: Effects wave-current interaction
Appendix E: Storage interval flow data
Appendix F: Test proposed smoothing procedure
Appendix G: Averaged transport full and reduced tide
Appendix H: Spacing wave grid and longshore current
Appendix I: Friction coefficient and friction model
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Appendix L: Results stationary case with groyne
Appendix M: Transport tidal and stationary case
Appendix N: Results tidal case vs. stationary case
Appendix O: Results tidal case, increased time step
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Note:
The appendices L, N, O, Q, R and S describe the results of a number of morphological simulations. The definitions of the quantities used in the graphs can be found in Section 8.1.
Appendix A: Sensitivity test hydrodynamic time step

Figure 1: Velocity field around the groyne, dt 15 s

Figure 2: Velocity field around the groyne, dt 60 s

Figure 3: Velocity field around the groyne, dt 120 s

Figure 4: Velocity field around the groyne, dt 240 s

Figure 5: Difference between dt=120 s and dt=60 s

Appendix A shows the initial flow field around a groyne, computed with different time steps. The applied time steps are 15 s (original), 60 s, 120 s and 240 s (Figure 1-4 respectively). The simulation with a time step of 240 s shows a distorted velocity field close to the waterline. The differences between the flow field of the 15 s and the 60 s simulation are not observable. In Figure 5 the velocity field computed with a time step of 60 s is subtracted from the velocity field computed with a time step of the 120 s. The differences are of the order cm/s.
Appendix B: Input data

*Input parameters Delft3D-Flow*

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**Input parameters Delft3D-RAM**

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Appendix C: Number of wave fields

The flow and sediment transport computation require wave data on every time step. Computing the wave field every time step, however, would lead to too high a computational effort. Therefore the wave fields are only computed for a number of characteristic time points during the tidal period. The flow and transport module subsequently interpolate the available wave data to the time points on which the data is needed.

In the graph presented in Appendix C the cross-shore distribution of the tide-averaged sediment transport is shown for three cases. In the first case wave fields are only computed during high water, low water and mean sea level (5 wave computations per tidal cycle). In the second case, wave fields are also computed halfway these time points (9 wave computations per tidal cycle). In the last case wave fields are computed every 30 minutes (25 wave computations per tidal cycle). The location of the waterline at MSL corresponds to the value of 1000 m on the x-axis.

The graph shows that the transport distribution with 9 and 25 computations per tidal cycle is almost equal. The results of a simulation with only 5 computations per tidal cycle differ from the other results, especially in a 150 m wide zone seaward from the waterline at MSL.

The yearly transport, found by integrating the transports over the cross-shore profile, differs only 0.1% for the cases with 9 and 25 wave computations. The yearly transport with 5 wave computations is circa 5% less.
Appendix D: Effects wave-current interaction

When the current fields from the flow computation are included in the wave computation some unphysical circular flow patterns develop during the tidal cycle. Examples of this phenomenon are shown in the Figures 1 to 4. Flow patterns A and B (in Figure 1 and 2) can be understood considering the opposite direction of the wave driven flow and the tidal flow. Circular flow C (Figure 1-4) is caused by the difference in wave set-up along the waterline at the lee side of the groyne. The flow patterns D, E and F (in Figure 1,2 and 3) are likely caused by inaccuracies in the computation of the wave-current interaction. Possibly in areas where waves are low and velocities are small an accurate computation of the wave-current interaction is difficult and the solution converges oscillating to the actual wave-current interaction.

Figure 1: Current field at t = 3 hr

Figure 2: Current field at t = 6 hr

Figure 3: Current field at t = 3 hr

Figure 4: Current field at t = 3 hr
Especially the flow pattern just upstream of the groyne disturbs the tide-averaged sediment transport field, as can be seen in Figure 5. When the current fields from the flow computation are not taken into account (Figure 6) or when the flow and wave computation are repeated (Figure 7) three times instead of two times the circular flow patterns diminish and the averaged transport field is not disturbed. Except for the disturbance directly upstream of the groyne, no differences are observed in the tide-averaged sediment transport field.

Figure 5: Averaged transport field, influence of current field taken into account

Figure 6: Averaged transport field, influence of current field not taken into account

Figure 7: Averaged transport field, flow and wave computation repeated three times
Appendix E: Storage interval flow data

The sediment transport computation requires data from the flow computation on every time step. Because the flow conditions (water level, current) vary considerably in time, the data must be available on a sufficient number of time points. On the other hand, storing all flow data is computationally inefficient. The flow module therefore writes the flow data with certain “storage” intervals to the so-called communication file. The transport module reads the data and interpolates it to the time points on which the data is needed.

