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Calculation of cliff retreat on sandy coasts in Denmark using XBeach

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Photograph by Coastal Engineer Karl-Søren Geertsen

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Project manager (PM)	Ane Høiberg Nielsen
Project leader (PL)	Per Sørensen
Project staff (PS)	Karl-Søren Geertsen
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Author	Karl-Søren Geertsen and Per Sørensen
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Contents

List of symbols

The main symbols used in this report are listed below.

a	Linear fit-parameter used in the cliff retreat equation.
d_{cliff}	Cliff top.
d_{50}	Median diameter.
E	Wave energy per unit area.
fnyq	Highest frequency generated from the Jonswap spectrum.
g	Acceleration due to gravity.
H_{max}	Maximum wave height.
H_{m0}	Significant wave height.
h	Local water depth.
k	Wave number.
L	Wave length.
MAD	Mean absolute deviation.
R	Cliff retreat.
s	Wave spreading parameter in the Jonswap spectrum
T_p	Peak wave period.
V_{beach}	Beach volume.
WL	Water level time integrand.
wl_{peak}	Peak water level.
γ	Peak enhancement factor.
α	Angle of computational x-axis relative to “East”.
β	Coastal orientation.
Θ_{max}	Upper directional limit of incident wave angle.
Θ_{min}	Lower directional limit of incident wave angle.
Φ	Cliff retreat parameter.
ω	Angular frequency.

Summary

Denmark has more than 7,300 km soft coastline and a significant part of this coastline is sandy coast. The presence of more than 13,000 groynes, shore parallel breakwaters and revetments highlight the need to protect infrastructure and property against coastal erosion in a changing climate. This study investigates how to assess the risk of storm erosion, as a retreat of a cliff during a single storm, utilizing the numerical storm erosion model XBeach.

A XBeach 1D model is calibrated to different coastal profiles measured after a storm. Furthermore, the calibrated model is validated on three different types of Danish coast using the same model setup and information on the real coastal cliff retreat. The calibrated model was able to predict the storm erosion in eight profiles during the calibration and validation study. The mean absolute deviation (MAD) of the model is estimated to 1 meter, based on all model runs.

By extending the 1D model to a 2D model covering two of the geographic validation cases, Gedesby and Vedersoe, it was found, that the 2D model delivered comparable results to the 1D model, in all of the covered validation profiles using the same model parameters as found in the 1D calibration and validation study.

In an investigation of storm erosion on the west coast of Denmark, the calibrated model is applied as a state-of-the-art tool to determine the correlation of relevant storm parameters and shoreface morphological parameters to the amount of cliff retreat during one storm. A linear relationship with a R-squared value of 0.71 and a MAD of approximately 6 meters is found. Based on the cliff retreat analysis, a cliff retreat equation is developed as an analytical tool to regularly assess the safety of the Danish west coast dunes during storm, and in future climate storm scenarios.

1. Introduction

This report is part of the EU-InterReg project Building with Nature (BwN). The overall objective of Building with Nature is to improve coastal adaptability and resilience to climate changes by means of natural measures. Being a partner in the project, the Danish Coastal Authority (DCA) analyses different aspects of using natural processes and materials in coastal laboratories on Danish coasts.

This project seeks to improve our understanding of the processes and interactions within the coastal system.

The BWN-project is a combination of six different work packages, as seen from Figure 1. This report on Calculation of cliff retreat on sandy coasts in Denmark concerns Work Package three (WP3): Resilient Coastal Laboratories. However, the coastal stretch in this report is not a laboratory site.

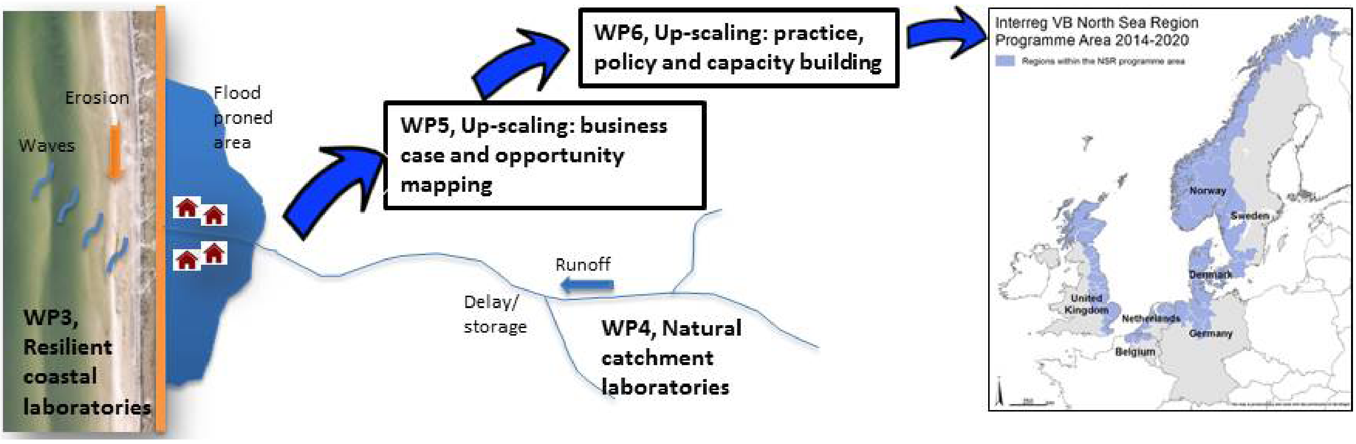

Figure 1 - The six work packages in the Building with Nature project. WP1 - Project Management, and WP2 – Communication is not included as these WPs are in-office activities.

WP3 generally focuses on coastal challenges such as chronicle erosion, aeolian erosion, cliff retreat during storm and storm induced flooding. The goal is to estimate and understand the effects on the coasts of these challenges and implement BwN-solutions to mitigate and control future risk of coastal erosion and coastal flooding.

The research for this part of the Building with Nature-project calibrates and validates a numerical model for investigations of storm erosion of the innermost part of the pathway. Previous validation studies by (Bolle, et al., 2011) show that XBeach can reproduce the dune face morphological changes during a storm on different site locations. To hold a validated numerical storm erosion model, which can perform on a national scale, to predict the storm impact on the coastline is an indispensable tool in assessing coastal resilience in Denmark. In this numerical project, the open source XBeach process model is tested against real historical coastal profile measurements after a storm. In this report, storm erosion is used as a general term, only, describing loss of sand volume due to storm impact. The term cliff retreat is used as an exact measure of storm erosion by determining the retreat of the dune top during one storm.

This BwN report presents the calibration and validation work of the numerical model XBeach for calculating cliff retreats, in Denmark, during storms using real measured storm data. As one of the first of its kind, this work will validate a calibrated XBeach model on different coastal profiles representative of most of the Danish coastline with the same model settings in both 1D and 2D model setups. The validated coastal profiles represent levels of coastal exposure ranging from low to very high.

A numerical study, based on Delft3D simulations, by (Hopkins, et al., 2018) suggests that the shoreface morphological changes during storm depend on storm duration and storm intensity. They presents a correlation between storm erosion and storm intensity. Inspired by their findings, this project applies the calibrated XBeach model as a state-of-the-art tool to assess relevant morphological and hydrodynamic quantities against the amount of cliff retreat during a storm. This led to an interesting first attempt to develop an analytical cliff retreat equation.

In the chapter Technical background, a descriptive explanation of the physics of infragravity waves based on the literature by (Roelvink, et al., 2015) and (Munk, 1950), is given. Finally, the implementation of XBeach in this project is described , along with the XBeach model parameters used.

In the chapter Method, the methodology applied to calibrate and validate the XBeach model in both 1D and 2D model approach is presented, followed by a list of model-setting parameters investigated in the calibration and validation study. In the Model result chapter, the model results from the calibration and validation study along with the found values of the model-setting parameters are shown.

In the chapter Cliff retreat analysis, the calibrated and validated XBeach model is used as a tool to investigate the correlation of storm erosion with characteristic beach and dune morphological quantities and relevant storm parameters.

The main objective in this project is to set up a numerical storm erosion model, which can perform on a national scale.

In summary, the research questions motivating this project are:

1. Will a single XBeach model set-up be able to mimic the storm induced cliff retreat on most types of coastline in Denmark?
2. What is the relationship between cliff retreats and the characteristic storm surge parameters, beach and dune morphological parameters?

To answer these questions 1D and 2D XBeach cliff retreat models are used as numerical tools.

2. Technical background

This section briefly explains the physics of infragravity waves. Furthermore, it shows the importance of including infragravity wave processes in storm erosion models. Finally, a short description of the model and model parameters used in this study will be given.

2.1 Infragravity waves

Infragravity waves are ocean waves with long wave periods (between 30s – 5min), generated from a phase-shift of the incoming waves as described by (Munk, 1950). The difference in phase and height of the incoming waves generates a bound wave oscillation, called infragravity wave or "Surfbeat", by temporally raising the water level (high breakers) and lowering the water level (low breakers) in the surf zone (Munk, 1950).

Based on field experience from DCA and common literature, the dynamics of infragravity waves are essential in predicting hotspots of cliff retreat. In this project the XBeach model is applied, which includes the induced processes from long period infragravity waves, from interactions between short waves (blue line) and long waves (red line) to determine storm erosion, as seen from Figure 2.

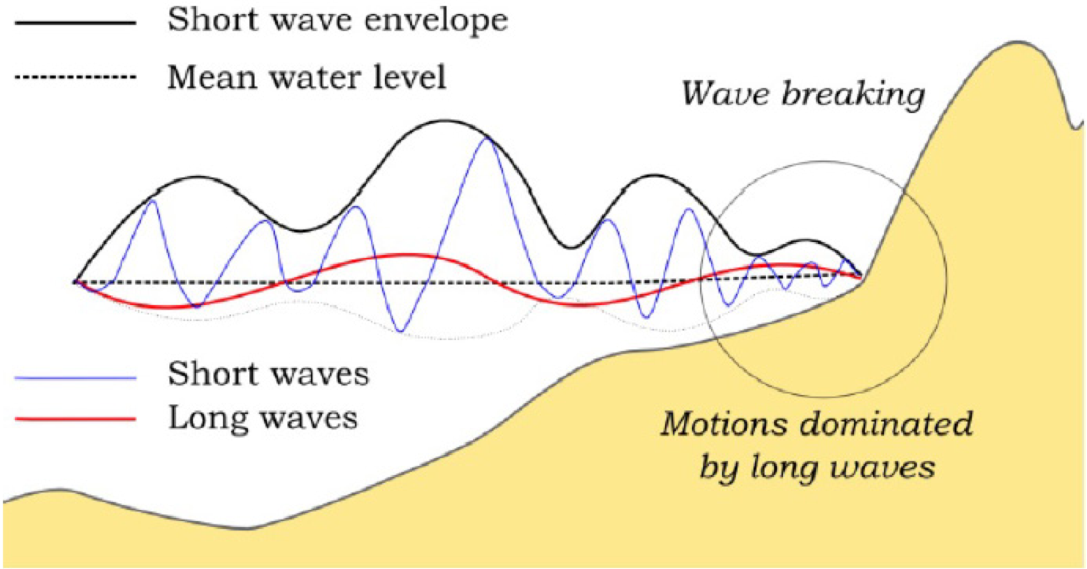

Figure 2 – Process illustration of incoming waves (short waves and long waves) and the dominated motion in the surf zone determined by XBeach. The illustration is from (Roelvink, et al., 2015)

2.2 XBeach model implementation

The retreat of moraine cliffs in Denmark has previously been studied by (Frederiksen, 2018) contributing to common literature on the subject by (Halcrow, 2007) and (Earlie, et al., 2015). In conclusion, moraine cliffs do not erode during single storm events, therefore they are not included in this project. Furthermore, all types of coastal protection measures are disregarded in this project. Retreat of sandy cliffs in Denmark without any coastal protection is estimated by applying XBeach.

XBeach is a numerical model for wave propagation, long waves and mean flow, non-cohesive sediment transport, morphological changes and dune erosion in the nearshore area during a storm (Roelvink, et al., 2009). In this section, this work focusses on the 1D model set-up as used in the calibration and validation study. The extension to a 2D model set-up will be described later in section 3.3.

From the wave and tide inputs, XBeach solves the swash dynamics by combining a wave action equation with a roller equation on the scale of wave groups. The flow dynamic is based on the wave forcing determined by the wave action equation and the roller equation, and then calculated by applying a depth integrated shallow water equation for long frequency and mean flows (Roelvink, et al., 2009). XBeach decomposes the input wave spectra into a time varying wave signal on group scale, hence it resolves the large underlying motion of infragravity waves, which is thought to have the largest impact on the dune face (Roelvink, et al., 2009). As one of the first models of its kind, XBeach includes infragravity waves in the morphological processes, which makes it excellent to determine morphological changes in the dune-face. In this XBeach set-up, the “surf beat” model is applied.

The wave input data is converted to Joint North Sea Wave Observation Project (JONSWAP) spectra, to approximate hourly sea states during a storm for all calibration and validation model setups. The JONSWAP spectrum is valid in fully developed seas as well as in fetch-limited seas, where waves cannot reach an equilibrium state (Rossi , et al., 2020). The North Sea is very well described by the JONSWAP spectrum, however the JONSWAP spectrum is also assumed applicable for the Baltic Sea based on the study by (Blomgren, et al., 2001), and for the Kattegat.

Standardized JONSWAP parameters were set to s = 20, gamma = 3.3 and fnyq = 1 for all model cases. The values are based on (Sumer & Fredsoe, 2006) and (Roelvink, et al., 2015), where s is the directional spreading, gamma is the peak enhancement factor and fnyq is the highest frequency used to generate the spectrum (Roelvink, et al., 2015). In the calibration and validation study, available storm data was imposed as offshore forcing conditions. Whereas in the cliff retreat analysis, in section 06, storm duration is set to 48 hours prior to and after the peak water level. In both studies, a temporal resolution of 1 hour was used for the tide input on the offshore boundary.

In the 1D calibration and validation study, the coastal profile before a storm is constructed from available field measurements. However, some locations are merged with a low resolution bathymetric model, if no bathymetry measurements were available. All profiles are constructed in a UTM coordinate system perpendicular to the coastline.

The 1D XBeach model grid is gradually refined towards the coast with maximum cell size of 10-15 m at the offshore boundary and minimum cell size of 1 m in the nearshore region. The refinement was based on automatic mesh generation from the MATLAB Toolbox available through the OpenEarthTools repository developed by Deltares, TU Delft among others. The profile was extended seaward to ensure, as a minimum, intermediate water depth based on maximum wave height, Hmax and corresponding peak wave period, Tp using the dispersion relation formula from linear wave theory taken from (Sumer & Fredsoe, 2006)

$$\omega^2 = gk \ \tanh(kh)$$

Where ω is the angular frequency , $\left(\omega = \frac{2\pi}{T}\right)$, g is acceleration due to gravity, k is the wave number $\left(k = \frac{2\pi}{L}\right)$ and h is the local water depth.

