AALBORG UNIVERSITY
STUDENT REPORT

Coastal erosion in Faxe Ladeplads

Alternative approach

Master Thesis Report

Structural and Civil Engineering
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4^{th} *semester*
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AALBORG UNIVERSITY
STUDENT REPORT

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Synopsis:

This project deals with the study of the erosion phenomenon which occurs in *Faxe Ladeplads* Municipality. The focus is on the evaluation of the coastal modification throughout a different software approach.

The paper ha the intent of comparing the standard Sediment Transport module, running on *MIKE 21* with the brand new Shoreline Morphology module.

An analysis of the erosion phenomena is performed, to allow a better understanding of the processes on which the new software is based.

A brief comparison of the theory behind the two approaches is given before introducing to the real case study.

In the last part of the paper the results of the simulation performed with the new module are presented and discussed through a brief comparison with the results previously obtained using the standard method.

Preface

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1 | Introduction

This paper is intended to analyse in some aspects the behaviour of a coast prone to erosion. This is a very common issue that all the world coasts are experiencing and for this reason it is a very actual problem. Though, since it is also depending on several and not completely understood variables it is important to specify that the results obtained from the analysis are to be considered as a guideline rather than a picture of what will be the real coast behaviour.

The report is organised in a way of giving the reader a comprehensive view of the whole process, thus it starts with an brief overview of the erosion phenomenon before introducing the real case taken as subject of studying which, will be based on the erosion that is taking place in the beach of Faxe Ladeplads Kommune, in the souther part of Denmark.

The harbour and the beach are modelled with a Finite Element software that tries to give a overview of the future developments of the shoreline by simulating the behaviour after one year of standard winds and waves conditions.

Finally, a comment on the results will be given also considering the work carried out by Rambøll which gave its precious contribution during the development of this paper.

Part I

Theoretical introduction

This part deals with the analysis of the motion of the material inside a harbour with the focus on the waves and currents processes which tend to modify the shoreline profile by removing the sediments constituting the coastline.
Afterwards a brief overview of the numerical model usually used to describe these phenomena is given with a particular core in the description of the basis of the Shoreline module, used later on in this paper.

2 | Sediment transport

In this chapter the foundamental basis of the motion of the material nearby the coastline are explained.

2.1 Theoretical overview

Coast evolution is strictly connected with the motion of the sediments constituting the beach, both above and below the water level, namely is dependent on the integration between the wave motion and the beach.

The shape of the beach is called beach profile and it depends on the external environmental conditions such as water levels, winds and waves and for this reason the coast profile is in continuous change. This change it is quite evident in the re-allocation of bars between the summer period and the winter period, indeed, during winter season, usually, the bars are taken far from the beach profile due to the high and steep storm waves occurring in this part of the year and the wave breaking makes the sea bottom to change by removing and eroding the near-shore area forming the bars where the wave breaks. During summer period, calmer sea causes a restore of the original beach conditions by moving back on-shore the material thanks to the smaller and flatter waves, the bars become berms and the off-shore profile results much flatter. The change of the sea bottom profile with the two different kind of bars can be seen in Figure 2.1

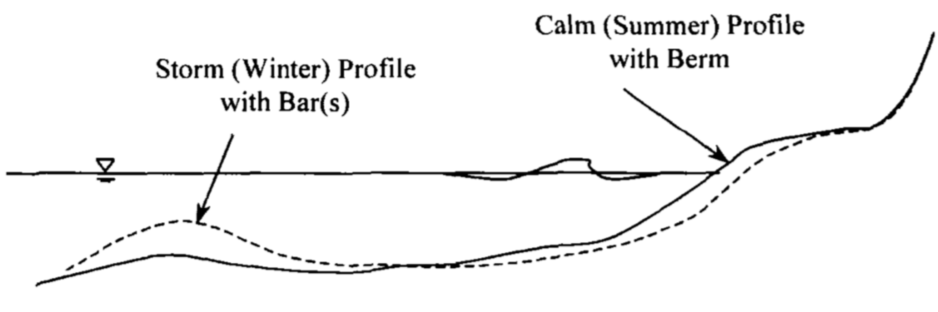

Fig. 2.1. Change of the sea bottom profile during different periods of the year.

The sediment transport is based on the definition of the term *erosion* that can be gathered by the definition given by a publication of the USACE: CETN-II-2 (1988) in which it is said that the erosion "..usually describes sub-aerial erosion, meaning the removal of material from the visible beach that often to produce a gentle slope in the surf zone and one or more large long-shore bars in the offshore. The term accretion usually describes sand accumulation in the form of one or more berms on the visible beach and, typically, a steep profile in the surf zone with relatively small offshore bars. Although erosion and accretion commonly refer to the response of the sub-aerial beach, material may not be lost or gained in the total system, but only displaced and rearranged."

From this definition it is clear that the material is not moving in or out the system but simply reallocated, this consideration, though, must be carefully meditated since it is true if the system is considered to be the entire seabed, if the area of interest is restricted to a shoreline and the sea stretch next to it the material can actually acknowledge to be lost, as it is discussed in the following.

2.2 Sediment motion

The beach evolution depends also on the type of the sediments of which is composed, these different materials have different behaviours depending on the nature of the deposit itself; depending on the specific density and the grain diameter the setting velocity changes; it is interesting to notice the relation between the sediment characteristics and its setting velocity for a quartz grain, that is the most common material that forms beaches.

Figure 2.2 shows that the setting speed increases with the increment of the size of the grain, which is quite obvious since the velocity depends on the mass of the sediment.

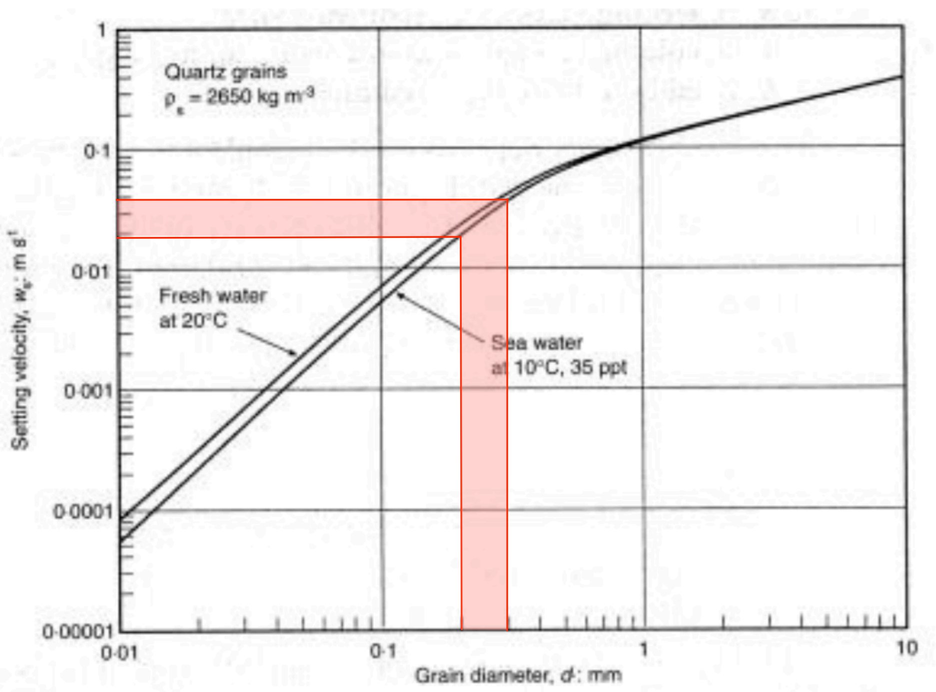

Fig. 2.2. Setting velocity of quartz grains of sieve diameter d at low concentration.

In the real case analysed in this paper the average grain has an approximated diameter of $d_{50} = 0.2\,\text{mm}$ which leads to a medium high setting velocity, as shown above. Though, it is important to say that the beach has been subjected to a process of nourishment and it has been decided to use a larger diameter for the new material in order to ensure a better slope stability, the new grain size is therefore $d_{50} = 0.3\,\text{mm}$.

Once determined the main characteristics of the erosion and accretion of beaches it is now interesting to understand which are the forces that allow the transport of the material.

2.3 Acting forces

In the study of the coastal processes it is very common to separate the sediment transport into two different classes: the cross-shore transport and the long-shore transport. The difference is mainly on the direction taken by the transport with the respect to the shore profile, as it is shown in Figure 2.3

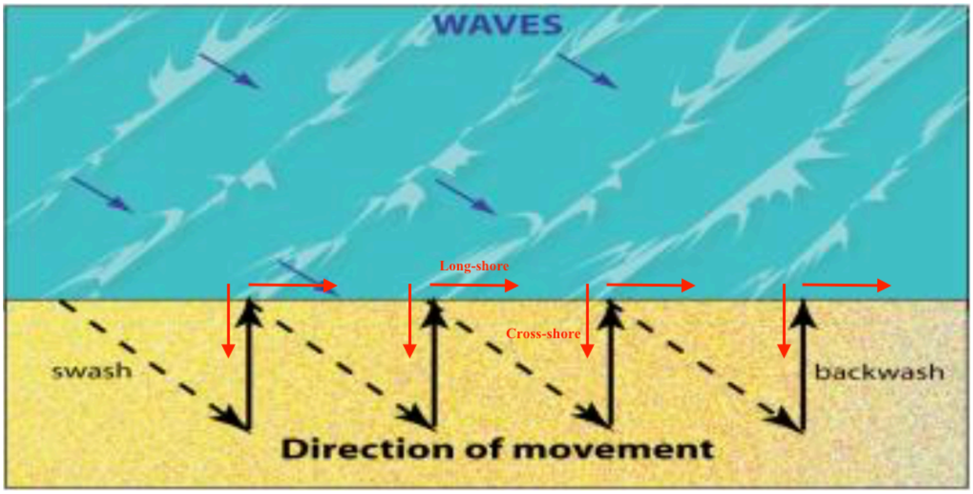

Fig. 2.3. Direction of the particles motion in the two main transports.

The different influences that these transports have on the evolution of the coasts are analysed in the followings.

2.3.1 Cross-shore transport

Cross-shore transport happens when the motion of the material is mostly perpendicular to the coast line and it is mainly determined by the wave speed, the diameter of the grains and the beach profile slope; this kind of transport is responsible to the short-terms changes of the beach's shape and it is related to the equilibrium between the shoreline and the external conditions. If the beach slope is stable, thus in equilibrium with the external conditions, namely, the water conditions, a very small cross-shore movement occurs, but, whenever a quick change in the wave and wind conditions takes place, the movement of the material in the cross-shore direction is really responsive. This phenomenon is quite obvious when it comes to visual observations of the coasts, usually it is clear that after a big storm there is a higher chance to notice a relevant erosion of the beach whereas peaceful sea with long-crested waves helps restoring the original conditions with a refill of the sand.

Short-period variation in the coast profile are mainly dependent on this kind of transport, in fact this process affects the coast profile during a normal year time, in the change between summer and winter period. During the winter season the coast is eroded by stronger winds and wave conditions which move the material off-shore. During the summer season the calmer seas allows the material to be brought on-shore again, restituting the sediment to the original position. This process is therefore completely balanced and it is quite well described by Figure 2.4

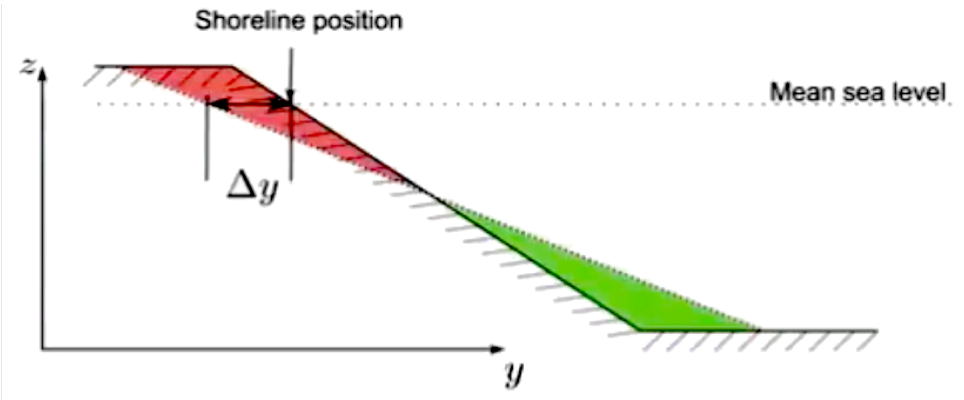

Fig. 2.4. The red area show the eroded portion of the shore during winter storms, the green is the off-shore deposited material.

From the figure above it is pretty clear that the two areas (red and green) are totally equal and therefore the process is totally conservative.

For an average period time, approximately one or several years, it is assumed that the erosion phenomenon carried out by cross-shore transport is balanced by the reconstituting process of the normal sea action, which, takes back the material to its original on-shore position, throughout the cross-shore accretion phenomenon. For this reason it is quite a fair assumption to consider the variation of the beach profile depending on the long-shore transport only; this assumption is obviously quite rough whether considering longer periods though the effect that the cross-shore transport has on the modification of the shoreline still remain not totally explained and due to this it is still not possible to get the knowledge of the contribution of the cross-shore phenomenon for longer time steps.

The mostly used criteria to determine the cross-shore transport is based on the evaluation of the shear stress acting between a particle and the sea bottom. The stress depends on the wave period and the significant wave height and since it is directly related to these inputs it is clear that the higher and the more frequent the wave is, the higher the sediment motion will be; thus it is likely that the steep waves ($H/L > 1$) tend to cause erosion phenomena dragging the sediment far from the beach towards open sea, whereas long waves ($H/L < 1$) tend to restore the beach profile.

In the early days of the coastal engineering it was believed that the wave steepness only was a sufficient indicator of the behaviour of the sediment transport, with steep wave causing erosion and low steep waves causing accretion, though, it was later realised that the wave height has a strong impact on the phenomenon and the median grain size, composing the shore, are of importance too since "...fine-sand beaches typically undergo greater variations than coarse-sand beaches." For these reasons, after laboratory tests, it has been discovered that the factors influencing the behaviour of the shore are:

- wave steepness (H_0/L_0)
- wave height H_0
- wave period T_0
- median grain size d_{50} or its equivalent
- sand fall velocity w (for different grain densities and shapes)

where

H_0	deep water wave height
L_0	deep water wave length

2.3.2 Long-shore transport

When a wave approaches the shore with an angle the long-shore transport occurs. The angle with which waves hit the coast causes a sediment movement in the direction of the wave propagation, which is composed by two different contributions:

- beach drifting in the swash zone
- material transport in the breaking zone

The first mechanism indicates the diagonal motion of the material, firstly the sand is pushed onto the beach by the wave strength, afterwards, thanks to the gravity effects, it is drifted downwards, following the shore slope, perpendicularly to the coastline. The second phenomenon is the transport that occurs in the breaking zone, in this area waves stir the sediment into suspension and due to the along-shore current, it is drifted parallel to the shore. In this way the sediment are driven in the direction of the hitting waves causing a change in the shape of the shoreline.

It is thus clear that through the wave action the material slowly shifts in the direction of the incident wave, and if this is constant along the entire year the coastline will be eroded in the southward area and accreted in the northward part, or the other way around.

This kind of transport affects the very nearby beach area and it depends mostly on the wave height, the wave direction and on the strength of the along-shore current.

For a clearer idea the two mechanisms are explained in Figure 2.5 in which the coastline develops horizontally between the breaking zone and the up-rush zone.

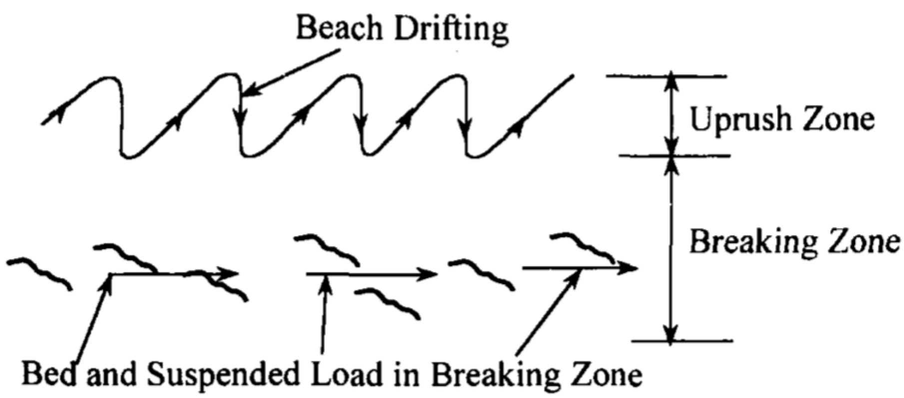

Fig. 2.5. Mechanisms occurring during and after the wave breaking.