A sensitivity test was carried out to investigate the influence of the storage interval on the cross-shore distribution of the tide-averaged sediment transport. The results of simulations with storage intervals of 5, 10 and 20 minutes are compared in the graph below. The location of the waterline at MSL corresponds to the value of 1000 m on the x-axis.

It appears that the sediment transports following from the simulations with storage intervals of 5 and 10 minutes are almost identical. The simulation with a storage interval of 20 minutes shows different results, especially in the zone around the water level at MSL. Apparently, the effect of drying and flooding of the beach on the sediment transport is not represented well, when a storage interval of 20 minutes is applied.

The yearly transport, found by integrating the transports over the cross-shore profile, differs only 0.5% for the storage intervals of 5 and 10 minutes. The yearly transport with a storage interval of 20 minutes is circa 4.5% less.
Appendix F: Test proposed smoothing procedure

Figure 1 and 2 (more detailed) show the morphological development after 1 year for several smoothing coefficients. The figures show the displacement of the waterline and the depth contours relative to MSL. The depth contours start at MSL and decrease with steps of 1 metre to the MSL –8.0 m contour. The original waterline (at MSL) is indicated with a dotted line. The applied morphological time step is 2 days. In Figure 1 it is visible that the differences between the smoothing coefficients are generally small. In Figure 2 it is visible that with a smoothing coefficient of 50 m$^2$ both the erosion and accretion are somewhat smaller.

Figure 1: Position depth contours after 1 year for smoothing coefficients of 0, 10 and 50 m$^2$

Figure 2: More detailed view on the situation around the groyne for smoothing coefficients of 0, 10 and 50 m$^2$
In Figure 3 and 4 (more detailed) the morphological development after 1 year is considered for morphological time steps of 2, 6 and 10 days. The smoothing coefficient is taken 50 m$^2$. Again, the depth contours start at MSL and decrease with steps of 1 metre to the MSL –8.0 m contour.

In Figure 3 and 4, it is visible that the morphological time step affects the accretion and erosion rate. The most accretion/erosion is found with a time step of 10 days, a time step of 2 days causes the least accretion/erosion.

*Figure 3: Position depth contours after 1 year for morphological time steps of 2, 6 and 10 days*

*Figure 4: Position depth contours after 1 year for morphological time steps of 2, 6 and 10 days*
Appendix G: Averaged transport full and reduced tide

Figure 1 and 2 show the initial tide-averaged sediment transport field of a simulation with a tidal period of 12 hours and 6 hours respectively. Visually, hardly any differences can be found between the two cases.

**Figure 1:** Initial tide-averaged sediment transport field, tidal period 12 hours

**Figure 2:** Initial tide-averaged sediment transport field, tidal period 6 hours
Appendix H: Spacing wave grid and longshore current

The velocity distribution of the longshore current is dependent on the resolution of the computational grid that is used by Delft3D-WAVE. This phenomenon explains the difference found in results between the application set up in this study and the application set up by Jørissen (2001).

In Figure 1 the results of several simulations are shown of the significant wave height ($H_s$) on the computational wave grid and the RMS-wave height ($H_{rms}$) on the flow grid. The significant wave height ($H_s$) on the flow grid is equal to $H_{rms}$ on the wave grid, multiplied with a factor $\sqrt{2}$ and including some interpolation effects. In Figure 2 the associated velocity profiles are shown.

The grid sizes of the computational grid in cross-shore direction are 12.5 m, 25 m and 50 m. The grids are defined in such a way that one grid point corresponds with the waterline at MSL ($x=1000$ m), except for one simulation, in which the waterline is exactly in between two grid points ($Dx=50$ m II). For all simulations the same flow grid was used.