The wave grid was constructed as a one bin 180 degree with Θ_{min} and Θ_{max} defined as the minimum and maximum wave angle relative to “East” in nautical coordinates, determined as ±90° from the coastal orientation, β. This was done to cover all wave energy exerted on the beach during the storm.

2.3 Model settings

In this section, the parameter file param.txt is presented to clarify the final model settings in the calibrated and validated 1D XBeach model in a simple way. The parameter file holds all information needed for running an XBeach model. A MATLAB program, see attached appendices, was developed in this project, to automatically setup and run XBeach models based on storm data and coastal profiles.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%
%%% XBeach parameter settings input file                                     %%%
%%%                                                                          %%%
%%% date:     01-Sep-2020 13:44:44                                           %%%
%%% function: xb_write_params                                                %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%

%%% Bed composition parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%

D50          = 0.000400

%%% General %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%

tidelen      = 98

%%% Grid parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%

depfile      = bed.dep
posdwn       = -1
nx           = 1265
ny           = 0
alfa         = 0
vardx        = 1
xfile        = x.grd
yfile        = y.grd
xori         = 0
yori         = 0
thetamin     = 178
thetamax     = 358
dtheta       = 180
thetanaut    = 1

%%% Model time %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%

tstop        = 349200

%%% Morphology parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%

morfac       = 5
morstart     = 100
dryslp       = 0.800000

%%% Sediment transport parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%

facua        = 0.300000
```

```
%%% Tide boundary conditions %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%

zs0file      = tide.txt
tideloc      = 2

%%% Wave boundary condition parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%

instat       = jons

%%% Wave breaking parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%

gamma        = 0.550000

%%% Wave-spectrum boundary condition parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%