For a large incident wave angle the wave breaking process generate a strong momentum that causes strong along-shore currents, and for this reason the transport of materials parallel to the coast line is quite relevant. In the case of interest the waves hit the coast with an angle of about 30° with the respect to the shoreline normal, this leads to a considerably high long-shore southward sediment motion that affect the entire bay.

This process leads to a not-reversible coastal erosion since the sediment are totally removed from the system as shown in Figure 2.6

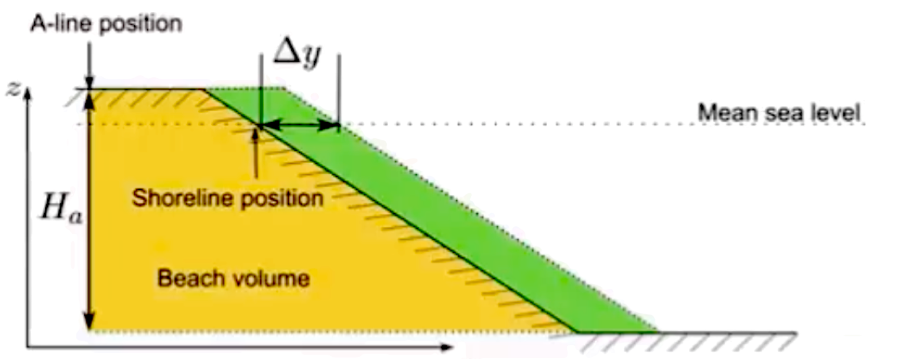

Fig. 2.6. Long-shore erosion: green area shows the amount of material lost.

Once determined which are the forcing causes to the motion of the sediment near a shoreline it is now of interest to understand how to evaluate the entity of these components, and this can be done by determine the total transport rate.

2.3.3 Kamphuis equation

The best known expression to evaluate the sediment transport is suggested by *CERC* (1984) that states that the material transport is directly proportional to the significant wave height and the wave incident angle, as shown below

$$Q_c = 330\, H_{sb}^{5/2} \sin(2\alpha_b) \tag{2.1}$$

where

Q_c	material net flux
b	breaking conditions
α	incident angle with the respect to shoreline normal.

Though, as it is possible to notice, Eq. 2.1 depends on the wave height and the incident angle only, for this reason another approach is usually preferred, this approach is suggested by *Kamphuis* (1991) and states that the transport rate depends also on the wave period T, the grain size d and the beach slope m, as shown in Eq.2.2

$$Q_s = 2.27\, H_{sb}^2\, T_p^{3/2}\, m_b^{0.75}\, d^{-0.25} \sin^{0.6}(2\alpha_b) \tag{2.2}$$

Kamphuis model is based on empirical proves and it is stated that usually the model over-predicts the transport of gravel composed beaches, and this is because it doesn't take into account the critical shear stress of the gravel that is higher rather than in sand particles.

Throughout the use of these equations it is possible to determine how much material is transported in and out a cross sectional area that usually develops along the shoreline. Though, these equations only provide a rough estimate of the real conditions and even though the shoreline behaviour predictions based on those can give an overview of the processes occurring in the harbour, this cannot be considered reliable for design. For this reason in present days it is common use to rely on estimates obtained throughout computer programs, carefully calibrated through the use of a large amount of data as an input.

Thanks to these softwares it is possible to simulate the behaviour of a coastline with a higher reliability and accuracy. Though, even using the Finite Element software uncertainties can be found in the results; this is because the data used as calibration factor are not always available and the models are still a simplification of the real conditions, thus the use of the results of these programs for design must be carefully considered.

It is decided to rely on the use of the Finite Element analysis since it is the best tool to try to predict the coastal conditions and to carefully design a solution for problems with the knowledge of the likely evolution of the system. The software used in the next chapters is a program based on the Finite Element Analysis called *MIKE 21*.

3 | Mike 21

MIKE 21 is a software developed by *DHI* and it is stated as being by far the most versatile tool for coastal modelling allowing the simulation of physical, chemical or biological processes in coastal or marine areas; for this reason it is the tool to be used whenever it is required to simulate with a high level of accuracy the behaviour of any hydrographic scenario.

It is a Finite Element software which provides a better understanding of the physical processes by combining different modules; in this paper, in which one of the aims is try to investigate the behaviour of the sediment material in Faxe Ladeplads harbour, four of them are used, the Spectral Wave (SW) module, the Hydrodynamic (HD) module, the Sand Transport (ST) module and, finally, the Shoreline Morphology module. These modules are combined together in order to give a comprehensive view of the entire process combining wave, wind and sediment informations throughout the use of the Coupled Model FM.

As stated previously this approach only tries to simulate the real conditions therefore, even the validity of the method has been proved in several years and by different authorities, the results of the calculations must be handled carefully.

A short overview of the characteristics of the different modules is now given so to allow the reader to understand the process that lays under the simulation and to have an idea of the inputs required for each module and the outputs it is possible to obtain. The following sections do not claim to be a deep investigation of the modules, which can be found in the respective manuals.

3.1 Hydrodynamic module

The HD module gives the basis of the future calculations performed in other modules, meaning that it provides, for an unsteady flow, the informations about the water level fluctuations starting from density variations, bathymetry of the site and external forces such as the wind conditions. The outputs include the surface elevation, the water depth and the velocities field, An overview of the inputs that need to be set in order to run the Hydrodynamic module is shown in Figure 3.1 in which the user interface of the Hydrodynamic module is presented

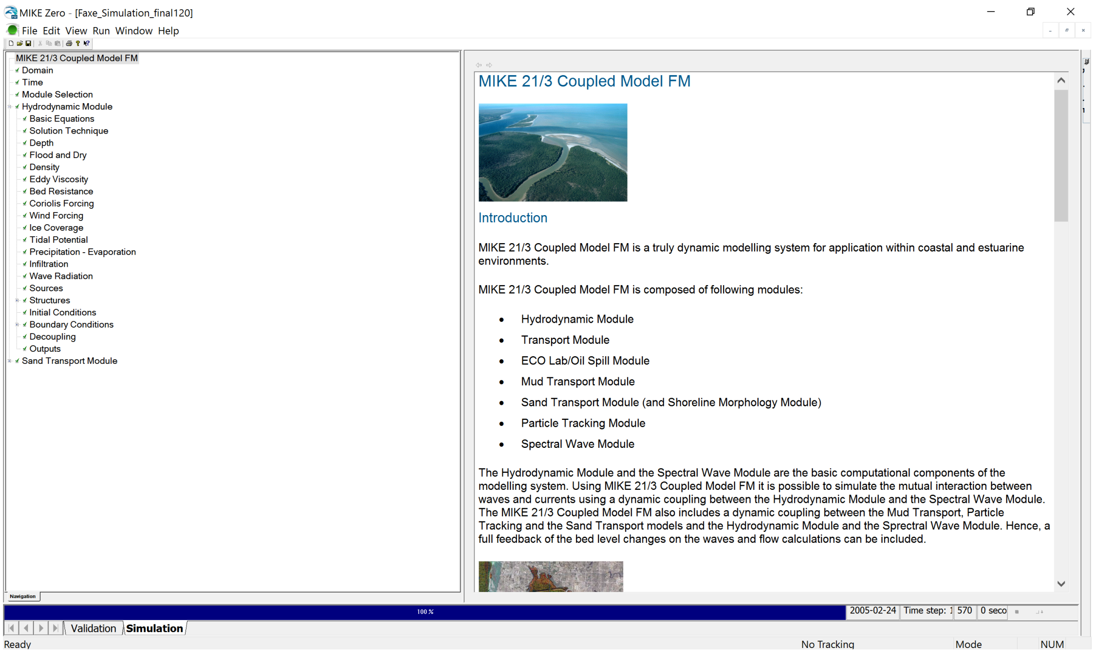

Fig. 3.1. The *MIKE 21* user interface of the Hydrodynamic module with the required inputs.

In order to run this module a particular input is required, namely the wave radiation. This parameter is the excess of momentum flux caused by the presence of waves that results in a generation of an additional force which changes the mean surface elevation and it leads to the development of a wave-driven long-shore current which is responsible to the long-shore transport that affect the coastal erosion phenomenon the most. Due to this required input a second module needs to be run.

3.2 Spectral Wave module

The Spectral Wave module simulates the growth, decay and transformation of wind-driven waves, therefore it requires as input the wind data obtained through field survey. Running this particular module ensures obtaining a set of outputs that describe in a very complete way the waves occurring into the harbour, thus, by setting as an input the hindcast data from the wind, the significant wave height H_{m0}, the wave period T_0, the mean wave direction θ_m, and the radiation stress tensor needed for running the HD module can be obtained.

It is important to be said that the model has been set to run as an in-stationary solution, this is because the waves analysed in Faxe Ladeplads are wind-driven and, due to this, highly non-linear, therefore a stationary solution, even if it is much more stable and faster, is impossible to be obtained. This setting has a fairly large impact on the calculation time that is considerably extended.

3.3 Sand Transport module

Thanks to the coupled modelling it is possible to combine the Spectral Wave solution with the Hydrodynamic calculations in order to derives from the wind data the correspondent water fluctuations and currents which form the basis of the motion of the material in the harbour and affect the profile of the coast; the Sand Transport, in fact, allows to calculate the sediment transport rates on a flexible mesh using the characteristics of the materials. The inputs necessary to run the module can be seen in Figure 3.2

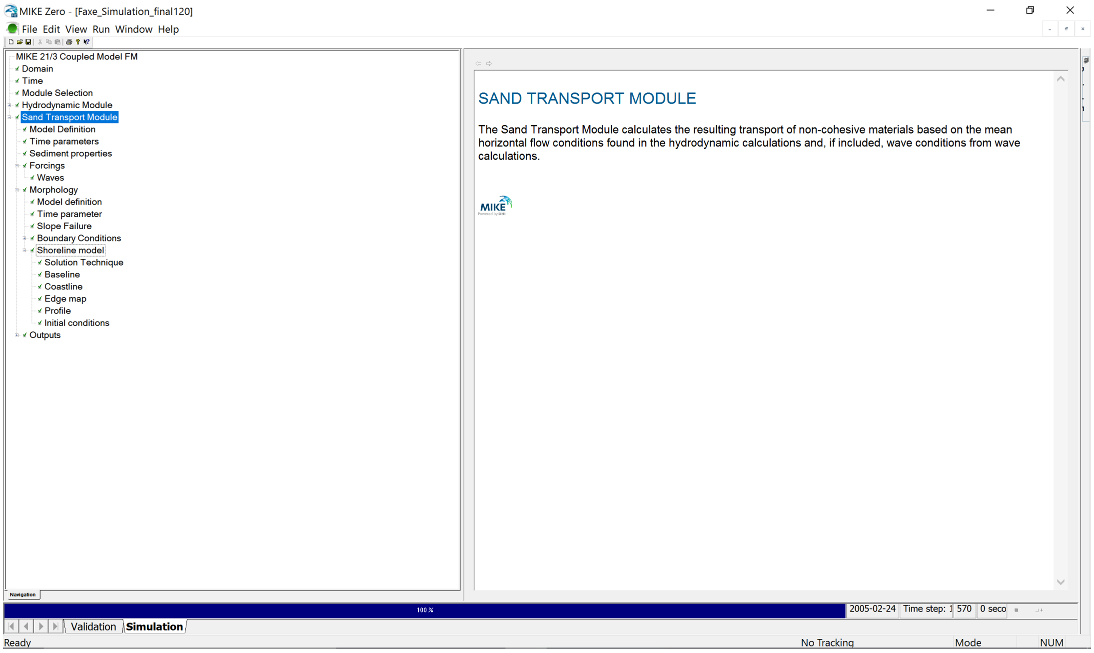

Fig. 3.2. The MIKE 21 user interface of the Sand Transport module with the required inputs.

Two types of output can be obtained from the ST model, the sediment transport rate, which gives informations about the entity of material motion in and out the harbour, and the resulting morphological changes that affect the bed level and the coastline profile.

The state of art of the tools used to simulate the coastal behaviour were composed by these software and for this reason Rambøll decided to avail on Sand Transport module to reproduce Faxe Ladeplads conditions; in 2016 though, a new tool was developed by *DHI*, in order to overcome some of the limits affecting the *old* models. This new module is named *Shoreline Morphology* (SM) and it is based on two different approaches.

3.4 Shoreline Morphology module

To describe the material changes happening inside a harbour two main tools were available:

- 1D Shoreline model
- 2D Integrated model

The first one is called *LITDRIFT*, and it is a model that provides very reliable long time scale prediction for the coastal behaviour, though this approach deals with 1D effects only and does not take into consideration 2D processes such as a 2D mesh with a complex bathymetry or 3D waves. In order to overcome this problem the 1D Shoreline model implements some parametric formulations that try to simulate the characteristics of more complex models; this dodge, though, has no effects on complex cases and it is reliable only with very simplified and idealised problems. In addition to that the *LITDRIFT* does not provide any sediment transport pattern and for this reason usually it is preferred to use the 2D integrated module, meaning Sand Transport module.

This model, as previously stated, provides very detailed sediment transport pattern and can deal with very complex morphology, though the long time calculations and the fact that the cross-shore processes are not still well defined contribute to make this model unsuitable for long time scale simulations, since the morphology in the Sand Transport module breaks down over time leading to results which show costal profile shapes to become unnatural.

To overcome this issues the SM module can be used.

This module is an extension to the classical Sand Transport module and it combines the flexibility of integrating a flexible mesh, which covers very complex bathymetry, with the result of a very detailed sediment transport pattern, this applied for a very long time scale simulation. The concept of the module can be reassumed by Figure 3.3

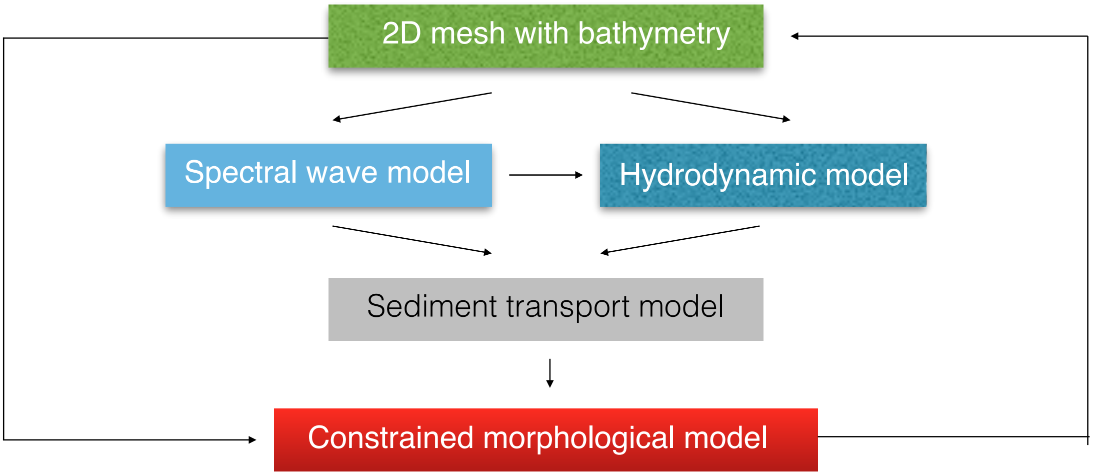

Fig. 3.3. Scheme of the ShoreLine Morphology module.

The main problem with the Sand Transport module is that the long time simulation breaks the coastal profile down, through the use of the *SM* this issue is overcome by prescribing what the coastal profile should look like, thus it is possible not to worry about the knowledge of the cross-shore not being accurate enough since the shoreline shape is constrained.

