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Seacode project: Efficient Modelling of Sand Wave Field Dynamics for Offshore Engineering Activities

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CONTENTS

1 INTRODUCTION

1.1 Context

Over the past decades the amount of offshore activities in shallow seas, such as the North Sea, has rapidly increased. With often densely populated coastal areas, the offshore space may serve many purposes, such as navigation, energy production and sand mining. The European Union is, for example, planning to increase the offshore wind capacity from 12 to 300 gigawatts between 2020 and 2050 (Van Raaij, 2020). However, many shallow seas throughout the world are covered with rhythmic bed patterns, such as tidal sand waves (Van Dijk et al., 2008). These bed patterns result from the complex interaction among hydrodynamics, seabed topography and sediment transport (Hulscher, 1996). Tidal sand waves are generated in several years time, they can grow up to 25% of the water depth, have wavelengths of hundreds of meters and migrate at a speed of several meters per year (Damen et al., 2018). Due to their size and dynamic character, sand waves may pose a threat to offshore activities (Németh et al., 2003). Moreover, sand waves may also serve as source of sand for building and nourishment purposes (Damveld et al., 2020b). In the Dutch North Sea sand waves are found in crowded areas intended for amongst others shipping and offshore windfarms (see Figure 1.1).

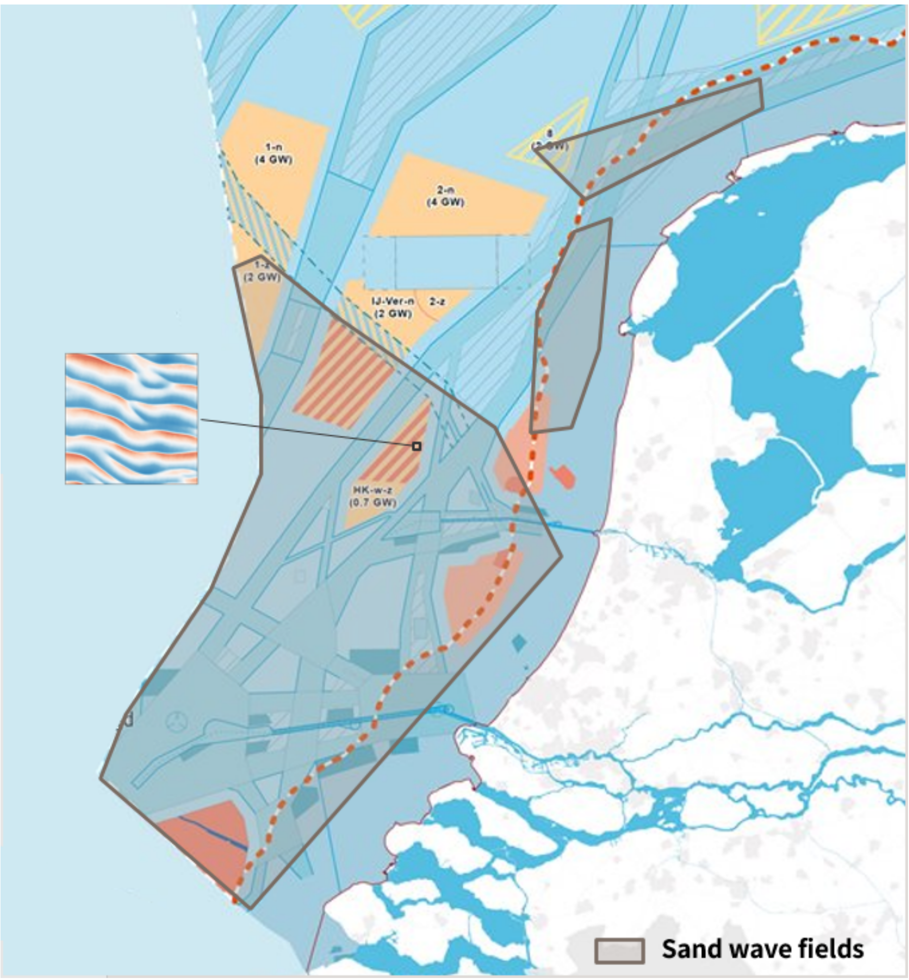

Figure 1.1: Planned and constructed offshore wind farms in the Southern Dutch North Sea (indicated by the coloured areas). Shaded regions indicate approximate locations of sand waves (areas retrieved from Németh (2003), figure adapted from RVO, Rijksoverheid (2022))

Sand wave dynamics may cause a significant rise or drop in local bed level over the lifespan of offshore structures, such as wind turbines (Van Dijk (2011), Deltares (2016b)). This bed level variation may decrease the stability of the foundation or bed protection or cause exposure of cables and pipelines. Furthermore, the growth and migration of sand waves can accelerate siltation of navigational channels and reduce navigation depth (Campmans et al., 2021). The prediction methods for sand wave growth and migration, and thus the associated bed level changes, are however still in their infancy. For the safety of these offshore structures and navigational routes located in the vicinity of sand waves, continuous monitoring and in some cases dredging is required (Knaapen and Hulscher (2002), Németh et al. (2003), Deltares (2016a), De Koning (2017), Kubicki et al. (2017), Campmans et al. (2021)). These monitoring and dredging activities make construction in these areas more expensive and the lack of knowledge about the prediction of sand wave dynamics poses safety risks. Furthermore, these dredging activities can negatively affect marine life as it increases turbidity and demolishes the marine micro-environments formed by the sand waves (Damveld et al., 2018). Despite the disadvantages, dredging is in some cases necessary to ensure the safety of offshore structures and navigational routes. More insight into sand wave dynamics and the prediction thereof, will decrease the need for dredging and monitoring. This in turn will make the construction and maintenance of offshore structures, such as wind farms, less expensive, safer and more environmentally friendly.

Currently data-driven methods are used to determine the range of expected bed levels. The uncertainty in these predictions is however significant, with sand wave dynamics being the largest source of uncertainty. Recent studies of sand wave dynamics in the North Sea show that the envelope of possible future seabed levels, over the lifetime of an offshore wind farm, is in the order of meters (Deltares, 2016a). In these studies the combined uncertainty due to sources other than sand waves only accounted for an uncertainty bandwidth in the order of decimeters. The remainder of this uncertainty is caused by sand wave dynamics. Furthermore, these bed level predictions are not based on understanding of the systems at hand, but rather on historical data. This makes the trustworthiness of the predictions disputable, especially in changing environments. Process-based numerical models, which compute flow and sediment transport, could potentially increase the accuracy of these predictions. Moreover, these models would allow for in-depth understanding of the processes behind sand wave dynamics.

1.2 Objective and research questions

1. What are offshore sand waves?
    (a) What field data of sand waves is available?
2. Which processes are drivers for offshore sand wave dynamics?
3. Which (modelling) methods exist to predict sand wave dynamics and what are their strengths and weaknesses?
    (a) What is the influence of various (numerical and physical) model settings on sand wave dynamics?
4. Which potentially significant influences are missing in the current modelling methods?
5. What methods exist for increasing model efficiency?
6. How do human interventions influence sand wave dynamics and how fast do sand waves recover?

1.3 Outline

In the body of this report, from Chapter 2 up to Chapter 5, the research questions above are answered. Chapter 2 starts of with a definition of sand waves and a comparison with other bed features in Section 2.1. In the remainder of this section methods for identifying and filtering bed forms are introduced. In Sections 2.3 and 2.4 the mechanism behind sand wave formation and dynamics are explained. In the remainder of the Chapter the available field data is discussed. In Chapter 3 attention is given to the different methods used for modelling or predicting sand wave formation and dynamics. Three different methods are explained and compared, followed by a more in depth study into the influences of model choices and the missing influences. In Chapter 4 methods to increase model efficiency are discussed and finally, in Chapter 5 attention is given to the influence of human interventions on sand wave dynamics. Chapter 6 summarizes the answers to the research questions given in Chapter 2-5 and summarizes the knowledge gaps.

2 SAND WAVE CHARACTERISTICS, FORMATION AND DYNAMICS

In this chapter the first two literature questions will be answered. These are: *What are offshore sand waves* and *Which processes are drivers for offshore sand wave dynamics?*

To answer these questions first various types of oceanic bedforms and the differences between those are described in Section 2.1. Subsequently existing methods for gathering bathymetric data on sand waves and a overview of field data in the North Sea are presented in Section 2.2. In Section 2.3 the physical processes which lead to sand wave formation are explained. Lastly the processes causing sand wave dynamics (growth and migration) in Section 2.4

2.1 Sand wave characteristics

2.1.1 Bed form characteristics

To classify bed forms a few characteristics are often used. Four main characteristics of bed forms are: wave length (L), wave height (H), migration and wave skewness (A). These and a few other measures are shown in Figure 2.1.

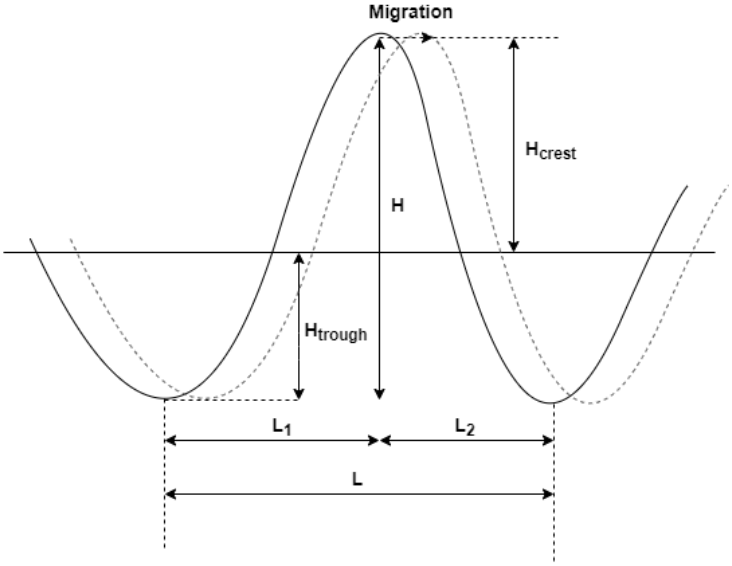

Figure 2.1: Schematic overview of bed form characteristics

The wave skewness can be calculated as shown in equation 2.1 (Knaapen, 2005). A positive skewness means that the bed form leans over in the chosen direction. A skewness of 0 indicates a symmetric bed form. A relation between the bed form asymmetry and migration speed has been observed for sand waves (Knaapen, 2005).

$$A = \frac{L_1 - L_2}{L} \tag{2.1}$$

2.1.2 Bed form classification

Depending on the measures mentioned above and the processes responsible for their existence, bed forms are often classified into different categories. Firstly a distinction can be made between environments in which bed forms are observed. Since the focus of this study is on the offshore area, an environment where the forcing is dominated by a reversing tidal currents, only bed forms found in this environment are discussed in this literature study. Subsequently, a classification can be made based on the different sizes of rhythmic bed patterns. Here it is often observed that the larger bed forms tend to be more stable than the smaller bed forms, which might migrate over a distance of several wave lengths in a matter of months or even weeks. Since the different types of bed forms are often present in the same areas (see Figure 2.2), before classification first filtering is necessary, which is discussed in Section 2.1.3. The characteristics of the various bed forms described below are found in Table 2.1.

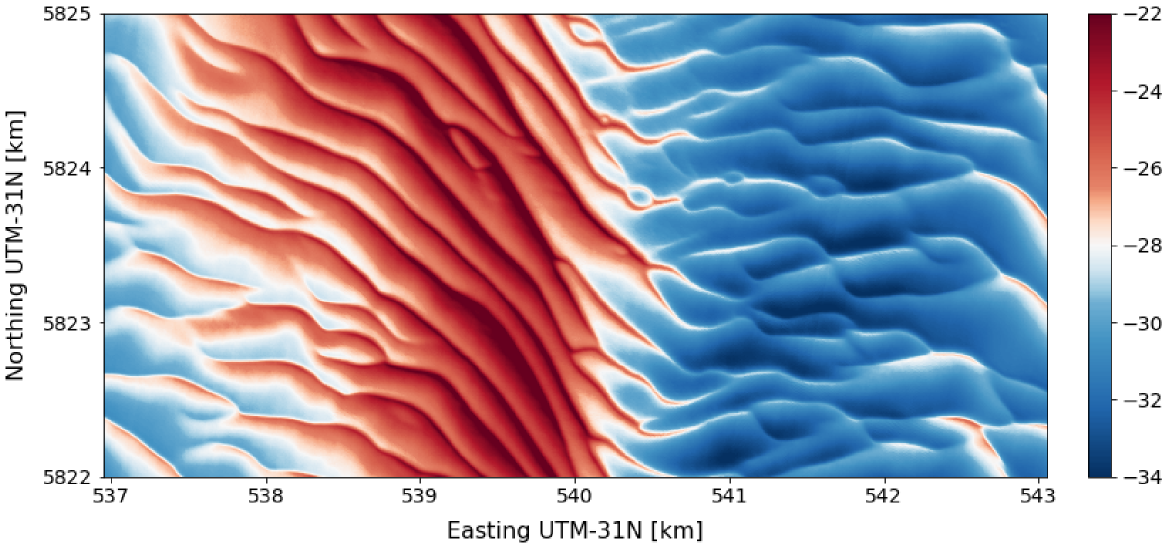

Figure 2.2: Measured bathymetry at Hollandse Kust West (HKW) windfarm area, with tidal sand waves superimposed on a sand bank (megaripples are also present, but not visible at this scale)

Tidal sand banks

The largest rythmic bed features found at the sea bed are tidal sand banks. These banks have lengths in the orders of kilometers and are tens of meters in height (up to half the waterdepth). Hulscher (1996) explained the presence of sand banks using linear stability theory. These bed features are generated by interaction between initial bed perturbations and the tidal flow. When the crest have a certain rotation with respect to the principal tidal flow direction, a residual flow towards the crest of the bed feature is generated. The flow is distorted due to Coriolis forces and bed friction which causes tide averaged horizontal circulation to occur (Hulscher, 1996). The orientation of the sand banks is 10-30° anticlockwise (in the Northern hemisphere). Due to their size, tidal sand banks may have a major influence on tidal currents (Zimmerman, 1981). Observations show that sand banks are often static, with bathymetry changes in the order of centimeters over periods of years (Deltares, 2015, Deltares, 2016b, Deltares, 2020), while migration of sand banks has been observed in some cases. Some of these exceptions were summarized by Idier and Astruc (2003): ”Due to the slow evolution of sandbanks, there are few data on the migration rate of these structures. Whereas the Norfolk Banks (Caston, 1972) moved toward the northeast direction by about 300 to 600 m during the last century, the Flemish Banks have only slightly moved during the last 300 years (Eisma et al., 1979) and the Hinder Banks seems to be stationary for the past 40 years.”

Long bed waves

The second largest bed form found in offshore setting is the long bed wave, which was first described by Knaapen et al. (2001). This type of bed form shows quite some variation in orientation with respect to the principal tidal direction and has a wavelength of about 1.5 kilometer. Long bed waves have not often been observed. This could be caused by the fact that they are difficult to distinguish due to interference with other bed forms. Blondeaux et al. (2009) used linear stability analysis to explain the appearance of these bed forms and found positive growth rates for very specific conditions. This could mean that these type of bed forms are rare and could therefore explain the scarceness of observations.

Tidal sand waves

A more often encountered bed form is the tidal sand wave. Hulscher (1996) modelled the formation of sand waves using linear stability methods. Due to interactions between bottom perturbations and tidal flow, tide-averaged vertical circulation cells are formed, which cause the perturbation to grow in height (see Figure 2.8). These type of bed forms are called tidal sand waves. Sand waves are generated in typically several years time, can grow up to 25% of the water depth and have wavelengths of hundreds of meters. Due to tidal asymmetry and residual currents sand waves may migrate over time (Besio et al., 2004). Observed migration rates vary widely over different areas. In the Dutch North Sea migration rates up to 10 m per year are observed (Meijden, 2021). However, in high energetic tidal environments sometimes migration rates of close to 100 meters per year are observed (e.g. Marsdiep tidal inlet, the Netherlands (Buijsman and Ridderinkhof, 2008) and Banks Strait Australia (Auguste et al., 2021)). Due to their dynamic nature and size, sand waves may pose a threat to offshore activities, such as offshore wind farm construction.

(Mega)ripples

Superimposed upon sand waves often smaller rhythmic bed forms are encountered. The smallest of these bed forms are ripples. These ripples are found on sandy surfaces in many environments (e.g. seabed, beach and desert) and are created due to the transport of sediment (Cataño-Lopera and Garcia, 2006). The orientation of ripples is thus based on the local sediment transport direction. Damveld et al. (2018) observed differences in ripple occurrence, regularity and length between sand wave crests and troughs. These inequalities could be the result of differences in flow regimes due to shadowing by the sand wave. Damveld et al. (2018) observed ripple lengths of 5-30 cm. In conditions with high bed roughness these ripples might grow into megaripples, which have wavelengths in the order of tens of meters, wave heights up to 2 meters and are highly dynamic with migration speeds of approximately 100 meters per year (Brakenhoff et al. (2020), Idier et al. (2004)). In dynamic environments even migration speeds of up to 1 meter per hour are observed (Idier et al., 2004). Mega ripple orientation is observed to vary over the length of sand waves (Van Dijk and Kleinhans, 2005).

Summary

Tidal sand waves can thus be identified by their distinct wave length, wave height and orientation, which are a product of the hydrodynamic forcing mechanism. The offshore bed form showing the closest resemblance to sand waves are mega ripples. Although the range of possible wave heights overlap the observed wave length are different. Mega ripples are thus a distinct higher node in the frequency spectrum of the bed perturbations and can be separated from the sand wave spectrum. Moreover, although mega ripples can grow to significant wave heights, when superimposed on sand waves their wave heights are often observed to be around 1/5 to 1/10 of the sand wave height (Van Dijk et al. (2008), Van Dijk and Kleinhans (2005), Deltares (2016b), Deltares (2016a)).

Table 2.1: Bed form characteristics, based on North Sea data (Morelissen et al. (2003), Hulscher (1996), Knaapen et al. (2001), Blondeaux et al. (2009), Damveld et al. (2018))

Bed form	**Length [m]**	**Height [m]**	**Orientation**[*]	**Migration rate**
Ripples	0.05-0.5	0.01-0.05	-	1 m/day
Megaripples	1-20	0.1-2	∼ 0° **	100 m/year
Sand waves	100-1000	1-10	0°	0-10 m/year
Long bed waves	∼ 1500	∼ 5	∼ 45°	unknown
Tidal sand banks	5000-10000	10-30	10-30°	∼ 0-1 m/year

2.1.3 Bed form identification and filtering

Various methods and algorithms have been created to identify the different types of rhythmic bed forms mentioned above. These algorithms can be used to subtract bed form characteristics or to split bathymetry data into different subsets including the separate bed form types. In this way bed forms can be filtered out of the bathymetry data. This might be necessary for certain studies such as numerical modelling. Due to the numerical grid size ripples and megaripples might be too small to accurately include in the model. Moreover, ripples are often indistinguishable in bathymetry measurements due to their size, which means that their contribution to the local bed level can only be seen as noise. These bed forms thus become sub-grid features, which implicitly need to be included in the local bed roughness. The extracted megaripple and ripple characteristics can then be used to estimate the local bed roughness (Idier et al., 2004). In this way their influence on the hydrodynamics and sediment transport can be included even on larger grids.

