Impact of short-term bed level changes on wave characteristics at the Frisian dikes
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Title: Impact of short-term bed level changes on wave characteristics at the Frisian dikes

Abstract:

The aim of the Strength and Loading of Coastal Structures (SBW: Sterkte en Belasting Waterkeringen) project is to improve the quality of the models and methods used to derive the Hydraulic Boundary Conditions (HBC). This will enable managers and experts to have sufficient confidence to use these tools for the five-yearly assessments. Among other activities this is achieved by performing hindcasts of storm events in the Wadden Sea or comparable tidal inlets. The hindcasts (WL, 2006; Haskoning, 2006) and the additional analyses (Alkyon, 2007a, b) provided insight in the performance of SWAN in the Wadden Sea.

The current policy is to use the most-recent measured bed levels in the wave computation. Besides this, morphological changes are not taken into account in the evaluations. However, the measured bed levels consist of inherent inaccuracies and are subject to changes. Three different time scales can be distinguished for changes in the bed levels: period of several years, period between measurement and storm event and the period during a single storm. At least the changes during the latter period should be included in the determination of the boundary conditions at the primary coastal structures. The present investigation will focus on the effects of neglecting morphological changes during a yearly-averaged storm.

The objective of this study is to assess the effect of bed level changes on the wave transformation at the primary coastal structures along the Frisian coast. The present study focuses on the bed level changes during a 1/1 year storm. The outcome of this study also provides insight in to where the main bed level changes in the inlet occur and where updated bed level measurements are necessary.

References:

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I Introduction

1.1 Reliable wave boundary conditions for the Wadden Sea

In compliance with the Flood Defenses Act (“Wet op de Waterkering, 1996”), the primary coastal structures must be assessed every five years (2001, 2006, 2011, etc.) for the required level of protection on the basis of the Hydraulic Boundary Conditions (HBC) and the Safety Testing Regulation (VTV: Voorschrift op Toetsen op Veiligheid). These HBC must be derived anew every five years and established by the Minister of Transport, Public Works and Water Management.

There is a degree of uncertainty concerning the quality of the current HBC, in particular those for the Wadden Sea. This is because they were obtained from an inconsistent set of measurements and design values (WL, 2002). For the rest of the Dutch coast (the closed Holland Coast and the Zeeland Delta) the wave transformation model SWAN (Booij et al.,1999, SWAN homepage http://www.swan.tudelft.nl) was applied. Presently, there is insufficient confidence in the performance of SWAN in the Wadden Sea. The available data from the Wadden Sea and from elsewhere, has not been studied sufficiently. SWAN needs to be validated, calibrated and if necessary, modified to achieve maximum performance in the Dutch Wadden Sea, using data from that area and from elsewhere.

The “Strength and Loading of Coastal Structures (SBW: Sterkte en Belasting Waterkeringen) project” (SBW, 2005) has the task of improving the quality of the models and methods used to derive the HBC to enable the managers and experts to have sufficient confidence to use these tools for the five-yearly assessments.

Among other activities this is achieved by performing hindcasts of storm events in the Wadden Sea or comparable tidal inlets. The hindcasts (WL, 2006; Haskoning, 2006) and the additional analyses (Alkyon, 2007a, b) provided insight in the performance of SWAN in the Wadden Sea.

The current policy is to use the most-recent measured bed levels in the wave computations. Besides this, morphological changes are not taken into account in the evaluations. However, the measured bed levels consist of inherent inaccuracies and are subject to changes. Three different time scales can be distinguished for changes in the bed levels: period of several years, period between measurement and storm event and the period during a single storm. At least the changes during the latter period should be included in the determination of the boundary conditions at the primary coastal structures. The present investigation will focus on the effects of neglecting morphological changes during a yearly-averaged storm.

1.2 Objective of the study

The objective of the study is to assess the effect of bed level changes on the wave transformation at the primary coastal structures along the Frisian coast. The present study focuses on the bed level changes during a yearly-averaged storm for which different types of data are available.
1.3 Study approach

The performance of SWAN in the Wadden Sea is evaluated with hindcast computations for the Amelander Zeegat (see Figure 1.1 for location of this inlet). Since 2003 wave measurements have been conducted at several locations in the Amelander Zeegat. This wave data together with wind fields will be input for the hindcast of the considered storm period. The storm period of 1 – 3 January 2005 has been selected for this study because of its relatively long storm period, its yearly-averaged character (typical return period of 1 year) and the availability of water level, wave and wind measurements.

To obtain insight in the effect of short-term bed level changes on the wave transformation, stationary SWAN computations for a hypothetical storm (return period of 4000 years) have been carried out with the bed levels prior and just after the 2005 storm. The former bed levels are obtained from the measured bed levels in summer 2004, while the latter bed levels are obtained from morphological simulations of the 2005 storm itself.

The morphological simulation has been performed with the advanced morphological module of Delft3D. The simulation, based on a hydrodynamic model (Delft3D-FLOW) and a wave model (SWAN) covers the full storm period. The boundary conditions of the wave model are based on the measured wave spectra of the two most offshore wave buoys (AZB11 and AZB12). During the simulation the wave fields are computed together with the current velocities due to forcing of tide, wind and waves. The wind fields are temporally and spatially-varying. The simulation includes a frequent exchange of information between the hydrodynamic and wave computation. The computed water level and current fields are provided to the wave computation, while the hydrodynamic computation regularly receives the computed wave fields. During this coupled flow-wave simulation the sediment transports are computed at every time step and the bed levels are directly updated.