The module is based on the one-line equation for shoreline movement that states that the change of the shoreline position is equal to the gradient in the long-shore divided by the height of the profile. This equation is based on the common observation that the shoreline profile maintains its shape along the normal shore-sea interaction and with the exception of extreme changes as produced by storms. This means that steep beaches tend to remain steep and shores with a gentle slope tend to remain gentle in long term. This means that the beach profile only moves parallel to itself with the respect to erosion or accretion and, due to this, one contour line can be used to describe the change in the plan shape; this contour line is the observed shoreline.

In the shoreline module this equation is slightly changed and reformulated in terms of volume, as shown in Eq. 3.1

$$\frac{dn}{dt} = \frac{vol}{dA_z} \tag{3.1}$$

stating that the change in the shoreline is equal to the volume of the sediment deposited in each strips composing the mesh in the model divided for the cross section area over which this volume is distributed.

Part II

Presentation of the case study

In this part of the paper the real case in study is presented. A geographical description of the area of interest and the wind and wave characteristics are illustrated with a particular focus on the historical changes that has contributed to the development of the erosional phenomenon.
In the second part of the chapter the approach implemented by Rambøll is explained and discussed in detail, focusing on personal beliefs regarding other possible solutions or different approaches .

4 | Case study

Faxe Ladeplads is a town in the southern part of Denmark in the region of Zealand, around 5 km southest of the Municipality of Faxe with which it is connected by a single road that develops along the coast line. Thanks to its position the harbour is quite sheltered by the strong winds coming from the ocean on the west direction, as it is possible to see in Figure 4.1 and Figure 4.2. Though, the bay is not sheltered enough from medium height waves, generated by a southwards oriented constant wind stream, which enter the harbour and crash against its coasts.

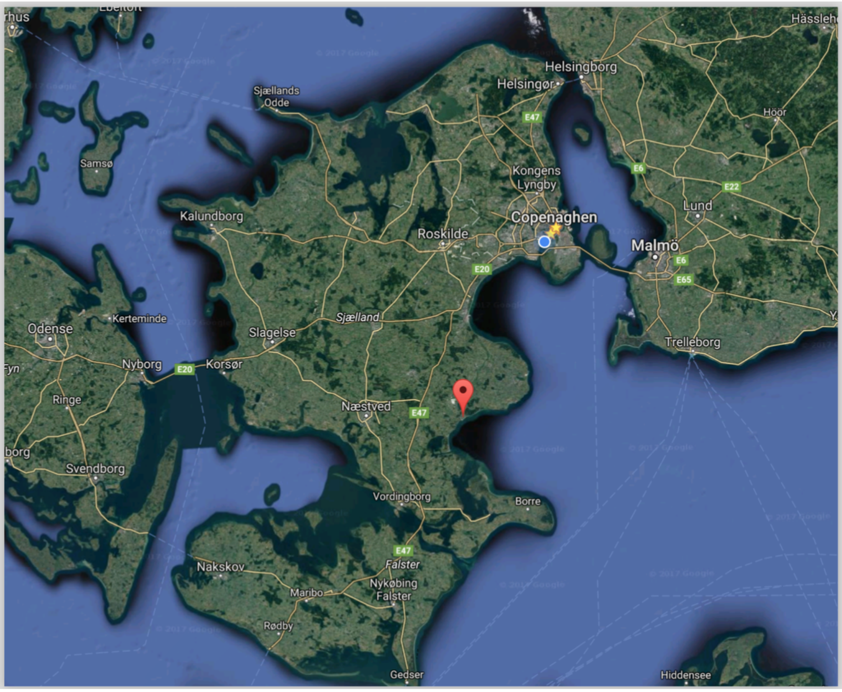

Fig. 4.1. Faxe Ladeplads position in south of Zealand.

Due to this reason the harbour is currently experiencing an erosion phenomenon that has increased over the years. In order to better understand the reasons why this process has been increased an historical picture of the development of the harbour is provided in the following.

Fig. 4.2. Faxe Ladeplads harbour detail, the North is upward.

4.1 Historical overview

Faxe Ladeplads in the past was mainly a site in which the limestone, forming the subsoil layer, was mined and shipped from the area to the city of Copenhagen. At that time there was no shelter for the barges and for this reason, in the second half of the 19^{th} century, a small port with piers has been built to offer some shelter to the ships waiting for their cargo.

Figure 4.3 shows the first development of the commercial harbour.

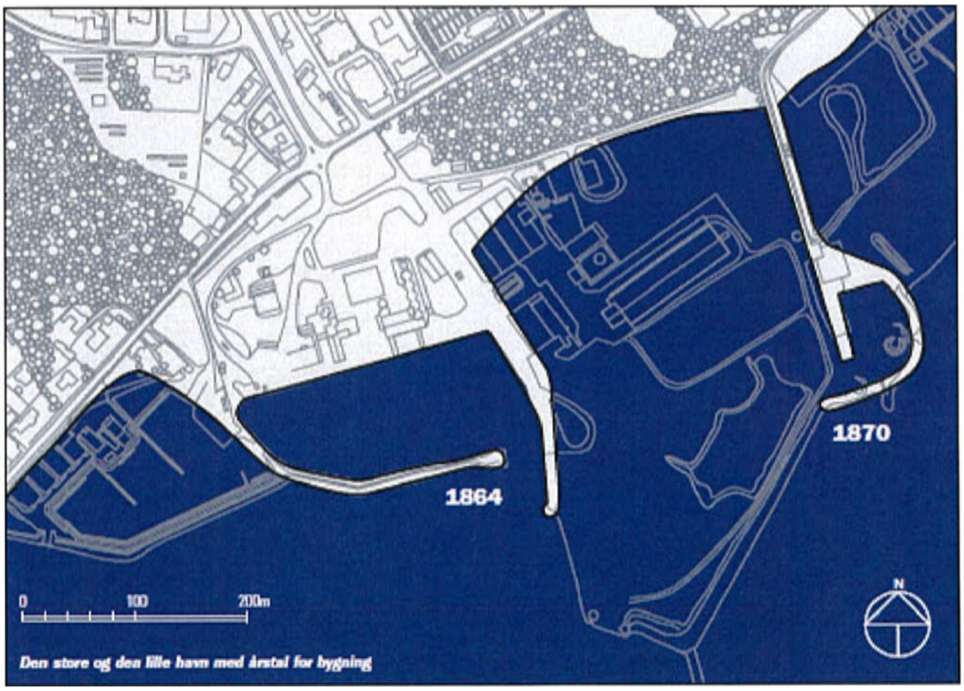

Fig. 4.3. First port, and port expansion at the end of the 19^{th} Century.

These piers were damaged considerably by a violent flood and the material transported off-shore resulted in the accumulation of sand along the beach in the north-east direction, which can be seen also nowadays. After the flood the whole port was completely rebuilt in 1940, the shape of this new port was almost the same as the one before the flood, except for an embankment built in the northern part and a slightly modified pier allowing a better defence against the incident waves, as shown in Figure 4.4.

Fig. 4.4. Second built in 1940 after the 1870 flood.

In the meanwhile Faxe Ladeplads became a very nice and popular coast stretch for holidays due to the nice beach shaped in the southern part of the piers, and lots of comfortable summer houses raised along the street facing the harbour, this of course implied a tourist and economical resource for the Municipality and contributes Faxe Ladeplads to transform from a simple industrial area to a tourist place.

The new port design, and especially the new groyne, immediately started contributing to modify the shape of the beach southwards and for this reason it has been decided by the municipality to protect the beach throughout the use of several groynes and a concrete wall against the embankment of the road. This allowed the restoration of sand beach as it can be seen in Figure 4.5

Fig. 4.5. Disposal of the groynes and beach in the early $'60s$.

It is interesting to notice that the decision of building groynes was not, of course, coming from a deep analysis of the waves, a hindcast study or a finite element sediment transport model, which allows to predict how the coast would react to the construction of these human works, though, the knowledge based on the experience determined a fast and effective solution to the problem since the groynes and the concrete wall guaranteed the restoration of the sand beach.

Though, in 2000, these breakwaters were completely dilapidated and a renewal was required. COWI was asked to take care of the operation and instead of fixing up the groynes and restore the original scheme, a new proposal was made, this was based in four ideas:

- removal of all the run-down groynes,
- removal of all stones and bedrock to beach plane,
- reuse of stones for a new revetment in front of the old concrete wall,
- supply little amount of sand on the beach in front of stone revetment.

This proposal has been mainly done because of the new approach suggested by the Coastal Authority that wants to keep the coastline as much attractive as possible, with no presence of breakwaters unless they are really necessary to offer a shelter and protect the beach. This low impact intervention has the problem of leaving the beach with no protection from the water erosion which removed completely the nourished sand in some years, partly washed northwards, partly removed and pushed between the revetment as much as the seaweeds which remain stick to the stone-blocks, allowing the growth of the vegetation. The actual situation shows a long beach in the northern part of the port, in which the sediment transport leads to an extensive accumulation that creates a long sandy beach, a big area, between the port and the northern beach is composed by a filling that created in the years an expansion of the land reclaimed from the sea, as it is possible to see in Figure 4.6.

The erosion that takes place in the southern part of the coast leads to a sediment movement northwards causing silting at the port entrance channel forcing a dredging of about $20\,000\,\mathrm{m}^3$ of sand and seaweed to be removed in order to allow the passage of the ships mooring in the harbour.

Finally a seaweed accumulation in the corner of the port causes unaesthetic conditions and odors in the bay.

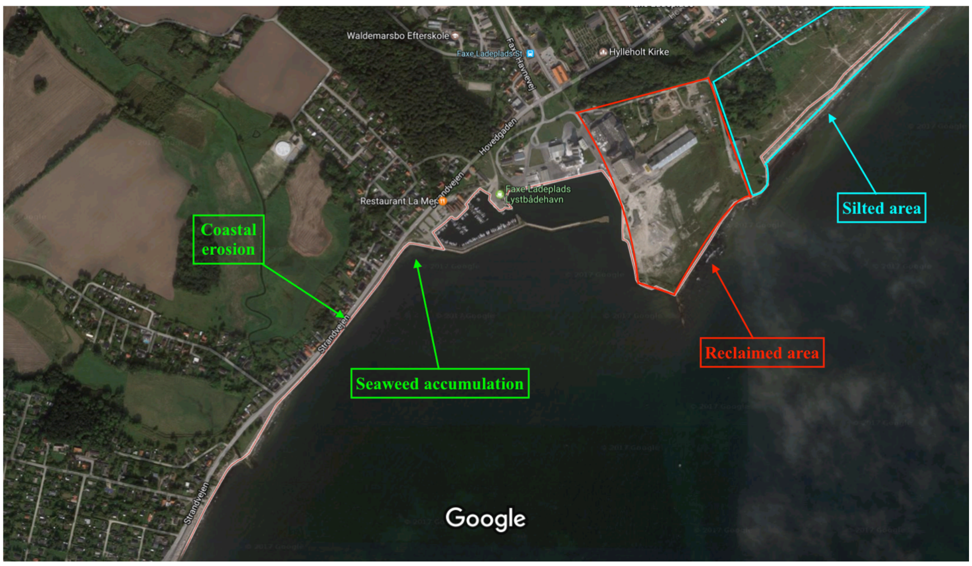

Fig. 4.6. View of the harbour actual situation.

The upcoming conflicts between fishermen sailors and the now large ship and the start of the erosion phenomenon in the south-west area of the harbour persuaded the municipality to a port expansion to its current shape that can be seen in Figure 4.7

Fig. 4.7. Today's shape after the last expansion in 2002.

This expansion of the port in 2002 had as a result a development of the activities linked with the a exchange of goods and people, due to a bigger shelter for larger ships, though, that implied also a change in the shape of the beach in the southern part of the coast due to an increase of erosion phenomena taking place because of the sediment transport occurring in the harbour. Because of the particular currents affecting the harbour the sand was removed from the southern beach and deposited north stream, this also caused the sediment to be moved towards the entrance channel of the port itself causing the municipality to take care of the deposit removal, by dredging the sea bed, yearly.

4.1.1 Consideration

The historical overview highlights that the net sediment transport, that usually is towards south in this part of the coastline, has been modified by human works; the need of offering a better shelter to follow the expansion of the activities related to Faxe Ladeplads had resulted in the failure to natural supply the usual sand transport with material coming from the northern coastline, in addiction to that the material in the southern part of the harbour is moved by the wave-driven currents towards north, affecting the entrance channel, and for this reason it is removed, causing an unstable condition that had leaded to the erosional phenomenon.

This critical situation has determined a loss of attraction of the site with direct economic consequences on the municipality budget, this is because Faxe Ladeplads used to be a summer destination with several houses that, now, have seen their upfront beach disappeared because of the erosion. Furthermore it is seen that the disappearance of the beach caused a lowering in the safety of the machinery movements on the scenic route just aside. For all these reason the municipality, together with the citizenship, has taken the decision of hiring Rambøll, asking for a new solution to guarantee the safety of the road and, at the same time, restore the beach attractiveness so to increase the value of the summer houses and give back the inhabitants the opportunity of a nice sand beach.

5 | State of the art

In this chapter the study that Rambøll performed is analysed.

5.1 Suggested solutions

In order to overcome the issue with the wave overtopping and the erosion phenomenon of the beach which causes unpleasant situations to the inhabitants, Faxe Municipality hired Rambøll to find an affordable solution to these problems. For this reason different options have been taken into account and analysed by Rambøll before suggesting the final solution. These options have been modelled using simulations based on finite element softwares which allow to obtain a quite accurate and comprehensive view of the phenomena occurring in the harbour. The options evaluated during these studies are:

- Sand feeding
- Sand feeding and creation of two groins
- Sand feeding and creation of a bypass pier outside the existing port.

5.2 Wind and wave conditions

Looking at Figure 5.1 it is notable that the surveys show that the fastest wind speed are blowing from the west direction but, remembering the morphology of the area, the harbour is naturally sheltered by these winds.

Figure 5.2, instead, shows that the maximum wave height, H_s for a standard year, as 2005, is approaching the beach from the south-east direction, forming an angle of 120°, with a significance wave height between 0.8 m and 1 m with a maximum wave height of 1.15 m that leads to an average overtopping estimate at 0.061/m/s.

It is interesting to comment that even if the wind direction would suggest a sediment transport along the same direction of the winds, and consequently, the same direction of the waves, it is known that the net transport along this part of the coastline is south oriented. For this reason it is believed that even if the direction of the waves and the winds is clearly well known, the current seems to have a totally different pattern and for this reason a solution with a breakwater facing the incident waves could be of not a great impact.

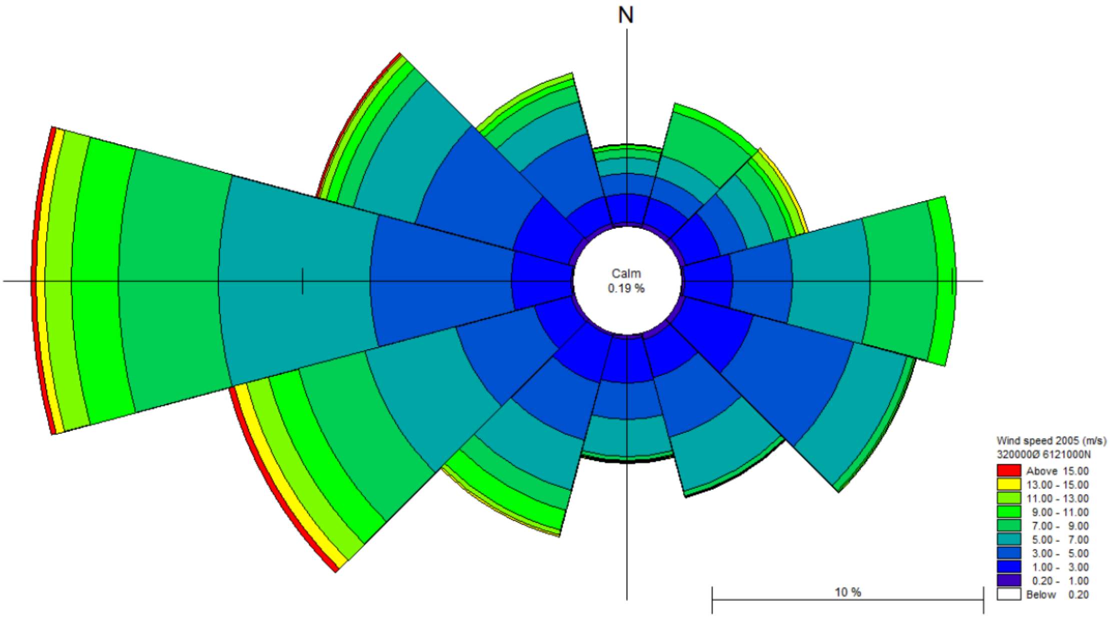

Fig. 5.1. Wind rose corresponding to the analysed period, 2005.