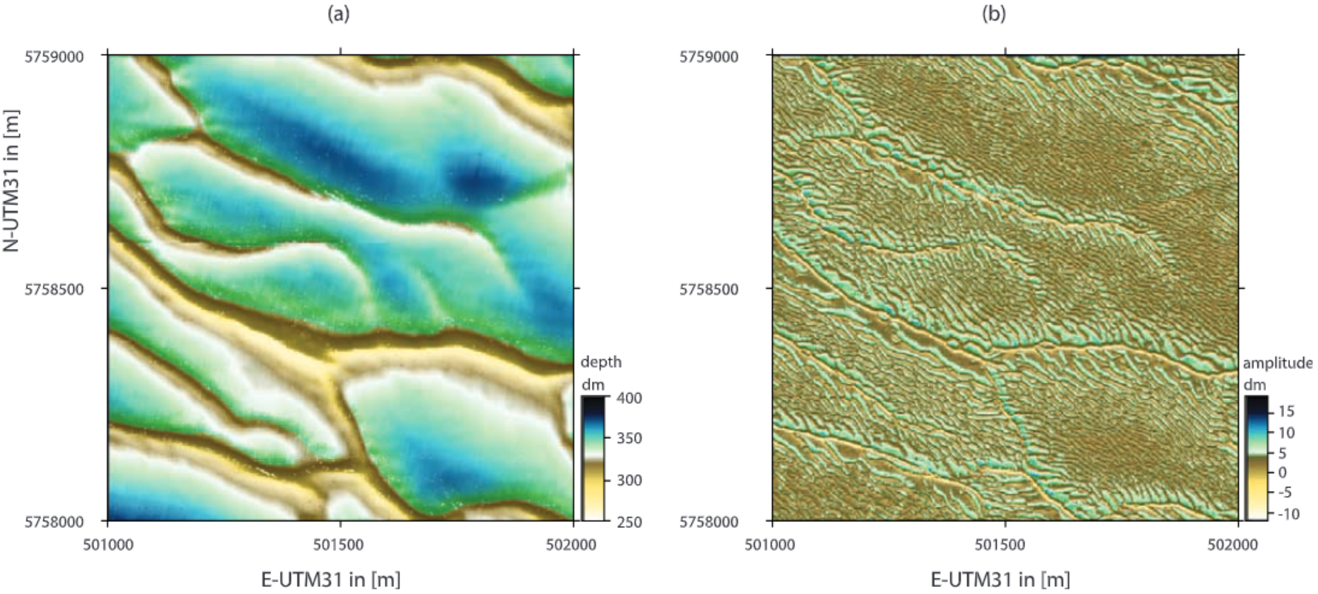

Figure 2.3: Filtered bathymetry of: (a) sand waves and (b) megaripples. Filtered using geostatistical filtering by Van Dijk et al. (2008)

The most commonly used method for identifying bed forms and determining their characteristics is Fourier analysis. Using a 2D Fourier analysis the wavelength, wave height and orientation

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[*] With respect to the major axis of the tidal ellipse (anticlockwise taken as positive in the Northern hemisphere)

**Varying orientation over sand waves

of various scales of bed forms can be determined (Van Dijk et al., 2008). By applying a cut-off frequency the different bed form nodes can be separated and individually analysed. Moreover, from these separated frequency spectra a new bathymetry can be formed which in- or excludes various bed forms, which might be useful in further study Knaapen (2005). When using this method in cases with superimposed bedforms the amplitude of the largest bed form (e.g. sand waves) is often underestimated due to due to spectral leakage (Wang et al., 2020). Another drawback of this method is that the cut-off frequency needs to be chosen manually and is thus subjective. However, in Van Dijk et al. (2008) it was found that in case of sand waves and megaripples this separation was in the low-power domain, reducing the sensitivity to the exact frequency which is chosen. Another widely used method for bed form classification and filtering is based on geostatistics. Using the variability of the bed level the bed form orientation, wavelength and wave height can be determined (Van Dijk et al., 2008). This is done step-by-step, where first the largest bed forms are filtered out, before the characteristics of the smaller bed forms can be determined (Van Dijk et al., 2008). Van Dijk et al. (2008) compared both methods and found a slightly larger underestimation of the wave height using the statistical method, which was attributed to a stronger smoothening, causing the crests to be included in the signal of the smaller bed forms, a phenomenon which can also be observed in Figure 2.3. Also in this method subjective choices need to be made on parameter values, the values of which were found to have a significant impact on the bed form decomposition results (Van Dijk et al., 2008). Wang et al. (2020) combined several methods in an automated algorithm, which determines the bed form orientation and characterics and the spatial distribution thereof, thus eliminating subjective choices. The only input parameter of the method is the wave length of interest, which can be determined by visual inspection of the data set, or through the use of an assisting algorithm from Wang et al. (2020).

When single sand waves are present the above methods are not appropriate, since they are created to discover patterns in the bathymetry. For this purpose an algorithm was created by Di Stefano and Mayer (2018), which first determines the shape of the underlying bathymetry, after which the separate bed features are identified and their characteristics are determined.

Lastly, extensive algorithms have been written to detect and filter river dunes (e.g. (Gutierrez et al., 2018)). These algorithms often assume the river dunes to be the largest bed form present, with a linear trend in the underlying bathymetry (i.e. the bedslope of the underlying riverbed). However, seabeds often show large scale variations in underlying bathymetry (e.g. underlying sand banks and slope of the continental shelf), which are not aligned with the sand waves themselves. This makes that these algorithms are unsuitable for direct application to offshore sand waves. The principles used in these methods can be distinguished in some of the methods for offshore sand waves mentioned above.

2.2 Sand wave field data

In this Section additional information is provided about sand wave observations. In Subsection 2.2.1 the presence of sand waves around the world and the global differences in their characteristics are discussed. Subsequently data collection and the related uncertainties are included in Subsection 2.2.2. In the last subsection more information is provided about the availability of field data in the Dutch North Sea, which is chosen as location for this study.

2.2.1 Sand wave locations and characteristics

Offshore sand waves are present in numerous places in the world. Between the various sand wave areas their characteristics and dynamics may vary widely. Where sand waves in the Dutch North Sea are observed to grow up to 10 meters, in the Taiwan Strait giant sand waves with heights up to 25 meters are observed (Damen et al. (2018), Bao et al. (2014)). In highly energetic areas sometimes extremely high migration rates are observed. During a study in the Australian Banks Strait, sand wave migration rates of close to 100 meters per year were observed (Auguste et al., 2021). Sand waves have been found in (amongst others) the following offshore areas: North Sea (Damen et al., 2018), Taiwan Strait Bao et al. (2014), Mediterranean Sea (Albarracín et al., 2014), Monterey Canyon (California) (Xu et al., 2008), Barents Sea (Bøe et al., 2015), Beibu Gulf (China) (Li et al., 2011), Banks Strait (Auguste et al., 2021) and Torres Strait (Harris, 1991) (Australia), San Fransisco Bay (Sterlini et al., 2009) and Long Island Sound (New York) (Fenster et al., 1990). There are probably many more locations where sand waves are present. Sand waves are mostly discovered when either a scientific or industrial interest is present in a certain area.

In the Dutch North Sea a large amount of high resolution bathymetry data is available, such that much is know about the (spread of) sand wave characteristics and their dynamics. Damen et al. (2018) studied the spatial dispersion of sand wave characteristics by using a Fourier transform on 10 by 10 km blocks of Dutch North Sea bathymetry. The distribution of sand wave characteristics in the Dutch part of the North Sea from this analysis is shown in in Figure 2.4 for areas with over 80% sand wave coverage. It is clear that the shape and size of sand waves varies significantly throughout the (Dutch) North Sea. Sand wave heights vary from 1-8 m and sand wave lengths are in the order of 100-1000 m. In the South-Western area the sand waves are higher, shorter and less asymmetric. Close to shore no sand waves are observed and another clear edge of the sand wave domain is present starting from about halfway the straight part of the Dutch coastline. The lack of sand waves in the Northern areas, where the sediment grain size is smaller, can be explained by the dampening effect of suspended sediment. This relation was first found by Borsje et al. (2014) and states that in areas with low Rouse numbers, where suspended sediment transport is dominant, sand waves are dampened. In the data analysis by Damen et al. (2018) similar results were found, where the areas with low Rouse numbers and areas lacking sand waves largely coincided.

Similarly the sand wave migration throughout the Dutch North Sea has been studied by Meijden (2021), who found migration rates ranging from a few meters up to over 20 meters per year. The highest migration rates were found in the North-East, close to the Wadden Islands and in the South West the sand waves were observed to be (nearly) static (Meijden, 2021). Sand waves located on top of sand banks showed higher migration rates and sudden changes in migration direction were observed, similar to what was found in the study by Leenders et al. (2021) (Meijden, 2021).

2.2.2 Data collection and uncertainties

To collect measurements of sand wave bathymetries ship-based echo sounders are used. These measurement devices send out sound waves which are reflected by the seabed. Two systems are available for these measurements (see Figure 2.5). Older bathymetry measurements were collected using Single Beam Echo Sounders (SBES), which can measure the seabed directly under the ship. By moving along a line, a bathymetry transect can be measured. Nowadays often Multi Beam Echo Sounders (MBES) are used. These are able to measure the bed over a wider area, of up to 7.5 times the local water depth (Mayer, 2006). Due to this transition more recent measurements have a better coverage and a higher data density.

In these echo sounder measurements various uncertainties are present. First of all the speed of sound in water needs to be estimated in order to convert the travel time of the signal to a travelled distance. This speed is however dependent (among others) on the salinity, temperature and pressure of the sea water (Knaapen and Wallingford, 2004). These parameters may be measured along with the depth measurements, but especially in environments with a high spatial and temporal variability, significant errors may still be present. Especially for MBES system, where the outer beams travel a significant distance through the water column, effects of

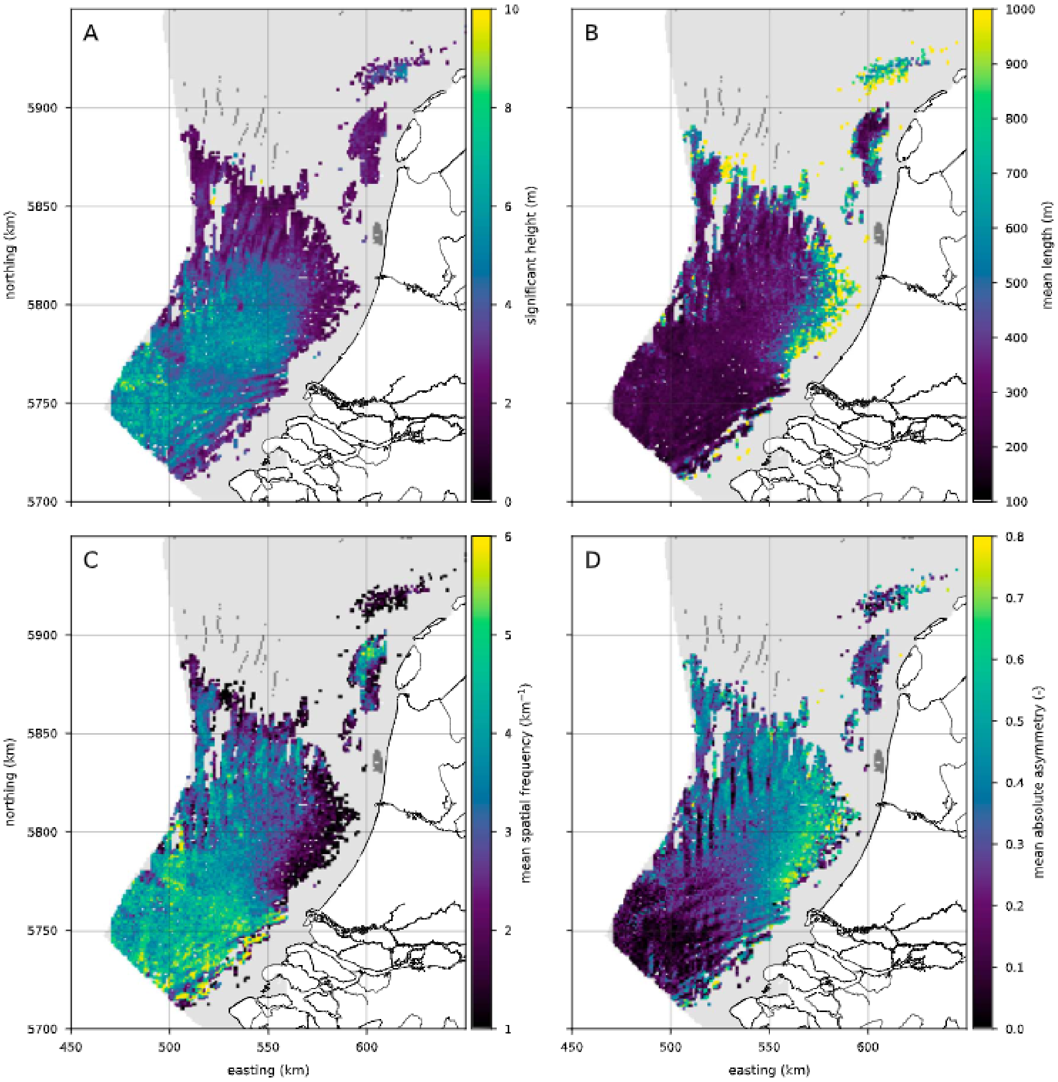


Figure 2.4: Sand wave characteristics (a) height, (b) length, (c) spatial frequency ($\xi = 1/L$), and (d) asymmetry aggregated per square km and for sand wave-coverage > 80% (Damen et al., 2018)

these inaccuracy may be visible in the measurements. This causes so-called 'droopy' or 'smiley' effects at the edges of the measured swathe (Simons et al., 2010). These inaccuracies can be counteracted by combining overlapping MBES measurements to achieve a more accurate estimate of the sound speed.

To determine the absolute bed level, a tidal reduction (correction for the local water level) needs to be implemented. Methods for this tidal reduction have become more accurate over the recent years. Where in the past these estimates were solely based on extrapolations of tidal measurements, nowadays data-assimilation processes are performed to arrive at more accurate estimates. This data-assimilation process, which is used by the Netherlands Hydrographic Office of the Royal Dutch Navy (NLHO), combines both measurements and model data (Hounjet et al., 2012). In addition to tidal variation the measured data also needs to be corrected for ship movements caused by surface waves. Lastly also (horizontal) positioning errors from the global position system (GPS) may result in inaccuracies of the measured bathymetry. These errors may affect the sand wave migration rate which is determined from the measurements. Recent advances in GPS positioning technology have however reduced these errors significantly.

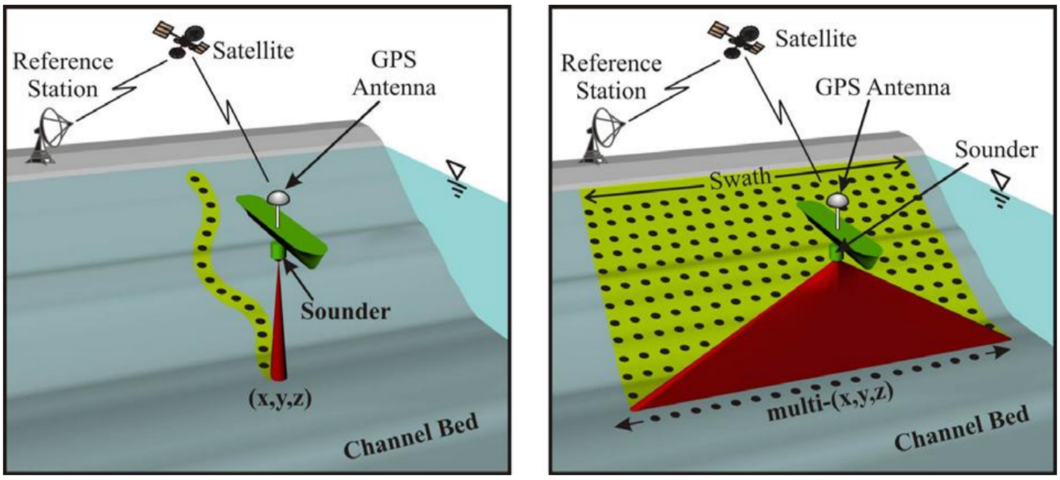


Figure 2.5: Bathymetry measurements using Single Beam (left) and Multi Beam (right) Echo Sounders (Muste et al., 2012)

2.2.3 Data availability

In terms of data availability the (Dutch) North Sea stands out amongst the other offshore sand wave areas. The NLHO has been measuring the seabed since the 80's of the last century. These measurements were done all over the Dutch offshore area with an interval of approximately 10 years. Moreover, these surveys are publicly available. These factors make that the Dutch North Sea is a very suitable place for modelling and data-assimilation studies and thus data of other sand wave areas is not elaborated upon in this literature review. The collected measurement data has been processed by Deltares and is publicly available (Deltares, 2017). For the majority of the sand wave areas in the Dutch North Sea at least two measurements with reasonable data-density are available (Meijden, 2021). For most areas more data is available with often 3 or 4 distinct measurements. Apart from this public data also industry data can in some cases be made available. This data consists of among others recent, high quality bathymetry measurement data at planned wind farm locations. At these planned wind farm locations also hydrodynamic measurements have been carried out in recent years. During these campaigns both the water level and current profile over depth was measured for a period of between 9 and 24 months. This data is publicly available via Netherlands Enterprise Agency (2021). This data also includes the measured wind wave characteristics over these periods. Additional data on wind wave characteristics can be found via the Deltares Matroos service (Deltares, 2021c). More information on hydrodynamics in the North Sea can be extracted from the DCSM model (Deltares, 2018). This large scale Delft3D FM model is made available for this research by Deltares. It includes the tidal propagation throughout the North Sea, which can be simulated for specific periods in time. Moreover, wind and pressure fields, which can be used to compute large-scale wind driven currents, are available for the period of 2011-2021.