The hydrodynamic model has been validated with measured water levels at two locations. The wave model has been validated with measured wave heights along the transect of wave buoys in the inlet itself.

The computed bathymetry at the end of the storm period has been used for the wave computation for the hypothetical storm with a return period of 4000 years. The comparison between the two wave computations with the different bathymetries (prior and after the storm), firstly provides insight in the effect of the bed level changes during a single storm on the wave transformation in the inlet. Secondly, the subsequent effect on the wave conditions at the primary coastal structures at the Frisian coast has been determined.

1.4 Content of the report

The environmental conditions during the considered storm period have been described in Chapter 2. The model setup and the selected settings and model parameters are discussed in Chapter 3. The results of the morphological simulations are presented in Chapter 4. The effects of the bed level changes on the wave transformation and its effect on the wave conditions at the Frisian coast are assessed in Chapter 5. Conclusions can be found in Chapter 6. The internal review was conducted by Ap van Dongeren. An independent review of the report was conducted by Dano Roelvink (UNESCO-IHE).
2 Environmental conditions during storm

In 2003 a transect of wave buoys was deployed in the tidal inlet of Ameland. Since the deployment, several storms have occurred in this area. For the purpose of this study, the relatively long storm of 1 – 3 January 2005 has been chosen. Measured water levels and wind and wave conditions are available for this period, as well as spatially varying wind and pressure fields.

The storm of 1 – 3 January 2005 has the following characteristics: Around New Years Eve a cold front passed the Dutch coast, after which a western wind developed of 8 Bft in the southern North Sea and 9 Bft above the Wadden Sea. During 2 January, the wind remained stormy and started to decrease to 6 Bft in the morning of the 3rd January. The westerly storm caused significant increase of the water levels in the northern coastal areas, with a maximum additional water level elevation of 1.54 m at Harlingen.

2.1 Locations of measurement stations

At several locations water levels, wave and wind conditions are measured. These locations are depicted in Figure 2.1. In the following paragraphs the measurements for the storm period at these locations are discussed.

2.2 Water levels

Water levels were measured at two stations in the study area: Terschelling Noordzee and Nes (see Figure 2.1). The exact coordinates are given in Table 2.1. The measured water level elevations at both locations are presented in Figure 2.2. It is evident that the tidal range inside the tidal basin (Nes) is larger than the water levels at sea and consists of a phase lag of about 1.5 hours.

2.3 Wind and pressure conditions

The spatially varying wind fields were provided by RIKZ and derived from HIRLAM data on an 11 km grid. A downscaling technique was applied to improve the spatial resolution of these wind fields by including the effect of the local surface roughness on the wind flow. The downscaling was performed by KNMI downscaling software. The spatial resolution of the downscaled wind field was 250m. Detailed information on the principles behind the downscaling technique can be found in Verkaik (2006) and Verkaik et al. (2006). The HIRLAM data was delivered with a time interval of 6 hours.

Figure 2.3 shows the spatial variation of the wind speed and direction of the downscaled HIRLAM wind fields for 1 - 3 January 2005. The HIRLAM data indicates that the spatial
variation of the air pressure varies little for this tidal basin. The variation of the air pressure in time during the storm of January 1 – 3 is within the range of 990 mbar during the peak of the storm and up to 1018 mbar prior and past the storm event.

Figure 2.4 shows the wind speeds and directions of the wind at Huibertgat, Lauwersoog and Vlieland during the storm. See Figure 1.1 for the orientation of these stations in relation to the Amelander Zeegat. The direction during the storm period varies between 190 and 290 degrees (nautical). For all locations it holds that the wind speed increases during January 1 from about 3m/s up to the maximum occurring wind speed during the storm. This maximum differs for each location. For Vlieland, located west of the inlet, wind velocities of 22 m/s during the peak of the storm were measured. The maximum occurring wind velocity for the stations east of the Amelander Zeegat was around 20 m/s.

### 2.4 Wave conditions

Ten wave buoys were located in the area of interest, of which two did not collect any relevant data (Svasek, 2005). The locations of the wave buoys and the corresponding depths at those locations are summarised in Table 2.1. The measured wave heights at the eight locations are presented in Figure 2.7 for the period between 1 and 5 January 2005.

Four of the remaining eight wave buoys were directional wave riders, which provide a directional variance density spectrum as well as a mean direction and directional spreading per frequency bin at every ten minutes. The other four wave buoys are non-directional wave riders. The measured spectra are provided as energy density, mean wave direction and directional spreading as function of frequency. These frequencies are linearly distributed between 0.01 Hz and 0.5 Hz with a resolution of 0.01 Hz. The convention of the directions in the dataset is nautical. The directions indicate where the waves are coming from.

The measured data transformed to $H_{m0}$ is presented in Figure 2.5 for each of the eight wave buoys separately. The maximum occurring wave height of 6.3m is measured at buoy AZB11. Along the propagation of this wave towards the inlet the wave height decreases to 2.3m at AZB31. Further inside the inlet (AZB51) the wave heights decrease to 1m during the peak of the storm.