![Graph](image)

**Figure 1: Development of the wave height for several resolutions of the computational grid**

First the results on the computational wave grid are considered. It is visible that the model with the 25 m grid spacing has twice as much computational points as the model with the 50 m grid spacing. Therefore the model is able to make a more gradual prediction of the evolution of the waveheights. This apparently results in a somewhat faster decrease of the wave height in the deeper zone of the coast profile. However, close to the shore line an almost equal wave height is computed. There both models agree on the percentage of broken waves. However, due to the more gradual decrease of the wave height (breaking) in the model with the finer resolution, the driving force for the longshore current is also more spread out resulting in a lower peak velocity.
Considering the results on the flow grid, it appears that a finer resolution of 12.5 m results in an even more gradual decrease in wave height, causing an even lower peak velocity. The results on the flow grid also show that in the case of a coarse computational wave grid, the location of the grid points also have a strong impact on the results. The breaker zone is shifted over half the grid size, resulting in a different velocity profile.

Figure 2: Velocity distribution for several resolutions of the computational grid
Appendix I: Friction coefficient and friction model

The velocity distribution of the longshore current is highly dependent on the assumed bottom friction model and bottom roughness. The bottom friction is dependent on the joint influence of currents and waves. For the computation of the actual bottom friction generally distinction is made between the friction due to currents alone and the friction due to waves alone. The friction due to the currents is often related to the depth-averaged velocity, while the friction due to the waves is related to the orbital velocity near the bottom. Various methods exist to describe this effect of combined current and wave action, among which the formulations of Bijker and Fredsoe (User Manual Delft3D-FLOW p.9-53/9-56, WL/Delft Hydraulics, 2001). The Bijker formulation gives a rather high bottom friction, while the Fredsoe formulation provides a rather low friction.

In this study the bottom friction due to currents alone is computed with a Manning formulation. The assumed Manning coefficient \( n \) of 0.028 s/m\(^{1/3} \) is rather high compared to other studies. Usually Manning coefficients of 0.020 to 0.028 s/m\(^{1/3} \) are applied. In the graph below a comparison is made between results with the Bijker formulation \( (n=0.020 \text{ s/m}^{1/3}) \) and the Fredsoe formulation \( (n=0.028 \text{ s/m}^{1/3}) \).

In the graph it is visible that the occurring longshore current is highly dependent on the applied friction coefficient and friction model. The simulation with the friction according to Fredsoe shows a maximum velocity that is twice as high as the velocity found with the Bijker approach, although the friction coefficient is taken equal. The velocities following from the Bijker formulation with a friction coefficient of 0.020 s/m\(^{1/3} \) and 0.028 s/m\(^{1/3} \) differ approximately a factor 1.5.

The results of a simulation are thus highly dependent on the chosen friction coefficient and friction model. As long as the results cannot be compared to field data, the outcome of a simulation should be handled carefully.
Appendix J: Velocity distribution during tidal cycle

In the graph below the velocity distribution cross-shore is shown for several characteristic stages during the tidal cycle. It is visible that at high water slack and low water slack the velocities at deep water are zero, as could be expected. The ebb current, which has a direction opposite to the wave-driven current, reduces the longshore velocities in the breaker zone, while the flood current enlarges the velocities. It can also be observed that the centre of the zone with the wave-driven current is displaced in time due to the varying water level.

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The velocity distribution cross-shore for several stages during the tidal cycle

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- MSL
- Initial bed profile
- high water slack
- low water slack
- maximum flood
- maximum ebb
Appendix K: Undisturbed development tidal model

A simulation without groyne was carried out for a case including tidal effects in combination with a wave-driven current. The characteristic development of a bed profile from the initial situation to the situation after 1 year is shown in the graph below.

The graph shows erosion in the zone with water depths (relative to MSL) between 3.5 m and -7.0 m. On deeper water, which is not shown in the graph, hardly any bed level changes are found. In the zone between the beach plain and MSL -3.5 m accretion is found. Sediment is likely transported from the zone with intermediate depths towards the shore. This results in a seaward shifting beach profile.

![Graph showing the undisturbed development of the bed profile with the tidal model](image-url)
Appendix L: Results stationary case with groyne

1. Morphological development case with Bijker friction
2. Morphological development case with Fredsøe friction
3. Transport reduction at the groyne

Remarks:
- The averaged reduction of the sediment transport at the groyne is 43.6% in the case with the friction formulation of Bijker and 29.6% with the friction formulation of Fredsøe.
- For both cases the tendency of the transport reduction decreases in time.
- The case with the Bijker formulation shows a very gradual decrease of the reduction, while the case with the Fredsøe formulation shows considerable irregularities. These irregularities are likely caused by the uneven development of the bed seaward of the groyne.