bcfile       = filelist.txt

%%% Output variables %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%

outputformat = fortran
tintg        = 100
tstart       = 0

nglobalvar   = 5
H
u
v
zs
zb
```

3. Method

In this BwN-project, the primary task is to set up a numerical XBeach model for storm erosion along the coastline of Denmark and deliver adequate results on different types of coastlines. In the end, the model is applied as a numerical tool in an investigation of cliff retreat during storm. The end-product is a XBeach model applicable, in Denmark, on national scale in both a 1D and a 2D model approach.

This section of the report describes the methodology of the calibration and validation of the model in 1D and 2D set-up, respectively.

3.1 1D model calibration

During a storm event, the cross-shore sediment transport is considered the dominant. However, the longshore transport is not negligible and by setting up a 2D XBeach model, the longshore wave induced sediment transport component is taken into account.

The XBeach model is calibrated at a location, Vedersoe, on the Danish west coast during a severe storm in January 2005. The west coast of Denmark consists of sandy dunes protecting a large flat hinterland from coastal inundation during storm. Model parameters are analyzed to find the best model calibration results.

3.1.1 1D Calibration case

Coastal measurements are available before and after a severe storm in 2005 at a location close to Vedersoe, see Figure 3. After the storm in January 2005, cliff retreats at Vedersoe were reported to the Danish Coastal Authority. The retreats were characterized by a significant variation along the coast. The location of Vedersoe is exposed to the North Sea and is located on a high energy coastline, hence the longshore sediment transport is significant and continously change the sandbar system, which acts as a natural wave breaker. A foreshore, containing a weak berm of crest height of less than one meter is followed by a 100 m wide beach. The beach is followed by a sandy dune, with the dune top located in 14 m (DVR90) and the dune foot located in 2 m (DVR90). The coastal orientation of the profile is close to 270°. In this 1D calibration study, a coastal profile at Vedersoe (Vedersoe 01) is investigated before a severe storm measured in January 2005. During the storm, the dune top undergoes a retreat of up to 15 m.

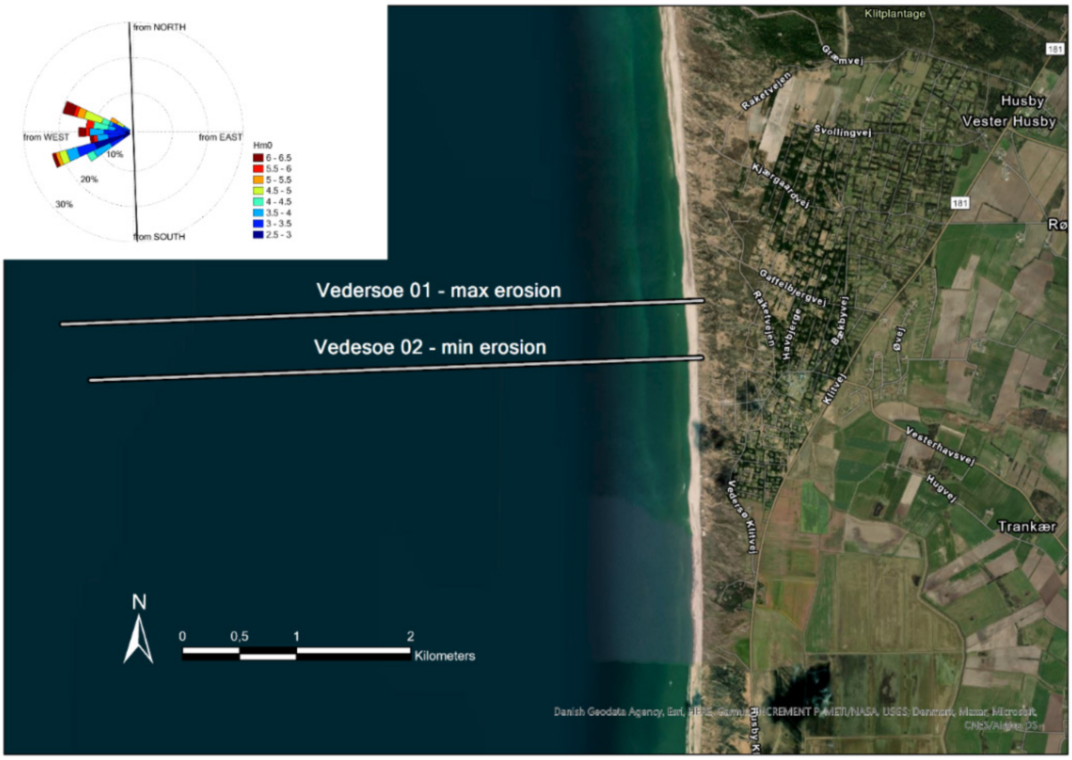

Figure 3 - Aerial photo of the calibration area on Vedersoe Klit (Vedersoe). Lines orthogonal to the coast indicate yearly measured profiles.

The wave climate during the storm is measured on deep water by wave buoys outside Nymindegab and water levels are measured outside Ferring, as can be seen from Figure 4. Water level measurements equipment is located on the open coast, installed onto coastal structures, to measure water levels, including the wave set-up, close to the dune foot.

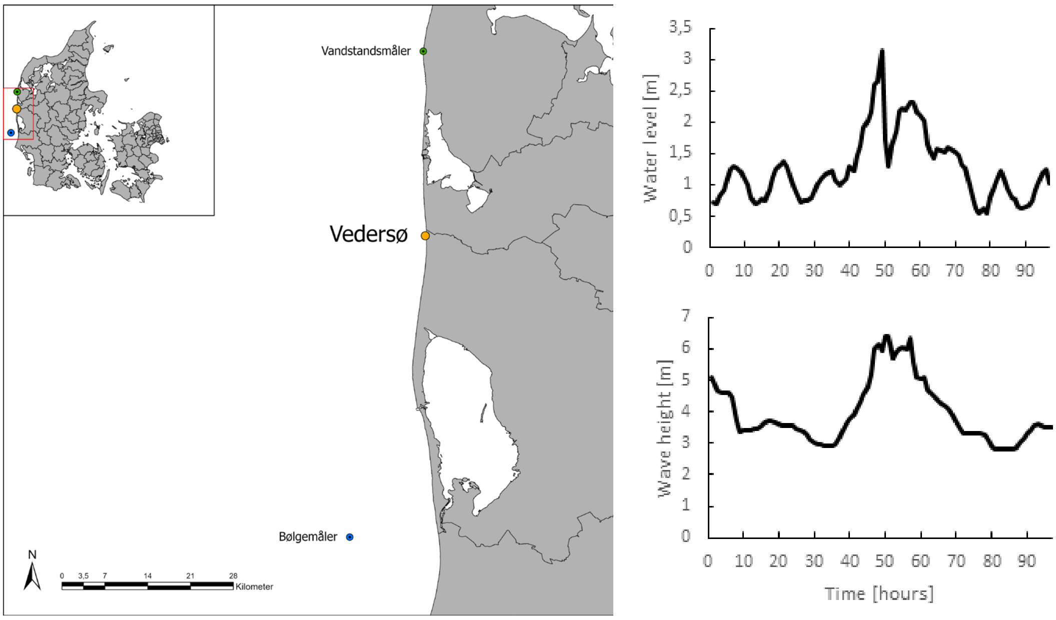

Figure 4 - Location of wave buoy (blue marker) and water level measurement location (green marker). Time series of both water level and significant wave height are included.

Numerous parameters can be investigated and changed in the XBeach model. In this project, a pragmatic approach was used and only parameters controlling physical processes have been adjusted. However, we have tuned the Morfac parameter to enhance the computational efficiency. The calibration parameters focused on in this calibration study are listed in Table 1. All other parameters in the model set-up are default.

CALIBRATION PARAMETERS	[Dimensions]
Gamma	[-]
D50	[m]
Morfac	[-]
Dryslp	[-]
Facua	[-]

Table 1 - Main calibration parameters investigated in this calibration study.

The main calibration parameters are described in the following:

Gamma: The wave breaking index, controlling the wave breaking height criteria in the wave breaking model formulation described in (Roelvink, et al., 2015).

d_{50}: The median sediment diameter. Changes of d_{50} showed significant effect on cliff retreat and smoothing of the beach.

Morfac: A morphological acceleration factor, (Roelvink, et al., 2015). We find that high values of Morfac (>5) has a significant effect on cliff retreat and smoothing of the beach.

Dryslp: The critical avalanching slope, (Roelvink, et al., 2015), of the dry part of the profile.

Facua: A parameter controlling the wave skewness and wave asymmetry. The Facua parameter is implemented in the sediments transport equation of XBeach to adjust for wave skewness and wave asymmetry, (Roelvink, et al., 2015).

3.2 1D model validation

The calibrated model set-up is validated on up to seven different coastal profiles covering most types of the Danish coastline. Corresponding storm data is collected from available physical measurements, elsewhere metocean hindcast storm data from DHI (DHI, 2019b), covering more than 20 years (1995-2017), is used as input data. All validation cases together with their respective storm event are listed in Table 2.

Validation	LOCATION	STORM
Case 01	Vedersoe (west facing coast)	Jan - 2005
Case 02	Gedesby (east facing coast)	Jan - 2017
Case 03	Havstokken (north facing coast)	Dec – 2013
Case 04	Heatherhill (north facing coast)	Dec - 2013

Table 2 - Validation cases are listed together with their respective storm event.

3.2.1 1D validation case 01

Only 500 m south of the coastal profile Vedersoe 01, used in the calibration of XBeach, the profile Vedersoe 02 is located (as seen from Figure 3). This coastal profile undergoes minimal cliff retreat during the January 2005 storm, which resulted in a large retreat in Vedersoe01. A foreshore, containing a berm, with a crest height of 3 m followed by a 130 m wide beach. The beach is followed by a sandy dune, with the dune top located above 18 m (DVR90) and the dune foot located in 4 m (DVR90). The coastal orientation of the profile is close to 270°. This profile will test if XBeach is able to mimic significant local variations in cliff retreat along a straight coastline. Therefore, validation of a zero cliff retreat result is at least as important as validating large retreats.

3.2.2 1D validation case 02

The coastline of Falster is exposed to the Baltic Sea and is considered as a low energy coastline due to a general time difference in the occurrence of large wave heights and high water levels during a storm based on hindcast storm data (DHI, 2019a). The Falster dike protects vacation houses from flooding. The crest of the dike on this stretch is located in 4 m above sea level due to the tremendous storm surge in 1872 with a peak water level of 3.5 m in this area. On the seaside of the dike, a dune landscape has developed which protects against dike-erosion. In early January 2019, cliff retreats of about 3-4 m were reported to DCA from local stakeholders just after the storm Alfrida, between January 1st and January 2nd.

DCA conducted field measurements at Falster close to the city of Gedesby, see Figure 5. The measurements were collected just after the storm in January 2019. In total, four profile transects were measured by a Trimble GPS and compared to four XBeach sumulations, hence the validation case 2 holds four retreat estimates. The profiles before the storm are generated from a merged terrain and bathymetric model from 2015 and 2007 respectively. This work validates the calibrated XBeach model set-up on all four profiles at Gedesby.

The Xbeach simulation of the storm in January 2019, does not explain the cliff retreat using the calibration set-up. Either the calibration set-up lacked fine-tuning or the storm did not cause, based on XBeach, in coastal cliff retreat in this area. Based on metocean hindcast storm data from (DHI, 2019b), historical storms, between 1995 and 2017, were filtered by their wave heights and water levels to investigate if an earlier storm could explain this cliff retreat. During the hindcast data period, the largest wave height in combination with a high water level was found between January 4 and January 5 ("Den stille stormflod") in 2017. At that time, Denmark was hit by the storm, Urd, late December 2016, which forced water into the Baltic Sea. During the first days of January, strong easterly wind intensified the backup of the flood waters from the Baltic Sea and caused a rapid rise in water levels of up to 1.6 m, exceeding a 20 years return period based on (Danish Coastal Authority, 2017), in combination with onshore wave heights measured up to 1.4 m, at Gedesby.

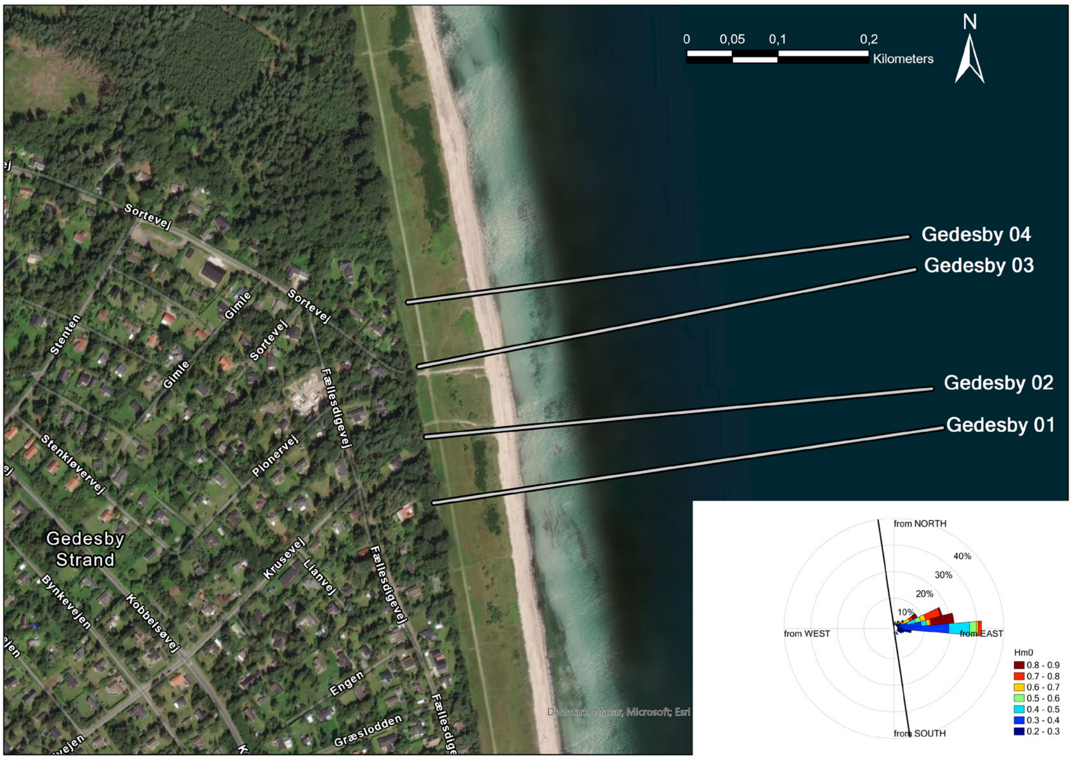