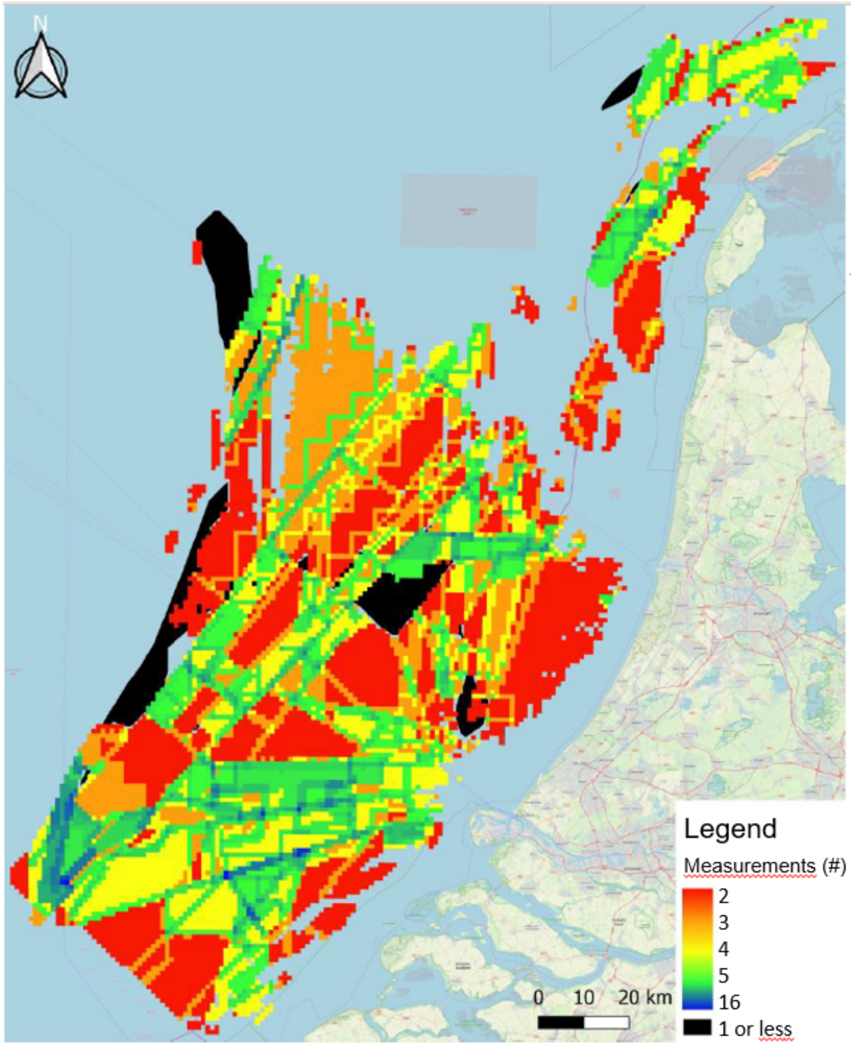
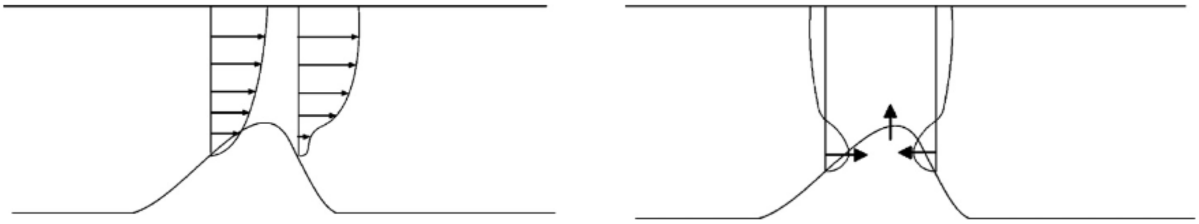


Figure 2.6: Bathymetry data availability per 1 km x 1 km block of Dutch sand wave fields, adapted from Meijden (2021). Only publicly available data with a reasonable density is included (SBES and MBES)

2.3 Sand wave formation

The formation and dynamics of sand waves has been thoroughly studied in the past decades. As mentioned above Hulscher (1996) explained the occurrence of sand waves by the interaction of tidal currents and bed forms. Due to shadowing of the tidal current a residual average current is formed from the trough of the sand wave in the direction of the crest. This is shown in Figure 2.7 where the velocity profiles during the maximal tidal current and the tide-averaged residual currents are shown.



(a) During maximum flood flow

(b) Tide-averaged

Figure 2.7: Velocity profiles over a sand wave (Tonnon et al., 2007)

For a symmetrical tidal motion, the averaged flow over the vertical is zero. This means that these residual currents near the bottom are compensated in the vertical and a circulation cell is formed. These circulation cells are shown in Figure 2.8. The residual currents in these cells support the growth of these bed forms. Due to this circulation, grid refinement over the vertical is necessary to simulate sand wave formation.

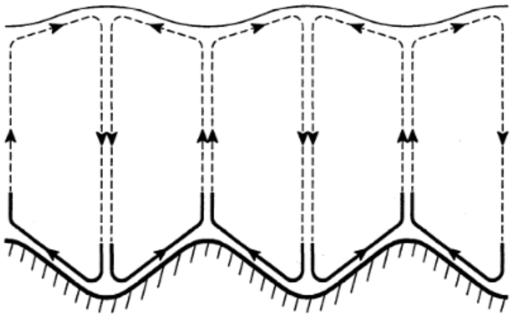


Figure 2.8: Tide-averaged circulation cells over a sand wave field (Hulscher, 1996)

Sand waves are observed to be very regular in wavelength and shape over certain areas. This degree of order is a result of the driving forces which act as a self-organizational mechanism (Matthieu et al., 2013). Looking at the dominant mechanisms for sand wave formation will give insight into which sand wave lengths are expected to grow and which will not grow (Borsje et al., 2014). Borsje identified the following three mechanisms: bed load transport, slope induced transport and suspended sediment transport. The first of these mechanisms causes sand wave growth, while the latter two cause decay of the sand waves as can be seen in Figure 2.9. The bed load transport instantly follows the currents. Under the influence of the flow circulation cells this transport mode moves sediment from the trough of the sand wave to the crest. In this way the bed load transport supports sand wave growth. Sediment is more easily transported downhill than uphill. This mechanism is called slope induced transport and causes the sediment transport rates to be higher when directed down a slope. Slope induced transport thus causes a net sediment transport from the crest towards the trough. The importance of this effect is however dependent on the steepness of the slope. This means that short waves will experience more decay than long waves, with the same wave height, due to slope induced transport. From the model study by Borsje et al. (2014) it is clear that suspended sediment have a damping effect on sand waves. Borsje et al. (2014) explained this with the phase lag between suspended sediment transport and sand waves. The extend of the damping is dependent on both sediment size and strength of the tidal current, which is supported by observations, showing no sand waves for certain Rouse numbers (Borsje et al., 2014).

The three dominant mechanisms discussed above play a major role in determining which wave lengths will grow and which will not. At the short end of the spectrum sand waves are dampened

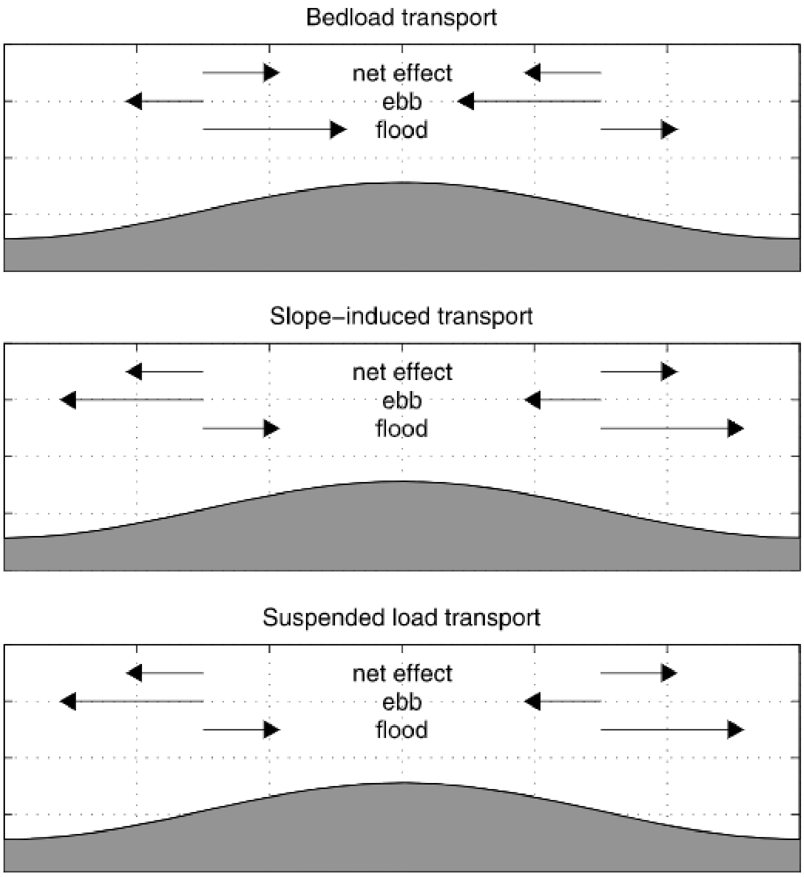


Figure 2.9: Schematic overview of the dominant processes in sand wave formation: bed load transport, slope induced transport and suspended load transport. Sand waves and fluxes not to scale (Borsje et al., 2014)

by slope induced transport. At the long end on the other hand the suspended sediment transport dampens the sand waves. Furthermore, in regions where suspended sediment transport is dominant sand waves might not occur (Borsje et al., 2014).

2.4 Sand wave dynamics

Sand waves are usually not static. Growth and migration of sand waves and changes in shape can cause bed level variations in sand wave areas. Together these changes in the sand wave bathymetry are called sand wave dynamics. In this section influences on sand wave dynamics will be discussed. To predict future bed levels in sand wave areas the processes mentioned will have to be taken into account.

Tides and residual currents

The tide has been identified as the main forcing mechanism for the formation of sand waves (Hulscher, 1996). When only taking into account the symmetrical M2 tidal constituent, sand wave growth is observed, but no sand wave migration. The growth rate of sand waves is dependent on the strength of the tidal current (Wang et al., 2019). Relatively strong tidal currents result in higher growth rates, when sand waves are present. Whether sand waves are formed is dependent on the strength of the tidal current relative to the grain size (Borsje et al., 2014). These findings are supported by data analysis on sand waves on the Dutch continental shelf. For low Rouse numbers, indicating strong tidal currents with respect to the sediment grain size, and thus dominance of suspended sediment transport, no sand waves were found (Damen et al., 2018).

When the tidal forcing is not symmetrical, the vertical tide-averaged circulation cells (see Figure 2.8) will get distorted, leading to sand wave migration. When a residual current is superimposed on the M2 tide sand wave migration in the direction of the current occurs (Németh et al. (2002), Besio et al. (2003)). For an increasing strength of the residual current Sterlini et al. (2009) as well as Van Gerwen et al. (2018) found an increasing migration rate and a decreasing equilibrium sand wave height. Sand wave migration can also be caused by higher tidal constituents. Besio et al. (2004) explored the effect of a combination of the M2 and M4 tidal constituents. It was found that the M4 tide can give rise to sand wave migration in both directions along the major axis of the tide, dependent on the phase difference between the two tidal constituents. This also explained sand wave migration opposed to a residual current which was observed in the North Sea. Lastly the spring-neap tidal cycle can have a significant effect on sand wave formation (Blondeaux and Vittori, 2010). It was found that whether the modulation of the tide caused bed level stabilization or destabilization was dependent on the dominant sediment transport regime.

Storms and surface gravity waves

Campmans (2018) elaborately studied the effect of surface gravity waves on sand waves. With the use of linear and nonlinear modelling it was found that surface gravity waves can enhance the migration rate of sand waves when migration is already present. However, surface gravity waves do not cause migration themselves. When, for example during a storm, wind waves and a wind driven current are combined this can cause significant sand wave migration in the direction of the wind driven current. This migration may be in opposite direction of the long term migration direction of the sand waves. Furthermore, wind waves cause a decrease in equilibrium sand wave height (Campmans, 2018). These conclusions are supported by a study by Bao et al. (2020) who observed large sand wave migration and a significant decrease of sand wave height during a tropical storm on the Taiwan Shoal. Campmans (2018) also compared the effect of mild, intermediate and extreme storm conditions, representative for the North Sea. It was found that the intermediate conditions had the largest absolute effect (when scaled to occurrence) on the sand wave migration, although they have a lower chance of occurrence than the mild conditions.

Underlying seabed topography

Underlying seabed topography can have a significant effect on sand waves. Several data-analysis and modelling studies have pointed to a maximum sand wave height with a linear dependence on water depth (Damen et al. (2018), Németh (2003)). Tonnon et al. (2007) pointed out that at smaller water depths surface gravity waves have a larger effect on sand waves and can significantly decrease sand wave height and increase migration. Leenders (2018) showed that the diversion of currents by tidal sand banks, as explained by Roos and Hulscher (2003), can cause opposite migration directions of sand waves over a small area. These large scale bedforms deform the tidal flow which causes an opposite residual flow on both sides of the tidal sand bank averaged over the tidal cycle. This causes the sand waves to migrate towards the crest of the tidal sand bank for a symmetrical tide, see Figure 2.10. In case of residual flow or asymmetrical tide the migration rates and/or directions are also influenced by the underlying topography (Leenders, 2018). Due to orientation of these sand banks with respect to the sand wave orientation (see Section 2.1.2), these features cannot be included in transect (2DV) sand wave models. In areas with underlying sand banks 3D models are thus required to simulate sand wave migration.

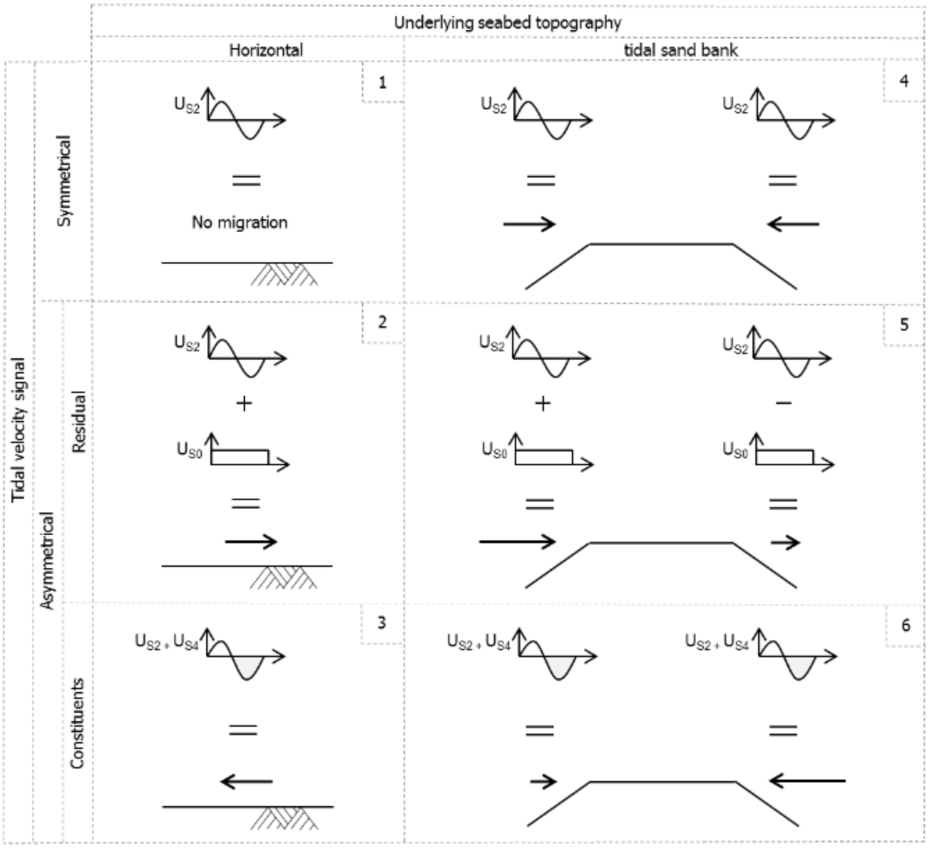


Figure 2.10: Schematic overview of sand wave migration direction on a flat bed (left) and on a tidal sand bank (right) (Leenders, 2018)

Biological influences

It is well known that organisms can influence hydrodynamics and morphology. The presence of certain organisms is dependent on environmental conditions. (Borsje et al., 2009) looked into possible effects of the presence of three different organisms. These organisms influence hydrodynamic parameters and sediment transport. It was concluded that these organisms could have a significant effect on sand wave length and more importantly, they could stabilize or destabilize the bed causing changes in the spatial distribution of sand waves ((Borsje et al., 2009)). (Damveld et al., 2018) looked into the spatial distribution of organisms over a sand wave and found a significantly higher count in the sand wave troughs. It was also found that the sand ripple characteristics varied significantly between trough and crest areas, which could possibly be caused by biological influences ((Damveld et al., 2018)).

Sediment size and sorting

As explained before the different sediment transport regimes have opposite effects on sand wave growth, see Figure 2.9. This means that a change in sediment size, which influences the dominant sediment transport regime can have a significant impact on sand wave characteristics. In several studies it was found that grain size sorting takes place over the length of a sand wave (Van Oyen and Blondeaux, 2009), Damveld et al. (2020b), Cheng et al. (2020)). Through modelling with graded sediment Van Oyen and Blondeaux (2009) found that whether coarse sediment piles up at the trough or crest regions depends on the relative strength of the tidal current. For weak tidal currents the coarser fractions pile up at the trough of the sand wave, while the finer fractions move towards the crest. In this case the graded sediment stabilizes the bottom relative to a uniform sediment of the mean grain size. On the other hand, in case of strong tidal currents the coarser sediment fractions are mostly found in the crest region, while fine fractions move towards the trough. The sediment grading then acts as a destabilizing factor (Van Oyen and Blondeaux, 2009). Damveld et al. (2020b) studied the effect of graded sediment on sand wave growth and migration. While excluding hiding and exposure effects a higher standard deviation of the sediment diameter lead to decreased sand wave growth and increased migration.

The influences discussed in this section have been studied thoroughly using stability analysis and complex numerical models (see Chapter 3). However, the sand wave system in these models is often simplified. The sand wave shape is, for example, represented by a sine function and forcing is purely periodical, while reality often deviates significantly from these idealized conditions. Although these simplifications are not expected to affect the qualitative results of these sensitivity analyses, in quantitative sense there might be significant deviations with reality. This leads to the following knowledge gap:

Knowledge gap:

What is the importance of various environmental influences on sand wave dynamics in real life cases?

And how does this differ from idealized cases?

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3 REVIEW OF STATE-OF-THE-ART SAND WAVE MODELLING METHODS

In this chapter the third literature question is answered: *Which (modelling) methods exist to predict sand wave dynamics and what are their pros and cons?*. Moreover, attention will be given to the application ranges of these models and the influence of model settings on sand wave dynamics within these models.