4. Accreted volume upstream

Remarks:
- The accreted volume upstream of the groyne increases in time for both cases. The accretion rate, however, decreases. This tendency corresponds to the results of the sediment transport reduction.
- The case with the friction model of Fredsøe shows more accretion upstream of the groyne than the case with the friction according to Bijker.
- The irregularities, found in the reduction of the sediment transport with the friction according to Fredsøe, result in only small disturbances in the development of the accreted volume.
5. Volume change per metre

Remarks:
- The volume changes per metre increase in time, but the growth rate decreases.
- The area with morphological changes increases in time.
- The affected area upstream of the groyne is larger than the affected area downstream.

Remarks:
- The volume changes per metre are considerably higher compared to the results of the simulation with the Bijker friction model.
- The effect of the irregularities in the geometry directly downstream of the groyne is also visible in the volume change per metres.
- The irregularities upstream and downstream of the groyne increase in time.
- In the area before location 10,000 m in the graph disturbances are found that were absent in the results of the simulation with the friction according to Bijker.
Appendix M: Transport tidal and stationary case

The results of a simulation including tidal effects are compared to the results of a simulation without the tide. The results are compared based on the initial (tide-averaged) sediment transport field around a groyne. Figure 1 shows the results of the stationary case, Figure 2 shows the results of the case including tidal effects. The main differences are:

- The undisturbed sediment transport entering the model area at the left side is spread out over a wider zone when tidal impact is included. The maximum transports are lower.
- In case tidal effects are included, the sediment transports directly upstream of the groyne vary more gradually from place to place compared to the stationary case, where the changes are rather abrupt.
- There are differences in the circular flow pattern downstream of the groyne.
- The direction of the transports seaward of the tip of the groyne differs for both models.

Figure 1: Initial sediment transport field stationary case

Figure 2: Initial tide-averaged sediment transport field tidal case
Appendix N: Results tidal case vs. stationary case

1. Morphological development tidal case

after 03 months

after 06 months

after 09 months

after 12 months
2. Transport reduction at the groyne

![Chart: Relative reduction of transport at the groyne](image)

**Remarks:**
- The reduction of the sediment transport is mostly higher for the case including tidal effects.
- The averaged reduction of the transport at the groyne is 31.8% for the case including the tide and 29.6% for the case without tidal effects.
- Initially, the sediment transport reduction is higher for the stationary case.
- The case including tidal effects shows a gradual decrease of the transport reduction, while the development of the reduction for the stationary case shows disturbances.

3. Accreted volume upstream

![Chart: Accretion upstream of the groyne](image)

**Remarks:**
- For both cases the accretion upstream of the groyne increases in time.
- The accretion rate decreases in time due to the decreasing reduction of the sediment transport in time.
- The case including tidal effects shows more accretion than the stationary case.
- Disturbances in the reduction of the transport at the groyne cause only small disturbances in the development of the accreted volume.
4. Volume change per metre

Remarks:
- The volume change per metre of the case including tidal effects shows more accretion in the first kilometre upstream of the groyne, compared to the volume change per metre for the stationary case (see also Appendix L.5). Further upstream, more accretion is found for the stationary case.
- The area upstream of the groyne evolves gradually, with only minor disturbances.
- In the area before location 10,000 m no volume changes are found for the case including tidal effects. These results are in contrast to the results of the stationary case, where disturbances were found.
- Downstream of the groyne a disturbance in the development is found. In contrast to the results of the stationary case, this disturbance decreases and disappears after some time.
- The affected area after 1 year is smaller than found with the simulation without tidal impact.
Appendix O: Results tidal case, increased time step

1. Morphological development tidal case, time step 5 days
2. Morphological development tidal case, time step 10 days
3. Transport reduction at the groyne

Remarks:
- The reduction of the sediment transport at the groyne is somewhat higher with larger morphological time steps. The averaged reduction at the groyne is 31.8% with a time step of 2 days, 33.5% with a time step of 5 days and 34.2% with a time step of 10 days.
- Initially, the relative reduction is equal for all time steps. This is logical, because initially no influence of the time step is felt yet.
- The original time step of 2 days results in a gradual decreasing reduction of the transport, while the decrease with larger time steps slightly oscillates.