### 2.5 Topography

The topography of the Amelander Zeegat is rather complex due to the presence of several channels and flats. The main channel is the Borndiep, which is sheltered by a large ebb delta often named the Bornrif (see Figure 2.1). The channels and flats in the Amelander inlet are constantly moving. According to Israël (1998) there is a cyclic pattern visible in the inlet, with a morphologic period of about 50 to 60 years. The cyclic patterns develop from a one-channel system in a two-channel system and back into a one-channel system.
3 Model schematization

3.1 Introduction

To simulate the hydrodynamic and morphodynamic processes the process-based numerical model Delft3D has been used. Two modules of Delft3D are used in this study: Delft3D-FLOW and Delft3D-WAVE. Delft3D-FLOW is the central module that provides the hydrodynamic basis for all the other modules of Delft3D. In this module the hydrodynamic flow, sediment transport and bottom changes (morphology) are computed simultaneously with the ‘Online Sed’ module. Delft3D-WAVE is used to simulate the evolution of wind-generated waves and uses SWAN (version 4051A).

These two modules are coupled with a pre-defined frequency when information is communicated in two directions. Therefore Delft3D-FLOW is able to include wave forces in the hydrodynamics and sediment transport and conversely Delft3D-WAVE is able to use the hydrodynamics and calculated bathymetry of the Delft3D-FLOW model.

The first section describes the model schematization and setup of the hydrodynamic model. Section 3.3 describes the wave model. Finally, Section 3.4 will go into the morphological model.

3.2 Hydrodynamic model

3.2.1 Boundary conditions

The computational grid of the hydrodynamic model is shown in Figure 3.1 and is based on Roelvink and Steijn (1999). The grid in the Wadden Sea covers the area up to the two watersheds (west and east) and is extended in nearshore direction towards the Frisian dikes.

The bathymetry used in the simulations was composed from various available data sets. The main model area was covered with data from yearly surveys (soundings) in the area with a minimum depth level of + 0.5m above N.A.P. (Figure 3.2). These soundings were processed by RIKZ to obtain a digital representation of regular grids with a resolution of 20m. A part of the model area was not covered by the survey of 2004, but was surveyed in an earlier or later stage. These missing values were filled by interpolating and extrapolating the depth values from earlier and (if available) later surveys. The depth information required for the more offshore areas is taken from Admiralty Charts.

At Terschelling and Ameland, data was available from Adviesdienst Geo-informatie en ICT Rijkswaterstaat (AGI) for depth contours 3m –NAP up till 10m +NAP dating from end of 2003. Near the Frisian dikes, the bathymetry was based on high resolution (5m) laser altimetry measurements from 2006.
Three open boundaries are located outside the Amelander inlet, offshore of Terschelling and Ameland. The remaining boundaries are set as closed boundaries for flow as well as for sediment. From the three boundaries, the offshore boundary is prescribed as a water level type of boundary condition. The water level is forced with astronomical components. The two lateral boundaries are prescribed as Neumann boundaries, meaning that instead of a pre-defined water level, alongshore water level gradients are imposed at the lateral boundaries. The alongshore gradient is assumed to be the same over the entire length of the lateral boundary, since with a limited cross-shore extent the gradient will not vary much in cross-shore direction.

The wind and pressure fields applied in the model are derived from the HIRLAM fields. This downscaled data, delivered by RIKZ, has a frequency of six hours. As the time step of the hydrodynamic computation is a fraction of the six hours time step of the HIRLAM fields, the data is interpolated in between.

Additionally to the tidal components prescribed at the alongshore boundary, the measured surge levels at station Terschelling Noordzee are applied uniformly along the boundaries. This enables Delft3D-FLOW to include a surge level in the results without using an overall larger scale model to provide wind setup at the boundary conditions.

### 3.2.2 Model settings

The hydrodynamic time step is set at 15 seconds which fulfils the Courant number criteria for free surface waves. Furthermore, the hydrodynamic model is run in depth averaged mode.

The bed roughness is prescribed with a Chézy coefficient of 65 m$^{1/2}$/s for the hydrodynamic computations (tidal forcing only). For the morphodynamic computations the bed roughness predictor model has been activated which results in a time- and space-varying roughness field.

### 3.3 Wave model

#### 3.3.1 Boundary conditions

Measurements of the wave buoys provided wave energy density spectra at every ten minutes during the considered storm period. The measured wave spectra at the two most offshore wave buoys (AZB11 and AZB12) have been used as boundary conditions for the wave model. Along the northern (offshore) boundary of the domain west of AZB11 the measured spectra of AZB11 have been imposed uniformly. East of AZB12 the measured spectra of AZB12 have been applied. For the area between the buoys of AZB11 and AZB12, SWAN interpolates the components of the spectra linearly. Along the western and eastern cross-shore boundaries (at sea), the spectra of AZB11 and AZB12, respectively, are imposed uniformly.
3.3.2 Model settings

The computational grid of the wave model is shown in Figure 3.1. Most of the parameters used in the Delft3D-WAVE computation are default values of SWAN. Only the settings below are prescribed to enhance the physics concerning whitecapping and quadrupletts.

The latter line leads to more dissipation in the high-frequency range of the waves and improves the behaviour of the wave field near the offshore boundary (WL | Delft Hydraulics, 2006).

```plaintext
GEN3 WESTH
QUAD IQUAD=8
WCAP KOM 2.36E-5 3.02E-3 2.0 1.0 1.0
```

Triad wave-wave interactions are not included in the computations due to less satisfying results in previous-SBW-related assessments. Presently, insufficient experience and verification are available regarding the non-stationary mode in SWAN. Therefore, all wave computations in this study are performed in stationary mode.