3.1 Prediction of sand wave dynamics

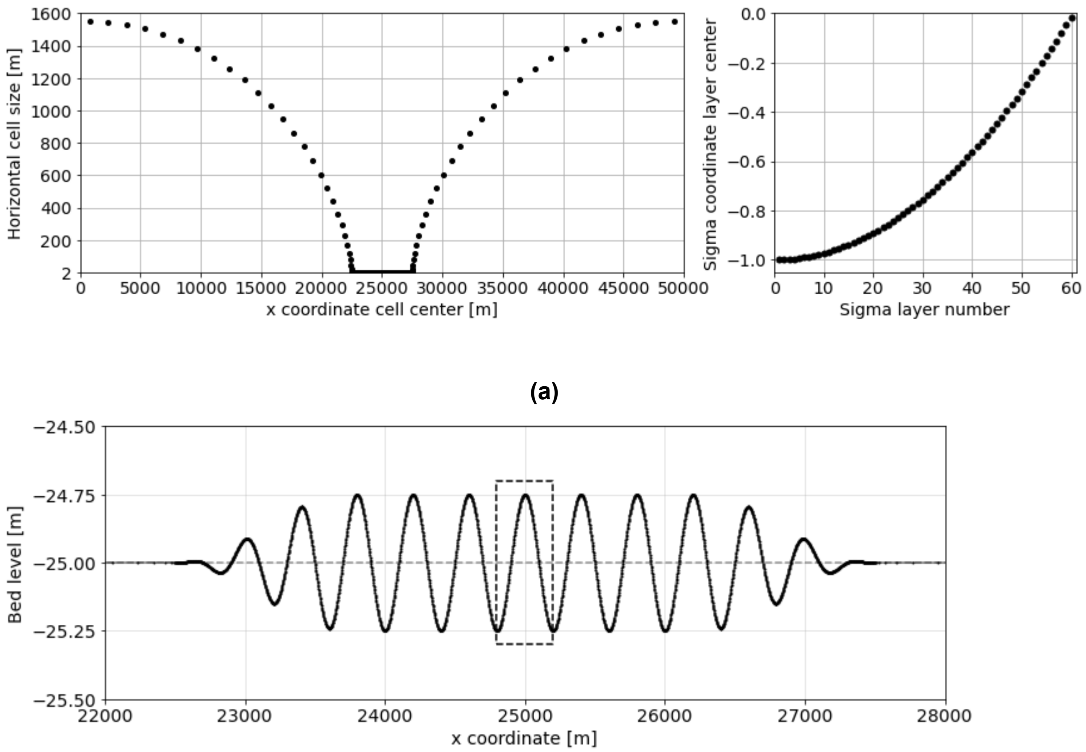
In this section three methods which have been used to model or predict sand wave dynamics will be discussed. First the earliest method for sand wave modelling based on stability analysis is explained. Subsequently the use of complex numerical models for sand wave cases is discussed. Lastly data-driven methods, which are often used in practice, are elaborated upon. The last sub-section includes a comparison of the methods and a discussion of the pro's and cons of each.

3.1.1 Stability analysis

Linear and non-linear stability analysis has widely been used to study effects on sand wave dynamics. Within these methods a numerical solutions is found for a simplified sand wave problem either with or without linearity assumptions (see for further explanation Dodd et al. (2003)). These models include a simplified sand wave geometry, which is usually homogeneous in one horizontal direction, with sinusoidal initial perturbations. This model domain is forced with a basic tidal current and additional processes, such as suspended sediment transport and surface waves, can be added to the problem.
First linear stability analysis was used to explain the formation and migration of sand waves (Hulscher (1996), Németh et al. (2002), Besio et al. (2004)). These linear models are however only valid in the initial stages of sand wave growth. To model sand wave behaviour in later stages non-linear models were introduced by Németh et al. (2007), Sterlini et al. (2009) and Van den Berg et al. (2012). Both models showed to be capable of simulating sand waves to an equilibrium stage with wave lengths similar to those found in reality. The equilibrium wave height was however overestimated in these models. Using non-linear theory Campmans (2018) showed that this equilibrium wave height decreases significantly when wave and wind effects are taken into account. The final wave height was however still overestimated when compared to field data.

3.1.2 Complex numerical models

Complex, process-based numerical models have been used to model sand wave dynamics. The most widely used model in this category is Delft3D-4, a complex model based on the shallow water equations. Tonnon et al. (2007) was the first to use Delft3D-4 for the purpose of sand wave modelling. In this 2DV (two-dimensional vertical) model study the influences of various model parameters and model set-up on the growth and migration of an artificially made sand wave in the Dutch North Sea is analyzed. Over the years the sand wave changed shape to form a steep slope facing the ebb current, but the sand wave migration in this direction was minimal. None of the model variations formed such a steep slope without significant migration.
The exploration of Delft3D-4 for sand wave cases was continued by Borsje et al. (2013), who showed that the Delft3D-4 model is capable of growing sand waves with characteristics matching those found in observations. Using the k-ε turbulence model more realistic results for the



(a)

(b)

Figure 3.1: Example of (a) model grid and (b) initial sand wave bathymetry based on Borsje et al. (2013) as adopted by Overes (2021)

sand wave length were found relative to the constant eddy viscosity turbulence model (which was adopted in stability analyses). The 2DV model set-up by Borsje et al. (2013) included an area with sinusoidal sand waves in the middle of the domain surrounded by a flat buffer area of 20 km on both sides (see Figure 3.1). This model set up was also adopted in various subsequent studies, such as: Matthieu and Raaijmakers (2012), Matthieu et al. (2013), Borsje et al. (2014), Choy (2015), De Koning (2017), Van Gerwen et al. (2018), Wang et al. (2019) and Damveld et al. (2020b).

Using Delft3D-4 Matthieu et al. (2013) showed the self-organizational properties of sand waves. From this study it was concluded that sand waves do tend towards a preferred wavelength, although antecedent bathymetry does have a long-lasting influence on the precise sand wave characteristics. Borsje et al. (2014) used the Delft3D-4 model to show the influence of suspended sediment transport on sand wave growth and migration. Van Gerwen et al. (2018) studied the behaviour of sand waves on long timescales using Delft3D-4. It was found that both the inclusion of suspended sediment transport and tidal asymmetry significantly reduce the equilibrium wave height. Damveld et al. (2020b) studied the effect of graded sediment on sand wave dynamics and bed composition in sand wave areas with a Delft3D-4 model including multiple sediment fractions. This Delft3D-4 model set up has also been applied to engineering problems such as dredging and the burial depth of pipelines. This was done by amongst others Matthieu and Raaijmakers (2012) and De Koning (2017).

Leenders (2018) was the first to use a 3D (landscape) Delft3D-4 model to study sand wave dynamics. In idealized and realistic setting the effects of underlying sand banks on sand wave migration were explored. However, during the realistic model study some problems were encountered related to the domain decomposition, which was used to reduce computational effort. Another study including a measured bathymetry in Delft3D-4 was carried out by Krabbendam et al. (2021). In a 2DV set-up similar to the one used by Borsje et al. (2013) the development

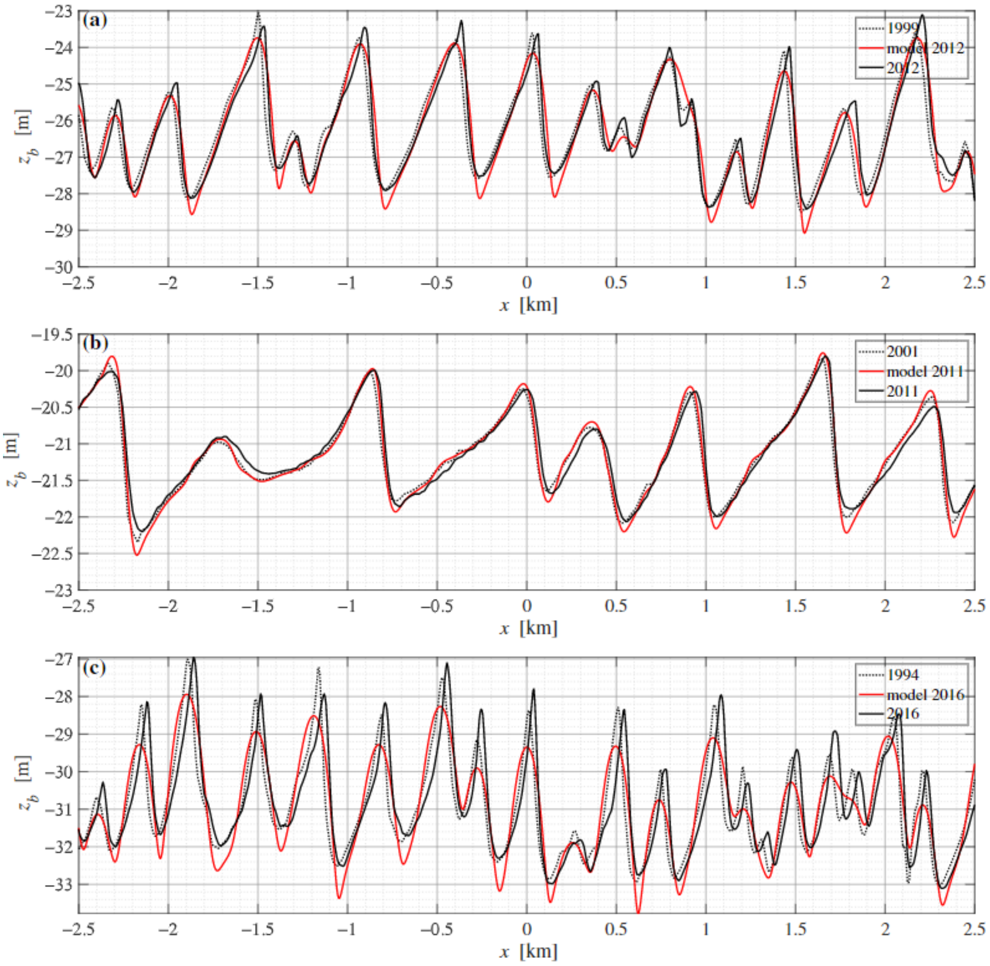


Figure 3.2: Measured bed level (black) and modelled bed level (red) using a callibrated Delft3D-4 model along 3 transects in the Dutch North Sea (Krabbendam et al., 2021)

of offshore sand waves at 4 locations in the North Sea was simulated. When the results of the calibrated hindcast model were compared to bathymetry measurements significant differences in sand wave bathymetry were observed, see Figure 3.2

Recently Delft3D Flexible Mesh (FM), a new, process-based numerical model developed by Deltares, has been applied to sand wave cases. The Delft3D FM model is the successor of Delft3D-4 and offers various opportunities to reduce computation time. For more information on the Delft3D-4 and Delft3D FM model and the differences see Appendix A. Overes (2021) tested Delft3D FM in both for both idealized and realistic sand waves. It was found that in an idealized setting the results of Delft3D-4 and Delft3D FM were highly comparable. However, when applying an uncalibrated Delft3D FM model to a measured bathymetry in a 2DV hindcast study the results showed differences with what was measured. These results show the importance of further improvements of the model, such as the inclusion of additional processes and variations and possibly calibration.
Auguste et al. (2021) used the MIKE21 FM numerical model to simulate sand wave migration in the highly energetic Banks Strait. In this model an estimation of the vertical velocity profile is made using hydrodynamic properties from a 2DH simulation. In this way the influence of for example surface waves on the vertical profile is taken into account. This method is however unable to account for the effect of the sand wave bathymetry on the vertical velocity structure. This simplification could explain the inability of the model to reproduce the large sand wave migration rates in the area. Moreover, some of the relations found in this study did not match what was found in previous idealized model studies.

3.1.3 Data-driven analysis

In preparation for future wind farms Deltares has carried out morphodynamic analyses for several planned wind farm locations in sand wave areas of the North Sea (Deltares (2015), Deltares (2016a), Deltares (2016b), Deltares (2019), Deltares (2020)). The main objective of these studies is to gain insight into the local seabed dynamics and classify areas as suitable or unsuitable for the construction of wind turbines, based on local seabed mobility. In these studies a data-driven analysis is carried out to characterise seabed features and historic seabed dynamics. This analysis is supplemented by numerical modelling of residual sediment transport patterns, to explain the dynamics found in the historic data. The found sand wave characteristic and dynamics are then used to obtain an estimation of possible future seabed levels. At the moment this is the most important tool for seabed level predictions in sand wave areas. This type of analysis yields the highest quality in cases where multiple historic bathymetry datasets measured over a period of several decades are available. Uncertainties in the future seabed levels increase significantly with lower spatial and temporal spread in available bathymetry data.

For the prediction of possible future bed levels the historic bathymetries (and thus seabed dynamics) are split into three classes of seabed features: megaripples, sand waves and large-scale bathymetry. All three classes are analyzed separately. Using Fourier transform spatial characteristics of the bed forms are extracted from the bathymetry measurements. The large-scale bathymetry is assumed to be static, which is checked by comparing the large scale bathymetry output from the different measurements (which have been gathered over a period of 10-15 years). In all cases only small differences due to measurement inaccuracies were found (e.g. streaks of heightened or lowered bed level in the same direction as the measurements). Megaripples are often very dynamic. Within the lifetime of an offshore structure multiple megaripples will thus pass by. This means that the full height of the megaripple has to be taken into account. A measure for the megaripple height (e.g. the 95% non-exceedence height) is thus included as an uncertainty band on the future bed level prediction.
Since the migration of sand wave is much slower than that of megaripples, but still causes large differences in future bed levels, an analysis into the migration speed and direction is carried out. In these reports first the migration direction of the sand waves is determined. This migration direction may show significant variations over the sand wave area, especially if underlying sand banks are present. The migration direction is thus determined either per sand wave (crest) or in blocks of sand wave bathymetry. The direction is determined either through a 2D cross correlation analysis (moving the sand wave bathymetry in various directions and comparing this with next measurement) or by assuming that the sand waves migrate in the direction of the steepest slope (based on Knaapen (2005)). Apart from differences in migration direction over the sand wave area also variations between the measured periods might be present. When a 2D cross-correlation method is used, the migration direction and migration speed of the sand waves can be extracted simultaneously. In case the migration direction is based on the steepest slope, transects of at least one sand wave length are drawn parallel to the migration direction determined earlier. From these transects the migration speed can be determined through either 1D cross correlation (translating the bathymetry over the horizontal) or the migration of crest and trough points. These values for the (minimum and maximum) migration speed and direction are used at a later stage to define possible future sand wave bathymetries.
To obtain more insight into the causes of this sand wave migration a large scale model is used for hydrodynamic and sediment transport simulations in the area of interest. This model simulates the main tidal components in a 2DH setting. The results of this model are not used for predictions of seabed dynamics, but function as a tool to gain more understanding of the mechanisms behind the morphodynamics. When no significant discrepancies between the data-analysis and the modelling results of hydrodynamics and sediment transport are found, the historic bathymetry data can be used to predict bed level changes.

Using the knowledge about the bed form characteristics and dynamics future bed levels are estimated. First different types of uncertainty are bundled to estimate the range of possible future bed levels. The identified uncertainties are amongst others: migration speed and direction of bed forms, survey inaccuracies, limited spatial resolution and the assumption of shape-retaining sand waves. Most uncertainties are included as an up- and downwards uncertainty bandwidth. However, the uncertainty due to sand wave migration (speed and direction) shows significant spatial variation and is thus treated differently. For the sand wave migration the previously described analysis is used. From this analysis statistical information about the migration direction and speed of the sand waves over the area is obtained. This information is used to determine the bandwidth of the possible migration direction and speed (for a certain part of the sand wave area). The sand waves are then translated according to these directions and speeds for the period considered in the analysis. This results in multiple possible sand wave bathymetries at the end of the chosen lifetime. After combining these bathymetries with the uncertainty bands a range of possible future bed levels can be determined.
For the study of the Hollandse Kust Zuid Wind Farm (HKZWF) location the estimated uncertainty bands, excluding sand wave dynamics, were 0.5 m upwards and 0.4 m downwards (Deltares, 2016a). By combining these uncertainty bands with the possible sand wave migration speeds

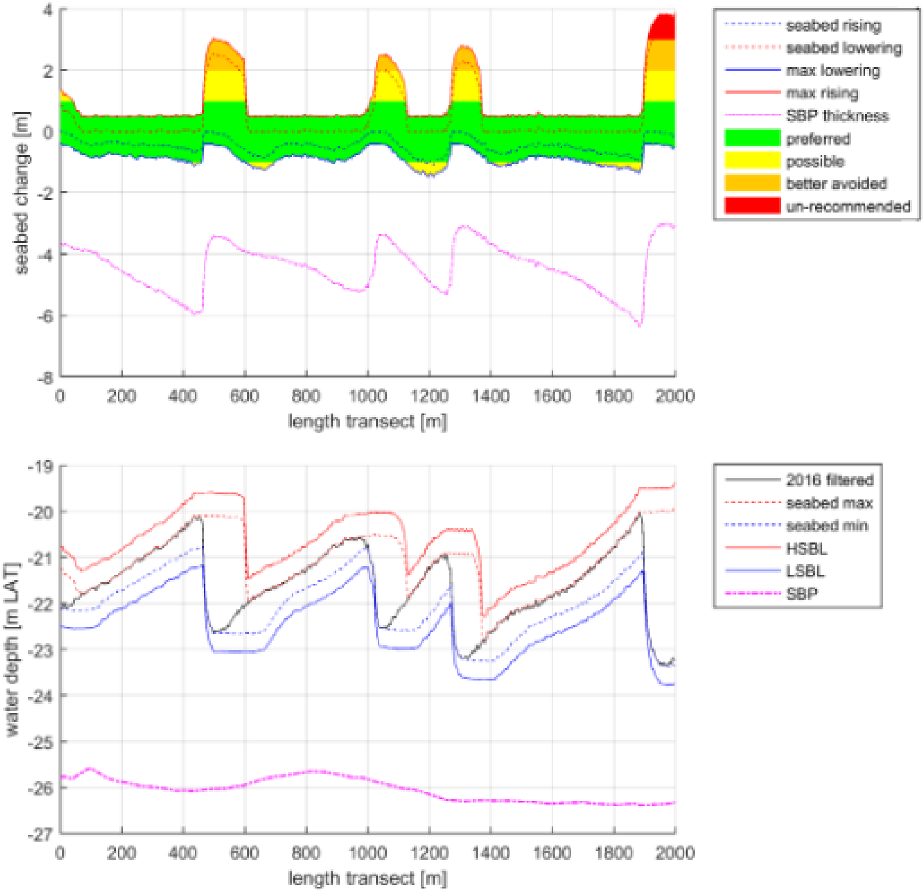


Figure 3.3: Upper plot: estimation of maximum lowering an rising of the seabed including uncertainty bands. Lower plot: 2016 measured bathymetr (black), lower and upper bed level due to sand wave migration (dashed blue and red line respectively) and the LSBL and HSBL (solid blue and red line) which include the mentioned uncertainty bands. Both plots represent a transect at Hollandse Kust (Zuid) Wind Farm (HKZWF) and a duration of bed level change of 35 years (Deltares, 2016a)

and directions a Best Estimate Bathymetry (BEB) as well as the Lowest SeaBed Level (LSBL) and Highest SeaBed Level (HSBL) were determined for 35 years in the future. This duration of bed level changes is based on a typical wind farm lifetime of a few decades. As can be seen in Figure 3.3 in the HKZWF case the total uncertainty of the bed levels amounts to up to 4.5 m locally, of which only 0.9 m can be ascribed to sources other than sand waves. From this band of possible seabed levels the maximum lowering and rising at a certain location during this period can be determined. Areas are classified based on this estimation of the local maximum lowering and rising. Such a classification is also shown in Figure 3.3. In the sand wave fields considered the majority of the area is deemed suitable for the construction of wind turbines, based on the expected change in bed level over the lifetime of the structure. Close to the crest of the sand wave fast lowering or rising of the seabed can take place. This makes the location less suitable for wind turbines, cables and pipelines.

3.1.4 Method Comparison

The different methods to predict sand wave dynamics described above all have their own strengths and weaknesses. These are explained below and summarized in Table 3.1.

The first method discussed above is stability analysis, which can be a powerful and efficient tool for the exploration of the influences of single processes on sand wave dynamics. This makes the method well suited for sensitivity analyses. However, when more processes are added creating a fitting model becomes more and more difficult and a solution to the problem might be harder to find. This results in simplifications of processes and other parameters. In these models sand waves are often assumed to be sinusoidal and tidal flows are simplified. Lastly, data on local hydrodynamics is needed to apply these models to realistic cases.