Figure 5 - Field measurements of 4 profiles at Gedesby was collected in January 2019 by DCA. Wave rose of the storm in January 2017 is included.

The wave climate and water levels are collected from the metocean data point Uslev as seen from Figure 6.

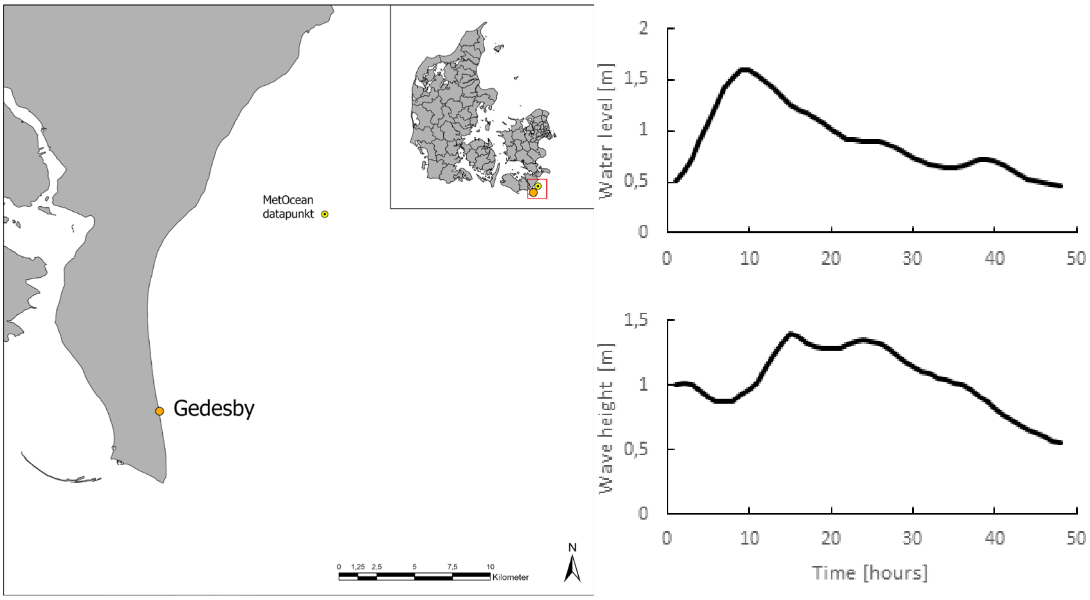

Figure 6 - Location wave climate and water level hindcast data from metocean model of the January 2017 storm. Time series of both water level and significant wave height are included.

An XBeach model is then set up to model the cliff retreat from the 2017 storm (flood event) and to see if this earlier storm can explain the cliff retreats at Gedesby.

3.2.1 1D validation case 03

Havstokken is located between Gilleleje and Rågeleje on the north coast of Zealand, see Figure 7. The north coast of Zealand houses high value assets close to the shore, which are considered in high risk of storm erosion.

In December 2013 a severe storm, with wave heights of nearly 3.5 m and a peak water level exceeding a 300 year return period (Danish Coastal Authority, 2017), hit the north coast of Zealand (Figure 7), resulting in coastal retreats. Cliff retreats of up to 8 m were reported from Havstokken during the 2013 storm. The coastal profile is characterized by a narrow beach (sand and gravel), approximately 10 m followed by a steep cliff, with the cliff top located above 5 m (DVR90) and the cliff toe located in 1-1.5 m (DVR90). The coastal orientation β of the profile is 343°.

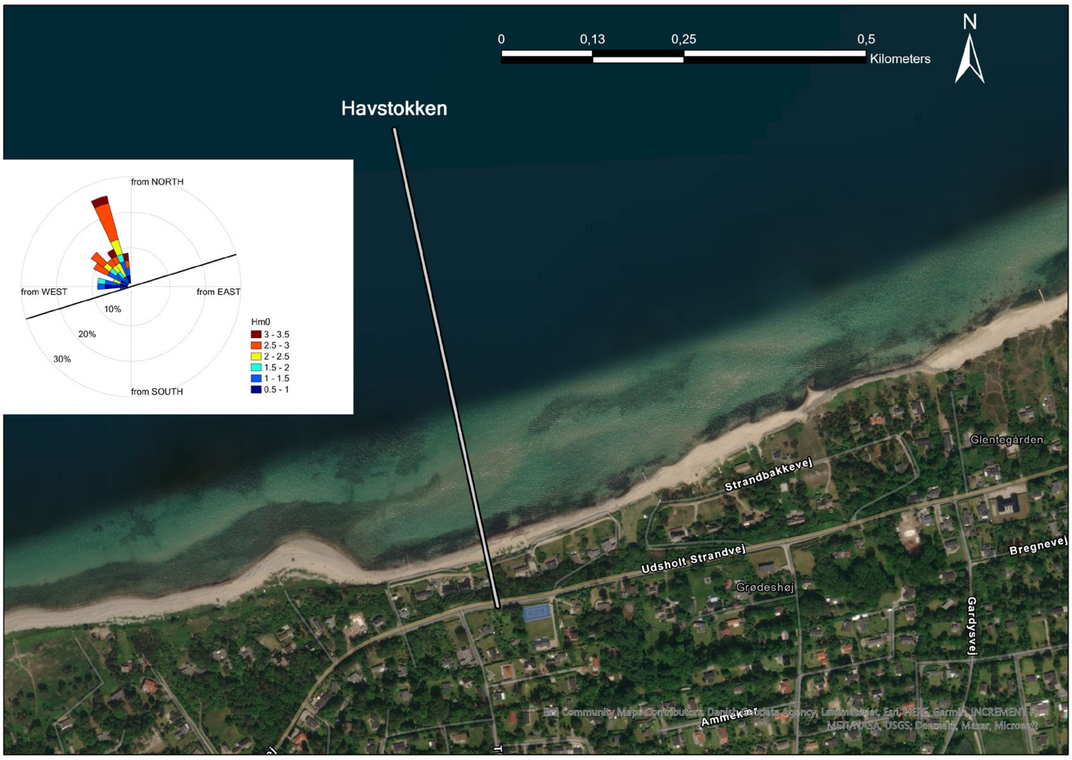

Figure 7 - Cliff retreats of up to 8 m was reported from Havstokken after the storm in 2013. The 2013 storm wave rose is included in the figure.

The north coast of Zealand is considered as a medium energy coastline, where large wave heights and high water levels are coincident during storm events. In November 2011, DCA carried out a shoreface and beach survey campaign at the north coast of Zealand, where DCA survey vessel covered the location of Havstokken. The 2011 bathymetric survey is combined with terrain models from 2007 and 2015, respectively and constitutes a coastal profile before and after the storm in 2013. Bathymetric data in the inner Danish waters is sparse, hence the 2011 bathymetry is used as a proxy for the bathymetry after the storm.

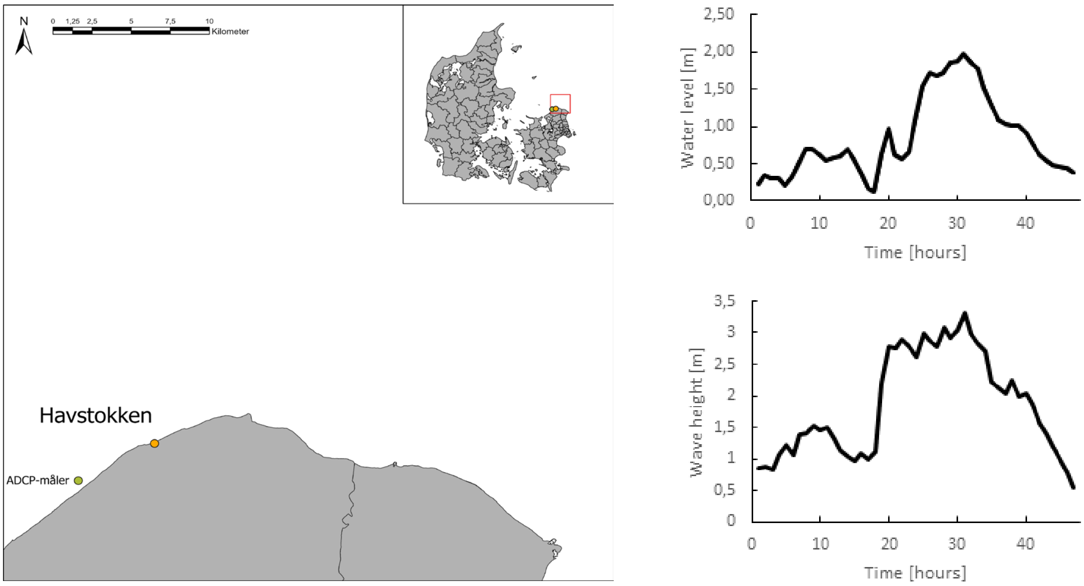

Figure 8 - Location where the wave climate and water levels are measured by ADCP during the storm. Time series of both water level and significant wave height are included.

Wave climate and water levels were measured during the storm by an ADCP (Acoustic Doppler Current Profiler) at 8 m water depth outside Heatherhill, as presented by Figure 8.

3.2.1 1D validation case 04

Heatherhill is located just a few kilometers south-west of Rågeleje. Along this coastline, high value houses are close to the cliff and strongly threatened by storm erosion as seen from Figure 9. The coastal profile is characterized by a narrow beach (sand and gravel) followed by a steep cliff, with a crest top located above 20 m (DVR90) and with the cliff toe located in 3 m (DVR90). The coastal orientation of the profile is 320°. The severe 2013 storm Bodil did not cause any cliff retreat at this location. However, this profile is applied to see if XBeach can mimic the zero cliff retreat. The coastal profile before the storm was measured by DCA, in April 2009, in a green LIDAR project (Danish Coastal Authority, 2013), whereas the coastal profile after the storm was measured by Niras in 2018.

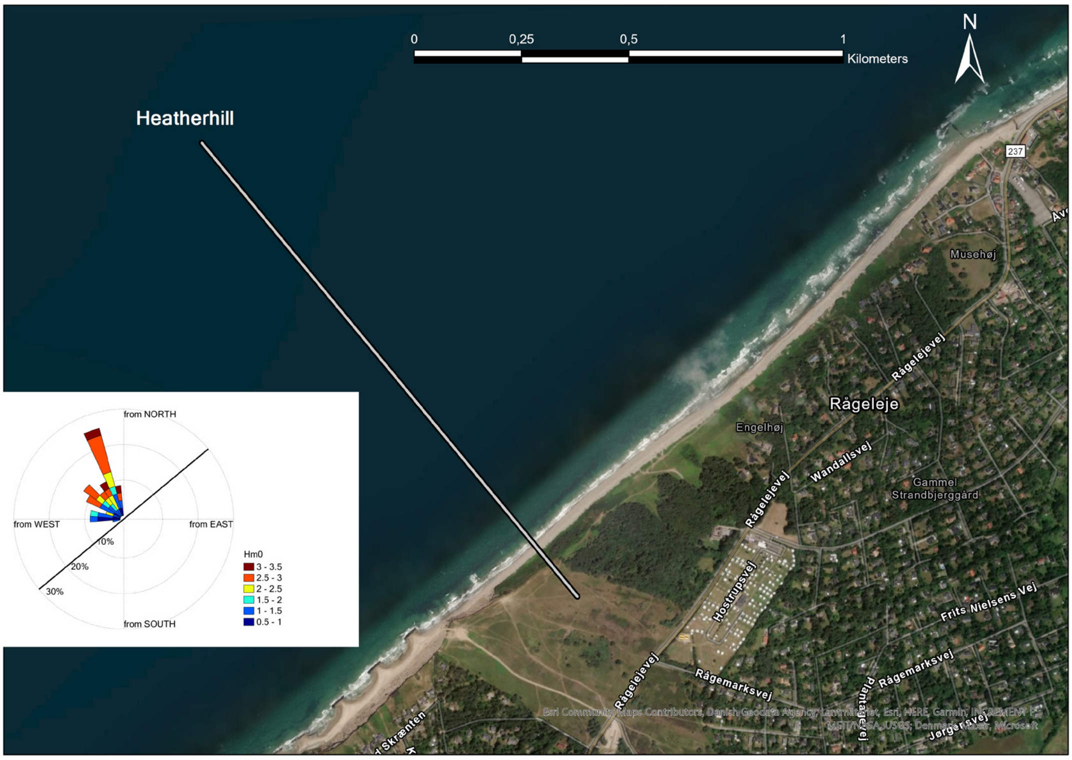

Figure 9 - No reporting of cliff retreat were found for Heatherhill. The 2013 storm is mapped onto the aerial photo.

Wave climate and water levels were measured during the storm by an ADCP (Acoustic Doppler Current Profiler) outside the coastline of Heatherhill, as presented in Figure 10

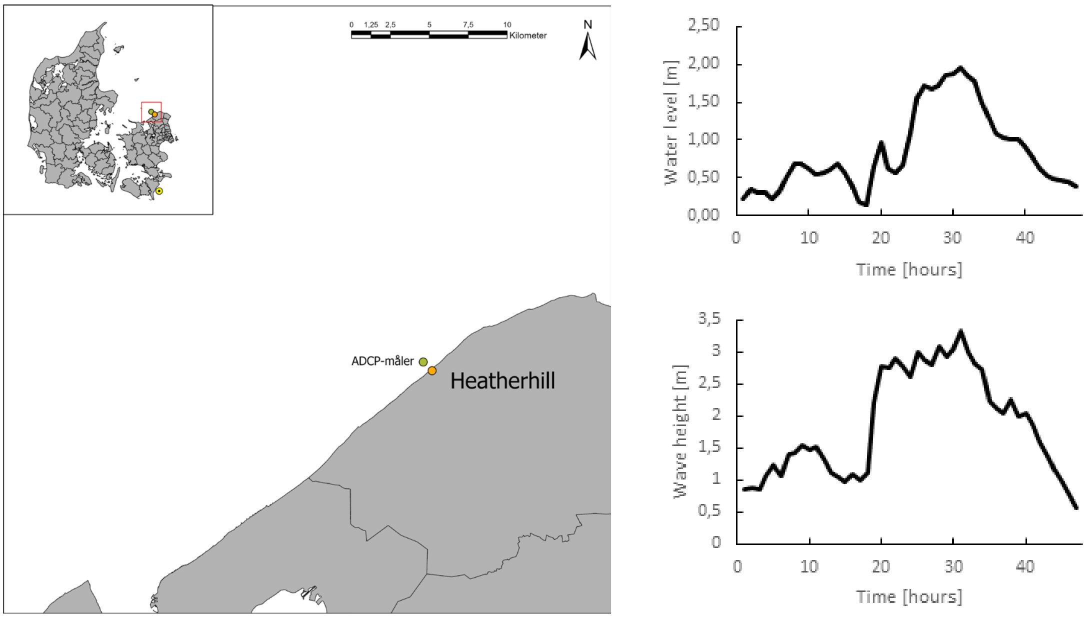

Figure 10 - Location where the wave climate and water levels are measured by ADCP during the storm. Time series of both water level and significant wave height are included..

3.3 2D model validation

The XBeach 2D model is used to investigate the difference in cliff retreat by taking into account the contribution of the longshore sediment transport and testing how well a 2D model compares to a 1D model. The 2D extension is applied on Gedesby validation case at the east coast of Falster and at Vedersoe validation case located on the west coast of Denmark.

3.3.1 2D model extension case 01

The 2D bathymetry is constructed using 15 measured profiles in the area of Vedersoe. Five profiles to the north of Vedersoe 01, four profiles in between Vedersoe 01 and Vedersoe 02 and four profiles south of Vedersoe 02. All profiles measurements are located on a straight line perpendicular to the coast. A natural neighbor interpolation routine is conducted to construct the 2D bathymetry. The 2D bathymetry is extended further seaward to fulfill at least intermediate water depth at the offshore boundary. A rectilinear staggered grid, with water levels computed in cell centers and flow velocities at cell faces, is applied with an orientation in the direction of the mean coastal orientation. The grid is constructed to vary towards shore and along the shoreline, with the largest cells (cell size of 25 x 4 m) in the offshore area along lateral boundaries and gradually refined towards the coast attaining minimum cell size of 2 x 2 m from the nearshore part of the profiles, as seen from Figure 11. This grid is chosen to obtain grid cells of aspect ratio (dy/dx) 1 in the part of the coast where the investigated profiles were located and to speed up the computational time.

The total dimension of the 2D model domain at Vedersoe is 6500 x 1400 m and the total amount of grid cells is close to 280.000.

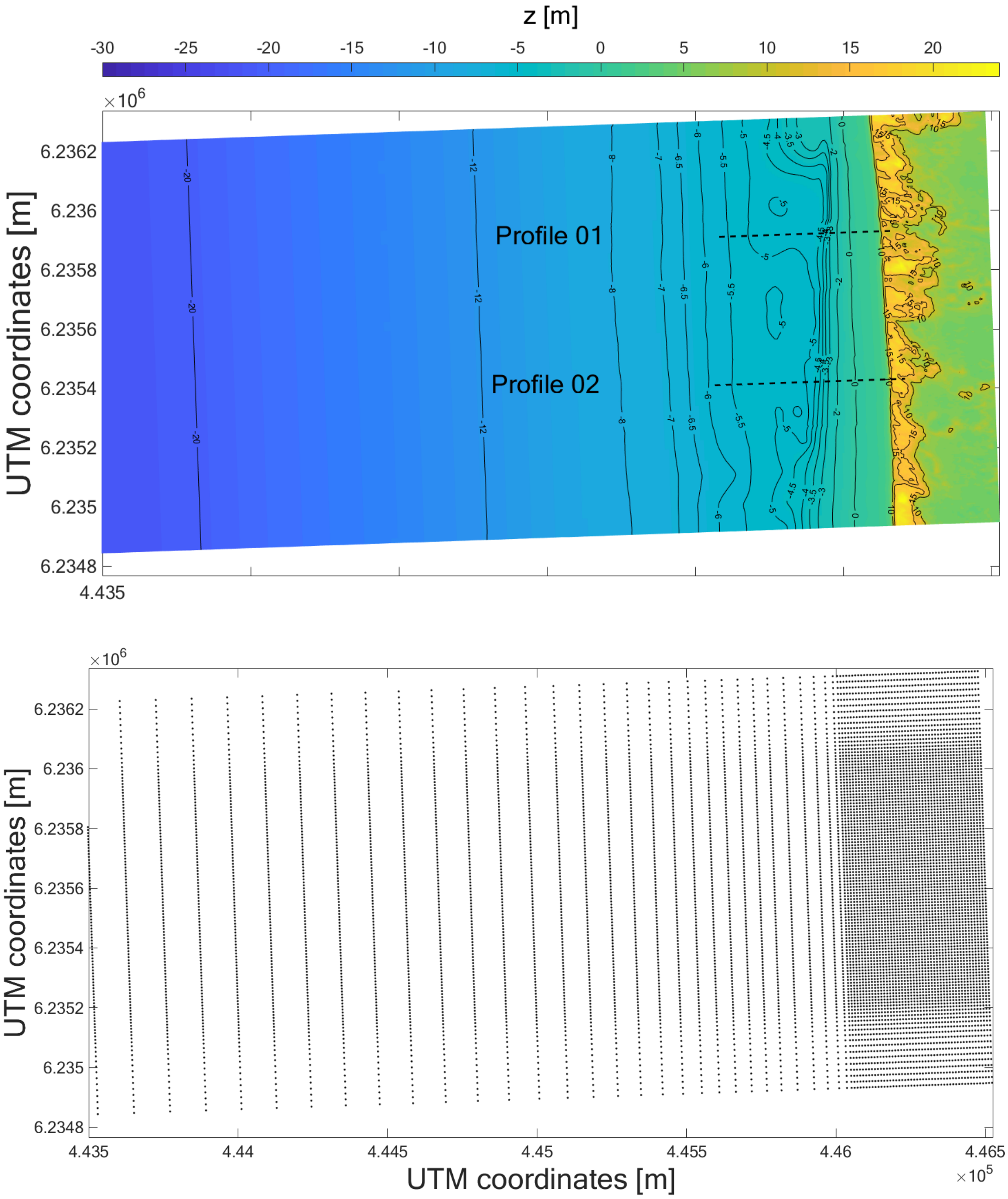

Figure 11 - 2D model layout of Vedersoe in UTM coordinates (upper figure). Coastal profiles are plotted as dashed lines. Colormap of bathymetri and topography is plotted together with depth and height contour lines. The model resolution is illustrated by black dots (lower figure). The resolution on the figure is shown coarser than true model resolution.

The total simulation time is 21 hours in parallel-run, using 16 computational cores.

3.3.2 2D model extension case 02

The 2D model at Gedesby is constructed from a merged terrain and bathymetric models from 2015 and 2007, respectively. A natural neighbor interpolation is conducted to construct the 2D bathymetry. The annual sediment transport is classified as small with an annual retreat in the order of 0.05 m (5 cm). Due to the stability of the coastline, an agreement to compare topographic data, between 2007 and 2015, to assess cliff retreat is made. The bathymetric model used covers depth of up to 8 meters, which fulfill at least the intermediate water depth criteria based on the forcing conditions. An equidistant rectilinear staggered grid is then applied with a cell resolution of 2 m x 2 m throughout the whole model domain. The grid orientation is aligned with the direction of the mean coastal orientation.

The total dimensions of the model domain at Gedesby is 1000 m x 1000 m, see Figure 12. The total amount of grid cells are 236,000. The total simulation time was 4 hours in parallel run on 32 cores.

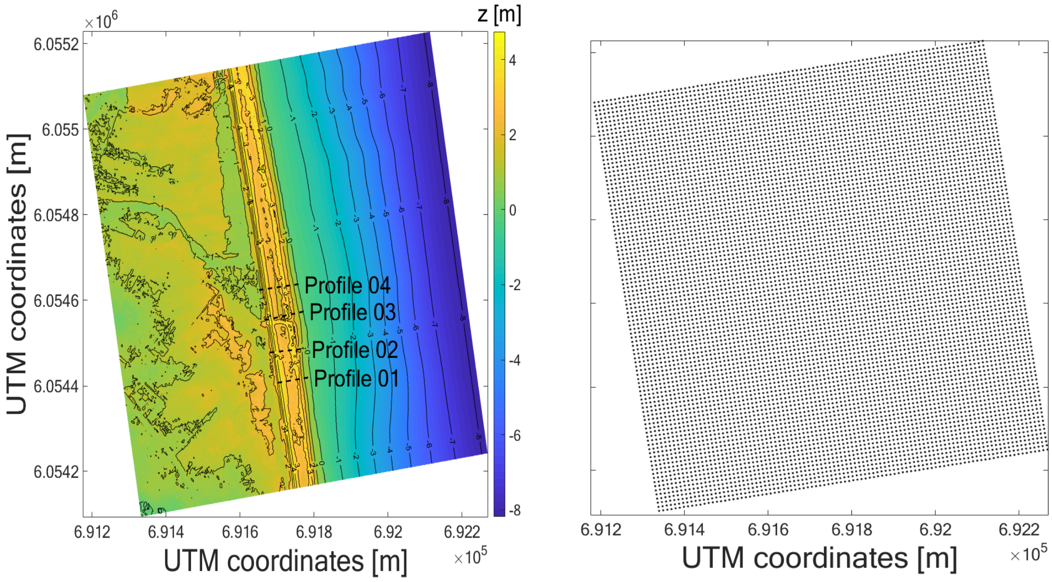

Figure 12 - 2D model layout of Gedesby in UTM coordinates (left). Coastal profiles are plotted as dashed lines. A color map of bathymetry and topography are plotted together with depth and height contour lines. The equidistant model resolution is illustrated by black dots (right). The resolution on the figure is shown coarser than true model resolution.

3.4. Model calibration and validation parameters

Based on the calibration and validation study, the calibration parameters leading to the best simulation of the cliff retreat are listed in Table 3, together with their found values.

CALIBRATION PARAMETERS	Value
Gamma [-]	0.55
D50 [m]	0.0004
Morfac [-]	5
Dryslp [-]	0.8
Facua [-]	0.3

Table 3 - Calibration parameters leading to the best overall model results are listed together with their found values.

All other model parameters are left as default.

5. Model results

In this section, the model results from the 1D calibration and validation study are presented along with the model results of the 2D model . First, the results from the 1D calibration and validations are listed in Table 4. The model results from the 2D extension are shown in section 5.3 2D model validation results as profile plots together with 1D-model results.

COASTAL PROFILES	MEASURED [m]	MODELED [m]