3.3.3 Wave-current interaction

The wave measurements provided spectral wave data for every ten minutes. This wave data consists of frequent relatively large differences in wave heights from one measurement to the other. For the communication between the hydrodynamic and wave model an interval of 20 minutes has been chosen. This means that SWAN performs a (stationary) computation every 20 minutes with the corresponding measured wave spectra as boundary conditions.

Besides the imposed averaged wave spectra SWAN uses the water levels, currents and bed levels, provided and computed by the hydrodynamic model for that specific time. After the SWAN computation, the wave results are provided to the hydrodynamic model in order to compute the wave-driven currents, setup and sediment transports. After a 60-minute hydrodynamic computation, the recomputed water levels, currents and bed levels are provided to SWAN again. This exchange frequency of information is kept constant throughout the hydrodynamic simulation.

3.4 Morphological model

3.4.1 Sediment transport formulae

In order to compute bed level changes during the storm period, the sediment transports need to be calculated. In this study, the state-of-the-art formulation of Van Rijn, called TR2004, has been applied (van Rijn, 2004).

This formulation categorizes sediment transport not only into bed load and suspended load transport, but also distinguishes current-related transport and wave-related transport.
TR2004 uses the advection-diffusion equation to calculate the current-related transport. The depth-averaged concentration in this advection-diffusion equation is determined using the method of Galappatti. For the wave-related and current-related bed load transport Van Rijn developed a bed load transport formula. The influence of waves is included in this formula by modifying the bed shear stress based on a new approach. TR2004 also accounts for suspended transport due to wave-asymmetry. This transport component can be significant in the shallow areas. The wave-related suspended transport is added as an extra component to the bed load transport.

An additional feature in TR2004 is a bed roughness predictor. The bed roughness does not have to be pre-defined in this way. By applying the roughness predictor the bed roughness is calculated every time step. Van Rijn relates the roughness to the grain size in case of small-scale ripples and to the form roughness in case of mega-scale ripples and dunes. The mobility parameter is also considered in the approach to predict the ripple dimensions. On the basis of the mobility parameter the prevailing wave-flow regime is determined.

### 3.4.2 Sediment characteristics and bed updating

Limited available data indicates that the sediment diameter ($D_{50}$) varies from 220-260μm on the intertidal beach to 150-160μm in the lower shoreface (Guillen and Hoekstra, 1996). However, no further data was available on the spatial variation of the sediment grain sizes. Therefore, a mean sediment diameter is prescribed uniformly at 200μm in the model.

The morphological factor, normally used to speed up the morphological activity is set at one.
4 Results and analysis of the morphodynamics during the storm

4.1 Introduction

This chapter presents the results of the morphodynamic simulation of the storm of 1 – 3 January 2005. This simulation was conducted with the coupling between Delft3D-FLOW and Delft3D-WAVE. These results are compared with the measured available data during the period. First the hydrodynamic results are described (Section 4.2) followed by the wave results (Section 4.4). Finally, the bed level changes are discussed which is the most relevant input for Chapter 5.

4.2 Water levels

The measured water levels, shown in Figure 2.2, are compared with the computed water level results. Figure 4.1 shows the time series of both datasets (indicated by the blue respectively the green line). Due to the tidal components and the surge level prescribed at the offshore boundary, the computed water level at the offshore location “Terschelling Noordzee” fits the measured data well. This computation includes the wind and pressure fields. When the tidal wave propagates into the inlet, a slight difference in the computed and measured data is determined. The measured water level at Nes around the peak of the storm is higher than the computed water level.

A harmonic analysis is conducted for the water levels at Terschelling and Nes for ten major tidal components (see Figure 4.2 and 4.3). The analysed results are based on a neap spring simulation with only tidal forcing. The computed results are compared with the available values of components from RWS. The figures indicate the amplitude of each component and the phases. It is concluded that the water levels of Terschelling Noordzee and Nes are very well represented by the model compared to the RWS tidal components. Differences between the amplitudes of the computed and measured water levels are within 10% of the observed values.

The differences in Figure 4.1 between measured and computed water levels at Nes are therefore expected to be induced by the meteorological (already included) and wave conditions. Figure 4.1 also shows the results of a conducted simulation where Delft3D-FLOW is coupled with Delft3D-WAVE (the red line in the figure). As a result of including waves in the simulation, the water level around to peak of the storm fits somewhat better with the measured data. This effect is explained by the waves forcing extra water volume inside the tidal inlet (e.g. by breaking of waves, see Section 4.4) and therefore resulting in higher water levels inside the inlet.

However, much of the discrepancy remains and must probably be ascribed to large-scale wind setup within the Wadden Sea, which is not represented because of the closed boundaries inside the basin. Another cause of the discrepancy can be sub-grid
meteorological effects like squalls or wind oscillations, which are presently not included in the wind and pressure fields.

4.3 Discharges through the inlet

Due to waves transformation towards the inlet an extra discharge into the tidal basin is induced, enhancing water level elevation. Figure 4.4 shows the effect of the waves on the discharge through the entrance channel. The lower panel shows the differences between the discharge induced by the tide alone and by the tide and waves. A positive value means inflow. It can be observed that up to the peak of the storm a slight increasing inflow is present. Just after the peak the inflow decreases and remains fluctuating around zero. The persistent inflow during the build up of the storm causes higher water levels in the basin. Taking into account the effect of waves has a positive effect on the water levels inside the basin. In this way the mismatch between the computed and measured water levels at Nes is reduced by about 30 - 40% during the high waters (see Figure 4.1).