Using complex numerical models a more realistic representation of reality can be created. Most of these models have built-in options for various processes. State-of-the-art formulations of processes such as turbulence and sediment transport are included in the models. The processes can easily be changed or in-/excluded. Moreover, the initial and boundary conditions can be implemented with a high accuracy and variability in space (and time). However, this high level of detail comes at a costs. The more processes and variations (such as different sediment sizes) are included, the larger the computational effort becomes. Due to this most sand wave modelling studies have applied a 2DV model set-up. The Delft3D FM model shows various opportunities to reduce these computational efforts, see Appendix A. The computational effort needed in Delft3D FM should thus be further explored to evaluate how adequate the model is for practical application. Another possible drawback of complex numerical models is ironically their complexity. Since these models may include an extensive amount of processes and offer many options for (numerical) model settings they also require a vast amount of code in complex programming languages. So, even though the code of for example Delft3D is open source, many engineers will not be able to, or will not have the time to fully understand the model. When the model is used by someone who does not fully understand its limitations it may be regarded as a black box. This will possibly lead to blind trust in the model results, even in cases which might not be suitable for the model. However, this problem can be mitigated through heightened awareness and the use of expert knowledge to analyse model results. Alike for stability analysis, some processes still have to be parameterized in complex numerical models. In addition the problem is discretized in space and time, which may lead to inaccuracies when too large grid sizes or time-steps are used. Lastly the predictions of complex numerical models can only be as good as their input. Detailed data on local hydrodynamics is thus necessary for accurate predictions.

Data driven analysis has often been used in practice. This method yields quite reliable results in stable environments with a relatively high spatial and temporal density of bathymetry data (e.g. multiple MBES measurements over a period of 10-20 years). When the spatial resolution of the measurements is low or only a limited amount of datasets is available the uncertainty of the predictions will increase significantly. In case only one (or less) data set is available, the prediction method as explained above cannot be used. The method itself also includes some simplifications, such as the assumption of shape retaining sand waves, which decrease its accuracy. Moreover, the physical base of the predictions is limited. The prediction are only based on historic changes, but give no clear indications on the causes of these sand wave dynamics. This limitation makes that in changing conditions, when hydrodynamics change due to e.g. climate change, the reliability of the results will decrease significantly.

Table 3.1: Comparison of prediction methods for sand wave dynamics

Method	Strengths	Weaknesses
Stability Analysis	- Computationally efficient - Fast sensitivity analysis	- Limited processes - Simplified representation - Process parameterization - Dependent on available hydrodynamic data
Numerical Models	- Easy inclusion of processes - Accurate representation of reality possible	- Possibly: large computational efforts - Complex - Process parameterisation and discretisation - Dependent on available hydrodynamic data
Data-driven analysis	- Fast analysis - Quite reliable under stable conditions	- Dependent on available (historic) bathymetry data - Limitations of method - Limited physical base - Unreliable in changing environments

All methods thus have there own strengths and weaknesses. Stability analysis and numerical models are most suitable to increase understanding of sand wave dynamics, since processes can be in- and excluded within these models. In this way the importance and effect of various processes on sand wave dynamics can be explored. For the prediction of future bed levels stability analysis is however unsuitable due to the various simplifications made. For this purpose thus data-analysis and numerical models are available. Preference is often given to data-analysis due to the efficiency of the method (since most projects are very time-sensitive) and due to the limited experience of modelling real sand wave dynamics using numerical models. The new Delft3D FM model however already offers opportunities to increase this model efficiency. More modelling experience in sand wave cases and possible further increase in efficiency will show if this new model might perform better than data-analysis.

3.2 Influences of Delft3D model choices

Complex numerical models offer a vast amount of choices for the model set-up. These choices include parameterization of physical processes, boundary conditions and numerical settings. The sensitivity of the Delft3D-4 sand wave results to these various model settings have been studied extensively. A summation of the influences found in previous studies is included in this section.

3.2.1 Parameterization of physical processes

As mentioned before, some modelled processes need to be parameterized in physical models. The reasons for applying such a parameterization vary widely. Some processes work at a smaller scale than the grid size or modelling the full process would be too complex. In various previous modelling studies the effect of these parameterization choices have been analysed.

Turbulence formulation
The creation and dissipation of turbulent kinetic energy is a process that often works on a smaller scale than the applied grid size. For this process various sub-grid turbulence models have been created with varying complexity. Within these models the vertical eddy viscosity (which is related to the amount of vertical mixing) is computed. The simplest of these models is the constant vertical eddy viscosity model, which assumes a constant value for the eddy viscosity over depth. This turbulence model has been used in most stability analysis studies on sand waves. In reality the amount of vertical mixing is dependent on the scale of turbulent eddies, which are in turn depending on the closeness to the bed and surface boundary of the flow. This means that in this type of model the eddy viscosity near the bed and near the surface is overestimated. The $k-\epsilon$ turbulence model, which was used by Borsje et al. (2013), accounts for variations of the vertical eddy viscosity in space and time. Borsje et al. (2013) found that when using this turbulence model the wave length and growth rate of the fastest growing mode would decrease. Herewith these characteristics would become more like what is found in reality. Moreover, Tonnon et al. (2007) applied the aforementioned models and the $k-L$ turbulence model to a case including an artificially made sand wave in the North Sea. Although the growth and migration rate from the model using the $k-\epsilon$ model were found to be most like the measurements, a strange dip in the bed level was formed near the toe of the sand wave. This phenomena was not observed in reality and is not yet fully understood. In these model studies the more complex turbulence models seem to perform better than the simpler constant turbulence model.

Bed roughness
Another process which is included as a parameterisation is the bed roughness. This variable determines the influence of the sedimentary bed boundary on the flow above and vice versa. A higher bed roughness causes the flow to slow down above the bed and more sediment to be entrapped by the flow. To simulate bed roughness various options are available. The bed roughness may be specified beforehand through a (spatially varying) factor, such as the Chézy or Manning roughness coefficients. Tonnon et al. (2007) tried different values for the Chézy roughness coefficient, varying between 65 and 85 $m^{1/2}/s$. It was found that this factor has a major impact on sand wave growth and migration (see Figure 3.4a). A more complicated method to define bed roughness is by using a roughness predictor. This predictor accounts for the growth and decay of certain bed forms which may increase the bed roughness. Tonnon et al. (2007) found that by using such a roughness predictor which accounts for ripple and megaripple growth the roughness would increase temporarily during low flow velocities, due to the growth of (mega)ripples. When the flow velocities increased these bed forms are washed away and the roughness decreases again. This predictor however caused unrealistic sand wave growth, see Figure 3.4b. When only ripples were included in the roughness predictor the evolution of

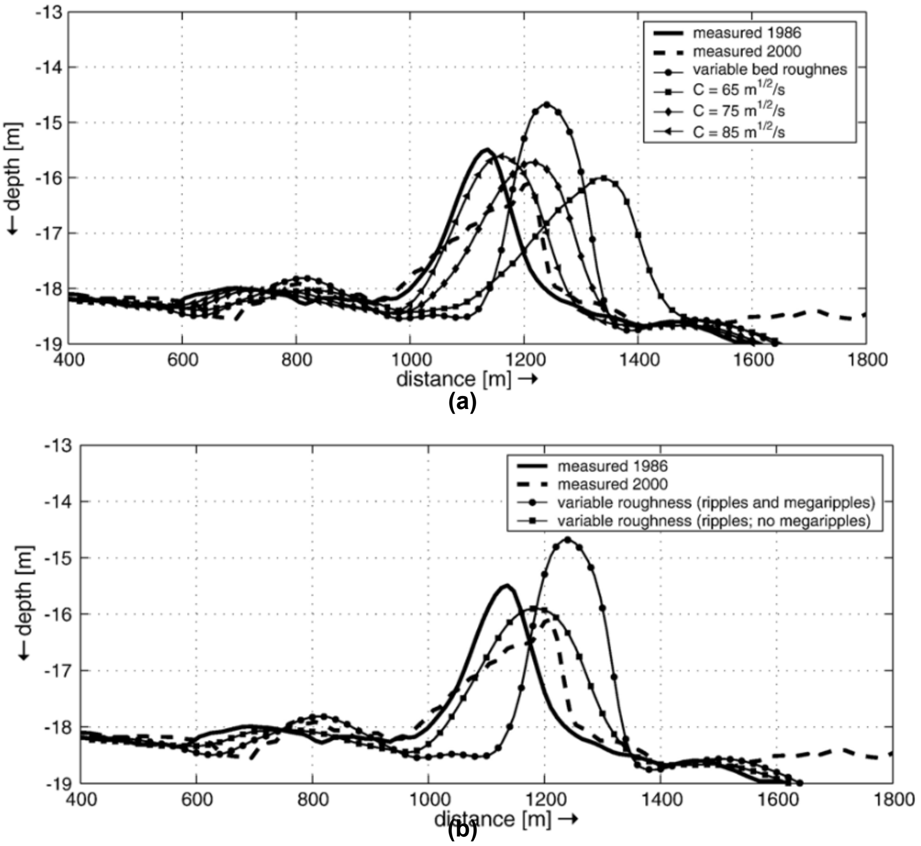


Figure 3.4: Influence of varying bed roughness in a Delft3D-4 sand wave model, used to model an artificially made solitary sand wave in the Dutch North Sea, including measurements (Tonnon et al., 2007)

the sand wave was most like the observations. In this case the use of the roughness predictor lead to a relatively smooth bed (would convert to Chézy values of 75-85 $m^{1/2}/s$) (Tonnon et al., 2007). Similar results were found by Bottenberg (2021), who tested the same bed roughness predictor in a 2DV model with sinusoidal sand waves. It was observed that for a tidal current of 0.65 m/s almost no change in ripple height over time was predicted. However, the height of megaripples was predicted to change significantly over the tidal cycle. The observed spatial variability of the roughness height was limited for a sand wave height of 3 m (Bottenberg, 2021). A study by Damveld et al. (2018) would however suggest that in reality there are significant differences in ripple height between the crest and the trough areas of sand waves. Through the roughness predictor used in these studies the predicted (mega)ripple height is however fully dependent on the local mobility parameter. This parameter is based on the local current velocity and sediment parameters. The lack of spatial variability in ripple height might in the study by Bottenberg (2021) be caused by the simplification of the sediment composition to one grain size. Including multiple sediment fractions would lead to sediment sorting over the sand waves (Damveld et al., 2020b), thereby amplifying the differences in mobility parameter between the sand wave crests and troughs.

Knowledge gap:

How to realistically represent the difference in bed roughness between sand wave crests and troughs?

Sediment transport
The transport of sediment is also parameterized in complex numerical models. For this parameterization the sediment transport is often split into contributions of different processes. These processes are: bed load transport, suspended load transport and bed slope related transport (see Section 2.3). To simulate bed load transport various formulae are available. Some make a distinction between bed and suspended load, while others calculate the total load. Moreover, some formula can also be used to calculate the increase in sediment transport due to wave actions, while other cannot. In this literature study only the sediment transport formulations which have been tested on sand wave cases will be discussed.
Most previous studies have used the Van Rijn et al. (2004) sediment transport model to simulate sediment transport in sand wave cases. This formulation distinguishes between bed load (below the reference height) and suspended load (above the reference height). This model includes a threshold for sediment motion and is able to account for wave influences on both bed shear stress and sediment transport. Moreover a roughness predictor has been implemented which can predict the increase in bed roughness due to various bedforms such as ripples and megaripples. Using this sediment transport formulation reasonable sand wave lengths and values for sand wave growth and migration have been achieved in various studies (a.o. Borsje et al. (2014), Damveld et al. (2020a)). The Van Rijn 2004 formulation is based on the Van Rijn, others (1993) transport model. The original formulation has over the years been extended and improved. In a study by Bottenberg (2021) it was shown that the transport rates (bed load and suspended load) in the model were significantly higher when using the Van Rijn 1993 transport formulation, compared to Van Rijn 2004. In this study the Van Rijn 1993 model showed larger initial growth rates and shorter sand wave lengths for the Fastest Growing Mode. In a study by Choy (2015) similar results were found for these transport formulations. In this study also the Engelund Hansen transport formula was applied. This simple formula does not make a distinction between bed load and suspended load transport, but describes a direct higher order relation between flow velocity and sediment transport. The model results using this formulation showed unstable behaviour, which might be caused by the lack of distinction between bed load and suspended load transport (Choy, 2015). Moreover, Choy (2015) found a significant effect of the bed slope factor on sand wave growth rate and shape. This bed slope correction factor determined the strength of bed slope processes on the bed load transport (increase of downslope transport and decrease of up-slope transport). Results by Tonnon et al. (2007) showed similar effects, with a steeper shape and higher growth rates for lower correction factors. Wang et al. (2019) also looked into the effects of varying the bed slope factor and concluded that this factor is an important calibration parameter.

3.2.2 Boundary conditions

To connect the model domain with its surroundings, which are not included in the simulation, boundary conditions need to be defined. In most model studies some boundaries are closed by a land boundary, such as the beach in a coastal model, or the banks in a river model. In case of sand wave modelling the model domain is often located in the middle of the sea, such that in principle four open boundaries should be included. Since detailed model studies, which only include part of the sea, do not belong to the base cases the Delft3D model is developed or used for, standards on which type of boundary conditions to use are often lacking. In previous research this problem has been tackled in various manners, which are discussed in this subsection.

2DV modelling
Most previous studies have used a two dimensional vertical (2DV) model domain. In these type of models one horizontal direction, approximating the sand wave migration direction, is

included, combined with vertical discretization in the form of layers (see Subsection 3.2.3). The bathymetry of the sand waves is superimposed upon a mean depth in the middle of the model domain. The boundaries along the transect are closed and the lateral edges two open boundaries are included (see Figure 3.6). In these type of models exactly two cells are opened by the boundaries where water levels, perpendicular velocities or discharges can be applied.

In the Delft3D-4 sand wave model initially developed by Borsje et al. (2013) and subsequently used in numerous studies (see Section 3.1.2) Riemann invariants are applied at both boundaries. Riemann boundaries include a combination between water level and current and are weakly reflective, which means that outgoing waves can cross the boundary without being reflected back into the model domain (Deltares, 2021a). In the model by Borsje et al. (2013) harmonic Riemann invariants are applied, with a 180 degrees phase difference between the boundaries, to represent the tidal current velocities. In the middle of the domain this leads to a perfectly symmetrical current velocity over time, while the water level remains approximately constant. In this way no migration of the sand wave is taking place. However, in reality the tidal wave in the North Sea approximates a progressive wave, meaning that the water level during flood is higher than during ebb. In the model by Borsje et al. (2013) the water levels at the both boundaries are out of phase, leading to a significant water level difference over the model domain. Although a propagating tidal wave would also show variations in water level over this domain length of approximately 50 km, the maximum difference is overestimated in this type of model. It is clear that although this combination of boundary conditions is able to create perfectly symmetrical tidal conditions, which is desired in these idealized studies, it is not suitable for the recreation of realistic tidal conditions.

For the purpose of realistically modelling the local tidal conditions multiple types and combinations of boundaries are possible. In case two Riemann boundaries are applied to represent a progressive tidal wave, at the outflow boundary the Riemann invariant should be set to zero since there is no incoming wave. Alternatively, water level or velocity boundaries may be applied. However, these types of boundary conditions are not as dampening as the Riemann boundary, which means that waves and other disturbances will be reflected back into the domain.

Krabbendam et al. (2021) tried all combinations of the above mentioned boundary condition types on a 2DV sand wave model in a North Sea case study. After a simulation period of 12 years the morphological development of the sand waves in the different models was compared to bed level measurement. The differences between the runs was in the order of decimeters, while in a qualitative sense similar results were found, see Figure 3.5. The combination of two Riemann boundaries (R_+ in the upstream and R_- on the downstream boundary) was chosen for the remainder of the study (Krabbendam et al., 2021).

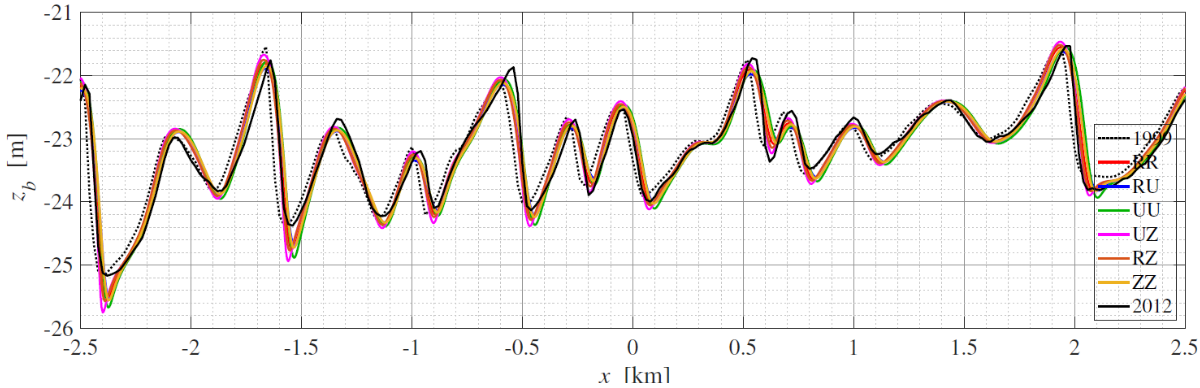


Figure 3.5: Modelled bed level z_b for 2012 along a transect in the North Sea for different boundary condition combination by Krabbendam et al. (2021). The boundary conditions used are represented by the letters: U - velocity, Z - water level, R - Riemann, where the first letter indicates the left (S) boundary and the second the right (N) boundary Black lines represent measured bathymetries.

Subsequently, Krabbendam et al. (2021) compared the hydrodynamic results (in terms of water level and depth averaged velocity) inside the sand wave domain to the large scale model from which the boundary conditions were retrieved. This comparison showed that the tidal motion was reproduced with reasonable accuracy by the combination of two Riemann boundaries. However, in the residual current (U_0) significant differences between the models were found at some locations along the transect. Since a study by Overes (2021) showed that small differences in the residual current can already lead to significant deviations of the growth and/or migration over the timescales considered, these differences should be considered when evaluating the results. Overes (2021) applied one velocity and one Riemann boundary in a 2DV case study. This resulted in a good match for the local flow velocities, but a poorer match for the water level between the sand wave model and the large scale model.

Simulating realistic hydrodynamics can be difficult, since often a compromise has to be made between accurate representation of velocities or water levels at the boundaries. To aid this a new type of boundary condition, which applies both velocity and water level at the same location for inflow boundaries, is included in the newly developed Delft3D FM model (Deltares, 2021b). When the current is directed out of the model domain, this boundary condition automatically reduces to a Neumann type boundary. This type of boundary condition could be used to improve the accuracy of the hydrodynamics in the 2DV sand wave models. Since most previous model studies have used Delft3D-4, the applicability and accuracy of this type of boundary for modelling realistic sand waves in 2DV cases is yet to be discovered.

Another difficulty which arises from the set-up of these 2DV models is the fact that the boundaries are defined at a distance of over 20 km from the sand wave area. The ’buffer’ area, between the open boundaries and the sand wave area, consists of large grid cells over a flat bed as shown in Figure 3.6. The reason to include this area is to let the flow adjust to the local conditions and keep boundary errors away from the area of interest. However, this large buffer area complicates the definition of boundary conditions for accurate representation of hydrodynamics within real sand wave areas. Namely, the hydrodynamics the boundaries (point A and D) could significantly differ from what is present at the location of the sand waves (point B and C, see Figure 3.6). Yet, an in-depth study into the need and influence of this buffer area is lacking.