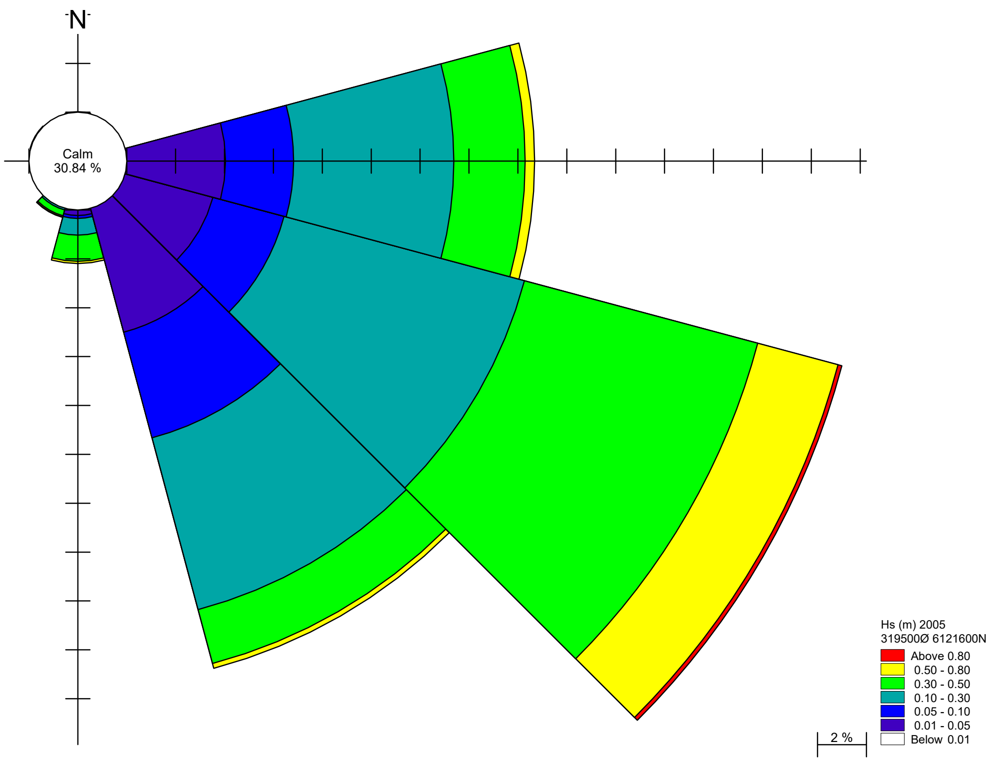

Fig. 5.2. Wave rose corresponding to the analysed period, 2005.

The 120° waves direction causes a movement of the sediment away from the beach due to the fact that they determine a cross-shore transport since they are crushing the shore perpendicularly, whereas the other two waves directions (90° and 150°) approach the coastline with an angle of approximately 30° causing a long-shore sediment transport. This can be easily seen in Figure 5.3

Fig. 5.3. Map of the harbour with the main waves directions highlighted.

The different proposals have both advantages and disadvantages, thus finding the proper solution requires an evaluation of different details.

5.3 Hard structures

Building two groins usually leads to an effective solution for the defence of the coastline, especially if it is possible to identify a dominant wind and wave direction, which, for the analysed year, it is done considering also the geographical position of the harbour. This can be done since in the Baltic Sea waves are mostly wind-driven. Though, experience states that the construction of hard structures usually disturb the equilibrium conditions and, even if good effects on the development, locally, of a sand beach protected from the incident waves can be seen, this corresponds to the introduction of a erosion process in coastal areas in the surroundings. In addition to this the construction of hard structure does not guarantee the solution to the problem of the interrupted natural supply of sediment from the north, which was caused by the port expansions. The calculations show that the groynes have no impact on the stability of the beach after the nourishment, also they have effects on the erosion south-stream. Another point against the groynes solution is that the beach view would suffer with two or more breakwaters along it.

For these reason Rambøll highly recommends to avoid any initiative involving hard coastal protection and search for a less immediately effective, but much less intrusive and long term, approach.

It is interesting though to point out the fact that it seems that groynes have been working for forty years, providing defence from the storms and ensuring the beach stability, due to this the effect they have on this particular situation are to be clarified.

5.4 Beach nourishment

The final proposal made by Rambøll it is based on the first solution, meaning providing a beach nourishment only. This is in line with the directives from Coastal Authority stating that a sand feeding will provide the most natural looking coastline without any visual impact and obstacles for bathers and summer houses along the coast, in addition to that the national strategy has been pointing in encouraging solutions which have as a general aim to find alternatives to hard coastal protection and search for intelligent beach nourishment schemes that preserve the natural beauty of the coast and provide more attractive coasts. In order to simulate the behaviour of the coast after the nourishment and verify the effectiveness of the sand feeding along the years a number of sediment transport calculations has been performed, this is done running different modules representing simulations of waves, currents and sediment on a Finite Element Software named $MIKE21$.

The net sediment transport driven by the current is south-stream oriented though, the construction of hard structures and their development during years has modified the equilibrium of the harbour preventing the natural feeding of the southern part with sediment upstream. This is also due to the fact that every year, around 20 000 m^3 of sand are dredged from the entrance channel depriving the system of large amounts of material, in addition to that, the piers constituting the port form a vortex which contributes to fill up the channel with a mixture of fine grained sand and seaweed. During strong wind events, the sediment transport presents also a north-directed component that helps making the assessment of the actual sediment pattern very uncertain.

A solution to the problem of the channel dredging can be found in a proposal by *DHI*, based on the establishment of a pier in the southern part of the port. This hard structure should guarantee a better flowing of the sediment from the north to the southern beach thanks to a reduced bottom falling material in front of the entrance of the port itself. This should lead to a natural sand supply for the southern beach and a lower amount of material to be excavated yearly to ensure the navigability of the entrance channel.

Though, even if this solution assure to overcome the problem of the vortex and consequently the accumulation of material in front of the port channel, in Rambøll analysis do not prevent a large impact on the south-stream coastline, since, even if the solution has been tested by Rambøll and does not present consequences on the beach profile, it has not been tested its impact on the near Faxe estuary and the general effects in the entire harbour. Due to this reason a better understanding of the consequences that building this new pier would have is mandatory, and in order to do so, a larger area of analysis should be taken into account.

In addition to this the solution proposed goes against the general strategy asked by the Coastal Authority of preserving the areas at their most natural level with delicate and very careful interventions and for this reason should be avoided.

5.5 Conclusions

The three solutions have been studied and from the results obtained it is possible to state that the option concerning the placement of two groins, perpendicular to the coastline, does not guarantee the required erosion protection effect, whereas the extension of the port with a pier does not influence the width or length of the sand beach south-stream. For this reason the fist solution may be adopted and a initial nourishment of 60 000 m^3 should be taken into account; on top of that a five year feeding of the beach to re-establish the original shape and face the adverse conditions has to be considered whereas the construction of a pier for a future expansion with no impact on the beach may be considered as a good solution even if there are no studies certifying the lack of impact of such a hard structure.

Part III

Numerical analysis and conclusions

This part of the paper deals with the analysis of the case study through the use of the Shoreline module (SM). In the first section the important steps for setting up the software are treaded so to allow the reader to have a better understanding of the behaviour of the software.
Later of the results of the calculations are discussed making a comparison between the results obtained with the standard Sand Transport module and the new Shoreline extension. In the last part the conclusions are drawn and the strong and weak point of the Shoreline module are highlighted.

6 | Shoreline morphology

Since the aim of the paper is to use a new approach to represent the behaviour of the beach profile after the nourishment, and since this new approach should be compared afterwards with the standard one used by Rambøll in order to investigate the possibilities and the improvements that this new software brings to the standard Sand Transport model, it is important to give a quite complete overview to the practical informations on which the model is based and analyse the settings of the new Shoreline Module. **?**,2

6.1 Module introduction

The new tool is called Shoreline Morphology module (SM) and it is an improvement to the original Sand Transport module, which allows to determine the movement behaviour of the particles under specific wind and wave conditions. The SM module combines a one-dimension module for the shoreline with a two-dimensions descriptions of the wave and current conditions, in this way the estimate obtained through the simpler Sand Transport simulation is enhanced due to the fact that in the ST module the sea bed level is usually simply updated in every mesh, in every iteration, with the respect with the sediment continuity equation and this leads, in long period calculation, to a modification of the coastline in a non correct way. The SM module, instead, starts with the definition of a fixed coastline and section profiles that guarantees the respect of the original shoreline conditions still considering the effects of the long-shore transport. The effects caused by the cross-shore transport are thus ignored since they are conservative and still not really understood, in addition to that it is fair enough to assume that they are not of a great importance in the permanent evolution of the profile. The long-shore transport is therefore the only contribution taken into account in this module.

The SM module is applied once gathered all the waves and current informations from running the HD and SW module and once the ST inputs are set. This process could lead to an increment of the time used to gather the solutions, though, using the SM module the uncertainties regarding the cross-shore transport are avoided and the coast profile should be the most probable estimate.

6.2 Bathymetry, mesh and boundary conditions

Starting from a bathymetry of the harbour, obtained through on fields single-beam surveys, a flexible mesh of the area of interest, meaning the beach stretch on the southern part of the port, can be built. This mesh is automatically generated by the software considering that the zones closer to the beach, the piers and the coast in general require a finer mesh in order to guarantee a better simulation and to capture in a better way the small changes in bathymetry just in front of the coast; faraway from the coastline, where it is not necessary to obtain this high grade of fidelity of the simulation, the mesh elements can be kept looser and for this reason they become progressively larger up to 20 m wide. It is interesting to notice that the bathymetry taken as the base of the model considers the first feeding of the beach, suggested by Rambøll, and this is because the study has his aim in determine the behaviour of this sand feeding after one year of standard winds and waves conditions.

The boundary condition taken into account are the same ones used in Rambøll simulation so to have the same conditions allowing a comparison between the results, the used boundary condition for the winds, waves and water level are obtained thanks to NOVANA model for Danish waters and from Rambøll wave model for Baltic sea. The two boundary conditions are set along the east and south border, where the model shows the open sea. Therefore the two conditions must set a surface elevation accordance in each time step with the SW module, along the entire border.

The bathymetry of the harbour with the mesh elements already set is shown in Figure 6.1.

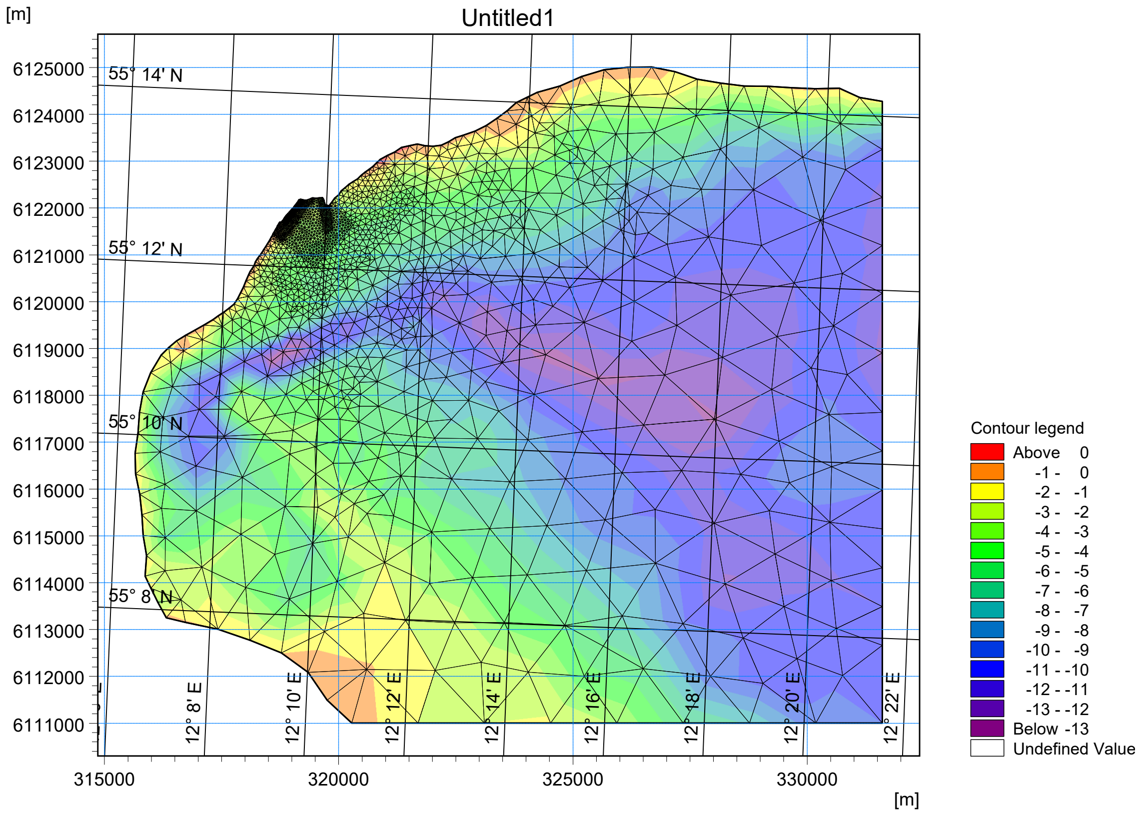

Fig. 6.1. View of the entire harbour considered with different mesh elements.

It is notable that the water depth close to the shoreline has a value varying from 0 m to −5 m; in this region the mesh elements are very dense in order to increase the accuracy whether they become wider moving away to the open sea.

The maximum distance from the coastline over which the mesh is set to be denser corresponds with the measured closure depth. This value can be obtained through a waves statistical analysis and for the analysed harbour it corresponds to $H_{S,12h} = 4m$.

By plotting the measured water depths against the distance from the coastline it is possible to determine the profile and obtain the distance at which the closure depth is reached, as notable in Figure 6.2

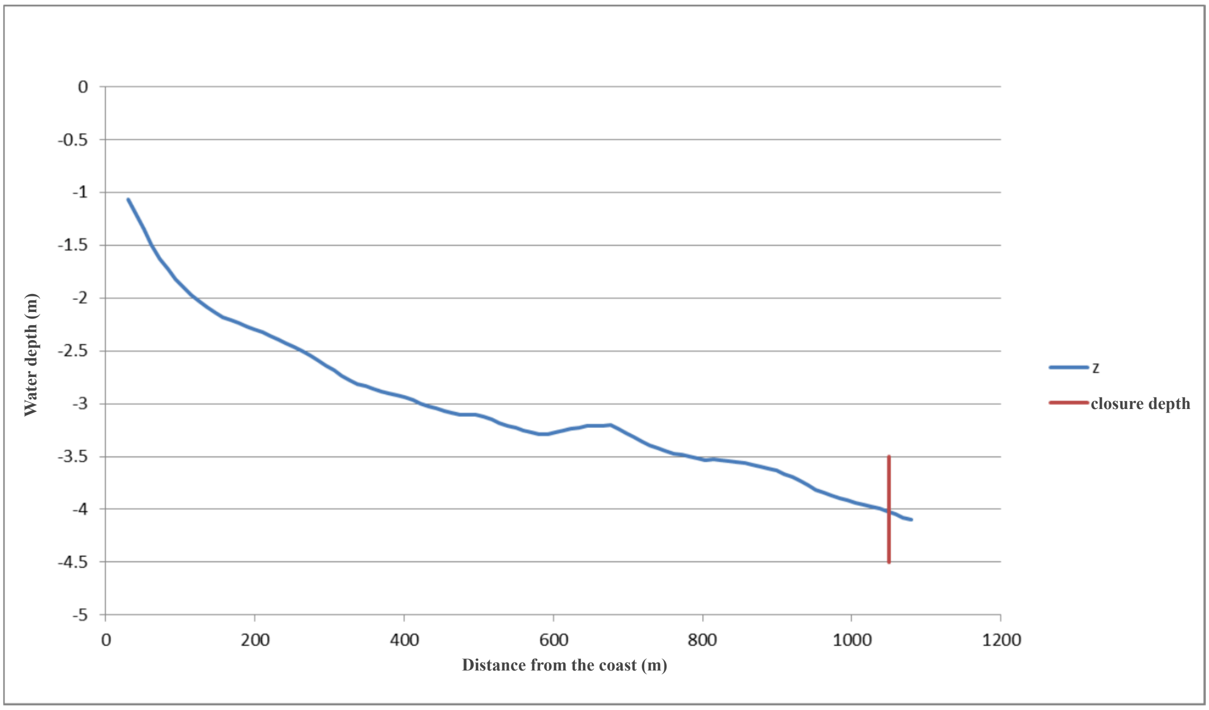

Fig. 6.2. Plot of the development of a general profile and closure depth value.