4.4 Wave computations

It is mentioned in Chapter 2 that along a transect of wave buoys in the tidal inlet wave data is measured during the storm of 1 – 3 January 2005. For the comparison, these measured wave data (significant wave heights) are plotted in Figure 4.5 together with computed results.

The figures show that high wave energy is found on the North Sea side of the barrier island, which is dissipated for the most part either on the coast of the barrier islands or on the ebb tidal delta. The high periods associated with these waves persist only a short distance beyond the tidal inlet. Moving from the barrier islands to the coast, the prevailing NW wind gives rise to young wind sea, producing significant wave heights of approximately 0.5m. The measured 1D-spectra of buoy AZB11 are similar compared to the computed 1D-spectra, only at the start of the storm, the computed wave energy of the spectral domain is less. The buoys AZB41 and AZB51 show large differences in wave energy when comparing the measured and computed results. During the whole storm, too much wave energy is generated in the entrance channel of the tidal inlet.

Figure 4.5 indicates the effect of the tidal elevation in the total water depth and subsequently in the wave height results. This is mainly visible for the wave buoys from AZB31 towards the Frisian dikes, due to limited depth affecting the wave heights. A peak in the wave heights can be observed about every 12 hours.

For a more detailed comparison between model and measurements, the wave spectra at the peak of the storm are presented in Figure 4.6. The corresponding velocity and wave height fields are plotted as well. The four measured wave heights are indicated with coloured circles in the wave height plot. As can be seen from the figure, the computed offshore wave spectrum agrees very well with the observed spectrum. For station AZB31 the model is slightly overestimating the two spectral peaks. For station AZB41 and station AZB51 the
agreement is poor. The model computations highly overestimate the wave energy propagation into the inlet at this moment of the storm.

Figure 4.7 shows typical wave fields ($H_s$ in m) and directions at various moments during the storm. This figure indicates as well that most of the wave energy is dissipated at the barrier islands or the tidal flat in front of the inlet and that the wave height in the area between the barrier islands and the Frisian dikes are young sea waves. The waves in the tidal channels are able to grow further, and some energy is able to propagate through the inlet. Figure 4.8 shows the spatial varying water levels during the same periods. The highest water levels (m + NAP) occur at the dikes during the hours after the peak of the storm.

Computed velocities are shown in Figure 4.9 during the same moments. The maximum computed velocities occur at the entrance channel of the inlet due to filling and draining of the tidal basin and are in the order of 1.8m/s. The maximum velocity occurs just after the storm when the wind setup reduces and extra high water inside the basin is drained through the channel with current of up to 2.0 - 2.2m/s.

As discussed in Section 4.2 the water levels inside the basin increase due to wave effects. Figure 4.10 depicts the computed wave forces at the peak of the storm. The wave forces are largest at the outer delta and at the breaker zones of both islands. The wave forces are slightly curved around the outer delta resulting in wave-induced currents towards the inlet.

### 4.5 Sediment transports

An indication of the mean transport magnitudes during the storm is given in Figure 4.11. The net transport (in $10^3$ m$^3$) is shown for different transects at the offshore side of the barrier islands, the entrance channel of the tidal inlet and in the tidal basin. The main sediment transport direction is from west to east. Sediment is transported around the north eastern head of Terschelling into the tidal basin. In this channel, east of Terschelling the sediment transport decreases, which will result in accretion. The more eastern channel has an export (offshore) component, transporting sediment in northern direction and around western end Ameland further longshore towards the east. The outer tidal delta, offshore of the barrier islands, shows a net eastern transport direction. Inside the tidal basin, the sediment transport is relatively small.

The gradients in the sediment transport under these conditions are mainly wave-driven. A simulation is conducted where no waves were included, resulting in very little transport. The area where the largest bed level changes occur is in the breaker zone. Most of the wave energy is dissipated here, stirring up sediment and inducing longshore currents, which can be increased by the tidal velocities, transporting the sediment. A gradient in the sediment transport will directly result in bed level changes, which are further described below.
4.6 Bed level changes during storm

The bed level changes due to the storm are shown in Figure 4.12. This figure indicates the cumulative erosion (blue) and sedimentation (yellow – red) at the Amelander Zeegat. Most of the changes occur in the outer delta. This is mainly due to the wave energy dissipating due to depth limited breaking of the waves and inducing sediment transport. The bed level changes, at the end of the storm, can increase to 1 – 1.2m at several locations near the inlet.

Bed level changes occur up to four kilometres away from the Frisian dikes. Closer to the dikes, the morphological activity is no longer significant on this time scale.

To have at least some (but rough) quantitative comparison, the yearly measured bed levels of 2004 and 2005 have been used to derive the yearly bed level changes in this area. These measured bed changes are presented in Figure 4.13 in the lower panel (blue is erosion, yellow – red is sedimentation). The computed bed level changes during the storm event are plotted on the same colour scale in the upper panel. Some similar erosion and sedimentation patterns can be found, like around the Bornrif area and in the nearshore areas. The erosion and sedimentation in and around the main channels differs somewhat. This might be attributed to the fact that these areas are more tide-dominated where the time scales play a larger role (three-days vs. one year).

The bed levels prior and after the storm are depicted in Figure 4.14. The upper panel shows several irregular depth contours, especially around the Bornrif, although some smoothing was already performed on the initial model bathymetry constructed from the depth samples.