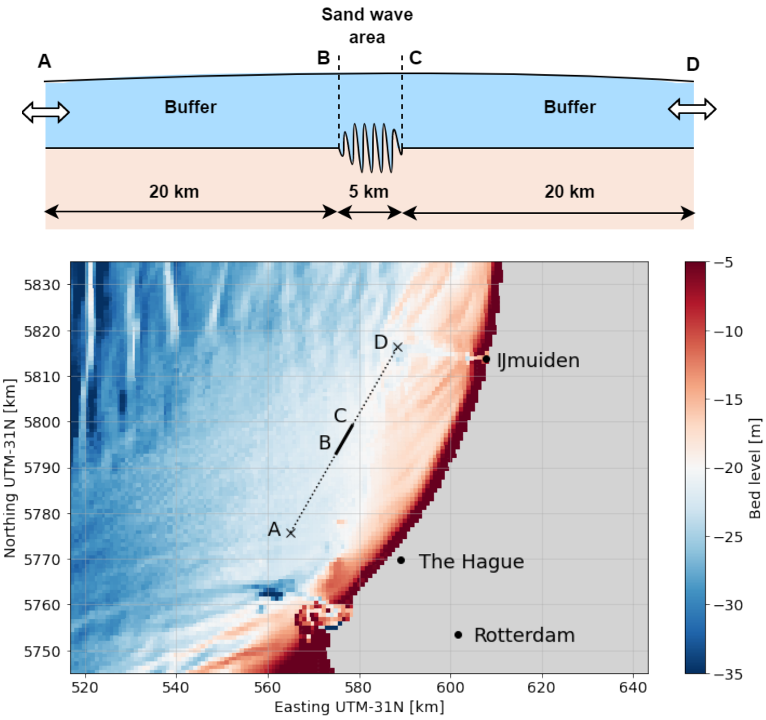


Figure 3.6: 2DV sand wave model set-up as used in Overes (2021)

Lastly it should be considered that in both of the model case studies the validation of the hydrodynamics was done using the results of a large scale model, from which the boundary conditions were derived. Although this large scale model has undergone an extensive validation (see Deltares et al. (2018)), still momentary differences can be found between the results and the measurements, especially when considering meteorological influences. Moreover, the grid sizes of this model are such that sand waves and their influence on hydrodynamics cannot be included. This makes that the large scale model also has its limitations and a perfect reproduc-

tion of its hydrodynamics is not the same as a perfect reproduction of reality.
In this section various limitations and uncertainties of the state-of-the-art 2DV sand wave model have been discussed. Together these brings us to the following knowledge gap:

Knowledge gap:

How to accurately reproduce local hydrodynamics in a 2DV sand wave model?

3D modelling
A few studies have made the leap from 2DV to 3D sand wave modelling. Firstly Leenders et al. (2021) used a 3D model to simulate the influence of underlying sand banks on sand wave migration rates. Since the orientation of these bedforms differs from sand waves (see Subsection 2.1.2) this influence can not be included in the above described 2DV models. In an idealized study Leenders et al. (2021) used the same set-up as in the 2DV model by Borsje et al. (2013), i.e. two open boundaries forced by out of phase Riemann invariants (see above). The only difference in this case was the extension of the model in the along crest direction of the sand waves. In this idealized model study the tidal current was thus simulated as being perfectly birectional (instead of ellipsoidal) and the same advantages and disadvantages apply as explained in the 2DV section above.
The second 3D sand wave model of this study by Leenders et al. (2021) included a real case and was embedded in the large scale Dutch Continental Shelf Model (DCSM). This large scale model includes the full North Sea and stretches beyond the British Isles. It is forced using tidal water levels at the oceanic boundaries and includes wind and pressure forcing within the model domain (Deltares, 2015). In the study by Leenders et al. (2021) domain decomposition is used to embed the 3D sand wave model in the DCSM model. This means that multiple domains, with varying grid sizes, are run in parallel and the overlapping domain boundaries are coupled through the momentum and continuity equation (Deltares, 2021a).
Although in this case the full 3D tidal signal including meteorological influences could be applied to the boundaries of the sand wave model, the domain composition was found to still have its limitations. Near the edges of the domains errors in the calculated sediment transport were found. These edges should thus be located far from the area of interest, although this will lead to a significant increase in computational effort. Within the Delft3D-4 model, which was used in this study, dom,ain decomposition is the only way to refine the grid locally within the model domain (Deltares, 2021a). In the Delft3D FM model unstructured grids can be applied, which allow for smooth refining, avoiding coupling errors at domain boundaries. This brings us to the following knowledge gap:

Knowledge gap:

How to accurately and efficiently couple a 3D sand wave model
to a large scale hydrodynamic model?

3.2.3 Numerical model set-up

To transform physical processes from a continuous spatio-temporal space towards discrete points in space and time (which can be solved by computers) various choices need to be made. Firstly the spatial grid is discussed, followed by the time discretization.

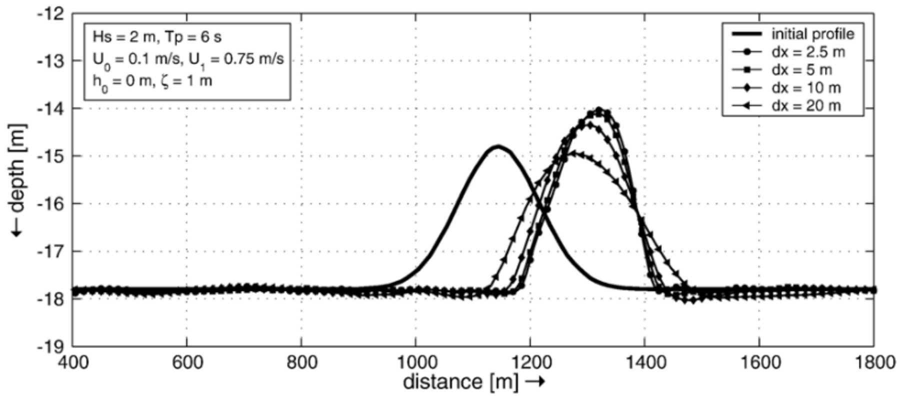


Figure 3.7: Influence of varying horizontal grid sizes on the Delft3D-4 model results for an artificially made solitary sand wave in the Dutch North Sea (Tonnon et al., 2007)

Horizontal and vertical grid size

For modelling studies choices have to be made regarding the horizontal and vertical grid sizes. When the horizontal cell sizes are chosen to be too big several problems may arise. Firstly the local flow parameters and sediment transport are solved only once per computational cell (per timestep) and the bed level of the flow is simplified to one level. Differences within the cell will thus not be accounted for. When these cells cover areas which have significant variations (such as differences in bed level or flow velocity) these simplification will have an effect on the model results. Secondly when sigma layers are used the computational grid needs to be transformed towards this new sigma grid. Within Delft3D 4 and Delft3D FM simplifications have been made is this transformation to reduce the computational effort of the procedure. When the level difference over a cell is however to large these simplifications can lead to numerical errors and thus artificial flow (see Deltares (2021a) and Deltares (2021b)). The required grid size should thus be determined relative to the amount of variation in the model (in this case: the size and steepness of the sand waves). Tonnon et al. (2007) tested various grid sizes within a model including an artificial sand wave, see Figure 3.7. It was observed that the model results converged for grid sizes of 2.5-5 meters. For a horizontal grid size of 10 meters some differences could be observed, but these were judged to be acceptable. For 20 meter grid size significant deviations were found compared to the other models. Since the scale of this artificial sand wave is similar to real ones in the North Sea, these results are expected to be applicable to real cases. In a model study using real bathymetry data by Krabbendam et al. (2021) (supplementary materials) various grid sizes were tested. Between the results obtained with 2.5, 5 and 10 meter grid sizes only small differences were observed.

Secondly also the vertical grid size needs to be specified. These vertical layers are needed to model the circulation cells created by interaction between the sand wave bed and the tidal currents. Since no material was found in which model results for variations in this setting were compared testing might be needed.

Time discretization

Additionally choices need to be made with respect to the time dimension. Within the Delft3D FM model the timestep is no longer a user-specified variable, but is defined by the model itself, based on the time-varying courant number (Deltares, 2021b). Influences of differences in timestep are thus not considered in this literature study.

Since changes in morphology happen on significantly longer time-scales compared to hydrodynamics, the morphological acceleration factor (morfac) was introduced to speed up morphological models. By multiplying the calculated bed level changes with this factor the morphological change over a longer time can be calculated while modelling hydrodynamics over a short timescale. However, when the morfac is taken too large the accelerated result might differ from the original results. Krabbendam et al. (2021) tested different values for the morfac on a realistic model and found no changes between the results with accelerations of 37, 74 and 148 times (NB the sediment transport was in this study already multiplied by 0.5 in an earlier stage, practically halving the used values for the morfac). Other studies have used even larger values for this factor, such as: 500 (Tonnon et al. (2007) and Damveld et al. (2020a)), 600 (Choy, 2015) and 2000 (Van Gerwen et al., 2018) and found no significant deviations with models using lower values. However, in a study by Matthieu et al. (2013) it was found that with a morfac larger than 250 the deviation from the original results (with a morfac equal to 1) would increase exponentially.

3.3 Missing influences

Due to simplifications, various influences are still missing in previous sand wave model studies. Firstly the hydrodynamics in sand wave models are often simplified, to enable studying of specific influences on sand wave dynamics. The tidal forcing is for this reason represented by specific tidal constituents. This is in some cases combined with a constant residual current, which causes sand wave migration (e.g. Van Gerwen et al. (2018)). In a physical sense, one could say that this constant current represents the average residual current in a sand wave area. However, in a study by Overes (2021) it can be seen that especially meteorological influences (wind and storms) cause a significant variation in this residual current, with instantaneous current speeds of up to 10 times the average, see Figure 3.8. Averaging out these variations might be too simplistic since the relation between current speed and sediment transport is non-linear and the timing with respect to the tidal currents are of importance. Small current speeds can already cause a significant migration over the decadal timescales considered in offshore engineering projects so these variations are likely to be of importance (Overes, 2021). However, a more in depth study of these influences is lacking.

Knowledge gap:

What is the influence of a time varying residual current on sand wave dynamics?

Another significant simplification of most previous sand wave models is the exclusion of the along crest direction. Most sand wave models are transect models, including only one horizon-

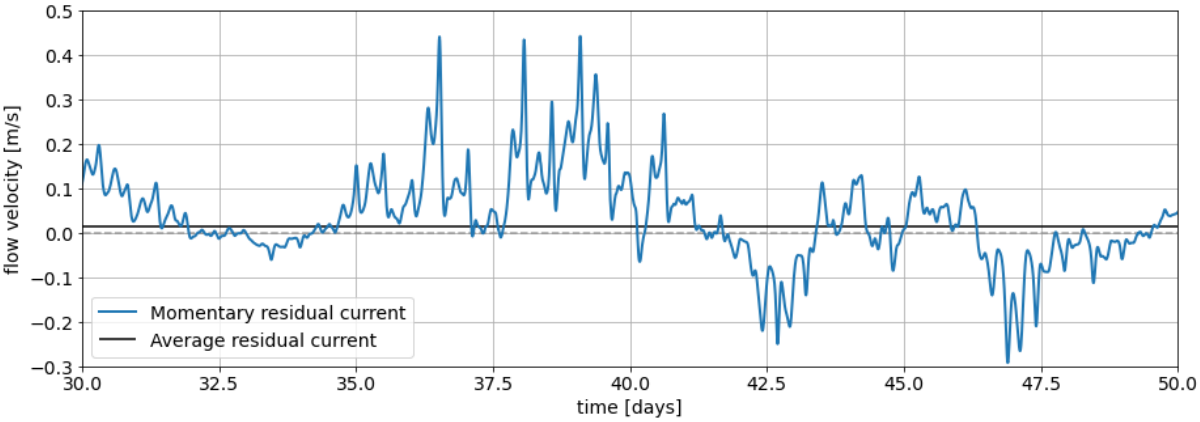


Figure 3.8: Residual current due to meteorological influences in the Dutch North Sea (HKZ area) (Overes, 2021)

tal direction, where the transect is taken in the approximate direction of sand wave migration. The underlying assumption is that the influence of processes working in the along crest direction on sand wave dynamics is limited. These kind of models represent an infinitely long-crested sand wave field. However, a study by Leenders et al. (2021) showed that underlying sand banks, which do not have the same orientation as sand waves, have a significant influence on sand wave migration. Moreover, various data studies, such as Van Dijk (2011), Deltares (2020) and Bellec et al. (2019), have found significant changes in sand wave bathymetry in along crest direction. In these studies 3D bathymetric features, such as sand wave bifurcations, gradual along-crest change in amplitude and change in crest direction were observed (see Figure 3.9).

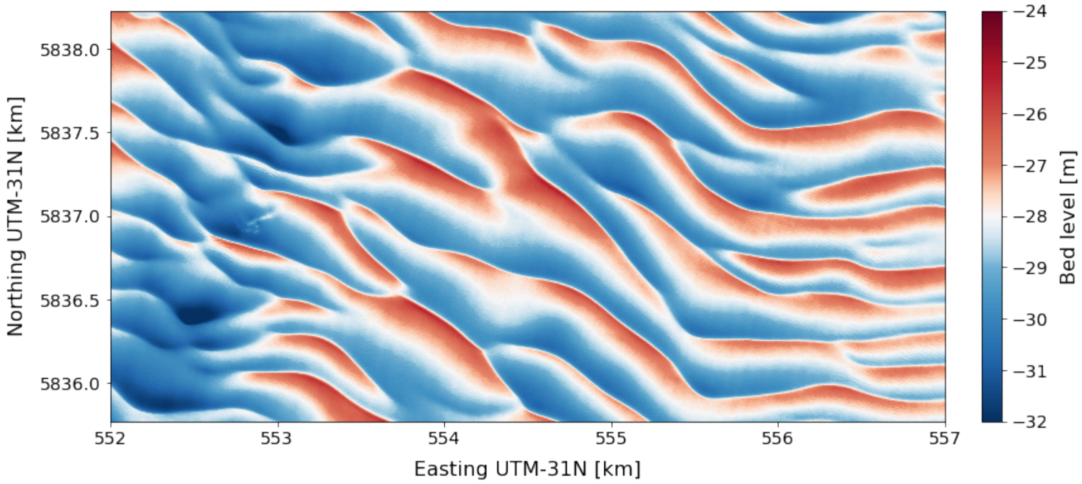


Figure 3.9: Example of an irregular sandwave field with 3D features like sand wave bifurcations, along crest changes in amplitude and changes in crest direction

This means that for these highly 3D sand wave fields as well as sand wave fields with underlying sand banks, the assumption of infinitely long crests is not valid. In most previous models the influences in this second horizontal direction are missing. An exception to this is a study by Leenders et al. (2021). They modelled the influence of tidal sand banks on sand waves in both idealized and realistic settings. To be able to model this phenomenon in realistic setting, including an observed bathymetry and hydrodynamics, domain decomposition was used, which significantly reduced the computation time. In this method grid cells of different sizes were coupled to enable modelling of a large area, with reasonable computation times, while using a finer grid in the area of interest. This study by Leenders et al. (2021) provided fundamental insight into the influence of sand banks on sand wave dynamics and revealed the need for a second horizontal dimension to accurately simulate real-life sand wave migration. However, the used numerical methods showed room for improvement. In the results effects of the domain decomposition were visible near the edges of the domains. This resulted in errors with respect to sediment transport in the area of interest. Leenders (2018) argued that avoiding these errors, by keeping the domain transitions well outside the area of interest, would results in unreasonable computational efforts. Although these models thus provided indications of important 3D influences, the real extend of these influences is still to be studied and requires state-of-the-art modelling tools. With these tools both the influence of 3D hydrodynamics, such as non-aligned currents, waves and storms, on sand waves and the influence of 3D sand wave bathymetries on the local hydrodynamics can be studied. This interplay will show how these features developed and how they will act in the future under various possible hydrodynamic forcing types.

Knowledge gap:

What is the influence of 3D forcing and bathymetry on sand wave dynamics?
And how significant are these effects?

Lastly, the influence of smaller bed forms is largely unexplored. These bed forms may alter the local hydrodynamics through increased bed roughness and they may be able to transport sediment themselves. Moreover, these bed forms, such as ripples, show a high spatio-temporal variation (Damveld et al., 2018). In Krabbendam et al. (2021) a roughness predictor is used, to predict the roughness height of the various bed forms (ripples and megaripples) based on the local conditions. However, the suitability of this method for sand wave cases is not further explored. Moreover, sediment transport through these bed forms is not included.

4 METHODS FOR INCREASING MODEL EFFICIENCY

In this chapter the following question will be answered: *What methods exist for increasing model efficiency?* A division will be made of methods which speed up the numerical models themselves and other methods outside of the model framework. The former includes for example surrogate modelling, where the accuracy of the results is improved, reducing the need for detail in the model. For all of these methods the expected computation time reduction as well as other strengths and weaknesses will be discussed. In Section 4.1 attention will be given to the upscaling of the models themselves, through for example input reduction, model reduction, the morphological scale factor and parallel model running. Subsequently the use of multifidelity modelling and data-driven surrogates is discussed in Section 4.2.

4.1 Upscaling techniques

In this section techniques which reduce the computational efforts of physical models are discussed. The potential of these methods is often immense, with possible computation time reduction by factors of up to 1000 for a single method (Li et al., 2018). However, the use of these methods requires sound judgement by the users (partially based on experience), since the highest possible reduction is based on a multiple of factors. In each individual case attention should be given to the validity of these upscaling techniques, since copying model set-up from different models could lead to unnoticed inaccuracies.

Input reduction

In case of input reduction system knowledge is used to determine which input is significant and which is not. In a study by Luijendijk et al. (2019) the wave forcing input was reduced by only considering the wave conditions which caused morphological changes (i.e. low wave heights were excluded). By excluding wave heights smaller than 1 meter, the computational time could be reduced by 40% (Luijendijk et al., 2017). Li et al. (2018) mentioned computation time reductions of a factor 10^2 up to 10^3 for river models were only bankfull discharge events would be included for determining flood risks. In other cases similar criteria can be used by including for example only the situations with a significant current speed or water level. As demonstrated by these cases significant computation time reductions are possible using this method. If the criteria for in- and exclusion are chosen well there is possibly barely any difference between the outcome of a model including full forcing and the model with a reduced input. How well suitable cases are for this method varies widely between the sort of models and the purpose of the study. Especially in case extreme events should be tested, this method is very appropriate. However, when the development of a system, including for example sedimentation and erosion, is modelled, care should be taken when using this method. The low impact conditions could still have some effect, especially if they are present for long timescales (relative to the high impact conditions) and could play a role in shaping the system. In these cases solid judgement should be made on whether these conditions should be included.

Another form of input reduction is created by replacing the input with a (or a multiple of) representative condition(s) such as a representative tide(s) or wave condition(s). This in itself does not reduce the computation time, but makes the model better scale-able through for example the morphological scale factor or parallel running of the conditions (both are discussed below). This representative condition can be tuned to correctly represent a certain effect of the complete forcing, such as longshore transport in case of waves (Luijendijk et al., 2019). This tuning can be done using either measured effects or through a model which includes a more complete forcing range. It should then be kept in mind that this representative condition might not be as good in representing other effects of the condition than the one it was tuned for.