6.3 Sediment characteristics

The suggested solution proposed by Rambøll considers a beach restoration using coarser sand rather than the one typical from the area, this is because using a larger diameter guarantees a higher stability of the slope and this increases the effect against the erosion phenomenon; for this reason the model is set to run with a grain size $d_{50} = 0.3\,\text{mm}$. In addition to that a map of the sediment, obtained through laboratory inspections, is loaded.

Once the bathymetry is loaded and the boundary inputs are checked the SM module is ready to be set.

The module requires four main inputs and, because of this, the definition of the following quantities is required:

- Baseline
- Coastline
- Edge map
- Profiles

Baseline

The baseline defines the direction to which the shoreline points are move and identifies also the stretch of the shore in which the sediments are set as insensible to the erosion process and, therefore, motionless considered. Usually this line is set onto the beach profile and for this reason the elevation values are always positive. Also, in this paper, the baseline is considered starting on the farthest beach edge. Because of this fact the definition of this line guarantees the shoreline behaviour to be as close as possible to the real behaviour of the shore, even over a long time simulation and for this reason it is very important to evaluate in a correct way the exact position of this line on the beach.

An important aspect of the baseline in the SM module to be highlighted is that it can be drawn as a curve, for a better approximation of the coastline.

Coastline

The coastline is, as quite intuitively, the line that separates the shore from the area in which the sea depth starts increasing. When setting the Shoreline Morphology model it is necessary to be aware of the number of vertices constituting this segment, since, for a correct setting, they must match the number of points composing the baseline plus one. Increasing the number of points of the two lines it is possible to increase the accuracy of the shore and, for the model analysed, it is decided to set a density of points so to obtain on point every 3 mesh element for a total of 13 points. The density of points has a large impact on the time of the calculation and in addition to that a too dense profile of the two lines often leads to issues during the setting of the profiles, as it will be discussed in the following.

The baseline and the coastline set in the model are shown in Figure 6.3

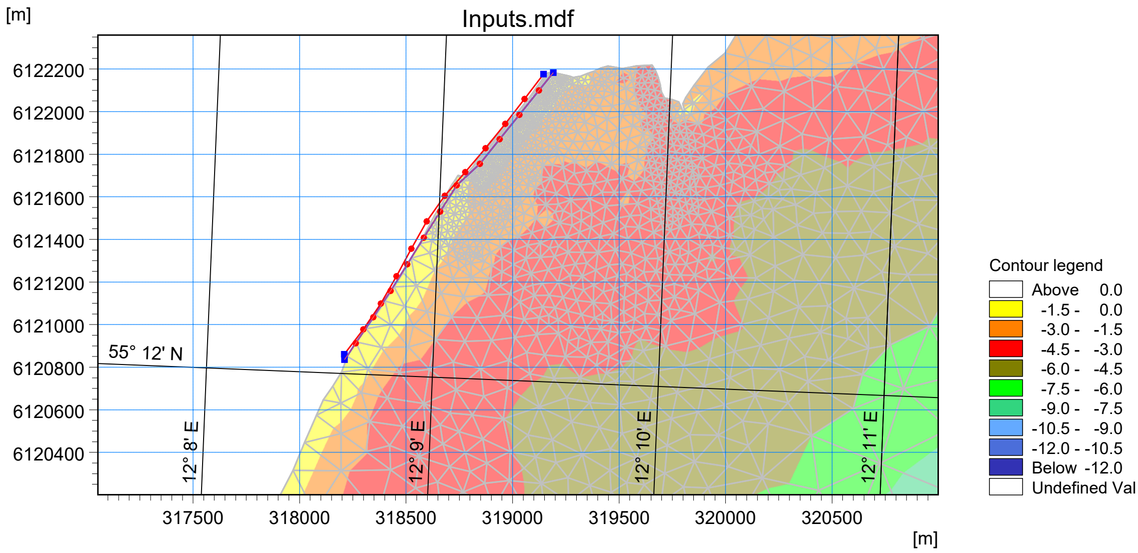

Fig. 6.3. Baseline and coastline applied on the mashed map.

Edge Map

The next step to take when setting up the module is to define the so called *Edge Map*, this shall be identified as the area limited by an arc that defines which shoreline edge each element belongs to, this arc is drawn by setting an off-shore boundary of the map. In this way the values in the edge map are calculated between the baseline and this off-shore arc, in a way that outside this area the values are zero and the shoreline morphology is not active. The arc is set to be further off-shore than the closure depth that identifies the depth at which the profile changes his nature and it switches between the buffer zone and the off-shore zone, and therefore it fixes the limit at which the transition between mobile and undisturbed sea bed.

Once created the Edge map the area between the coastline and the off-shore arc is divided into different stripes identified with different colours, these strips takes 3 or 4 mesh elements wide and, for a correct simulation, it is very important that these stripes do not cross each other, as show in Figure 6.4

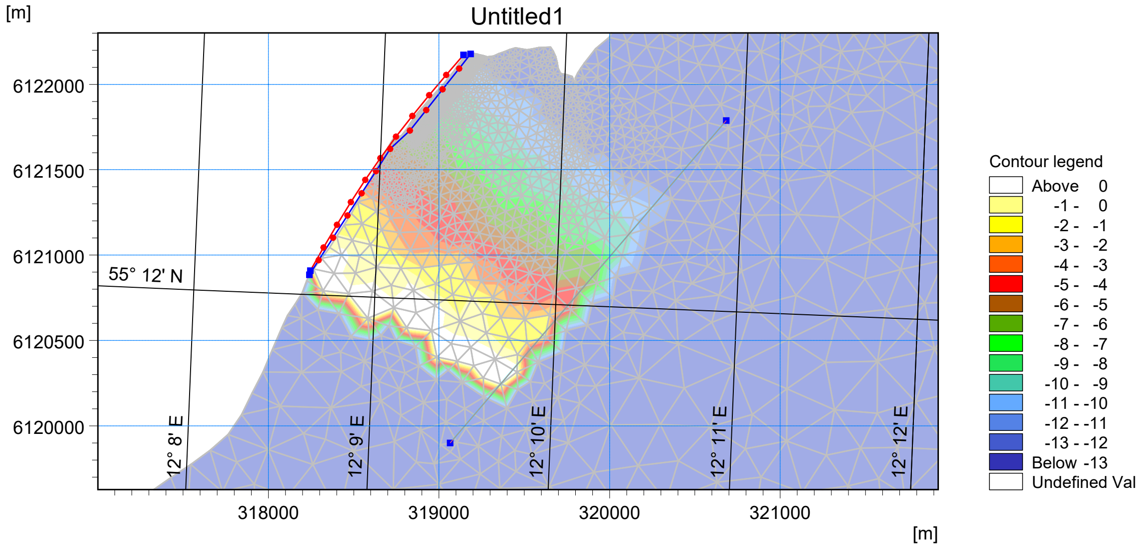

Fig. 6.4. Edge Map of the area including the beach of interest.

The sediment volume, deposited on the defined strip of shoreline and within the active profile, will contribute to the movement of the shoreline edge. It is fair to realise that by defining a higher density of stripes, that is correlated to the density of points constituting the baseline, a more accurate simulation of the behaviour of the sea bed is obtained, though, setting a higher density has impact on the calculation time that will be increased.

Profile

Including profile informations such as volume, slope and closure depth allow the software to understand how the beach is developed and which part of the slope will have effect of the sediment transport and how large is the contribution to the entire phenomenon. In fact the profile describes the representative cross-shore profile which moves back and forth with the shoreline edge at the given location. This parameter is defined by the z-coordinate and the distance normal to the baseline, it starts with a negative value of the distance, set on the baseline and it ends with a positive distance and a negative level value outside the edge map area. As it is shown in Figure 6.5 the profile can behave in two different ways.

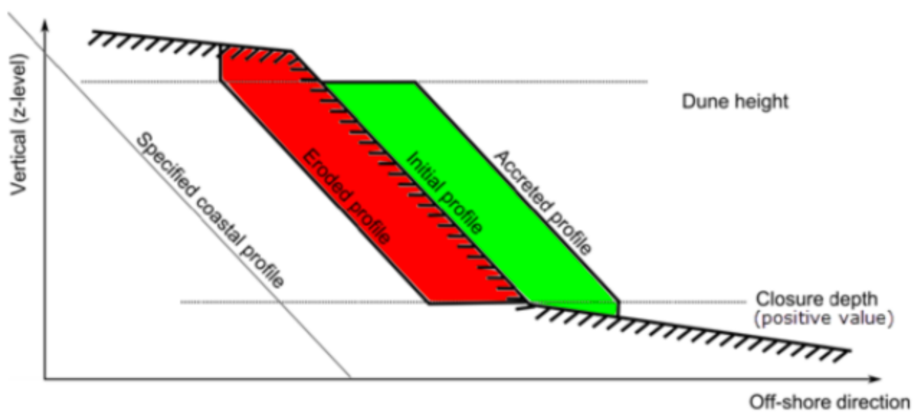

Fig. 6.5. Sketch of profile with the accretion and erosion zones highlighted.

When the shoreline is prone to erosion the profile will change considering every part of it that is on a higher level than the dune height, that for the analysed case is equal to 0 m, but without affecting any zone lower than the closure depth. On the contrary when the profile experience accretion the dune height remain constant and the sediment transport will affect only the area along the slope and below the closure depth, set to 4 m.

It is of interest to notice that the software allows to set this parameter either with a standard profile, that is constant throughout the all the bay or to determine a different number of profiles with different geometrical characteristics. These two approaches have of course different impacts on the solutions since whereas the standard profile guarantees a very fast calculation time it generates also a quite rough estimation of the behaviour of the shoreline, especially if the area considered is very spread or with a jagged profile. The second approach, on the contrary, assure a higher accuracy but a very long calculation time, for this reason the multiple profiles are preferable to be used for complex harbours or if a very high accuracy is required. In addition to this, for software requirements, the profiles cannot cross each other, and this can be challenging when considering a very high density.

Due to external reasons it was not possible to reach a high grade of accuracy, therefore this paper will discuss a single representative profile only, and because of that, the results cannot be considered reflecting the effective behaviour or the shoreline with a very high detail.

In Figure 6.6 it is shown the single profile chosen for the simulation.

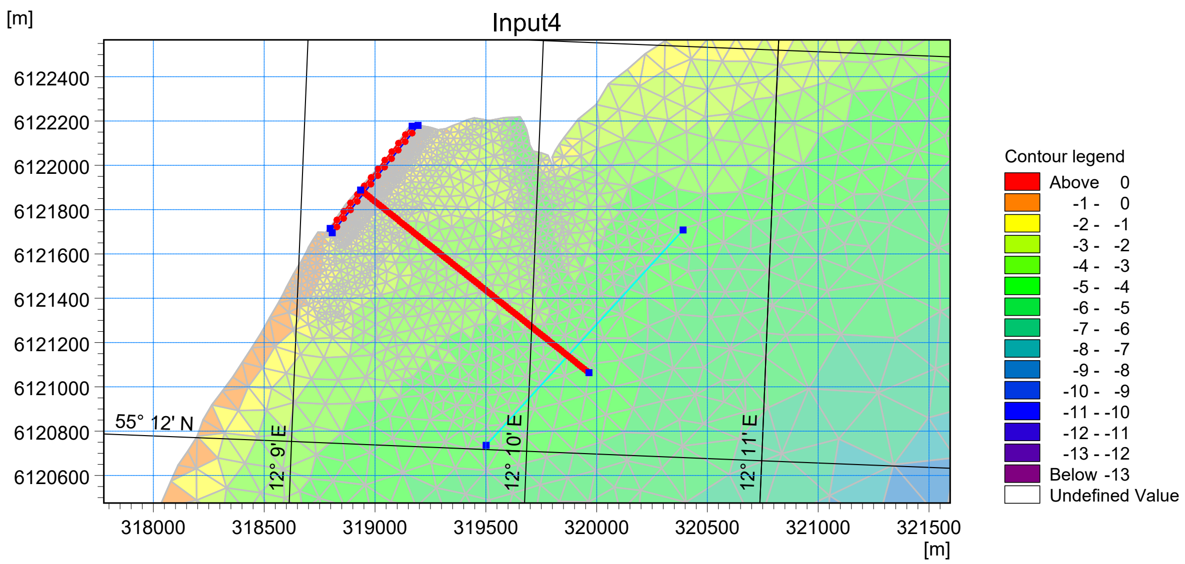

Fig. 6.6. Single profile (in red) used as input in the simulation.

It is notable to see that the profile starts on the baseline, defined above, and develops perpendicularly to that up to cross the line that defines the end of the edge map area; in this way the profile will for sure include all the elevation informations needed, including the closure depth. This profile is taken as representative for the entire length of the shore and is repeated constantly for 12 profiles.

In Figure 6.7 the setting with multiple profiles is presented, and they contain different depth informations depending on the bathymetry; as said in the previous this paper will consider the single profile solution only.

Once set all the required inputs to SM module it is possible to run the simulation. The results will be discussed in the following chapter.

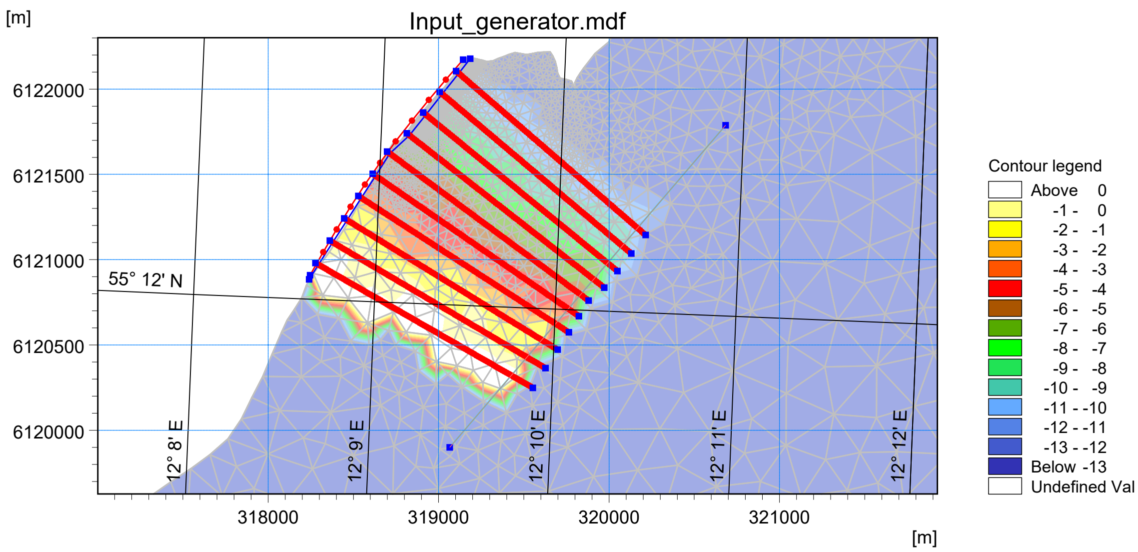

Fig. 6.7. Multiple profiles across the harbour.

7 | Presentation of the results

This chapter presents the results obtained after several simulations performed with *MIKE21 Shoreline Morphology*.