Vedersoe profile 01 (Calibration case)	14	15
Vedersoe profile 02 (Validation case 01)	4	2
Gedesby 01 (Validation case 02)	2	0
Gedesby 02 Validation case 02)	2	1
Gedesby 03 (Validation case 02)	0	1
Gedesby 04 (Validation case 02)	3	1
Havstokken (Validation case 03)	8	8
Heatherhill (Validation case 04)	0	1

Table 4 - 1D XBeach calibration and validation results are listed against the measured cliff retreats.

Based on the listed model results, it is demonstrated that the calibrated XBeach model can reproduce the measured cliff retreats with a mean absolute deviation (MAD) of approximately 1 meter from the measured retreat. In this calibration and validation study, the MAD is determined as the difference between modelled retreat and their respective measured value. All differences are totaled and further divided by the number of simulations.

5.1 1D model calibration results

The model calibration results for Vedersoe 01 are presented as coastal profiles before the storm (green line), after the storm (red line) and compared to 1D model profile (dashed line) as seen from Figure 13.

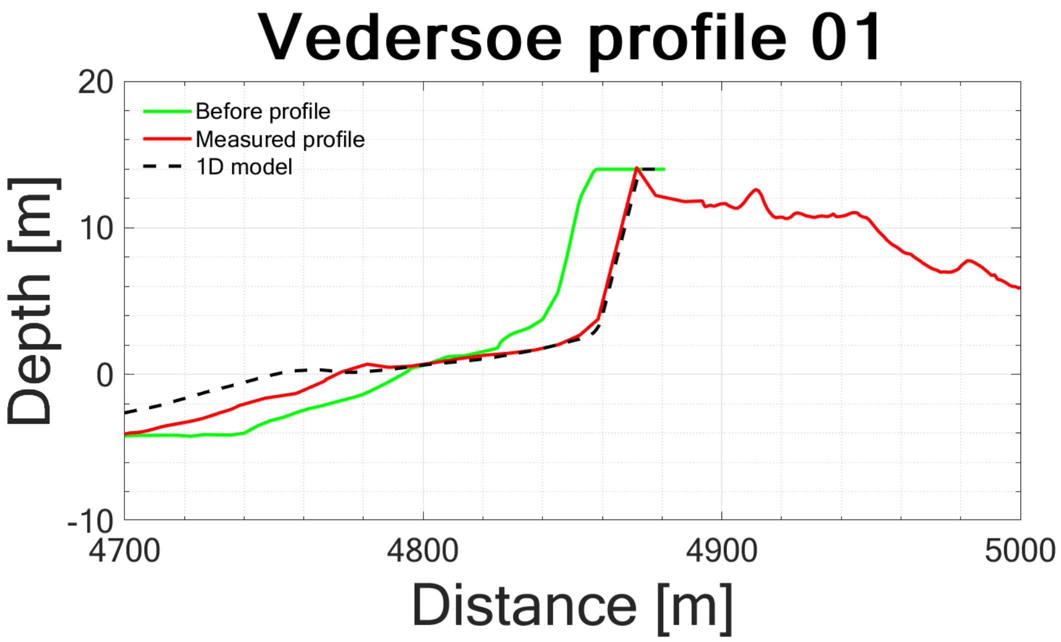

Figure 13 – Vedersoe profile 01 1D model result. The green line represents the profile before the storm, the red line presents the profile after the storm and the dashed black line represents the XBeach simulated profile.

The calibration result shows outstanding performance of XBeach. The model overestimates the retreat with less than a meter. It is not only the cliff retreat prediction, which is impressive, since nearly the whole beach and foreshore (except from the berm location) is well predicted.

5.2. 1D model validation results

In the following, the results from the four model validation cases are presented together with the measured profile before and after the storm event.

5.2.1 1D results for validation case 01

The model validation case 01 result for Vedersoe 02 is presented as coastal profiles before the storm (green line), after the storm (red line) and compared to 1D model profile (dashed line) as seen from Figure 14.

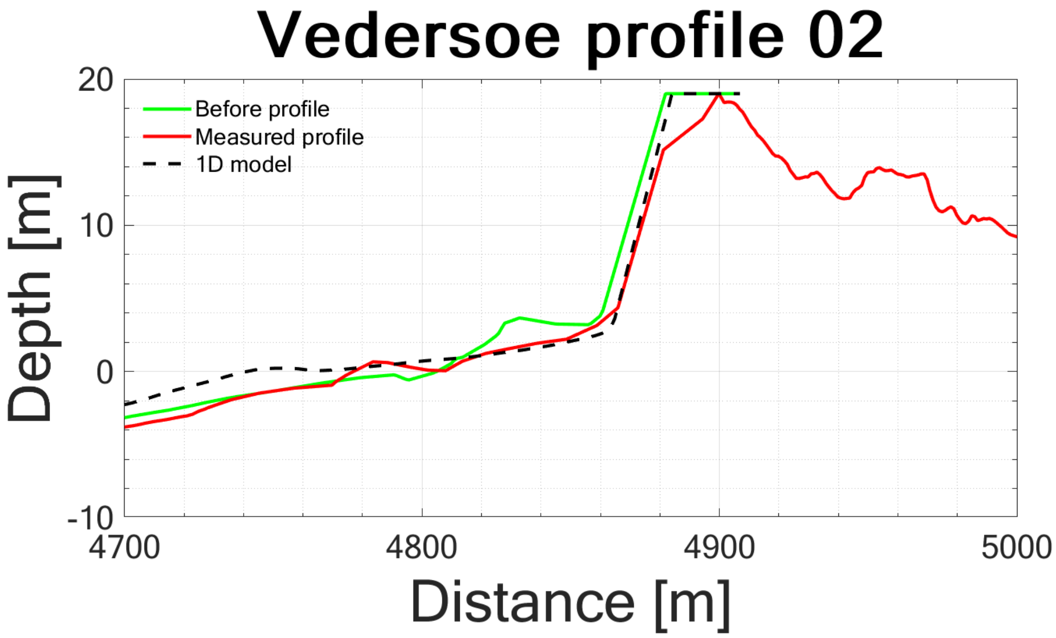

Figure 14 - Vedersoe profile 02 1D model result. The green line represents the profile before the storm, the red line presents the profile after the storm and the dashed black line represents the XBeach-simulated profile.

XBeach gives an excellent estimate of the cliff retreat at the profile Vedersoe 02. It is worth mentioning that it is the same hydrodynamic forcing, that resulted in a cliff retreat of 14 m in a nearby profile in the calibration case, Vedersore 01. Based on this result, XBeach shows exceptional performance in predicting local hot spots of cliff retreat.

5.2.1 1D results for validation case 02

The model validation case 02 results for Gedesby profile 01-04 is presented as coastal profiles before the storm (green line), after the storm (red line) and compared to 1D model profile (dashed line) as seen from Figure 15, Figure 16, Figure 17 and Figure 18.

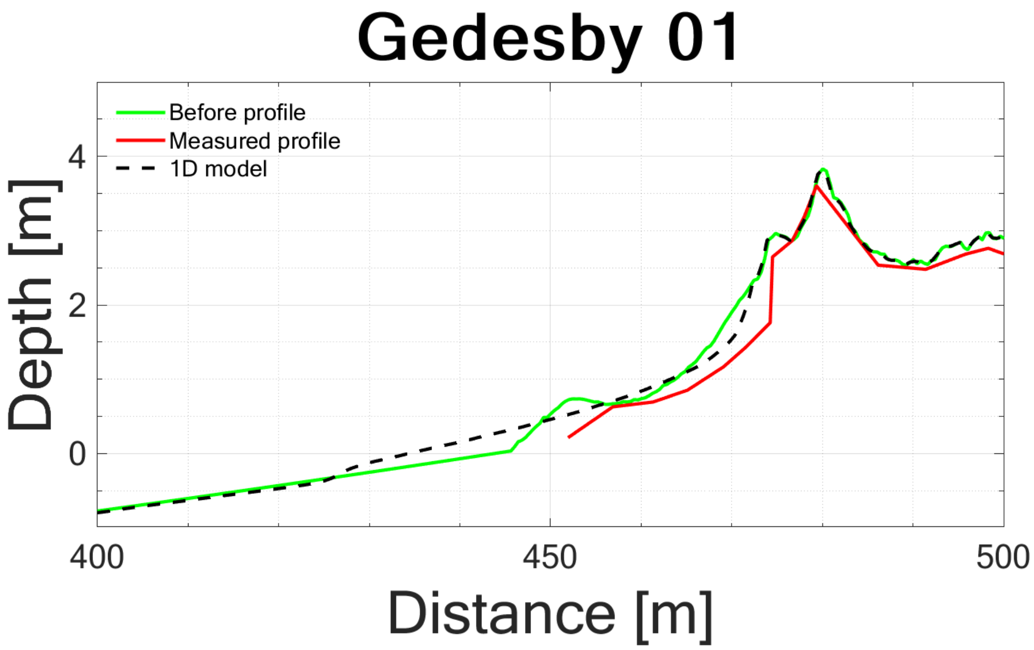

Figure 15- Gedesby profile 01 1D model result. The green line represents the profile before the storm, the red line represents the profile after the storm and the dashed black line represents the XBeach simulated profile.

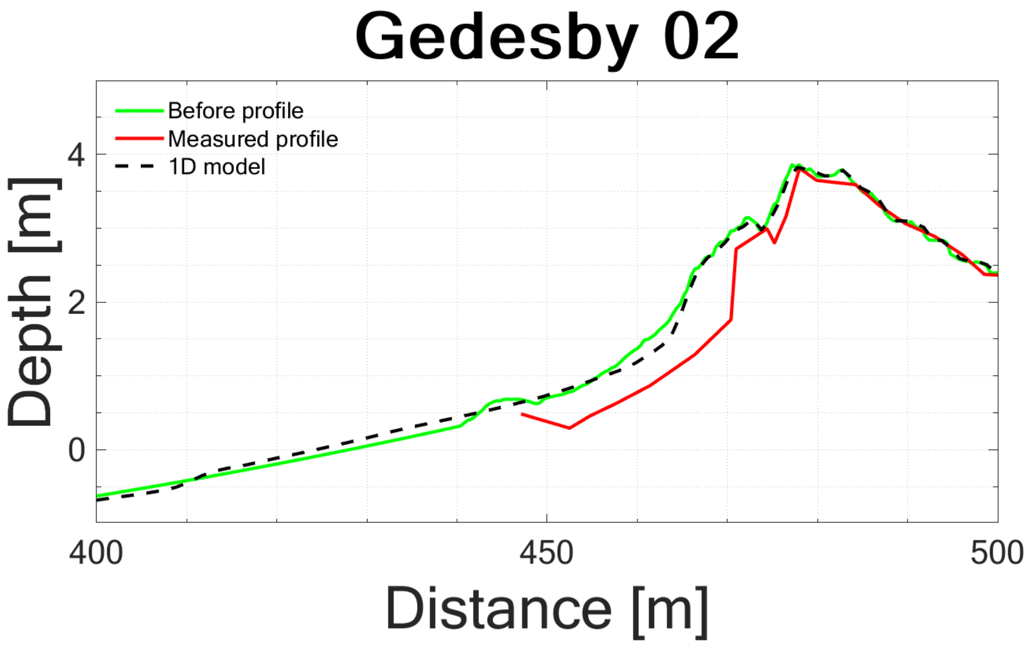

Figure 16 - Gedesby profile 02 1D model result. The green line represents the profile before the storm, the red line represents the profile after the storm and the dashed black line represents the XBeach simulated profile.

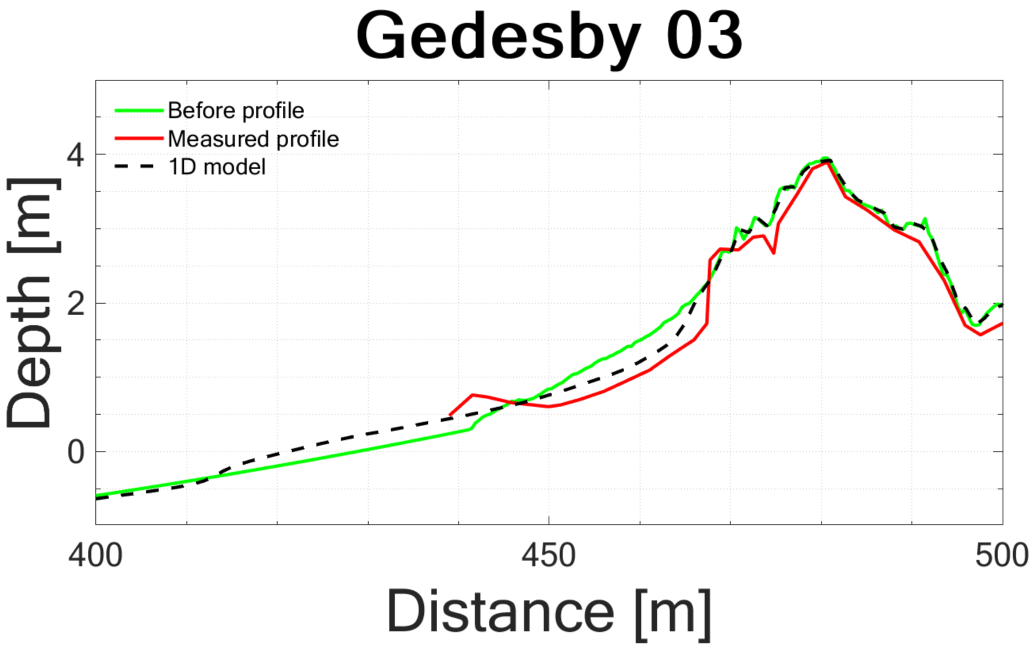

Figure 17 - Gedesby profile 03 1D model result. The green line represents the profile before the storm, the red line represents the profile after the storm and the dashed black line represents the XBeach simulated profile.

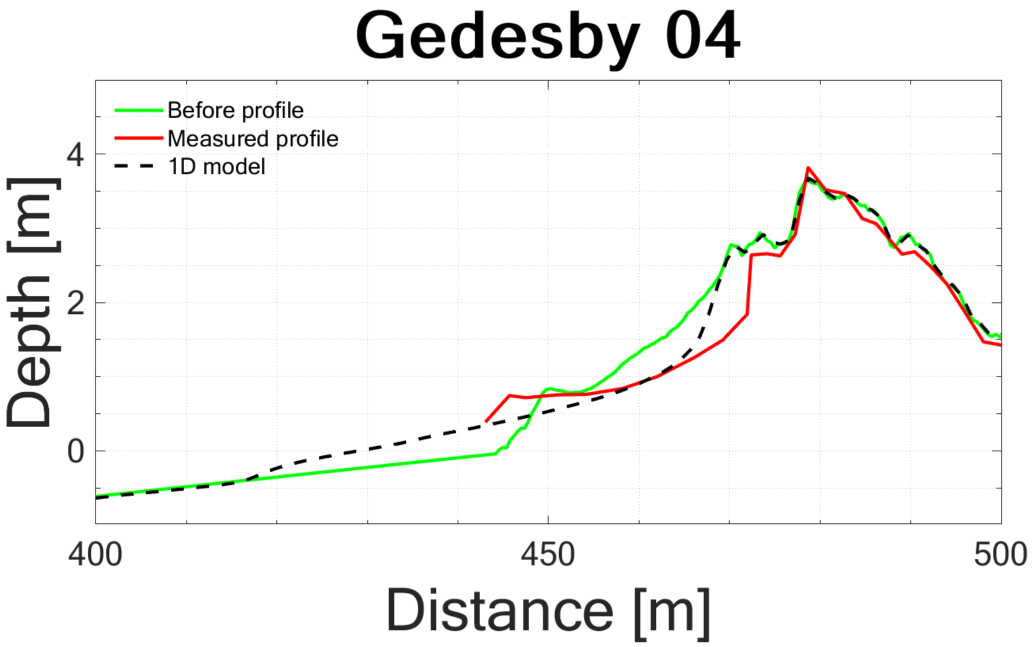

Figure 18 - Gedesby profile 04 1D model result. The green line represents the profile before the storm, the red line represents the profile after the storm and the dashed black line represents the XBeach simulated profile.

From all four simulations, it is clear that XBeach delivered adequate results on cliff retreats.

5.2.1 1D results for validation case 03

The model validation case 03 result for Havstokken is presented as coastal profiles before the storm (green line), after the storm (red line) and compared to 1D model profile (dashed line) as seen from Figure 19.

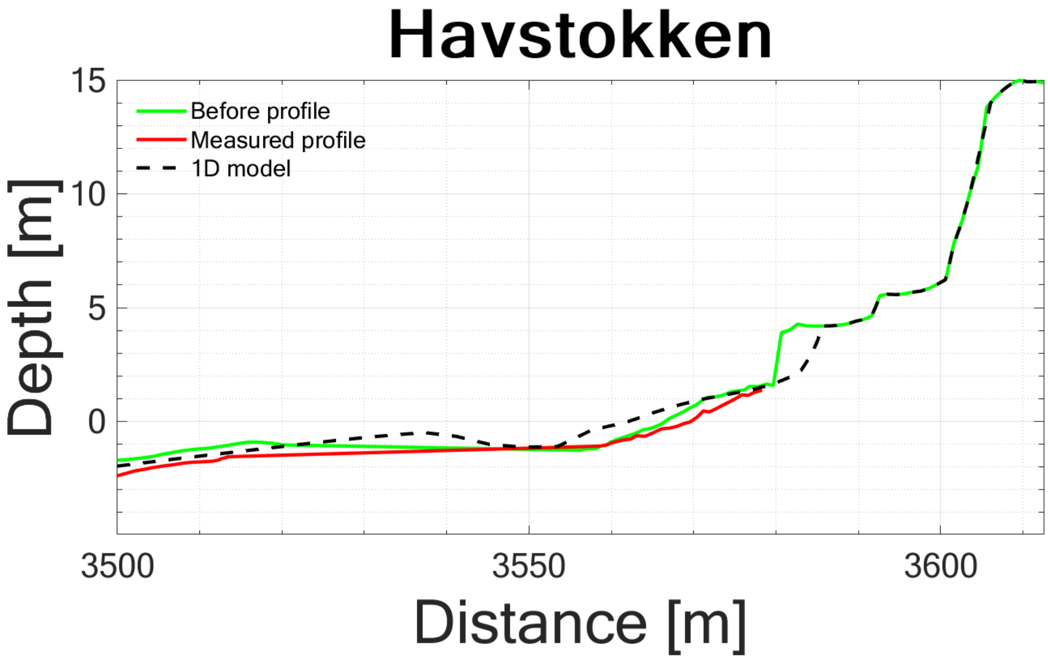

Figure 19 - Havstokken profile 1D model result. The green line represents the profile before the storm, the red line represents the profile after the storm and the dashed black line represents the XBeach simulated profile.

The measured profile (red line) after the storm at Havstokken does not cover the cliff. However, the measured profile and the 1D modelled profile becomes asymptotic at 1 m above sea level, indicating that XBeach is somehow able to reproduce the beach profile after the storm.

5.2.1 1D results for validation case 04

The model validation case 04 result for Heatherhill is presented as coastal profiles before the storm (green line), after the storm (red line) and compared to 1D model profile (dashed line) as seen from Figure 20.

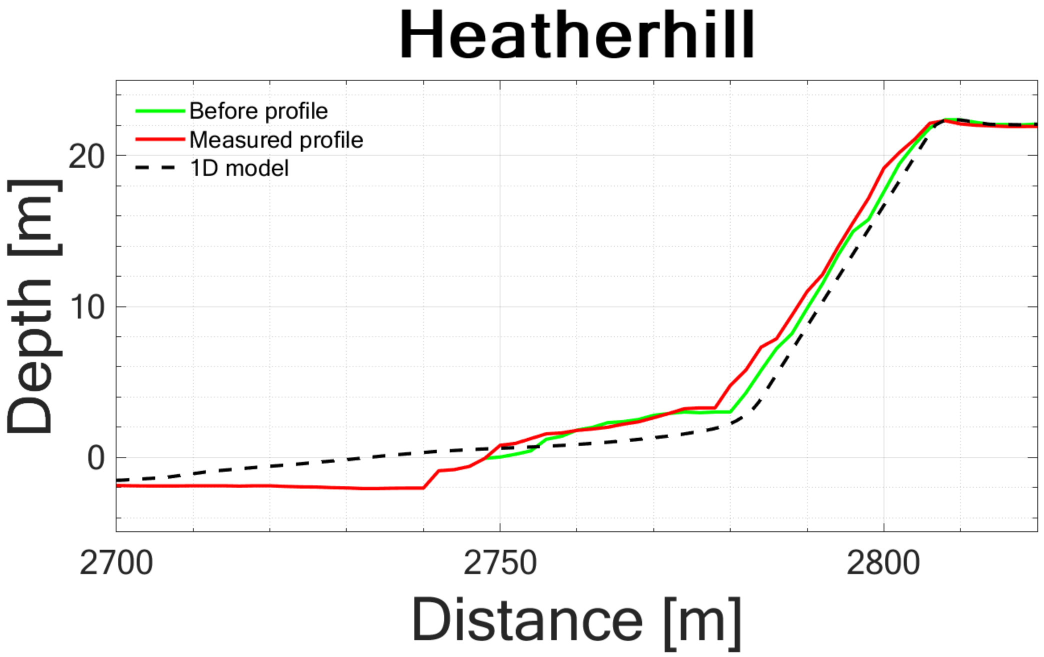

Figure 20 - Heatherhill profile 1D model result. The green line represents the profile before the storm, the red line represents the profile after the storm and the dashed black line represents the XBeach simulated profile.

The measured profile after the storm (red line) at Heatherhill is projected seawards compared to the profile measured before the storm. This inaccuracy is caused by a displacement between the profiles measured before and after the storm and is seen as zero retreat. The 1D model predicts a good estimate of the zero cliff retreat at Heatherhill.

5.3 2D model validation results

In this section, the 2D model results are presented for both Vedersoe and Gedesby. First, a difference plot is produced to show the coastal retreat after a storm as a 2D overview, see Figure 21. Contour lines before the storm are included to add information about the sand bar system in relation to the determined coastal retreat. Secondly, coastal profiles before and after the storm are compared with the 1D simulated coastal profile after the storm to further compare the 2D model with the 1D XBeach model, see Figure 22.

5.3.1 2D model extension case 01

The following figures represent the model results for the Vedersoe case. In this case, a clear sand bar depression is located in the northern part of the coast line before the storm, with the Vedersoe 01 profile intersecting close to the center of the depression, as can be seen from Figure 21.

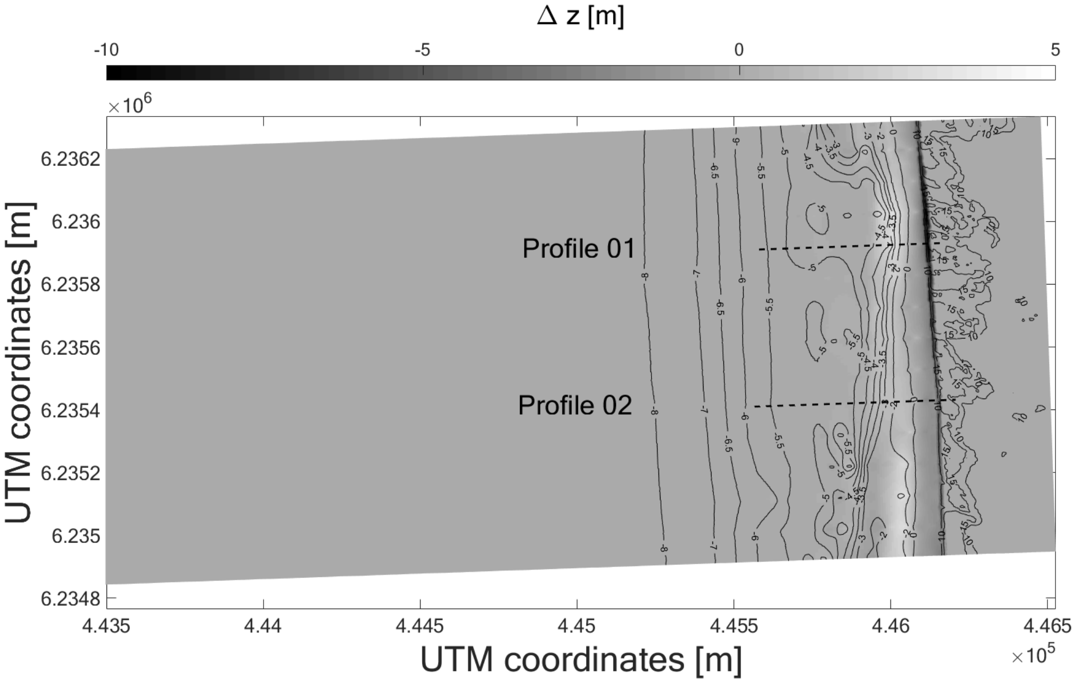

Figure 21 - Difference plot of Vedersoe. Black color indicates negative difference in elevation. Profile 01 undergoes a significant cliff retreat compared to profile 02. Depth contour lines of the before the storm bathymetry are included.

Significant retreat occurs in the surrounding area of Vedersoe profile 01, which is collocated at the sand bar depression. The depression in the outer bar allows the waves to reach further up on the shore and exerts more energy in the cliff, forcing the cliff to retreat.

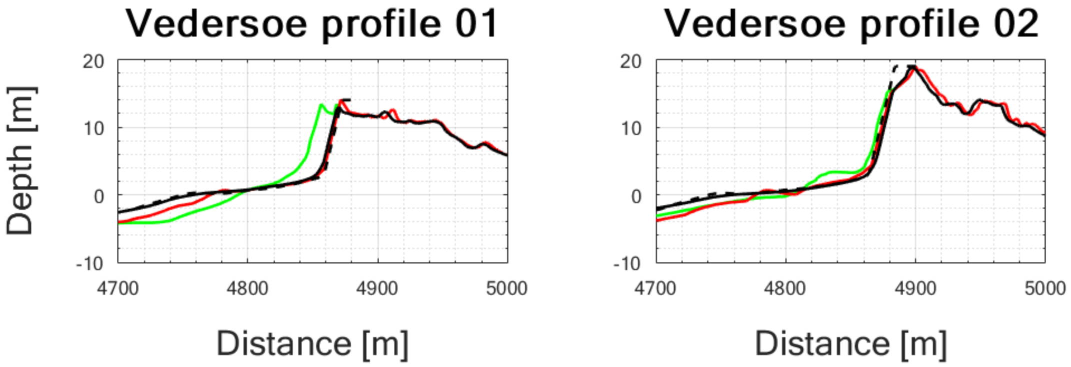

Figure 22 - Comparison of the before profile (green), 2D model (solid black line), 1D model (dashed black line) and the measured after profile (red line).

5.3.2 2D model extension case 02

Figure 23 and Figure 24 represent the model results for the Gedesby 2D case.

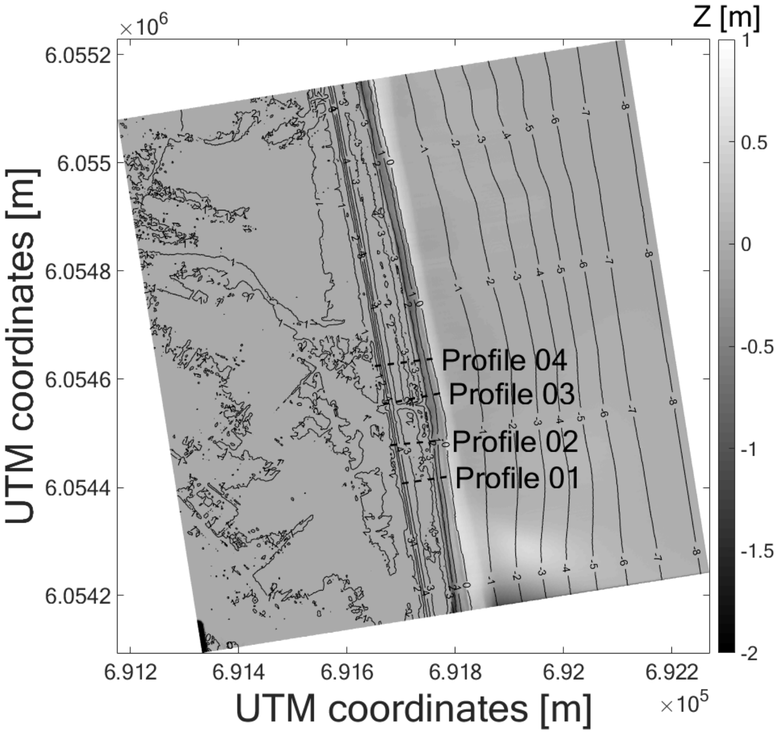

Figure 23 - Difference plot of Gedesby. Black colour indicates negative difference in elevation. Depth contour lines of the before the storm bathymetry are included

Figure 23 shows the differences in bathymetry before and after together with depth contours before the storm. No significant difference in cliff retreat in any of the four profiles appears. The model results from the 2D model are in overall agreement with the 1D model results. A boundary effect is seen along the southern lateral boundary from the coast and out to – 4 m. This boundary effect might have been mitigated by applying a non-equidistant grid, with coarser cells at lateral boundaries and refining it towards the model center to moderate the effect from boundaries.

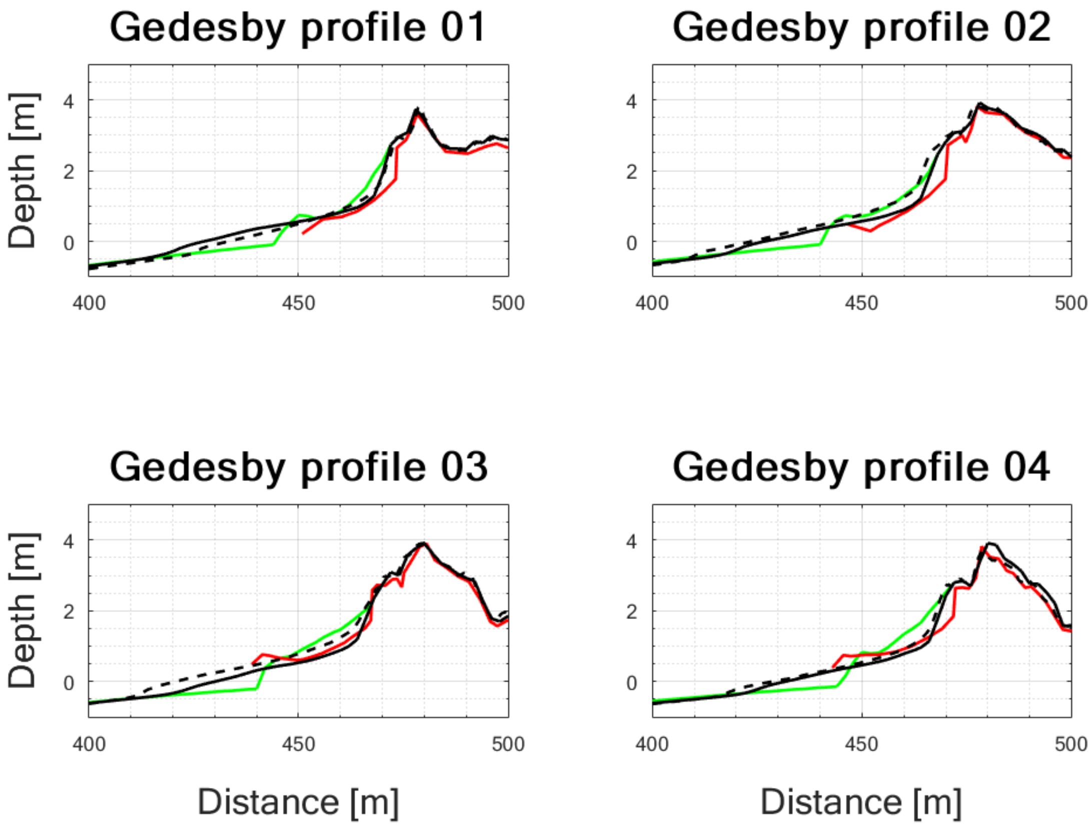

Figure 24 - Comparison of the before profile (green), 2D model (solid black line), 1D model (dashed black line) and the measured after profile (red line).