Model reduction

Similar to input reduction the complexity of the model itself can also be reduced. This is done by simplifying the included processes, scales or dimensions (Li et al., 2018). Such kind of reductions are frequently applied in various modelling fields and can also be found in sand wave modelling. Examples of this in case of sand wave modelling are: reducing the model domain from 3D to 2DV, simplifying the local sediment to one representative grain size and excluding hiding and exposure effects and the exclusion of suspended sediment transport. According to Li et al. (2018) model reductions typically lead to a reduction of computation time with a factor of 10-100. Determining which part of the models may be reduced is something which requires broad understanding of the modelled system. The validity of these reductions should thus be considered thoroughly, especially when moving to cases which are (slightly) different from the original model (e.g. applying it to a different location). A pitfall of this method is that model reductions are often blindly copied between studies or cases, without reconsidering their validity. However, with the huge complexity of some systems this method can in these cases not be avoided. Moreover, when the reductions have a solid physical foundation the reduced models are often able to produce very accurate results. Especially when dimensional reductions are applied computation times will drop significantly.

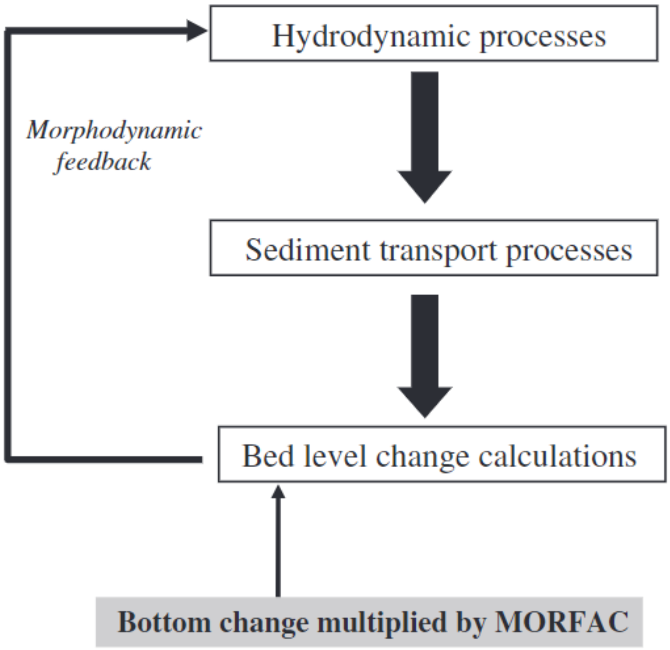


Figure 4.1: Base structure of morphological models including use of morphological scale factor (MORFAC) to accelerate bed level changes (Ranasinghe et al., 2011)

Morphological scale factor

A widely applied and accepted method for reducing the computation time of morphological models is the use of the morphological scale factor (MF) (Lesser et al., 2004). This method is based on the difference in typical timescale of hydrodynamic and morphological changes and assumes that the interaction between the hydrodynamics and the morphology is linear during one time-step (Ranasinghe et al., 2011). By multiplying the bed level change at the end of the morphological loop by a factor (morphological scale factor or MF), the morphological changes are sped up significantly, see Figure 4.1. This methods offers an elegant way to bridge the gap between fast, small scale hydrodynamic changes and transport processes and the long term, large-scale morphological change and is one of the most frequently used methods to increase numerical efficiency (Luijendijk et al., 2019). Using this scale factor the computations can generally be accelerated with a factor between 10 and 10^3, where the model acceleration is the same as the used factor (Li et al., 2018). In sand wave modelling applications similar values for the acceleration factor have been used in previous studies, with a MF of up to 2000 in some cases (see Subsection 3.2.3: Time discretization). However, when the adopted MF is too high the linearity assumption mentioned above becomes invalid. This may lead to numerical instabilities or unrealistic morphological changes (Ranasinghe et al., 2011).

Efforts have been made to derive relations to determine the maximum acceptable value for the MF based on local hydrodynamic and morphological conditions, such as Ranasinghe et al. (2011) and Reyns et al. (2015), but no generally applicable and robust relation has been found. However, some useful insights on the dependency of the critical value of the MF on various factors have been discovered in these studies, where a depth averaged one dimensional model was used to study the morphological development of a sand hump. Both studies found a positive dependency of the critical MF on the used horizontal grid size (dx) and no dependency on the Courant number of the flow (Ranasinghe et al. (2011), Reyns et al. (2015)). Moreover, no clear dependency of the critical value of the MF on the used time step was found (Ranasinghe et al., 2011). When applying a tidal current instead of the unidirectional current used in Ranasinghe et al. (2011), the critical value of the MF was found to be more than one order of magnitude smaller (Reyns et al., 2015). This shows the sensitivity of the factor to the model set-up and thus the need for tuning when using this acceleration method. Reyns et al. (2015) also found a negative dependency of the critical MF on the Froude number of the flow.

These dependencies and previous modelling efforts can help in determining an approximate critical value for the MF, but an iterative process to determine the acceptable value can not be avoided. In this process the morphological development in the model is compared to measurements or a simulation with MF = 1 for various values of the MF (Ranasinghe et al., 2011). Depending on the required accuracy of the model outcomes a critical value can be determined. Since this value is highly dependent on the model set-up, blindly copying it from previous studies is in most cases inappropriate. In case of harmonic forcing, such as tidal currents, the morphological results are only valid at the end of a hydrodynamic cycle when a MF is used.

A strength of this method is the considerable accelerations that can be reached while the morphological results are largely unaffected, especially in cases where morphological changes are slow. Moreover, since the hydrodynamics are not altered, this factor can easily be added to an existing, validated hydrodynamic model. Additionally, the MF works well with acceleration methods like time scale compression, which is discussed below. A drawback is the need to determine the acceptable value of the factor in an iterative process.

Parallel model running

Some numerical models offer the possibility to run models in parallel, such that the computations are spread over multiple cores or nodes, which carry out computations simultaneously (e.g. Deltares (2021b)). This method can accelerate the computations significantly and allows for full use of the available computational power when multiple cores are available on one computational node. Parallel model running can be utilized in multiple manners. In the most commonly used set up the model domain is divided into several partitions which run in parallel. These partitions run on separate cores and communicate with each other. In this way information on the hydrodynamics near the boundaries of the sub-domains is shared. The possible acceleration using this method is based on the computational size of the model. If too many partitions are used relative to the size of the model, the communication between the partitions will start to dominate in terms of time consumption relative to the time needed for the computations themselves. Moreover, for each partition a core should be available. Generally accelerations of a factor 10-20 for typical model sizes up to around 50 for large models sizes are possible. A strength of this method is that no concessions are made related to the numerical model itself, which means that the accuracy of the model outcomes is preserved.

Another way of utilizing parallel computations is by distributing the different forcing conditions over the cores. In a study by Luijendijk et al. (2019) different wave conditions were distributed in this way and applied to the same bathymetry. After a certain time period, such as one hydrodynamic time-step, the morphological changes are combined using weighing factors (representing the time a condition is present) and the bed level is updated, see Figure 4.2: Brute Force Merged (BFM). Using this BFM technique, model outcomes very similar to the Brute Force model (without acceleration) were found, while the computation times were reduced to 4.5% of the original (Luijendijk et al., 2019). When using this method it should be kept in mind that influences of original time order of the conditions are lost. So if a storm was originally present at the end of a timeseries, this storm is now spread over the full model period.

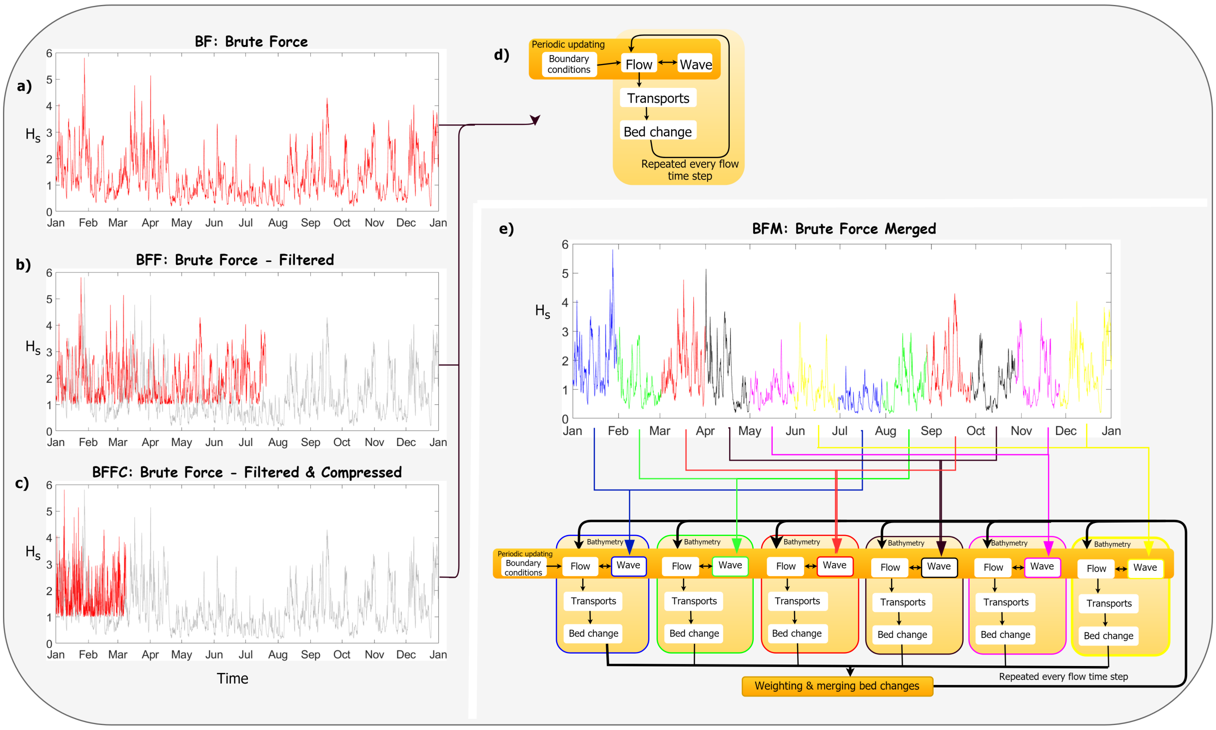


Figure 4.2: Schematization of acceleration methods used in Luijendijk et al. (2019) to reduce computation times of a flow model including waves: a) Brute Force (BF), no acceleration, b) Brute Force - Filtered, using input filtering, c) Brute Force - Filtered and Compressed (BFFC), using input filtering and time compression (combined with MF) and e) Brute Force Merged, using compression (combined with MF) and parallelization of wave conditions. d shows the morphological feedback loop in the BF, BFF and BFFC cases.

Time-scale compression

In the time-scale compression or simply compression method the hydrodynamics are compressed in time (see Figure 4.2). This is combined with a morphological scale factor to scale the morphological change with the hydrodynamics. This sort of compression is can not be used on each type of hydrodynamics. According to Luijendijk et al. (2019) compression oftidal currents and water levels could lead to unrealistic behaviour of tidal currents and/or filling of basins and lagoons. In this case the wave signal is thus compressed, with a factor 3, and applied in combination with a non-compressed tidal signal (Luijendijk et al., 2019). The possible acceleration using this method is limited, since the hydrodynamics should remain realistic and smooth. Too much acceleration may result in hydrodynamic changes which are too fast leading to unrealistic model outcomes. However, the MF can be higher that the time compression used, such that both time-scale compression and an additional MF factor are applied. An advantage of this method is that more variation in the hydrodynamic signal can be included in a shorter hydrodynamic model. A drawback is that the acceleration is limited and the method is not suitable for all situations.

Other methods
Various other methods have been developed to speed up numerical computations. In view of brevity some less common methods are mentioned here, but not discussed in depth. Firstly there is the tide-averaged approach, where the flow field over the full tidal cycle is computed to get the tide averaged sediment transport the resulting bed level changes are applied once or multiple times once before looping back to the hydrodynamics (Roelvink, 2006). In the Rapid Assessment of Morphology (RAM) a relation between the local water depth and sediment transport is derived, which is combined with the initial transport rate from a model run to formulate a simple analytical model (Roelvink, 2006). A more complex method, called the MASSPEED method, is discussed in Carraro et al. (2018) and includes upscaling of the spatial derivatives related to mass and momentum flux, to speed up both hydro- and morphodynamics.

4.2 Surrogate modelling

In this section surrogate modelling is discussed. In surrogate modelling a complex and (computationally) time consuming model is replaced by another physical or data-driven model. In case of a physical surrogate, another process based model is used of which the outcomes are assumed to be correlated with those of the original model, due to the application of the same principles (such as mass conservation) in both models (Berends et al., 2019). Due to this correlation a transfer function can be defined, which defines the output of the high resolution (or high fidelity) model based on the results of the low resolution (or low fidelity) model. This method is called multifidelity modelling. An alternative to multifidelity modelling is created by data-driven surrogates. In this case the link between the input and output of the model is made purely based on data, by for example a neural network. For both methods the surrogate of the model will have significantly lower computation times, but should retain as much of the accuracy of the original model as possible, leading to an increased efficiency. In the first part of this section multifidelity modelling will be discussed, after which attention is given to data-driven surrogates. The strengths and weaknesses of each method will also be discussed.

Multifidelity modelling
In multifidelity modelling the original complex model is replaced by a model with a simplified model. Such a simplification could be a coarsening of the used grid sizes, an increase of the time-step or even moving to a different amount of dimensions, as was done in Bomers et al. (2019), where the outcomes of a 2D model were linked to those of a 1D-2D coupled model. Alternatively the model equations or boundary conditions may be simplified (Razavi et al., 2012). Specific input parameters are used for both high and low fidelity model runs and using the model outcomes a transfer function is defined which represents the relation between the model outcomes, see Figure 4.3. The more high fidelity simulations are carried out, the better the transfer function can be defined, leading to a lower estimation uncertainty (Berends et al., 2019). This method has only recently gained popularity in water engineering, such that not much data is available on the possible efficiency gain using this method. In a study by Berends et al. (2019) this approach was used to carry out a Monte-Carlo simulation of channel siltation and an efficiency gain of 85% was observed relative to a direct Monte-Carlo simulation. Advantages of multifidelity model relative to other types of surrogates are that they are more reliable in discovering unseen relations in the system response, since they include the same physical principles, and that a clear trade-off can be made between reliability and efficiency (Razavi et al. (2012), Berends et al. (2019)).

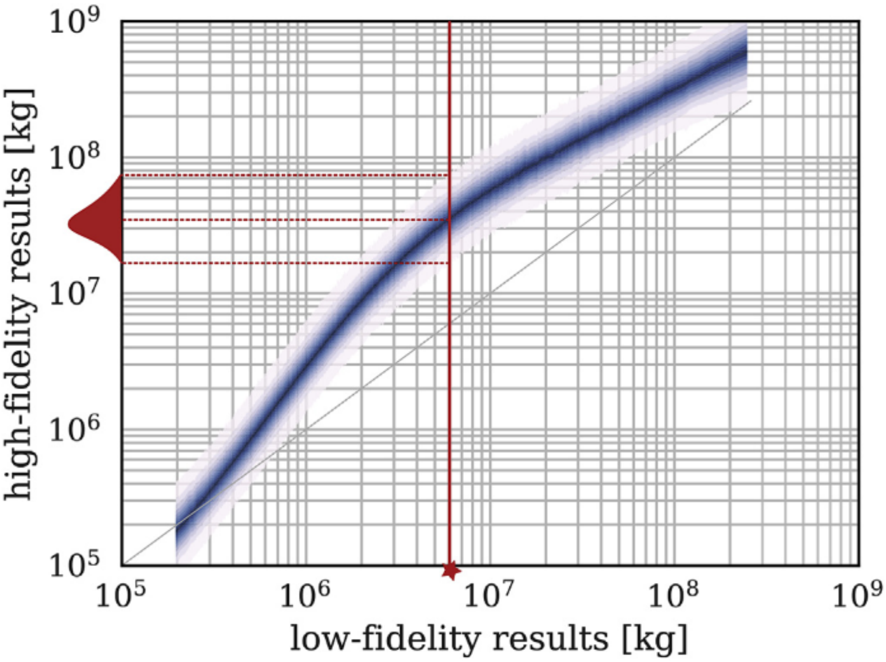


Figure 4.3: Example of using the transfer function in a multifidelity framework by Berends et al. (2019). Via this function the outcome of the lower fidelity model (in this case kg's of channel siltation) is transfered to a probability range of possible high-fidelity model outcomes.

Data-driven surrogates

Data-driven surrogates are a more common sight in water modelling. In this approach a data-driven model is used to find a direct relation between the model inputs and the model outputs. Razavi et al. (2012) identified various methods to define the relation between the model inputs and outputs, such as: polynomials, kriging, radial basis functions and artificial neural networkd (ANN's). The methods differ significantly in complexity and the choice of method requires carefull consideration. Razavi et al. (2012) compared 32 studies where data-driven surrogate models were used and found widely varying efficiency gains ranging from 20% all the way up to 98%. The computational gain in this case depends on the complexity of the surrogate model, and thus its computation time, and the amount of original model runs which are necessary. Especially in case of very limited computational budget or in case quick results are needed (e.g. Bomers (2021)) the use of such a surrogate model can thus be very useful. Razavi et al. (2012) found that the suitability of data-driven surrogate models rapidly decreases in case many input variables need to be considered. To map this high dimensional output space a large number of original model runs is necessary and the chance of blind spots in the transfer model increases significantly. Moreover, when using these types of models overfitting to the available data should be considered and avoided. Finally, where physical surrogates can be considered to also be valid outside of the training range, for data-driven surrogates this is not the case. These types of models should thus not be used outside of the training ranges.

Knowledge gap:

How can upscaling techniques and surrogate models contribute in sand wave cases and what is the order of the possible computation time reduction?

5 HUMAN INTERVENTIONS AND SAND WAVE RECOVERY

In this chapter the following questions will be answered: *How do human interventions influence sand wave dynamics and how fast do sand waves recover from dredging interventions?* First different types of interventions and their effects on sand waves will be discussed. Subsequently measurements of sand wave recovery as well as prediction methods are shown.