7.1 Real wave simulation: Entire year

In this section the real wave case is considered. The wave and the wind conditions, from which the waves are driven, correspond to the ones of the average year, 2005, but the simulation is run for the first two months only. This is because the simulation comprehensive of the entire year show results that are highly unlikely, as it can be seen from Figure 7.1

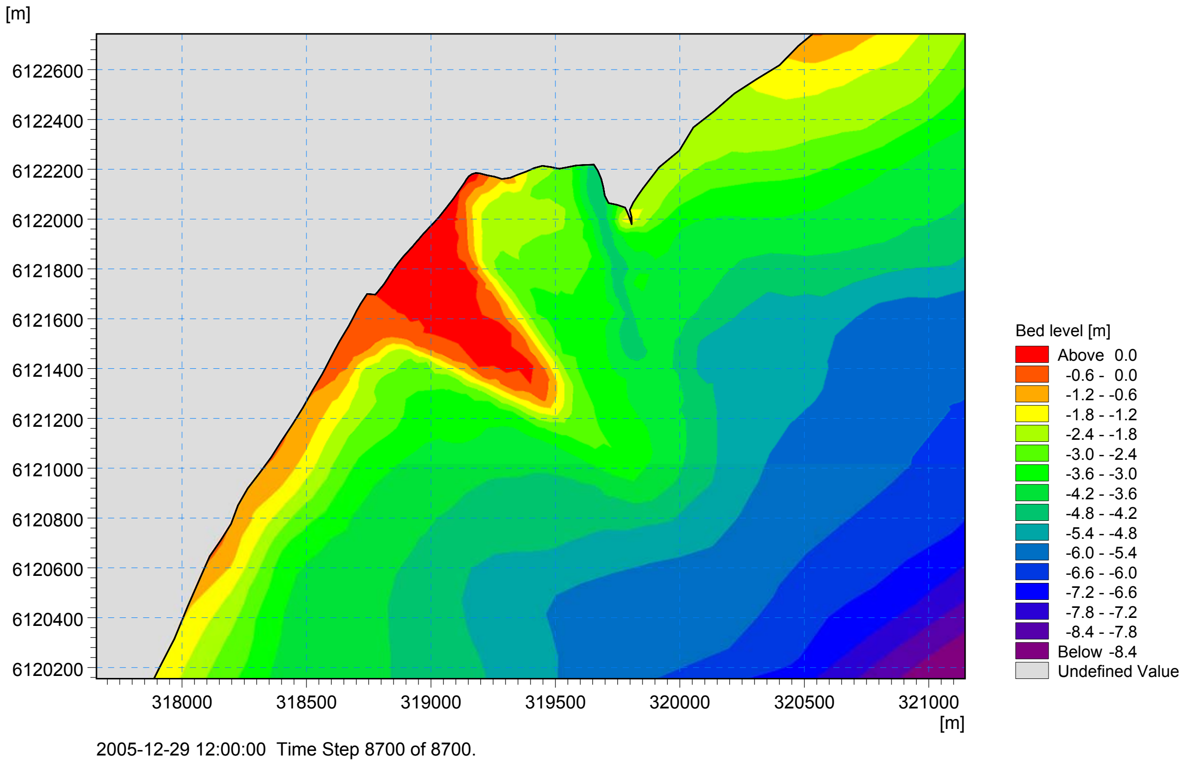

Fig. 7.1. Entire year simulation, bed level.

The development of the bed level is absolutely out of scale and the model itself seems to become unstable after approximately the start of the third months, presenting a huge accretion which leads to the final development. The reasons for this to happen are mostly unexplainable except for the fact that between the 27^{th} and the 28^{th} of February a storm occur, this storm represent the most severe conditions of the entire year and maybe the reason for the model to become unstable is this extreme condition.

Due to this reason it is chosen to present another simulation, generated by the same inputs, but stopped just before the February storm. The results of this simulation will be discussed and compared with the Rambøll results. It is decided to do so since the first two months results show a consistency with the ones presented by Rambøll and for this reason it is believed that the behaviour of the beach would follow this trend for the remaining part of the year.

7.2 Real wave simulation: First two months

Rambøll, after an initial nourishment of approximately 60 000 m^3, foresees a small decrement along the entire beach, that should be supported by a regular feeding every 5 years of approximately 15 000 m^3. The two time steps, before and after one year simulation are below presented.

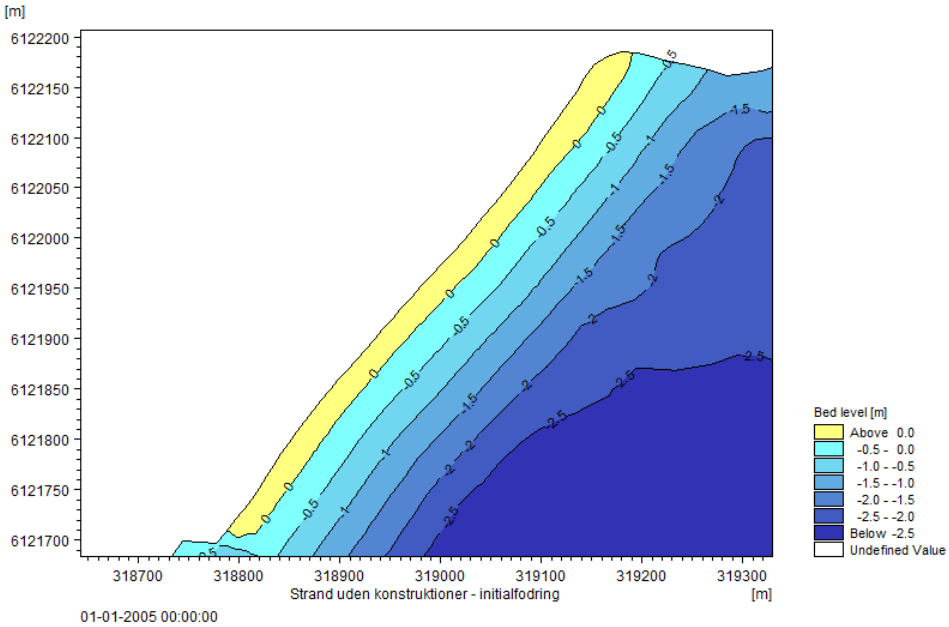

Fig. 7.2. Beach solution after initial nourishment.

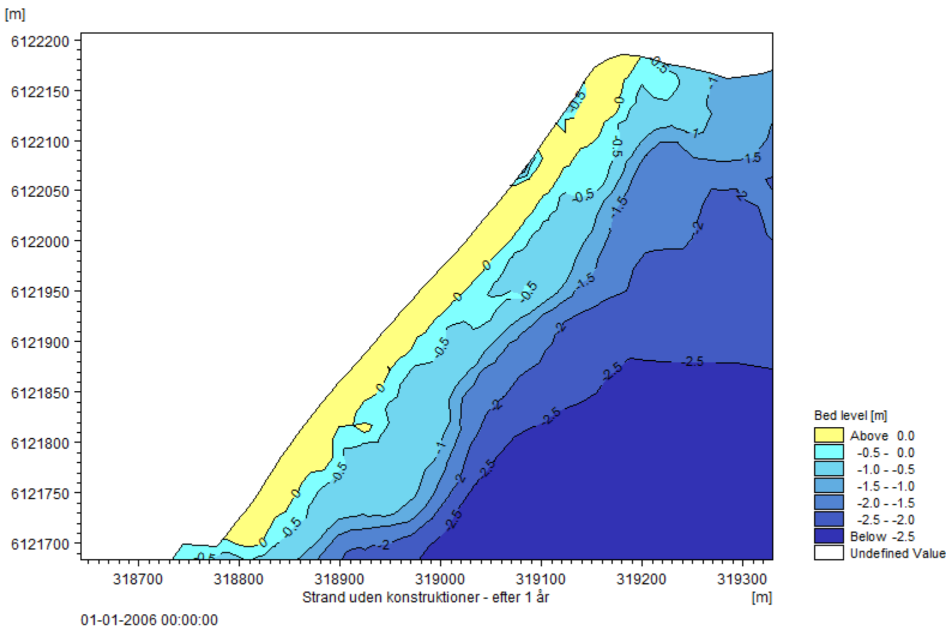

Fig. 7.3. Beach solution after one year simulation.

Comparing Figure 7.2 and Figure 7.3 it is possible to notice that the beach does not seem to change its profile in a sensible matter, though, it seems to be fairly constant along the entire shoreline, it is interesting to notice though, that throughout the simulation performed with the Sand Transport module it is not possible to obtain as an output the exact accumulated change of the shoreline. This is because there is no separate description of the shoreline which has to be defined on basis of the bathymetry, meaning that the on-shore limit is defined by an above zero water depth. The shoreline defined, results to be very dependent on the mesh element and therefore not as precise as what can be described through the SM module.

This is an important limit of the ST module and because of this fact the two time steps cannot be compared as simpler as with the SM module which allows a much more accurate description of the development of the coast profile and permits the comparison between the original state and its evolution with the time.

This can be easily seen below in which the two coastline profiles are compared, thanks to one of the output of the model that represent point by point the development of the coastline in coordinates.

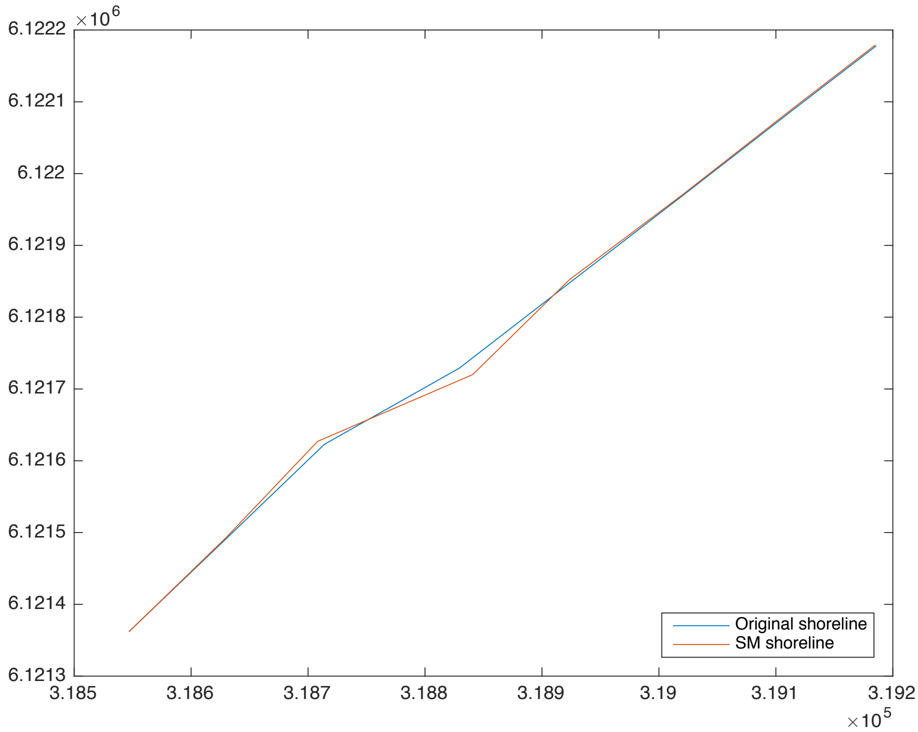

Fig. 7.4. Beach profile comparison between the original shape and after one year wave, for SM module.

It is notable that the different between the two profiles is not very pronounced and this is consistent with the ST simulation, though, in Figure 7.4 it can be easily seen that the SM module highlights a accretion in the southern part of the beach as much as the ST module. This effect can be better seen in Figure 7.5 in which the net littoral drift is shown.

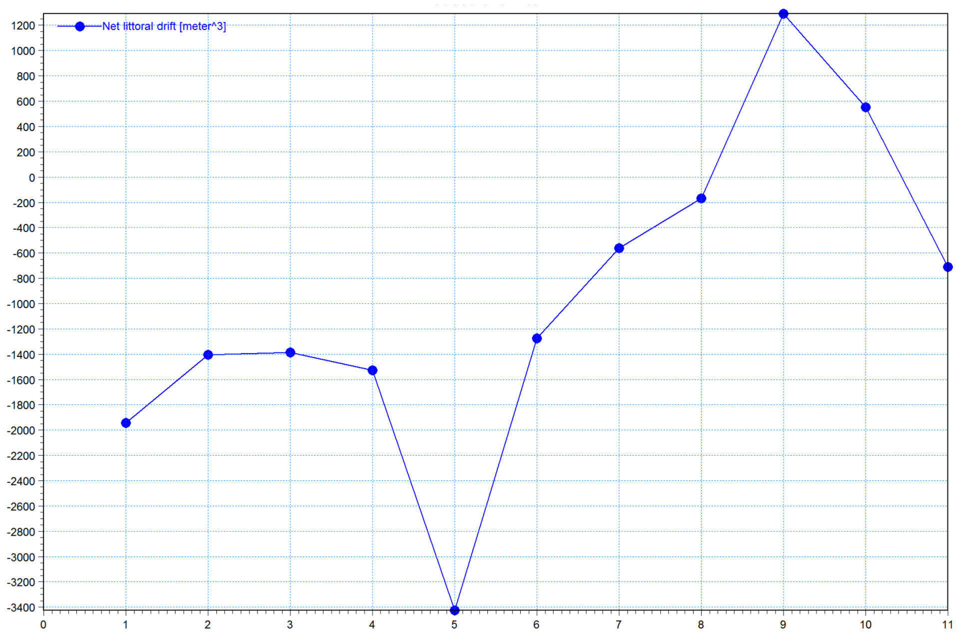

Fig. 7.5. Net littoral drift for the entire edge map.

The Littoral drift is a parameter that shows the net cumulative amount of material deposited step by step on every point of the shoreline. The points represents the points that compose the baseline and the first one on the left correspond to the northern point on the shoreline. The beach develops through the first 5 points whereas the other 6 are placed along the coast. The chart is divided into two zones, the upper zero area, that represents a motion of the material from left to right, and the below zero area that shows that the sediment movement from right to left. This means that for the first point up to point 8 the transport is directed towards north, whereas along the coast the transport moves southwards. In addition to that when the values increase the shoreline experiences erosion whereas accretion occurs when the plot decreases.

From this can be deduced that the very northern part of the beach experiences a quite regular erosion until, at the southern edge of the shoreline, the net drift shows a rapid decrement meaning that an accretion phenomenon occurs. This is consistent with the shoreline development shown previously and by the bed level changes shown in Figure 7.6

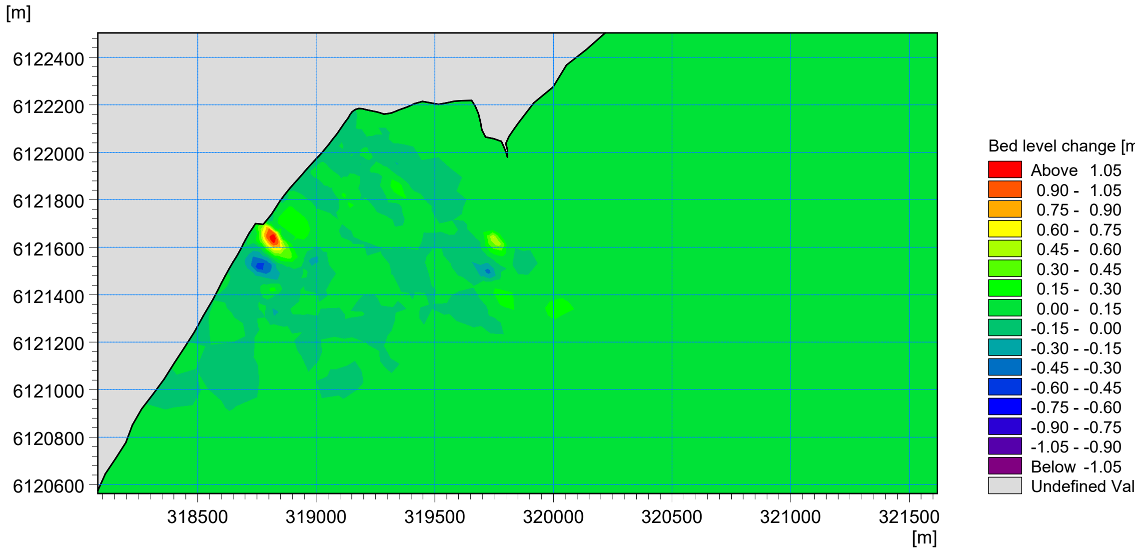

Fig. 7.6. Accumulated bed level change.