During a morphological simulation, such a bathymetry can be adjusted during the first phases of the simulation due to spin-up effects. In that case some unrealistic bed changes can occur due to the smoothing by the model itself. However, the present computations did not predict significant bed changes during the first tidal cycle (January 1st, 2005). A possible explanation can be that the areas with the irregular depth contours are not morphologically active in case of only tidal forcing combined with mild wave heights of about 1m. This area might only change significantly during storm events. Besides, the measured yearly bed level changes also indicate a somewhat similar pattern in the area east of Bornrif.

4.7 Discussion

The boundary conditions (tide, wind, pressure and waves) for the applied models have been obtained from various sources and directly imposed on the model. From the verifications with only tidal forcing it can be concluded that satisfying model results can be obtained.

However, when focussing on the 2005 storm conditions (including tide, wind, pressure and waves) relatively large discrepancies in water levels and wave heights inside the basin are observed. This model was subsequently applied to compute sediment transports and bed level changes during the considered yearly-averaged storm event. Unfortunately, no verification is yet possible for the morphological outcome of the model for this storm event. No bed level measurements are available for the short-term bed level changes in this area.
during such typical storm. Therefore, no quantitative calibration and verification was yet possible.

The morphological results indicate the areas which are subject to significant bed level changes. These areas should be surveyed more frequent to obtain more insight in the morphological activity and bed level variations at these locations.

After a qualitative interpretation of the morphological results, the computed bed level changes have been used to obtain a bathymetry after the storm event. With this after-the-storm bathymetry, wave computations have been set up and performed, which are discussed in the next chapter.
5 Impact of bed level changes on wave transformation

5.1 Introduction

In the previous chapter the bed level changes due to the storm of January 1 – 3, 2005 were computed. The objective of this study is to determine the effect of this bed level change on the wave propagation through the Amelander inlet towards the Frisian dikes. In the following section, the effect of the event-driven bed level changes on two storm conditions will be indicated by discussing the results of four wave simulations.

5.2 Wave computations prior and after storm

In this section the results of four SWAN simulations are discussed which present the effect of bed level changes on the wave propagation through the inlet. Two offshore boundary conditions were selected and are shown in Table 5.1 together with the wind and water level conditions. The first offshore wave condition is the peak of the storm (January 2\textsuperscript{nd}, 2005 at 07:20). The second offshore wave condition is a hypothetical storm condition with a return period of 4000 years and coming from northwest direction (315\textdegree\text{N}). The values related to the latter were obtained from the tables provided in Alkyon (1999). The return period of this condition corresponds with typical extreme conditions used for the hydraulic boundary conditions (HBC).

Both offshore boundary conditions were applied in the simulation for the bathymetry composed from measurements described in Section 3.2.1 and with the computed bed level after the storm of January 1 – 3, 2005 at 18:00. This resulted in four simulations. In the simulations the same settings and accuracy criteria were applied as in the previous simulations. Figures 5.1 – 5.4 show the results of the wave computation for the peak of the storm of January 1 – 3, 2005. Figures 5.5 – 5.8 show the results of the run for the academic storm with a return period of 4000 years. These figures are discussed separately hereafter.

The significant wave heights of the computation of the peak of the storm of January 1-3 2005 are shown in Figure 5.1 for the two different bathymetries. Relatively small differences are visible in the outer delta, where most of the morphological changes were computed (Section 4.6). Less wave energy, propagating through the inlet, is dissipated in the areas where erosion was computed. Due to a low water tide at the peak of the storm no wave height is computed for the large area at the toe of the Frisian dikes. Figure 5.4 shows the difference of the two wave fields. Differences in wave heights up to 0.6m are computed at the outer tidal area. Inside the Waddenzee, the differences are relatively small. The differences decrease with increasing distance from the inlet.

Figure 5.2 and 5.3 show spatial plots of the mean wave period and respectively the wave height over depth ratio. In the outer delta of the tidal inlet and the western entrance channel of the inlet, the largest differences in the mean period are visible. Inside the basin, the values
for both cases reduce significantly. Figure 5.3 indicates that at the offshore boundary of the outer delta the wave height over depth ratio is in the order of 0.6(-). At the offshore coastline of the barrier islands Terschelling and Ameland, differences in the two simulation results are visible. More wave energy is able to reach the coast for the simulation with the bed level computed after the storm. Due to depth-induced breaking, the wave energy is dissipated at the offshore coast of Terschelling and Ameland.

A similar analysis can be done for the results of the academic storm. The significant wave height of the computation of the academic storm is shown in Figure 5.5 for the two different bathymetries. Relatively small differences are visible in the outer delta. The wave heights behind the barrier islands are significantly reduced and relatively little wave energy is able to propagate through the inlet. Due to a surge level of 4.7m +NAP and the fetch length between the barrier islands and the Frisian dikes, a wave height is computed varying between 2.5 – 3 m at the toe of the Frisian dikes.

Figure 5.6 shows spatial plots of the mean wave period. Offshore of the tidal inlet the mean wave period is in the order of 12 – 13s and decreases significantly when approaching the inlet. Inside the Amelander Zeegat, the period is below 7 seconds, reducing to about 5 seconds at the toe of the Frisian dikes. In Figure 5.7 the computed wave height over depth ratio is shown. At the toe of the Frisian dikes, this ratio is in the order of 0.3 – 0.4(-).