4. Accreted volume upstream

Remarks:
- Most accretion is found with a morphological time step of 2 days. The accretion with this time step is considerably higher than the accretion found with a time step of 10 days.
- The higher accretion with a smaller time step is in contradiction to the transport reduction found at the groyne. From those results it could be expected that the smallest time step would lead to the least accretion, because the sediment transport was less reduced. This phenomenon is discussed in Section 8.5.
5. Volume change per metre, time step 5 days

Remarks:
- With a morphological time step of 5 days disturbances both upstream of the groyne (visible after 6 months) and downstream of the groyne (visible after 3 months)
- The disturbances increase in time and propagate through the model area. Especially downstream of the groyne the propagation of the disturbances is clearly visible.

6. Volume change per metre, time step 10 days

Remarks:
- With a morphological time step of 10 days, the disturbances are higher than with a time step of 5 days.
- The disturbances increase in time and propagate through the model area, as can be seen especially downstream of the groyne.
Appendix P: Effect increased time step

In Figure 1 and Figure 2 the morphological development after 1 month is shown for a simulation with a time step of 2 days and 10 days respectively. In the figures the depth contours are shown from MSL +0 m to MSL −6.0 m, decreasing with steps of 1 metre. The original shoreline is shown with a dotted line. The vectors represent the tide-averaged sediment transports.

When the morphological time step is large, the current field, wave field and sediment transport field are not updated often enough to account for the changed bathymetry. Upstream of the groyne the direction of the transports is then not adapted soon enough for the changed bed, so that the sediment is deposited in a small area.

In Figure 2 it can be observed that sediment is deposited concentrated in a small zone compared to the situation with a smaller time step (Figure 1). The concentrated accumulation of sediment leads to a distorted current field and thus a distorted sediment transport field. This is observable in the figures. Figure 1 shows a more gradual adaptation of magnitude and direction of the sediment transports upstream of the groyne compared to Figure 2. The distorted transport field causes new disturbances in the development of the bed.

Figure 1: Morphological development and tide-averaged transports after 1 month with a morphological time step of 2 days

Figure 2: Morphological development and tide-averaged transports after 1 month with a morphological time step of 10 days
Appendix Q: Results tidal case, reduced tidal period

1. Morphological development with reduced tidal period
2. Transport reduction at the groyne

Remarks:
- The highest reduction of the sediment transport at the groyne is found with the full tidal period. The average reduction with the full tidal period is 31.8%. With the reduced tidal period an average reduction of 28.2% is found.
- Both cases show a very gradual decrease in the transport reduction.
- The initial difference between the transport reduction of both cases is 3.5%. The difference stays more or less equal during the simulation time.

3. Accreted volume upstream

Remarks:
- With the reduced tidal period less accretion is found than with the full tidal period. This could be expected from the fact that the reduction of the sediment transport is less than with the full period.
- Both cases show a gradual development of the accretion upstream of the groyne.
4. Volume change per metre

Volume change per metre after 3, 6, 9 and 12 months
tidal model with reduced tidal period

Remarks:
- The volume change per metre shows a very gradual development in time.
- The small disturbances downstream of the groyne, found with the full tidal period of 12 hours (see Appendix N.4), are absent in the simulation with a reduced tidal period of 6 hours.
- The graph clearly shows that the erosion/accretion increases in time and that the change rate decreases.
Appendix R: Results with Soulsby-Van Rijn formula

1. Morphological development

- Tidal case after 03 months
- Tidal case after 05 months
- Stationary case after 06 months
- Stationary case, refined wave grid after 06 months
2. **Transport reduction at the groyne**

![Graph showing relative reduction of transport at the groyne](image)

**Remarks:**

- When a simulation including tidal effects is carried out with the Soulsby-Van Rijn formula, the reduction of the sediment transport at the groyne is less than with the Bijker/Bailard approach. Furthermore, the reduction decreases at a higher rate. In the reduction of the sediment transport at the groyne no irregularities are found.

- When a stationary situation is carried out with the Soulsby-Van Rijn formula, the initial reduction of the sediment transport is more or less equal to the reduction predicted with the Bijker/Bailard approach. However, the reduction of the transport decreases rapidly from 47% at the start of the simulation to only 12% after 3 months. From that moment the reduction increases again.