The particular behaviour of the southern end of the shoreline raises an interesting question about the influence the way the models is build has on the results.

The edge map used for the simulation and shown in Figure 6.4 is representative of a vast area of the coastline which is not only related to the beach surroundings, this is because even if a narrow profiles development guarantees a better focus on the area of interest, and therefore a higher accuracy of results, the wider area allows to get rid of some boundary effects that would affect the simulation. In fact, performing analysis with a narrow edge map, as the one shown in Figure 7.7, has, as a consequence, the development of an incomprehensible accretion nearby the border of the edge map, and this can be caused by a lack of sediment transport outside the edge map in that point.

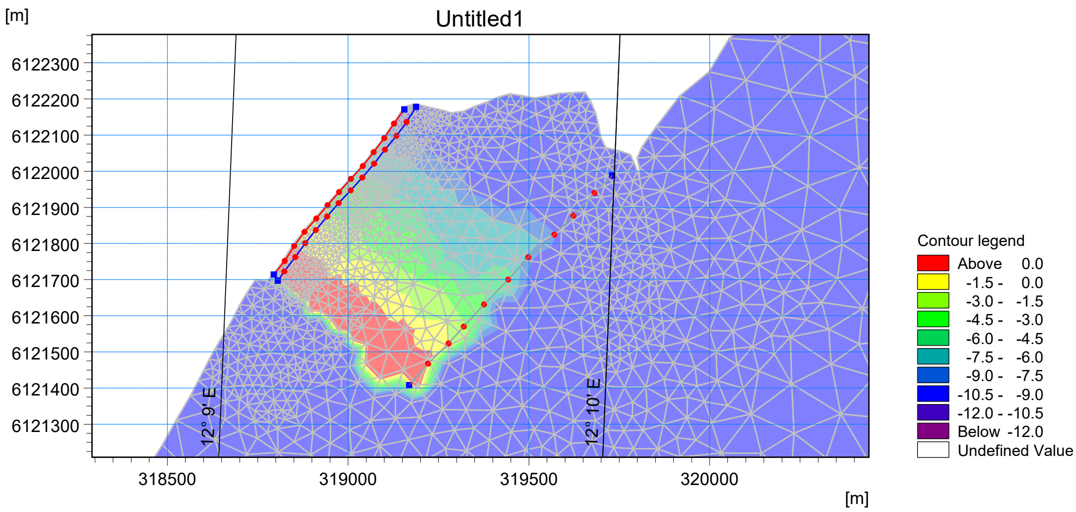

Fig. 7.7. Narrow mesh used during the first simulations.

The lack of transport in and out from this boundary condition generates, in this situation, an accumulation of material, as it is possible to be seen in Figure 7.8.

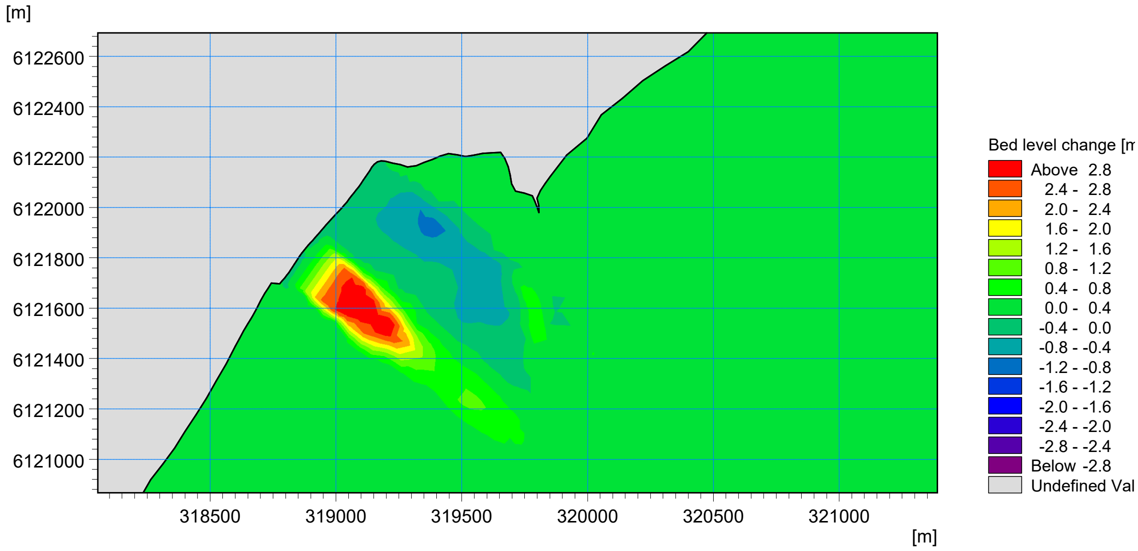

Fig. 7.8. Extreme accretion along the boundary layer.

Thus in order to avoid border effects and simulate the harbour conditions in a correct way it is important to keep in mind to extend the area covered by the edge map both south-stream and north-stream. It is not clear though how far the baseline should be set to avoid the accumulation of material at the edges and for this reason the accretion experienced in Figure 7.5 could be not completely representative of the effective behaviour of the shoreline.

In order to understand in a clearer way if this behaviour is caused by a certain motivation of particular wave refraction condition the current velocity pattern can be analysed.

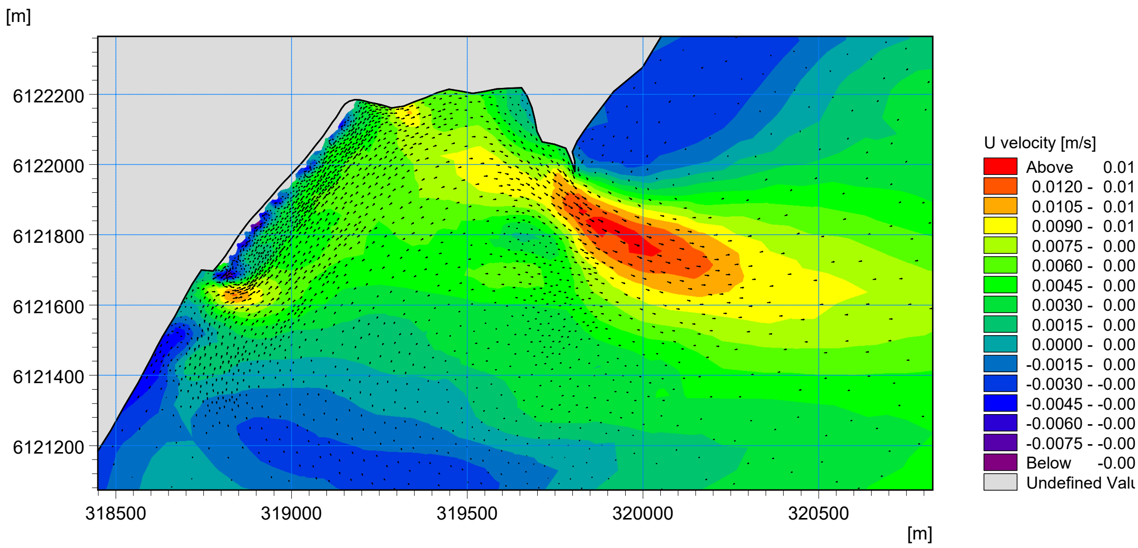

Fig. 7.9. Horizontal velocity pattern.

In the figure above the horizontal velocity near the coastline is shown, with vectors indicating the direction of the motion. The velocity is considered positive when the vector develops from left to right. Two areas are of major interest: the southern shoreline part and the area nearby the embankment.

The left of the figure presents a velocity pattern showing two different and opposite transport directions along the coastline, which collide at the southern part of the beach. This collision generates a disturbed motion on the sea bed that could actually be responsible of the accretion phenomenon showed previously. The upper right part, instead, shows a large velocity field that apparently is responsible to carry out the sediments from the port entrance to the off-shore direction. This current pattern can provide a reason for the lack of accretion in front of the entrance channel, that can be seen in Figure 7.6, though, it is very unlikely that the bed level changes chart does not show any accumulation of those sediment that in theory should be dredged yearly to guarantee the navigability of the entrance channel.

It is important to highlight that since the software is a tool that has the ambition of anticipating the behaviour of a coastal stretch by simplifying the external conditions it is likely that sometimes it could show results not completely in line with what is expected. The SM module, anyway, provides a good approximation of the beach behaviour agreeing with the results obtained with ST module, and for this reason can be said that both the modules show the correct harbour behaviour.

In addition to this, it must be reminded that the model agrees with the results obtained through the ST module for the first two months only, this is believed because of the storm conditions occurring in the last days of February. In order to investigate whether the model is actually sensible to the higher wave height it has been decided to include two simulations covering the same short period time during which the wind and wave conditions have been exaggerated so to investigate the trend of erosion occurring in the event of severe wave conditions.

7.3 Extreme events

In this section two critical events are evaluated. The reason for this two cases to be presented is to have an evaluation of how the nourished beach and the model react to strong wind and wave conditions. In order to do so, two wave series have been generated using MIKE SW, by forcing the wind-direction and the wind-speed magnitude; the wave series obtained are wind-driven and characterised by a constant wind direction. The simulation covers a period of two months and for both the simulations the wind-speed is set to be $15\,\mathrm{m/s}$.

7.4 Representative case

The first simulation deals with a wind blowing from an angle of 105° with the respect to the North direction. Thus, the waves generated, hits the beach at approximately 20° causing a large long-shore transport, that is believed to be the most responsible contribution to the shoreline erosion. This is the main reason for which this wind direction has been chosen, though, it is also important to say that 105° North is also the significant wave direction for 10 years waves, and due to this it can be assumed as representative of the direction that most of the waves take during a standard random year. It is possible to see the wave-rose on which this assumption is based on in Figure 7.10

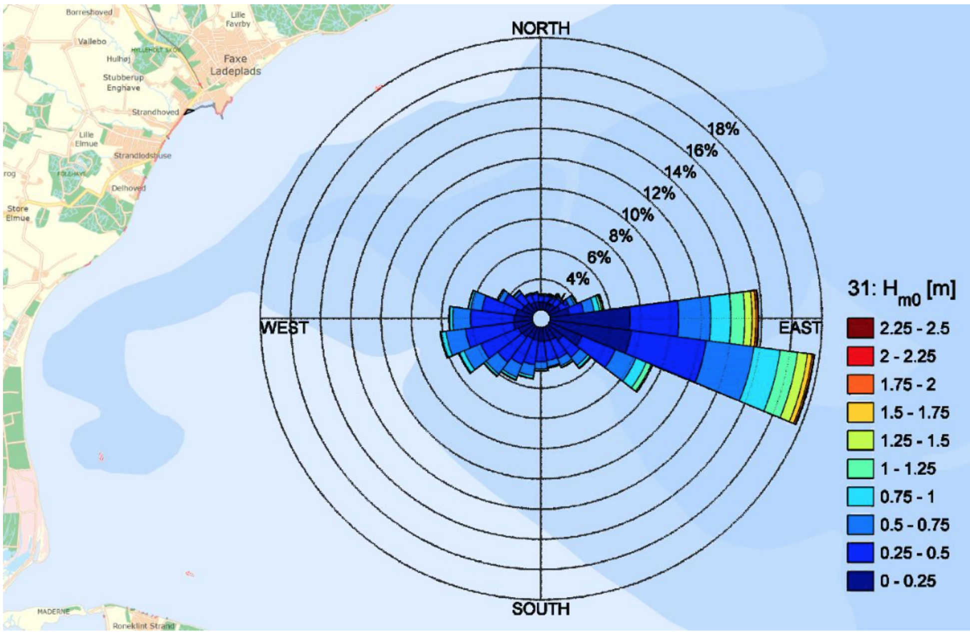

Fig. 7.10. Representative wave rose.

The significant wave height that is usually connected with this wave direction is approximately of 1 m though, since, the waves are forced, the modelled wave height crushing against the shoreline is equal to 1.3 m, as shown in Figure 7.12.

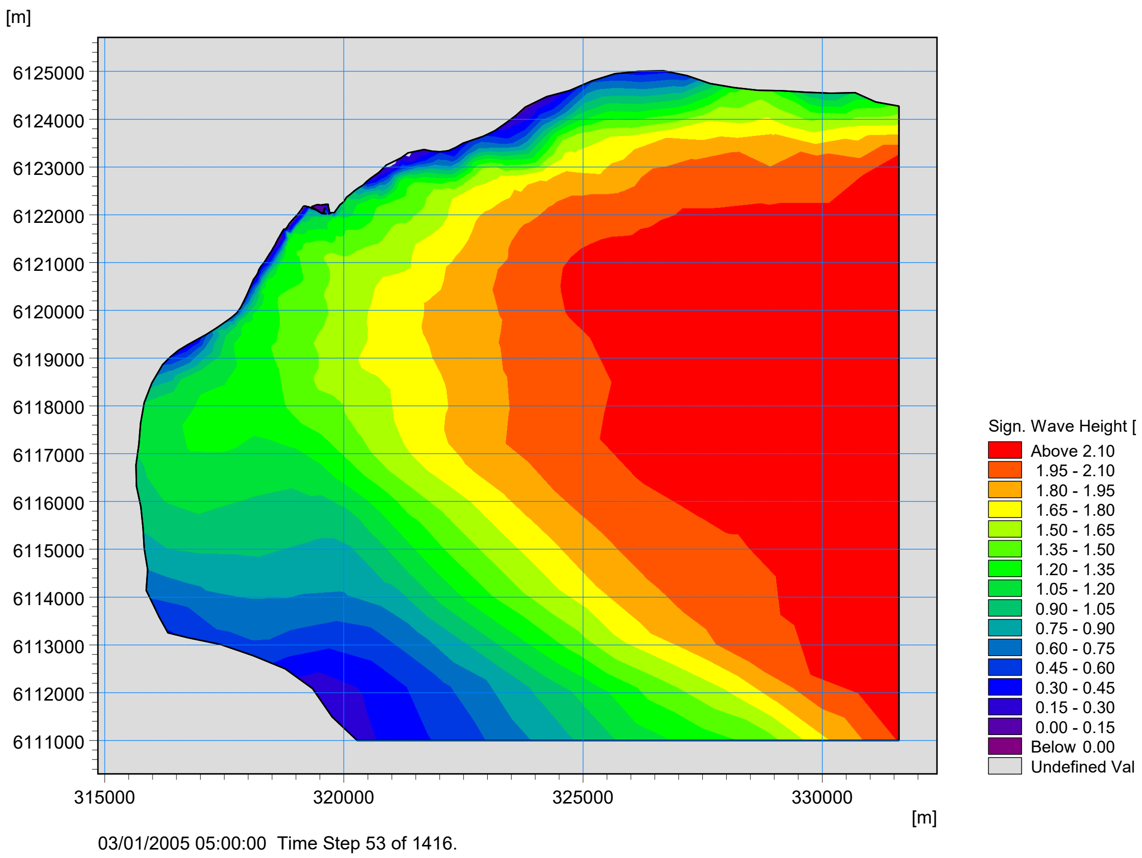

Fig. 7.11. Significant wave height in the harbour, from a 105° angle.

It is interesting to notice that the time step from which these waves are gathered is totally random, this is because, after a warming up period, the waves can be considered steady, therefore the wave height must be considered constant during the entire simulation.

The results obtained considering this set up are discussed in the following section.

7.5 Results

Bed level change

The very first interesting result of the simulation to look at is the *Accumulated bed level change*, this parameter shows the increment, or decrement, of the bed level during the entire simulation.