### 5.3 Differences in wave transformation

Figure 5.4 shows the difference of the two spatial wave height fields for the peak of the storm of January 1 – 3 2005. Differences in wave heights up to 0.3m are computed at the outer tidal area and at the coasts of the barrier island facing offshore. Inside the Amelander Zeegat, the differences are relatively small and only visible in the vicinity of the channels. No significant differences in the significant wave height were computed at the toe of the Frisian dikes.

Figure 5.8 shows the difference of the two spatial wave height fields for the academic storm. Differences in wave heights up to 0.3m are computed in the entrance channel and at the outer tidal area. At the coasts of the barrier island facing offshore the differences are in the order of 0.1 – 0.2m. Inside the Waddenzee, the differences are relatively small and only visible in the area between the tidal inlet and the Frisian dikes. No significant differences in the significant wave height were computed at the toe of the Frisian dikes.

When comparing Figure 5.4 and 5.8, it is expected that the differences are due to the wave height with respect to the water depth. In Figure 5.4, the surge level is relatively small and the depth at the outer delta determines for a significant part the propagation of the wave energy. In the academic storm, the surge level is 4.7m and the spatial wave propagation is less determined by the channel system. This is confirmed by comparing Figure 5.3 and 5.7.

Summarizing, the short-term bed level changes during a yearly-averaged storm have no significant impact on the computed wave characteristics at the toe of the Frisian dikes. This is the case for a yearly-averaged storm condition as well as for hypothetical storm condition with a return period of 4000 years.
6 Summary and conclusions

In this study, the effect of short-term bed level changes due to a storm event on the wave propagation was investigated with focus on the primary sea defences along the Frisian coast.

For the purpose of this study a hydrodynamic model was setup for the Amelander Zeegat to study the storm event of 1-5 January 2005. The model was driven by tidal, wind, pressure and wave forcing. The model includes computations for the wave propagation into the inlet during the storm event. Based on the hydrodynamic model morphological simulations have been conducted for a three-day period during the January 2005 storm.

The following conclusions can be drawn from the present assessment:

- The hydrodynamic model is able to reproduce the water levels at open sea as well as in the basin well. The computed tidal propagation into the inlet agrees well with measurements and shows differences up to 10% of the observed values.
- A relative large discrepancy between the computed and observed water levels at Nes is found, probably due to the lack of sub-grid meteorological effects. This discrepancy was 0.3m at Nes during high water close to the peak of the storm.
- The wave computations overestimated the wave heights further into the inlet compared with the measurements.
- The inclusion of wave effects in the computations results in higher water levels inside the basin and reduces the discrepancy in the water levels at Nes. The wave effects consist of additional currents due to wave breaking and a wave-induced water level setup.
- The morphological activity due to a yearly-averaged storm can result in bed level changes of 1 – 1.5m. The largest bed level changes occur at the outer delta of the Amelander Zeegat. Inside the inlet the model computes slight erosion of the banks of the flats.
- Bed level changes of up to 0.5m are computed inside the inlet at the slopes of the flats.
- Wave computations have been performed on a bathymetry prior and after the storm event of January 1-3, 2005. The wave condition was the peak of the January 2005 storm. Differences in wave heights up to 0.3m were found at the outer tidal area and at the coasts of the barrier island facing offshore. Inside the Amelander Zeegat, the differences are relatively small (<0.05m) and only present in the vicinity of the channels.
- Also wave computations have been performed on a bathymetry prior and after the storm event of January 1-3, 2005, but with a wave condition of a hypothetical storm event with a return period of 4000 years. Differences in wave heights up to 0.3m are computed in the entrance channel and at the outer tidal area. At the coasts of the barrier islands facing offshore the differences are in the order of 0.1 – 0.2m. Inside the Waddenzee, the differences are relatively small (<0.05m) and only present in the area between the tidal inlet and half way the Frisian dikes.
• No significant impact of the short-term bed level changes during a yearly-averaged storm has been found in the computed wave characteristics at the toe of the Frisian dikes. This has been verified with a typical wave condition of a yearly-averaged storm as well as for a hypothetical storm with a return period of 4000 years.

**Recommendations**

The present investigation resulted in the following recommendations:

• No bed level measurements were available for the short-term bed level changes in this area during a typical storm. Therefore, no verification is yet possible for the morphological outcome of the model for this storm event. It is recommended to measure the bed levels at a higher frequency in order to determine the short-term bed level changes.

• The morphological results indicate the areas which are subject to significant bed level changes. These areas should be surveyed more frequent to obtain more insight in the morphological activity and bed level variations at these locations.

• More information is required on the spatial variation of the mean sediment grain size. Better insight of this variation improves the computation on hydrodynamics, sediment transport and bed level changes.

• All wave computations in this study are performed in stationary mode. It is recommended to carry out a sensitivity analysis with the non-stationary mode of SWAN, which should perform better in such non-stationary situations.