In summary, the 2D model results, in both Vedersoe and Gedesby test cases, show good agreement with the 1D model results. For the Vedersoe case, the largest cliff retreat is coincident with sand bar depressions.

6. Cliff retreat analysis

Sandy coastal cliffs retreat when they are exposed to severe storm conditions, where high wave heights and high water levels coincide. This chapter aims to derive a cliff retreat parameter based on the nature of different storms. Such a parameter can be used to predict the coastal retreat based on a storm forecast. This will help the coastal mangers to manage the risk of erosion.

6.1 Cliff retreat analysis methodology

In this section, the calibrated and validated model is applied as a numerical tool to analyze which morphological and hydrodynamic parameters correlate with the storm cliff retreat. In this analysis, only sandy profiles from the west coast of Denmark are used. To represent the coastline between Nymindegab and Thyborøn, four profiles are used (A,B,C and D) together with the Vedersoe profiles from the calibration and validation study and can be seen from Figure 25.

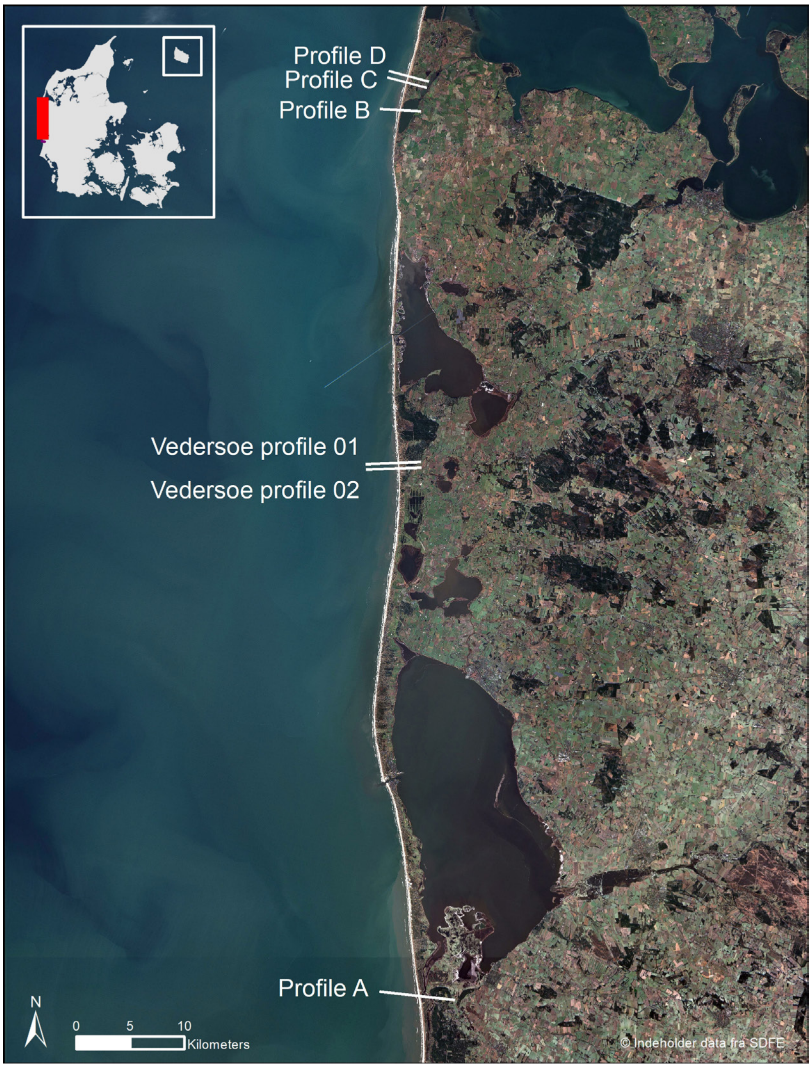

Figure 25 – Presents an overview of the coastal profiles comprised in this numerical analysis.

Retreat estimates in this analysis are determined on the coastal stretch between Thyborøn and Nymindegab, in total six coastal profiles and five historical storms constitute the basis of this analysis. Different storms are chosen as input for XBeach. Water levels from each storm are adjusted vertically to match a return period of 100, 500 and 1000 years, as determined for the coastline between Thyborøn and Nymindegab. Wave heights are not adjusted. 15 storms are generated from combinations of the historical storms and return periods. Together with the six coastal profiles, an analysis of 90 XBeach simulations are conducted (see Table 5).

Profile/storm	11	12	13	21	22	23	31	32	33	41	42	43	51	52	53
Profile D	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Profile C	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Profile B	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Vedersoe 01	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Vedersoe 02	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Profile A	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 5 - 15 storms are generated from combinations of the historical storms and return periods. Together with the six coastal profiles an analysis of 90 XBeach simulations is conducted.

6.2 Acting processes and stabilizing parameters

The calibration and validation work have together with previous model work, applied XBeach, and a physical understanding of the coastal system clarified important relationship between hydraulic, hydrodynamic, morphological parameters and cliff retreat. In this section, it is the intention to give a brief description of the parameters focused on in this study and to describe their relation. In this analysis, we distinguish between acting processes and stabilizing parameters.

The previously described XBeach simulations demonstrated that the peak water level is a key hydraulic parameter in the estimation of the cliff retreat. In this numerical study, we further investigate the time integral of the peak water level above wl = 1 m, between time t1 and time t2 as a measure of the potential for cliff retreat. This is a conservative choice, assuming that the water level has to reach a certain level (including wave set-up), to affect the cliff. It is clear, that the cliff retreat will only occur if the incoming wave energy is exerted during this time interval. Together with the peak water level, this time integral will constitute the governing hydraulic parameters, as seen from Figure 26.

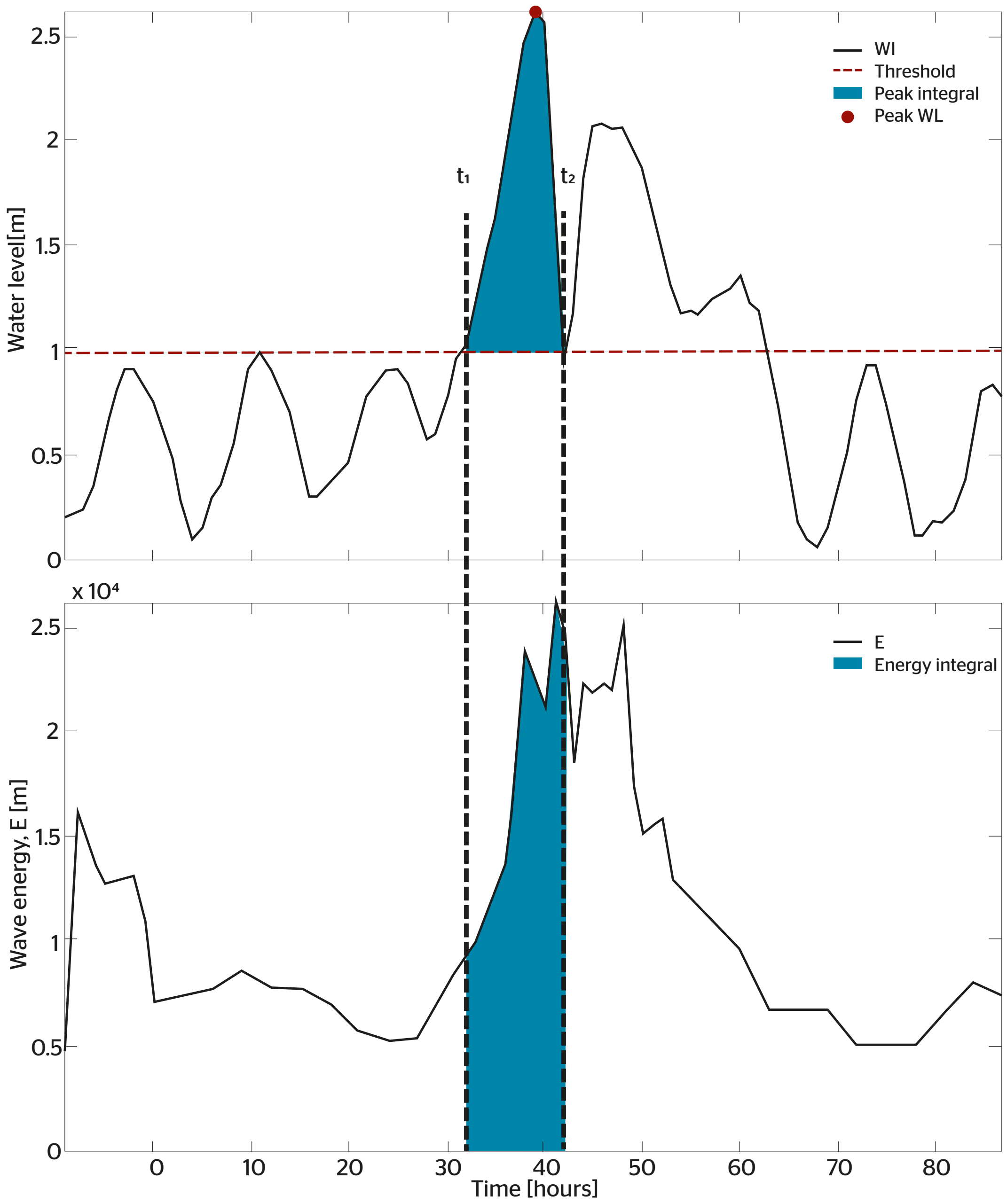

Figure 26 - Storm surge graph and wave energy graph. Water level and wave energy are presented each hour during a storm. The finite integral of the first coming water level peak above a threshold (blue fill). The total amount of wave energy perpendicular to the coast is determined as the area under the curve (blue fill).

During a storm, the water level can have multiple peaks, due to the tidal signal. Based on this numerical study, the largest peak in water level correlates with the largest amount of cliff retreat. Even though, the next coming water level peaks are large, relative to the largest, they do not add significantly to the total cliff retreat based on previous XBeach calculations.

Apart from the hydraulic parameters, the hydrodynamic parameters play a significant role in estimating cliff retreat, since no cliff retreat will occur if the waves were not present at the same time. As the governing hydrodynamic parameter in this study, we focus purely on the wave energy perpendicular to the coast. The wave energy scales with the wave height squared, whereas the significant wave height is used to calculate the wave energy, E.

$$E = \frac{1}{16}\rho g H_{m0}^2$$

In this investigation, we will determine the sum of wave energy perpendicular to the coastline during the same time interval, defined by t1 and t2, as the peak water level (see Figure 26). The total amount of wave energy in this interval equals the total amount of work acting on the cliff face.

The hydraulic parameters and the hydrodynamic parameters define the acting processes in this study.

In this investigation, the stabilizing parameters are governed by beach and dune morphological parameters. Berms represent a stabilizing effect as a barrier against water and waves and add sand volume which has to be eroded before the cliff. The top of the cliff toe reveals how large the wave run up has to be to reach the steep part of the cliff. Based on previous XBeach work, the cliff top compared to the peak water level is significant in the estimation of cliff retreat. If the water level is high, compared to the cliff top, large retreats have been observed. If the water level is higher than the cliff top, the profile is flooded and rapidly becomes smoothed out. The steepness of the cliff is obviously an essential parameter in estimating the retreat; however, it is not covered in this investigation. In total, the stabilizing parameters are: the beach volume, measured from the mean sea level (MSL) and up to the top of the cliff toe, and the top of the cliff (see Figure 27).

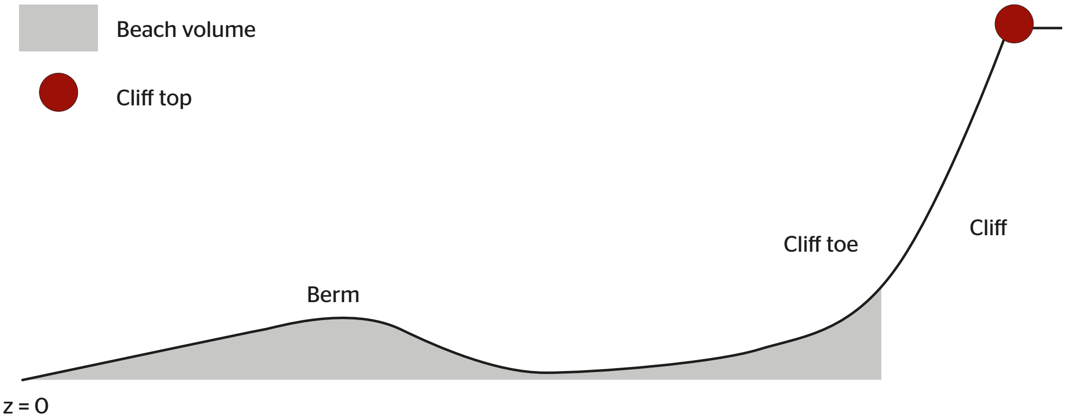

Figure 27 - Stabilizing parameters are; the beach volume, from MSL to the top of the cliff toe, and the top of the cliff, red marker.

6.3 The cliff retreat equation

Based on the acting processes and stabilizing parameters described in 6.2 Acting processes and stabilizing parameters, a retreat parameter is formulated as follows:

$$\Phi = \frac{wl_{peak}}{d_{cliff}} \frac{WL}{V_{beach}} \int_{t_1}^{t_2} E(t)\, dt \qquad for \qquad wl_{peak} < d_{cliff}$$

Where wl_{peak} is the peak water level, d_{cliff} is the cliff top, and *E* is the wave energy perpendicular to the coast and integrated over the time interval from ± 4 hours from the water level peak. Further, *WL* is the integrated water levels in the time interval ± 4 hours from the water level peak and V_{beach} is the volume of the beach between MSL and the top of the cliff toe, which cannot attain zero value. The dimensional analysis states:

$$\Phi = \frac{m}{m}\frac{Js}{m^3} ms = \frac{m}{m}\frac{\frac{kg}{s^2}s}{m^3} ms = \frac{kg}{m^2}$$

Based on the XBeach retreat estimates shown in Table 6,

Profile/storm	11	12	13	21	22	23	31	32	33	41	42	43	51	52	53
Profile D	30	35	40	19	23	25	34	40	43	8	11	14	34	38	39
Profile C	27	31	33	14	20	23	32	34	37	5	8	10	24	27	28
Profile B	13	16	19	8	10	12	12	15	18	1	3	5	11	13	15
Vedersoe 01	9	11	12	7	9	10	8	10	11	2	4	5	7	9	10
Vedersoe 02	0	2	3	0	0	1	0	1	2	0	0	0	0	2	2
Profile A	0	12	15	0	0	4	0	4	6	0	0	0	0	0	8

Table 6 - Table of model estimates of the cliff retreat from the 90 XBeach simulations

The modelled cliff retreats together with the corresponding cliff retreat parameter Φ are plotted on Figure 28. Some retreat estimates are highly overestimated and seems to differ from the linear relation. However, this is not explained from a geographic dependency in the cliff retreat results.

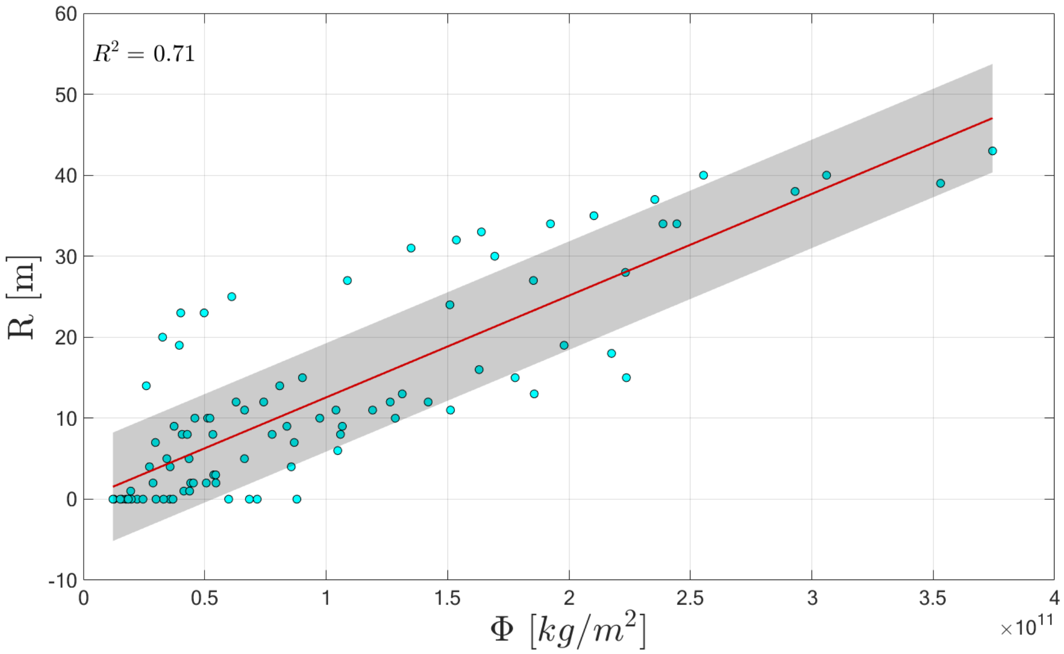

Figure 28 - Modelled cliff retreats R, from in total 90 XBeach simulations are plotted against the cliff retreat parameter Φ. A least square fit is revealing a linear correlation with a R² value of 0.71. Shaded area indicates total mean absolute deviation MAD_{tot} of ± 6.69 m.