- A stationary simulation with a more detailed computational wave grid and the Soulsby-Van Rijn formula shows a more gradually decreasing reduction which reaches a minimum after 6 months. From then on the reduction increases again.
3. Accreted volume upstream

![Graph showing accretion upstream of the groyne over time (months)]

**Remarks:**
- The accretion resulting from simulations with the Bijker/Bailard approach is considerably higher than the accretion from simulations with the Soulsby-Van Rijn approach.
- For the simulations with the Soulsby-Van Rijn formula, the accretion upstream of the groyne is comparable, both for a case including tidal effects and a case without the tide.
- A stationary case with the Soulsby-Van Rijn formula and a refined wave grid produces somewhat less accretion.
4. Volume change per metre, tidal case with Soulsby-Van Rijn

![Graph showing volume change per metre after 3 and 6 months with Soulsby-Van Rijn formula.]

Remark:
- The volume change per metre resulting from a simulation including tidal effects and the Soulsby-Van Rijn formula is highly disturbed.

5. Volume change per metre, stationary case with Soulsby-Van Rijn

![Graph showing volume change per metre after 3 and 6 months with Soulsby-Van Rijn formula.]

Remark:
- The volume change per metre resulting from a simulation without tidal effects and the Soulsby-Van Rijn formula shows an unstable development.
Appendix S: Results tidal case without waves

after 03 months

after 06 months

after 09 months
Appendix T: Bed friction models

Several models are available for the description of the enhancement of the bed shear-stress by waves. Among these models are the method of Bijker and the method of Fredsøe, which are used in this study. The existing models are known to produce varying results. Differences of 30% to 40% are commonly found, and differences of up to a factor 3 occur for strongly wave-dominated conditions (Soulsby R.L., 1997). Soulsby et al. (1993) derived an algebraic approximation for several friction models, which is used in Delft3D-FLOW.

The information presented below is a copy of page 9-53 to 9-57 of the manual of Delft3D-FLOW (WL | Delft Hydraulics, 2001). It describes the modelling of the enhancement of the bed shear-stress by waves.

9.7.5 Enhancement of the bed shear-stress by waves

The boundary layers at the bed associated with the waves and the current interact non-linearly. This has the effect of enhancing both the mean and oscillatory bed shear-stresses. In addition the current profile is modified, because the extra turbulence generated close to the bed by the waves appears to the current as being equivalent to an enhanced bottom roughness. The bed shear-stress due to the combination of waves and current is enhanced beyond the value which would result from a linear addition of the bed shear-stress due to waves, \( \tau_w \), and the bed shear-stress due to current \( \tau_r \). For sediment transport modelling it is important to predict the maximum bed shear-stress, \( \tau_{\text{max}} \), while the current velocity and the turbulent diffusion are determined by the combined wave-current bed shear-stress \( \tau_{\text{w}} \).

Various, often very complex, methods exist to describe the bottom boundary layer under combined current and wave action and the resulting virtual roughness. Soulsby et al. (1993) developed a parametrization of these methods allowing a simple implementation and comparison of 8 wave-current interaction models: Fredsøe (1984), Myrhaug and Slaattelid (1990), Huynh-Thanh and Temperville (1991), Grant and Madsen (1979), Davies at al. (1988), Bijker (1967), Christoffersen and Jonsson (1985), and O’Connor and Yoo (1988). All these methods have all been implemented in Delft3D-FLOW and can be applied in 2D and 3D modelling. However, as there are minor, but specific differences in determining certain quantities, such as determining the shear-stress at the bottom, we prefer to discuss the 2D and 3D implementation separately.

2D implementation

Following Soulsby et al. (1993), Figure 9-6 gives a schematic overview of the bed shear-stresses for wave current interaction.

Soulsby et al. (1993) fitted one standard formula to all of the models, each model having its own fitting coefficients. The parametrization of Soulsby for the time-mean bed shear-stress is of the form:

\[
|R_{\text{w}}| = y \left( |\tau_w| + |\tau_r| \right).
\]  
(9.165)
\[ y = x \left( 1 + b x^\epsilon (1 - x)^\gamma \right) \]  

\[ \bar{T}_{\text{max}} = \frac{1}{2} \left( \mid \bar{T}_c \mid + \mid \bar{T}_w \mid \right) \]  

\[ \tau = 1 + \alpha x^\nu (1 - x)^\xi \]  

Figure 9-6  Schematic view of non-linear interaction of wave and current bed shear-stresses (from Soulsby et al., 1993).

and for the maximum bed shear-stress:

\[ \left| \bar{T}_{\text{max}} \right| = \frac{1}{2} \left( \mid \bar{T}_c \mid + \mid \bar{T}_w \mid \right) \]  

\[ \tau = 1 + \alpha x^\nu (1 - x)^\xi \]  