• With the present study no insight is obtained yet in the possible bed level changes and their effects on the wave characteristics during an extreme condition, e.g. with a return period of 4000 years. However, this insight is still needed because the hydraulic boundary conditions are determined based on such extreme conditions. Therefore it is recommended to carry out a study to compute the bed level changes during an extreme storm (e.g. 1/4000 year storm). With the computed bed level changes, a similar analysis as in this study can be carried out. In this way the effect of short-term bed level changes during an extreme storm on the wave characteristics near the Frisian dikes can be determined.
7 References


Tables
### Table 2.1 Locations of measuring stations

<table>
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<tr>
<th>Location</th>
<th>X [m]</th>
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### Table 5.1 Wind water level and offshore wave conditions for two simulation

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<th>Condition</th>
<th>Wind direction [°N]</th>
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<th>Water level [m + NAP]</th>
<th>$H_{m0}$ [m]</th>
<th>$T_p$ [s]</th>
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<td>space varying as computed by Delft3D-FLOW</td>
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<td>10.7</td>
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Figures
Location of the Amelander Zeegat in the Netherlands
Relevant locations near the project area are marked

Amelander Zeegat

WLDelft Hydraulics
Overview of measuring stations around the Amelander Zeegat

Amelander Zeegat

WL|Delft Hydraulics

Fig. 2.1
Measured water level at Terschelling Noordzee and Nes during the storm between January 1 - 3

Amelander Zeegat

WL|Delft Hydraulics

Fig. 2.2
Wind fields at various time points during the storm of 1 – 3 January 2005

HIRLAM data

Fig. 2.3
Derived time series of wind speeds and directions during the storm event at three different stations near the Amelander Zeegat
Measured wave data at several wave buoys, as indicated in Figure 2.1, along the Amelander Zeegat
Overview of the computational grids
upper plot: computational grid for Delft3D-FLOW
lower plot: computational grid for Delft3D-WAVE

Amelander Zeegat

WL|Delft Hydraulics

Fig. 3.1
Typical used HIRLAM wind fields at several moments during the storm

Delft3D-WAVE

WL|Delft Hydraulics

Fig. 3.3
Results of harmonic analysis of water levels at Terschelling Noordzee
Upper panel: Amplitudes of tidal components (ten largest)
Lower panel: Phases of tidal components

Delft3D-FLOW
WL | DELFT HYDRAULICS

Ameland

Fig. 4.2
Amplitudes major tidal components Nes

Phases major tidal components Nes

Results of harmonic analysis of water levels at Nes - Ameland
Upper panel: Amplitudes of tidal components (ten largest)
Lower panel: Phases of tidal components

Ameland
Delft3D-FLOW

WL | DELFT HYDRAULICS

Fig. 4.3
Computed discharge through the inlet (red line in overview)
Upper panel: Wave heights and directions at location A; Middle panel: Discharges due to tide and tide & waves; Lower panel: Difference in discharge due to tide and tide & waves

Amelander Zeegat

WL|Delft Hydraulics

Fig. 4.4
Measured (red) vs computed wave heights at four locations during the storm of 1 - 5 January 2005
computed versus measured 1D-spectra and significant wave height

Wave height [m]

Wave height AZB11

AZB11

AZB31

AZB41

AZB51

Waterlevel Terschelling

Waterlevel Nes

02-Jan-2005 07:20:00
red line = measured data
blue line = computed results
Typical computed wave fields at several moments during the storm

Delft3D-WAVE

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Fig. 4.7
Typical computed water level fields at several moments during the storm

Delft3D-FLOW

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Fig. 4.8
Typical computed velocity magnitude fields at several moments during the storm

Delft3D-FLOW

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Fig. 4.9
Computed wave forces (N/m²) at the peak of the storm

Delft3D-WAVE

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Fig. 4.10
The computed total sediment transport $10^3 \text{ m}^3$ during the storm of January 1 – 3, 2005.
Computed cumulative erosion (blue) and sedimentation (yellow-red) after the storm event

Delft3D

WL|Delft Hydraulics

Fig. 4.12
Bed level changes at the Amelander Zeegat

Upper panel: Computed erosion and sedimentation during storm event
Lower panel: Measured erosion and sedimentation 2004 - 2005

Delft3D

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Fig. 4.13
Bed levels prior (upper) and after (lower) the storm event

Amelander Zeegat

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Fig. 4.14
Computed significant wave height prior (upper plot) and after the storm event (lower plot) on storm conditions: peak of the storm of January 1 - 3, 2005.

Delft3D-WAVE

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Fig. 5.1
Computed mean absolute wave period prior (upper plot) and after the storm event (lower plot) under storm conditions: peak of the storm of January 1 - 3, 2005

Delft3D-WAVE

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Fig. 5.2
Ratio of significant wave height / depth for the situation prior (upper plot) and after the storm (lower plot). Storm conditions: peak of the storm of January 1 - 3, 2005.

Delft3D-WAVE

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Fig. 5.3
Difference in significant wave height computed with the bathymetry prior and after the storm (yellow - red means higher wave heights after storm event).

Storm conditions: peak of the storm of January 1 - 3, 2005

Delft3D-WAVE

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Fig. 5.4
Computed significant wave height prior (upper plot) and after the storm event (lower plot).

Storm boundary conditions: Academic storm with return period = 4000yr

Delft3D-WAVE

WL|Delft Hydraulics

Fig. 5.5
Computed mean absolute wave period prior (upper plot)
and after the storm event (lower plot)
storm boundary conditions: Acedemic storm with return period = 4000yr

Delft3D-WAVE

WL|Delft Hydraulics

Fig. 5.6
Ratio of significant wave height / depth for the situation prior (upper plot) and after the storm (lower plot)

storm boundary conditions: Acedemic storm with return period = 4000yr

Delft3D-WAVE

WL|Delft Hydraulics

Fig. 5.7
Difference in significant wave height computed with the bathymetry prior and after the storm (yellow means higher wave heights after storm event). 

Storm boundary conditions: Acedemic storm with return period = 4000 yr 

Delft3D-WAVE

WL|Delft Hydraulics

Fig. 5.8
WL | Delft Hydraulics

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