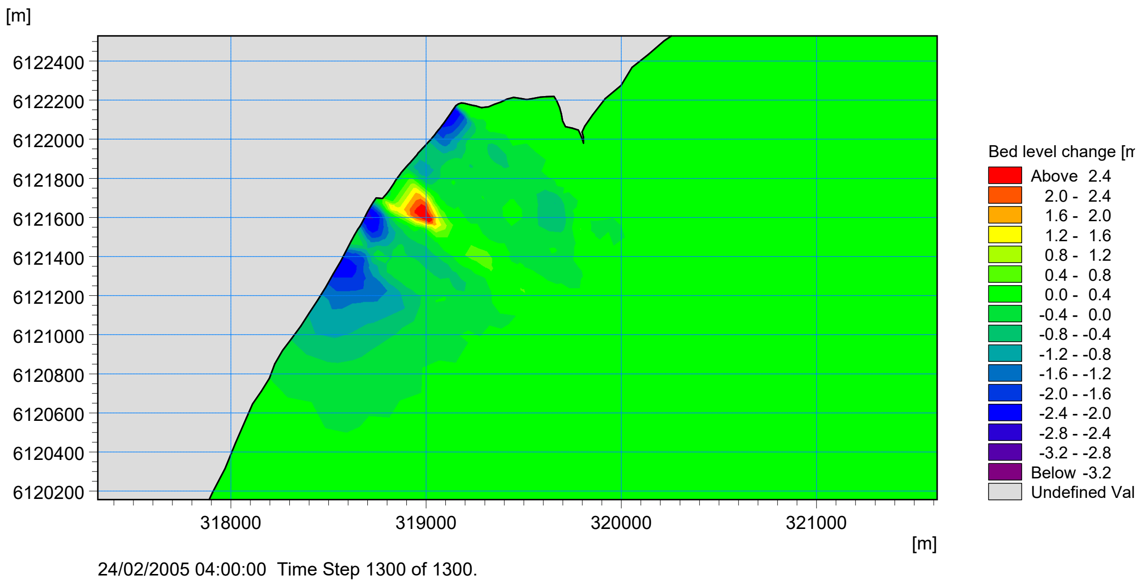

Fig. 7.12. Bed level changes after 2 months simulations.

The SM module shows that the profile of the shoreline, at the end of the process, mostly present three main areas in which the bed level is relevantly changed. The northern part of the beach, in fact, presents an important decrement, equal to $-1.5\,\text{m}$, and a general lower erosion along the stretch in front of this area.

In correspondence of the end of the end of the beach a major accretion occurs, with values above $2\,\text{m}$; whereas along the coastline a general phenomenon of erosion takes place.

The effects that these bed level changes have on the bathymetry can be see in Figure 7.13

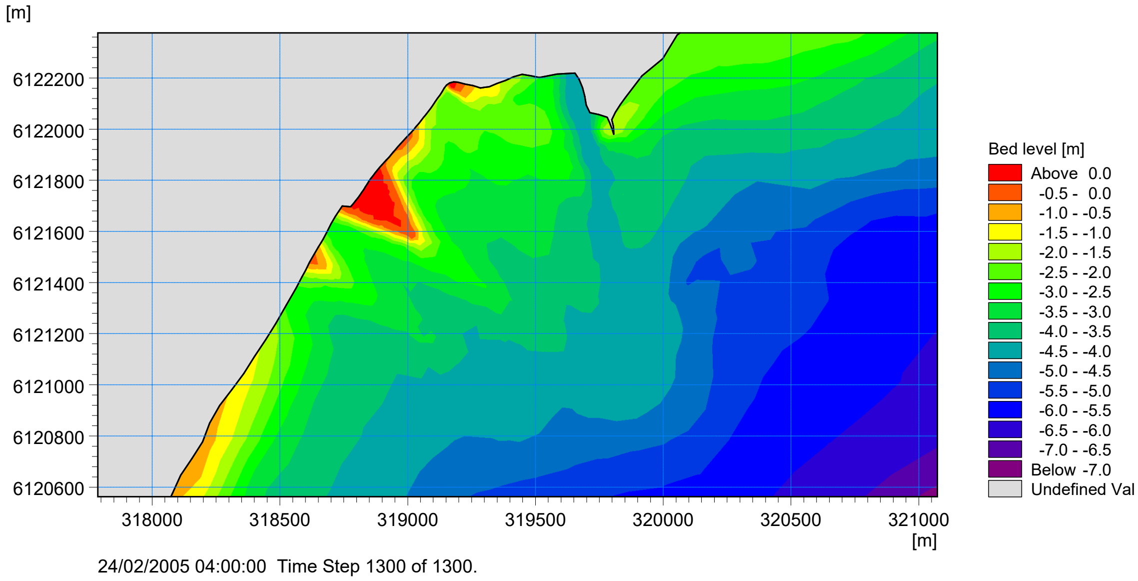

Fig. 7.13. Bed level after 2 months simulations.

It can be easily noticed that according to the SM module the 60 000 m^3 of sand nourished as a first instance are completely eroded after 2 months of severe weather conditions, or, most likely, they have been moved southwards, developing a sand groyne. This behaviour does not correspond to the one expected, since, even if a more severe wave conditions usually correspond to a larger erosion, the results shown by the SM module are too extreme. In addition to that it seems to be the same behaviour shown in the simulation covering the entire year. The reasons for such an important profile modification cannot be a fairly small increment of the significant wave hight and the sediment accretion in the southern part cannot be explained even considering the Net littoral drift in Figure 7.14

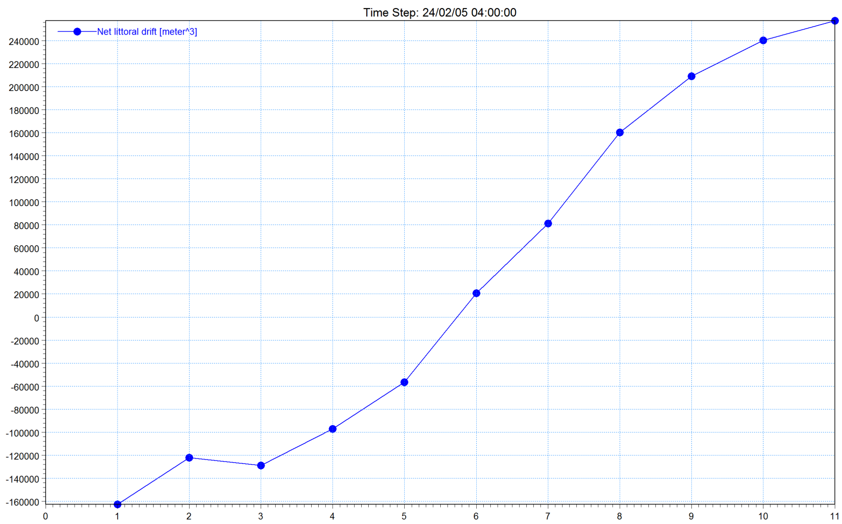

Fig. 7.14. Net littoral drift after 2 months simulations.

It is clear that the northern part of the beach experiences erosion, then accretion, whereas in the southern part of the coast an erosional trend occurs. This chart is consistent to what is highlighted in Figure 7.13 and for this reason it is possible to state that the model most likely tend to describe a very unlikely behaviour when it is prone to extreme wave conditions. This evaluation is based also on the results obtained for a 120° wind direction, that can be found in the Appendix.

It must be said that the inputs to the SM module are the same as the ones used for the simulation with standard waves. This inconsistent behaviour can derived from the fact that, imposing the baseline as a fixed boundary, the model must coniugate the need of high sediment transport, due to the extreme conditions, with the impossibility of modifying the coastline. Setting a boundary condition such as the one required in SM module could influence the action of the erosion and results in a wrong interpretation of the real conditions. The Sediment Transport module does not require to set the baseline boundary and therefore the model is free to modify the area, according with the calculations obtained from the HD module, and for this reason it reflects a more accurate picture of the reality.

8 | Conclusion

The aim of the paper was to analyse the *Shoreline Morphology module*, which is new tool developed by *DHI* for modelling the material transport behaviour inside along a generic coastline. A stretch of the Danish coast has been studied applying the new software and the results have been discussed and validated with the traditional approach, based on a largely accepted model, the Sand Transport module. The results of this comparison have generated interesting queries about the software strong points and limits.

The results highlighted a general agreement between the two softwares, when it comes to simulate two months with standard wind and wave conditions. Both the tools, in fact, show a similar erosional behaviour of the nourished beach even if the inputs required for the two modules are very different.

The results obtained analysing the entire year seem to tip the SM module over edge, for this reason two simulations with extreme weather conditions have been carried out, in order to test the stability of the SM module and it was found that the it show that findings raise when some kind of extreme conditions are applied. It is not clear if these findings are connected to the behaviour of the model itself or if the reasons have to be found in the particular morphology of the analysed area. A possible future study case could be to investigate how differently the two models reacts to severe wind and wave conditions since the ST module could not be investigated in this paper under the same assumptions.

Tanking into account the time step up to the end of February, according to both the results, Faxe Ladeplads coastline is eroded starting from the first day after the initial nourishment and for this reason the feeding suggested by Rambøll is necessary whether the Municipality decides to perform the restoration of the beach. This will surely have an impact on tourism and on the requalification of the entire area, allowing to Faxe Ladeplads to restore its original appeal.

Personal reflections

The implementation of the Shoreline Morphology module was not effortless both because of the lack of literature covering the module, and because of its being fairly recent. In order to overcome some issues with the results interpretation *DHI* support has been reached, though it has not been possible to understand the nature of the problems, this suggests that either the morphology has a huge impact on the correctness of the simulation, and therefore a critical analysis is always required, either the module is very sensible to large wave height and this could lead on a shrinkage of the applicability area.

The complexity of the morphology is a crucial element on the definition of the input parameters too, since a too curved coastline could generate findings in the definition of the profiles and the edge map.

Shoreline Morphology module, though, has its very strong points in the flexibility allowed by the use of a slightly curved baseline, instead of the straight line commonly allowed in the previous models; this guarantees a much larger applicability.

Another benefit that this module brings is the complex 2D bathymetry, wave field and currents on which it is possible to rely on and the accuracy of the results which allow to investigate deeply the erosional or accretion phenomena. Last but not least the module allows to investigate long-terms simulations with the certainty of a behaviour of the coastline consistent with the natural physical effects.

In conclusion the Shoreline Morphology module, like all the finite element software, must be handled carefully and the results must be critically analysed and even if the software provides a better overview of the sediment transport process its use should be considered for long terms simulations only, in which other softwares fail. Though, the problems occurred evaluating more severe wave conditions make me discourage its usage and suggest to opt for a more stable model.

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A | Extreme event, second case

In order to validate the results obtained in the simulations described 7.3 another model is tested characterised by the same wind speed but occurring with a different angle, which is equal to 120°.

In the following the results of this simulations are presented.

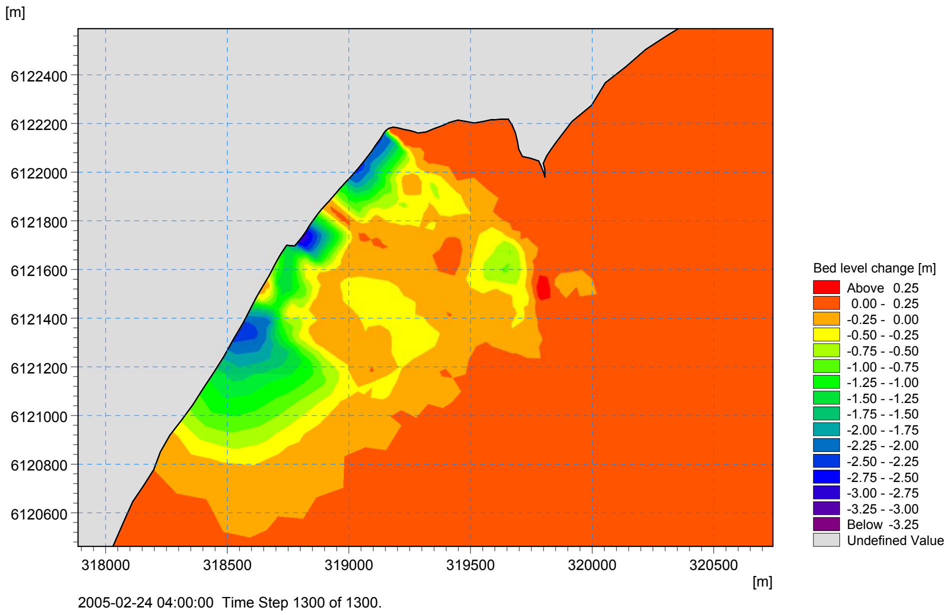

Fig. A.1. Bed level change, 120°.

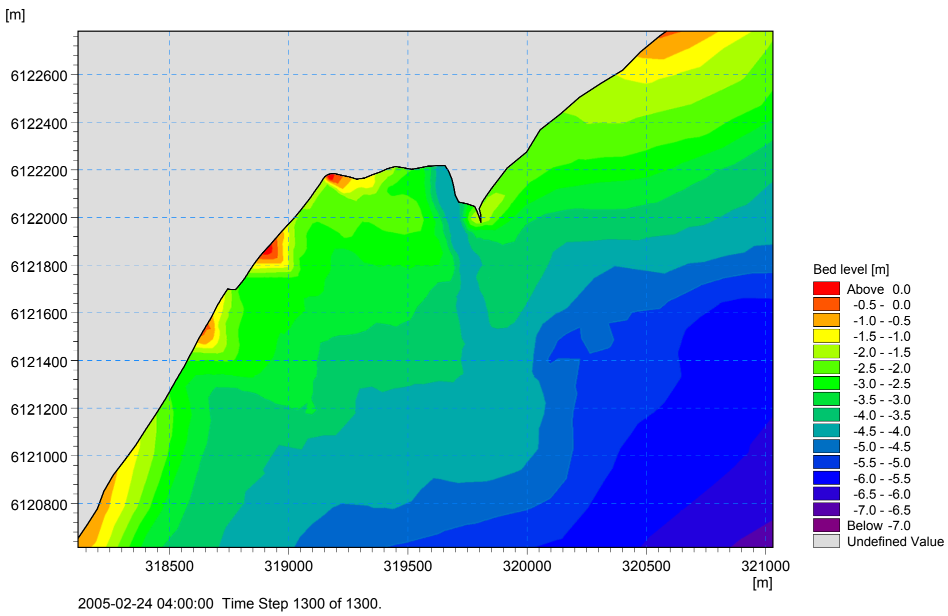

Fig. A.2. Bed level change, 120°.

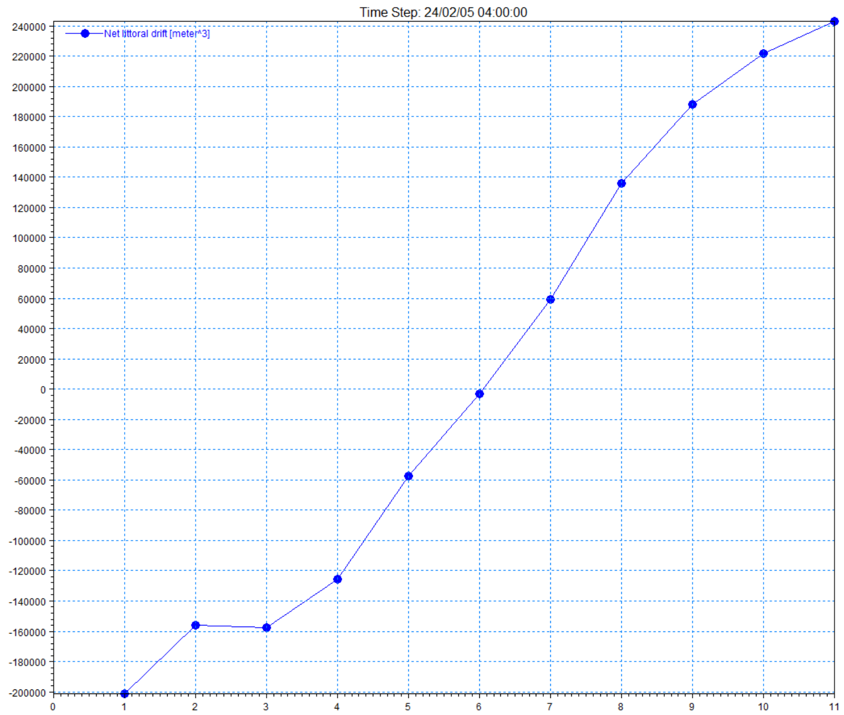

Fig. A.3. Bed level change, 120°.