The value of the parameters \( a, b, p, q, m \) and \( n \) depends on the friction model which is parameterized, and:

\[ x = \frac{\mid \bar{T}_c \mid}{\mid \bar{T}_c \mid + \mid \bar{T}_w \mid} \]  

with:

- \( \mid \bar{T}_c \mid \) Magnitude of the bed stress due to current alone.
- \( \mid \bar{T}_w \mid \) Magnitude of the bed stress for waves alone.
- \( \mid \bar{T}_m \mid \) Magnitude of the mean bed stress for combined waves and current.
- \( \mid \bar{T}_{\text{max}} \mid \) Magnitude of the maximum bed stress for combined waves and current.

Remark:
- The stresses \( \bar{T}_m \) and \( \bar{T}_{\text{max}} \) are assumed to have the same direction as \( \bar{T}_c \).
Following Soulsby et al. (1993) expressions for the parameters $a$, $b$, $p$, $q$, $m$ and $n$ have the form:

$$a = \left( a_1 + a_2 \left| \cos \phi \right|^{\frac{1}{3}} \right) + \left( a_3 + a_4 \left| \cos \phi \right|^{\frac{1}{3}} \right) \log \left( \frac{f_w}{C_{2D}} \right),$$

(9.170)

in which:

- $C_{2D}$ Drag coefficient due to current.
- $f_w$ Wave friction factor.
- $\phi$ The angle between the current direction and the direction of wave propagation.

As the radiation stress is always in the wave direction, we can derive $\phi$ from:

$$\left| \cos \phi \right| = \frac{|U F_x + V F_z|}{|U||F|}.$$  

(9.171)

Values of the parameters $a_1, a_2, a_3, a_4, p, q$ and $J$ in Eq. (9.171) have been optimised by Soulsby et al. (1993), see Figure 9-7.
Figure 9-7 Intercomparison of eight models for prediction of mean and maximum bed shear-stress due to waves and currents (from Soulsby et al., 1993).

The bed shear-stress due to flow alone may be computed using various types of formulations like Chezy, Manning or White Colebrook, see Eqs. (9.42) to (9.44). The bed shear-stress due to current alone can be written in the form:

$$\tilde{\tau}_c = \frac{g\rho_o \overline{U|U|}}{C_{2D}^2}. \quad (9.172)$$

The magnitude of the wave-averaged bed shear-stress due to waves alone is related to the wave orbital velocity near the bottom $\bar{u}_{orb}$ and the friction coefficient $f_w$:

$$|\tilde{\tau}_w| = \frac{1}{2} \rho_o f_w \bar{u}_{orb}^2. \quad (9.173)$$

The orbital velocity is computed from the linear wave theory and is given by:

$$\bar{u}_{orb} = \frac{1}{2} \sqrt{\frac{\pi}{2}} \frac{H_{1/2} \omega}{\sinh(\ell H)}, \quad (9.174)$$
where the root-mean-square wave height \( H_{m} \), and the wave period \( T = 2\pi /\omega \) are read from the communication file. The variation of the wave friction factor with relative orbital excursion at the bed under purely oscillatory flow is given by Swart (1974):

\[
f_{w} = \begin{cases} 
0.00251 \exp \left[ 5.21 \left( \frac{A}{k_{r}} \right)^{-0.19} \right], & \text{when } \frac{A}{k_{r}} > \frac{\pi}{2}, \\
0.3, & \text{when } \frac{A}{k_{r}} \leq \frac{\pi}{2},
\end{cases}
\]  
\[
(9.175)
\]

with:

\[
A = \frac{H_{m} \eta_{ch}}{\omega},
\]  
\[
(9.176)
\]

\( k_{r} \) is the Nikuradse roughness length-scale and \( \omega \) is the wave angular frequency.

As the bed is in rest and the equations are formulated in GLM co-ordinates, we must correct the bed shear-stress used in the momentum equations for the Stokes drift. The total or effective bed shear stress is given by:

\[
\tau_{*} = \frac{\tau_{*}}{|U|} (\bar{U} - \bar{U}^{s}),
\]  
\[
(9.177)
\]

where the components of the depth-averaged Stokes drift \( \bar{U}^{s} \) are given by Eqs. (9.153) and (9.154).