A least square fit reveals a proportionality between the cliff retreats and the cliff retreat parameter based on 90 XBeach simulations. And a first attempt of a cliff retreat equation is given by:

$$R = a \cdot \Phi \qquad a = 1.26 \cdot 10^{-10}\ \frac{m^3}{kg}$$

Where a is the linear fit-parameter. It is seen from Φ, if either the water level or H_{m0} is zero, the retreat is zero. The mean absolute deviation, MAD, of the modelled retreat data in comparison to the linear fit, was estimated to approximately ± 6 meters. It was determined as the difference between the modelled retreat data and their respective predicted values based on the linear fit. All differences are totaled and divided by the number of simulations. Based on the calibration and validation study the MAD, was added to the MAD of this analysis to obtain a resulting measure of the total mean absolute deviation MAD_{tot} of the cliff retreat analysis estimates of around ± 7 meters.

6. Discussion

In this section the XBeach model and the modelling approach, leading to the promising results found in this project, are discussed to highlight important focus areas to further improve model application.

6.1 Model limitations

The application of an XBeach 1D model in a cliff retreat analysis is chosen to balance a strict time schedule with the availability of resources. To use an XBeach 1D model, it is assumed that the crossshore sediment transport is much larger than the longshore transport during a storm. The 1D model only considers a coastal transect perpendicular to the coast, hence longshore sediment transport is neglected (longshore sediment transport equals zero). Oblique wave heights are downscaled to the wave heights perpendicular to the coast. This can be assumed when the focus is on the retreat of a cliff face during storm, as in this project. Waves will refract when they travel through the breaker zone, so the wave direction is nearly perpendicular to the dune face, when they reach the coast. Cliff retreat is at least a 2D process where the longshore transport component needs to be accounted for to improve simulations. Future storm-erosion analysis in DCA will cover 2D modelling to quantify longshore effects during storm.

In the calibration and validation study, coastal profile measurements are used when available, however the time span between measured profiles before a storm and measured profiles after a storm varies from months to years. In this time span, long term changes to the coast is therefore not possible to account for in the XBeach simulations. A thorough investigation of the coastlines was conducted by combining visual information from orthophotos and measured hydrodynamic data to establish which high energy event had an impact on the dune face.

Yet, XBeach is not capable to model cliff retreat of cohesive sediments, hence only sandy cliffs are considered in this project. However, this will induce limitations when applying XBeach on a national scale, since a large part of the Danish coastline consists of moraine cliffs.

In this calibration and validation study, most types of coastline in Denmark are covered; however, the validation study lacks types of coastline, such as the Danish Straits, which are essential in the conclusion that XBeach is able to perform on a national scale. Coastal measurements of the Danish Straits before and after a storm are rare, and was only available for the north coast of Zealand and for the east coast of Falster. Based on field experience in DCA and the model work done in this project. fetch limited coastlines are only subject to little (few meters) of cliff retreats during storm events. Falster is exposed to a fetch of hundreds of kilometers in easterly wind directions and still only undergoes few meters of cliff retreat during the storm in 2017, based on XBeach. Applying the model case of Falster and of the north coast of Zealand as a proxy for the rest of the coastlines in the Danish Straits, it is assumed that XBeach is applicable in predicting cliff retreats on coasts in the inner Danish waters.

In the cliff retreat analysis, we adjusted the peak water level of each of the five historical storms to match an extreme storm of a return period of 100, 500 and 1000 years, respectively. To generate the extreme storms for every historical storm, the shape characteristics of each historical storm surge curve is preserved by adding a constant value to all water levels. This omits the individuality of each set of extreme storms, since the shape of the storm surge curve is not changed, allthough by nature it will be different in all extreme storms. Furthermore, the wave height and wave period are not adjusted. This means that two different extreme storms (with for instance 100 and 500 years return periods), based on the same historical storm, contain the same wave climate. By using the same wave climate in different extreme storms, it is not possible to argue that two estimated retreats from these extreme storms are truly independent of each other, as seen from Figure 28. However, extreme storm data are rare and most extreme storms are based on statistics and have never occurred, therefore this methodology was developed based on available data. In this cliff retreat analysis, we purely focus on the morphological changes in the dune face. The waves in the inner part of the profile are strongly depth limited and assumed independent of the differences in extreme water levels.

6.3 Use of XBeach for safety assessments

The Danish Coastal Authority is responsible for managing the risk of coastal erosion and flooding along the west coast of Denmark together with municipalities. Therefore, it is of highest interest to incorporate the advantages of XBeach modelling into the assessment of the safety level of the Danish west coast. Every year, millions of cubic meters of sand are added to the natural sediment transport. Hopefully, the application of XBeach will contribute to an improved understanding of cliff retreat, that we can benefit from this by adjusting the dune protection level to match the dune retreat of a 100 years return period determined by XBeach.

To maintain the required safety level of the Danish dunes, it is essential to understand the morphological system and thereby the impact on the dune during a storm. In future work, we will investigate the effect from strategic placements of nourishments on the dune safety during a storm. By generating a lookup table containing storm surge parameters, morphological parameters and nourishment parameters, we will investigate the possibility of developing a dune safety-scoring matrix based on dune retreats.

7. Conclusion

During this project work in the Interreg Building with Nature project, a XBeach storm erosion model has been set up as a numerical tool for improving the understanding of cliff retreat and, as a storm-erosion risk assessment tool.

By comparing XBeach model results to physical field measurements of coastal profiles before and after a storm, Xbeach has been calibrated and validated, and has shown that it can reproduce the retreat of a coastal cliff during a single storm with a deviation of ± 1 meter. Furthermore, it has been demonstrated by testing the calibrated model set-up on seven different types of coastal profiles (covering most types of Danish coast lines ranging from low to high coastal exposure), during storm, that a single model set-up can perform on a national scale in both 1D and 2D model approach. However, it was demonstrated that a 2D XBeach model performed better overall compared to a 1D XBeach model and the 2D model are able to show that cliff retreat is coincident with sand bar depressions.

XBeach has been applied in a cliff retreat analysis, to investigate which acting processes and stabilizing parameters govern the amount of cliff retreat. The analysis was conducted on the basis of 90 XBeach simulations consisting of in total 6 different coastal profiles in combination with 5 different historical storms adjusted to a 100, 500 and 1000 years return period. Based on this analysis a linear relationship between a proposed cliff retreat parameter Φ and the retreat of a coastal cliff R, with a mean absolute deviation of ± 7 meters is presented.

This project-work lead to the following conclusions:

1 A single XBeach model set-up is able to mimic cliff retreats on most types of coastlines in Denmark

2 The relationship between cliff retreats and the characteristic storm surge parameters, beach and dune morphological parameters are described by a first attempt cliff retreat equation.

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Appendix

XBmodel.m

```
% This program sets up a XBeachx model in steps using functions
% inputpar, nelayer and vegetation.

% 0. loading input parameters from input parameter function.
% 1. Loading representative profile.
% 2. Loading storm data.
% 3. Generating XBeachx model and write model files to model destination.


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear all
close all
clc


format long g
%% 0. initialize

out = 'INITIALIZING'

par = inputpar(); % calling parameter function

addpath(['C:\Users\',par.user,'\Desktop\MatlabToolbox'])
oetsettings

destout = ['C:\Users\',par.user,'\Desktop\XBeach_produktion\',par.profile,'\',par.storm]


%% 1. Loading representative profile


ds = 1; % discritization along coastal profile

% check if x y and z is the same length
try
bathy = xlsread([destout,'\bc\bathy.xls']); % loading bathy file
catch ME

err_msg = ME.message
out = 'Model set-up terminated!!'
return

end



x = bathy(:,1); % x data
y = bathy(:,2); % y data
z = bathy(:,3); % z data


% check if offshore boundary is first element in z vector, else flip x,y
```

```
% and z.
if z(1)<0

x = x; % x data
y = y; % y data
z = z; % z data


else
x = flip(x);
y = flip(y);
z = flip(z);
end

% check if vectors are same size
x = x(~isnan(x));
y = y(~isnan(y));
z = z(~isnan(z));

try
[x,y,z];
catch ME
err_msg = ME.message
err_msg = 'x,y and z are not same size'
out = 'Model set-up terminated!!'
return
end


% determine orientation of represnetative profile
alfa = atan( (y(1)-y(end))/(x(1)-x(end)))*180/(pi);

% check if profile is a straight line
tol = 1;

for i = 1:length(bathy)-1
a(i) = atan(( y(i+1)-y(i) ) / ( x(i+1) - x(i))) *180/(pi);

if a(i) < alfa - tol || a(i) > alfa + tol

out = 'Profile is not a straight line, model set-up terminated!!'
return

else

end

end


% determine discitization along x-axis
dx = cos(alfa*pi/180)*ds;

% Asuming the representative profile is normal to shore = coastal
% orientation. Converting coastal orientation to nautical coordiantes
% (N,S,E,W).
if alfa > 0 & x(1) > x(end)
coastOrien = 90 - alfa;

elseif alfa < 0 & x(1) > x(end)
coastOrien = 90 - alfa;
```

```

elseif alfa > 0 & x(1) < x(end)
coastOrien = 270 - alfa;

elseif alfa < 0 & x(1) < x(end)
coastOrien = 270 - alfa;

```

```
ylabel('UTM y-coordinates','fontsize',12)
xlabel('UTM x-coordinates','fontsize',12)
subplot(2,1,2)
line2 = line([0 sind(thetaMin)],[0 cosd(thetaMin)]);
line3 = line([0 sind(thetaMax)],[0 cosd(thetaMax)]);
hold on
plot(rx,ry,'--k')
axis equal

legend('Thetamin','Thetamax','Coast normal')
set(line2,'color','b','linewidth',1.5);
set(line3,'color','r','linewidth',1.5);
set(gcf, 'PaperUnits', 'centimeters');
set(gcf, 'PaperSize', [25 14]); % Can also be set to 'a4'
set(gcf, 'PaperPositionMode', 'manual');
set(gcf, 'PaperPosition', [0 0 25 14]); % the position parameters is ['distance to left border, distance to bottom, width, height']

saveas(fig3,[destout,'\fig','\XBsetup_',[par.profile],'.png']);
saveas(fig3,[destout,'\fig','\XBsetup_',[par.profile],'.fig']);


out = 'MODEL GENERATED'

out = 'STARTING XBEACH SIMULATION'
```

Inputpar.m

```
function [strpar] = inputpar()
%Her listes alle input parametre, så man ikke behøves at åbne XbModel.m
% user skriv dit bruger navn.
% Profile: repræsentativ profil nr.
% stormnr: nummeret på den af de 5 historiske storme der gav mest
% erosion. Nummeret referer til arangeringen af største
% vandstand.
% storm: nummeret referer til
% struct Angiver om der er en structur (skråningsbeskyttelse) 1/0,
% ja/nej.
% sneStart distance ind i land hvor toppen af skråningsbeskyttelsen
% er.
% veg Vegetaions modul tænd/sluk (1/0).
% vegStart start af vegetation i profilet.
% vegEnd ophør af vegetation i profilet.
% filter Angiv om der skal anvendes filtrering af punkter
% til qx beregninger. 1/0 (ja/nej).



%%%%%%%%%%%%%%%%%%%%%%%%%% Kan Ændres under her %%%%%%%%%%%%%%%%%%%%%%%%%%
% brugernavn til pc
```

```
strpar.user = 'b044911';

% profile
strpar.profile = 'vedersoe_1D_2200_prod';

% storm
strpar.storm = '11';

% skråningsbeskyttelse
strpar.struct = 0;
strpar.sneStart = 11280;

% vegation
strpar.veg = 0;
strpar.vegStart = 1000;
strpar.vegEnd = 2000;

% output af punkter
strpar.filterpkt = 0;




%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%

end
```

Kystdirektoratet
Højbovej 1
7620 Lemvig

www.kyst.dk