5.1 Human interventions in sand wave fields

Sand waves can be found at many locations on the sandy seabed of shallow seas (for examples see Subsection 2.2.1). These shallow areas also form a suitable place for many offshore activities, such as sand mining and offshore wind energy production. Moreover, due to their closeness to shore shipping traffic may be present. Where these human activities take place the sandy seabed might be affected. The most drastic intervention is dredging of the seabed, and thus the sand waves present, which might be necessary for the construction or maintenance of offshore structures. Furthermore, human constructions, such as monopiles (wind farms) or oil platforms, may effect the local hydrodynamics and thereby influence sand waves. Other changes that could affect the sand wave system are for example changes in the local water depth or the introduction of sediments with a different grain size (for example a scour protection, see Matthieu and Raaijmakers (2012). In most cases the sand wave field will recover over time. However, when major interventions have taken place, it could be that the system is changed so much that the characteristics or even the occurrence of sand waves are affected. An example of such an intervention was found by Harris and Whitehouse (2014), where the installation of a monopile caused the formation of sand waves in a otherwise flat area, see Figure 5.1. The effects of this monopile on the local hydrodynamics was thus enough to turn this system into one where sand waves can grow. However, in most cases the interventions are

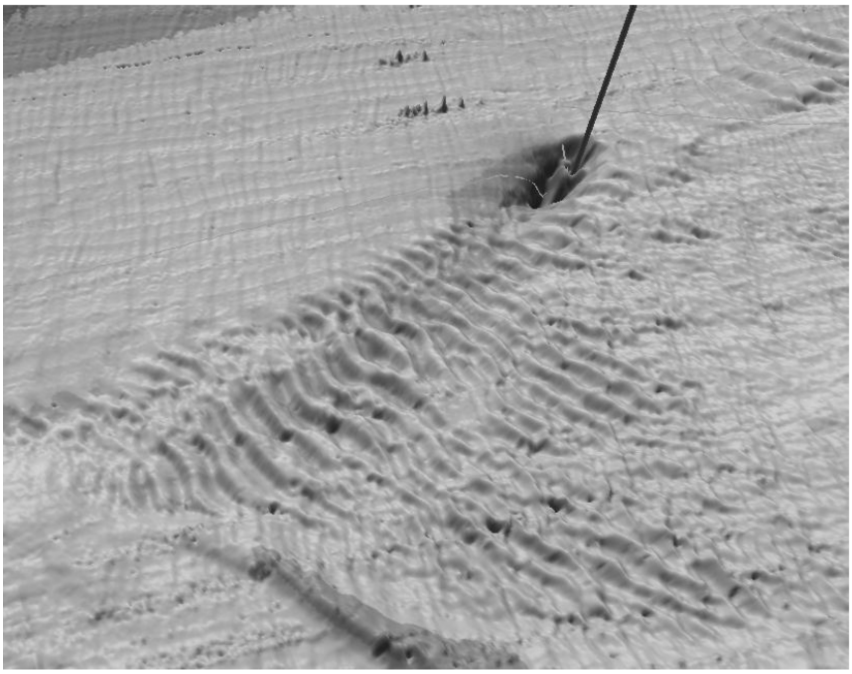


Figure 5.1: Sand waves in the wake of a monopile on an otherwise flat bed at the Scorby Sands sandbank, English North Sea (Harris and Whitehouse, 2014)

small relative to the size of the system (the sea) and lasting effects, such as subtle changes in the local hydrodynamics, are often hard to measure. In this literature review only the effect of, and the sand wave recovery after dredging interventions will thus be discussed in depth, since for other interventions scientific evidence is scarce. Nevertheless, for most system changes the effect on sand waves can qualitatively be described using the relations found in extensive modelling studies (see Section 2.4). When for example the water depth is increased, the (equilibrium) height of the sand wave is expected to increase as well, since this positive relation between water depth and sand wave height has often been observed.

Knowledge gap:

What is the influence of subtle, but lasting changes in hydrodynamics, due to offshore constructions, on sand wave characteristics and dynamics?

5.1.1 Sand wave dredging

For many activities, such as shipping and construction, dredging is needed in sand wave areas. A few examples of these dredging interventions in a sand wave field are shown in Figure 5.2. In these cases a distinction can be made between trenching and full dredging of the sand wave. These interventions and their intended purpose are discussed in this section, as well as dredging strategies.

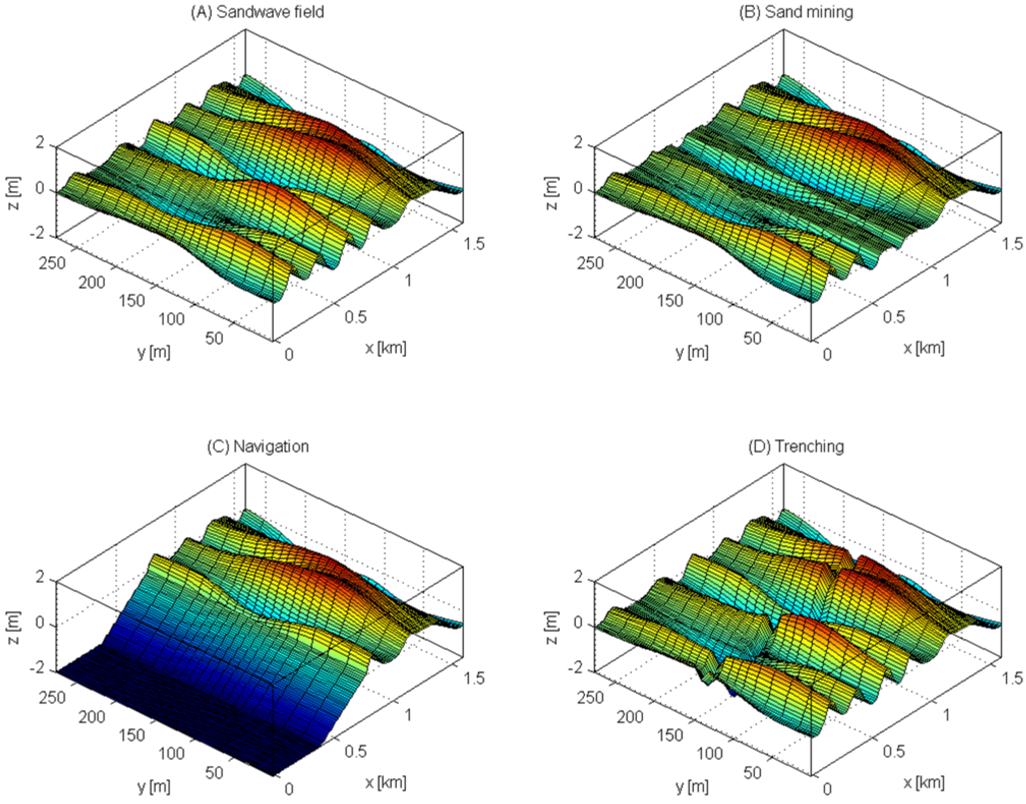


Figure 5.2: Different dredging interventions in a sand wave field, by B.W. Borsje

Trenching
When a cable or pipeline is installed a trench is dredged in the sand wave to ensure a correct installation depth. If the burial depth of the cable is insufficient, the cable is vulnerable to impact

from dragged or dropped objects (Warringa et al., 2019). When sand waves are present their dynamics, such as growth, migration and changes in shape, can cause exposure or even free-span of the cable, see Figure 5.3. Having a correct burial depth is thus vital for the durability of cables and pipelines.

Although in some cases cable trenching and cable laying can be carried out simultaneously, in other cases there is some delay between laying the trench. This could for example be caused by the availability of materials, such as specialized ships. This means that during this time the sand waves will start to recover and the trench will slowly fill. For this reason the trenches are often dredged wider than is necessary for the installation. Information on the recovery of sand waves is thus vital for planning of offshore activities.

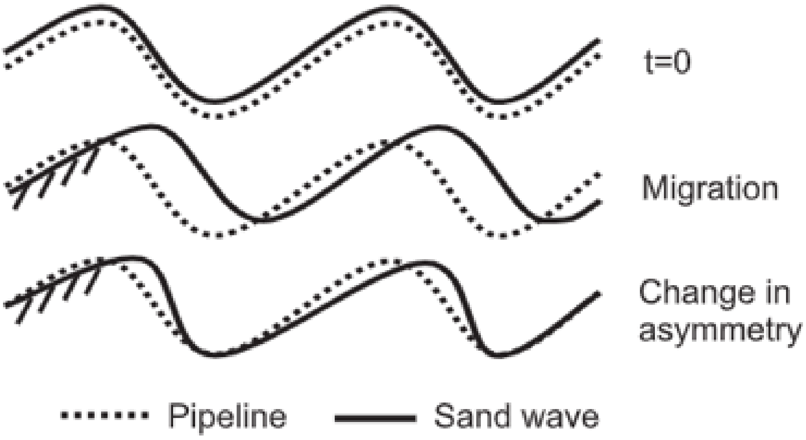


Figure 5.3: Effects of sand wave migration and changes in shape on cable/pipeline burial depth (Németh, 2003)

Full dredging

For various reasons it might be necessary to dredge the sand wave over the full width. This is often done in navigation channels or in case of sand mining, see Figure 5.2. In a navigation channel sand waves may affect the navigational depth. While the average depth may be below what is required, the sand wave crests could still form a threat to shipping traffic. For this reason, different dredging techniques have been developed, with varying success. A first technique, called peak removal, comprises of removing the crests or peaks of the sand waves, while leaving the troughs untouched. In this case the amount of dredged material is small, but since part of the original structure of the sand wave is still intact the tide-averaged vertical circulation cells which cause sand wave growth will still be present (see Section 2.3). Alternatively, the material from the crests could be used to fill up the troughs of the sand waves, thus returning to the mean bed level. This technique is often called cut&fill. In this case the averaged bed level thus remains unchanged, but the sand wave structure is removed completely. Lastly the sand waves may be dredged away up to trough level when total removal is applied. In this case the sand wave structure is removed and the mean bed level is lowered. However, depending on the size of the sand wave, a significant amount of material needs to be removed. Insight into the recovery of sand waves after these interventions is vital for efficient planning of maintenance dredging.

5.2 Sand wave recovery

Extensive attempts have been done to model or predict the recovery of sand waves after human interventions. By knowing the response of the system more efficient intervention strategies can be designed, leading to less frequent and less elaborate dredging interventions. First attention is given to the available data and observed sand wave recovery. Subsequently the attempts to predict sand wave recovery are summarized.

5.2.1 Data on sand wave recovery

Due to the industrial interest sand waves are often well monitored after interventions. In this section some examples of these interventions and the observed sand wave recovery are discussed. The interventions are separated into trenching and full dredging.

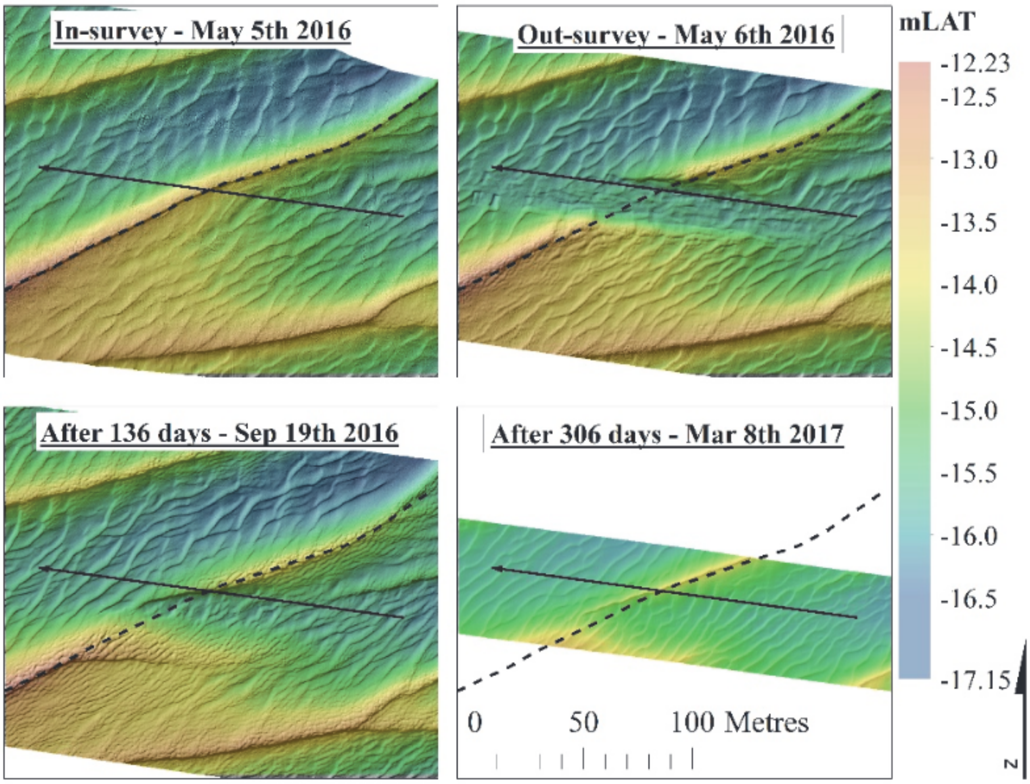


Figure 5.4: Sand wave recovery after cable trenching including development of bifurcation, Area 2 in Larsen et al. (2020)

Trenching

As explained trenching is often required when cables need to be lain. In a study by Orsted (2018) the recovery of sand waves after trenching was monitored at 15 locations to the east of England, where cables were lain to connect the Race Bank Wind Farm to the shore. Over a period of one to five months after dredging in most cases partial or full recovery was observed, leaving some cases were no evidence of recovery was found (Orsted, 2018). Significant differences in the recovery rate were thus found, even between adjacent sand waves. Two factors were identified which were thought to influence this recovery rate (Orsted, 2018). Firstly there is the dimension of the dredged area, relative to the size of the sand wave and the alignment of the trench with the sand wave crest. Shallower dredging was often associated with higher recovery rates. Secondly the local sediment mobility was found to be important, where a lower sediment mobility lead to lower recovery rates. Often lowering of the crest height around the trench was observed, indicating sideways filling of the dredged area (Orsted, 2018).

Larsen et al. (2020) analysed observations of two locations, both containing two sand waves, where trenches were dredged. The sand waves were very frequently monitored, especially shortly after the intervention, with 15-18 measurements within the first year. In these measurements a clear distinction between two periods in the sand wave recovery process could be made in both cases. In the first period, which was labeled the adaptation period, only limited regeneration of the sand wave was observed. This period lasted for 30 and 87 days after dredging in the considered areas. Subsequently the sand waves started to recover in the regeneration period, with a regeneration which followed an asymptotic exponential form (Larsen et al., 2020). Based on the recovery of the wave height it was expected that the full recovery would take 3 years, although a 90% recovery would already be reached after 1.8 years (Larsen et al., 2020). Interestingly, although both areas showed significant sand wave dynamics before the intervention, in one of the areas the sand wave migration stagnated after the intervention, see Figure 5.4, while in the other continued migration was observed, see Figure 5.5. The stagnated sand wave formed a bifurcation on side of the dredged channel, while the crest on the other side expanded into the channel (Larsen et al., 2020).

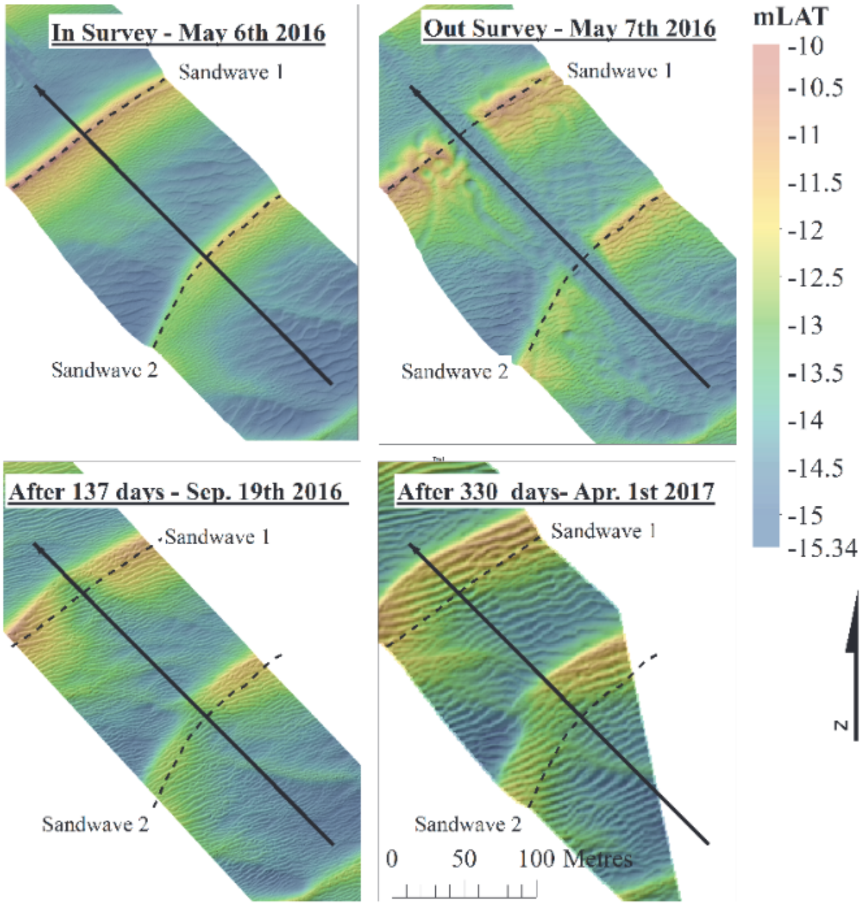


Figure 5.5: Sand wave recovery after cable trenching including migration at Area 1 in Larsen et al. (2020)

Full dredging

In many cases the sand waves have to be dredged in full, such as at the locations of navigation channels. This is quite a drastic measure, which imposes quite some uncertainty in how, and on what timescale the sand waves will grow back. It could for example be that the conditions have changed since the original formation and while the sand waves were slowly moving towards a new equilibrium, this is now accelerated by the dredging intervention.

Knaapen and Hulscher (2002) analysed the regeneration of sand waves after dredging in the Bisanseto Channel in Japan. It was observed that the sand waves the sand waves reached their equilibrium wave height approximately 10 years after dredging. In Verboven (2017) a similar timescale for regeneration was found for a sand extraction site of the coast of Belgium. Moreover, the sand wave length showed a large variation shortly after dredging, but converged over time (Verboven, 2017) towards a wavelength similar to what was found in surrounding areas.

Knowledge gap:

Why does the response of sand waves to dredging activities vary widely within small areas?

5.2.2 Predicting sand wave recovery

Several attempts have been made to predict the time-scale of sand wave recovery after dredging. Although this seems quite difficult for the case of trench dredging, based on the large variation in recovery manner and speed (see Subsection 5.2.1), in case of full dredging more similarity is seen in the different cases and steps have been made to predict this. In these cases also most benefit can be reached with such predictive tools, due to the recurring character of the interventions.

Knaapen and Hulscher (2002) developed a model to predict sand wave recovery based on the Landau equation, which is tuned through a genetic algorithm using field data. Although the results were similar to those of a linear trend analysis, the model based on the Landau equation has the additional benefit that it predicts an equilibrium wave height, which may be useful when defining dredging strategies (Knaapen and Hulscher, 2002). The model predicted similar recovery timescales as found in literature, but could not be validated due to lack of data (Knaapen and Hulscher, 2002). A disadvantage of this method is that multiple bathymetry data-sets after dredging are necessary to calibrate the model, especially since the calibration coefficient vary between sites.

Campmans et al. (2021) used a nonlinear process-based model in 2DV set-up to assess sand wave recovery after different types of dredging interventions. From the model results it was observed that the sand wave recovery immediately after dredging deviated from what is predicted by the Landau-based model introduced by Knaapen and Hulscher (2002), but convergence towards this model was observed relatively quickly in the non-linear model. Especially for accurate predictions immediately after the interventions more intricate models will thus be necessary. Moreover, a significant influence on surrounding sand waves was found when a single sand wave was dredged (Campmans et al., 2021).

In studies by De Koning (2017) and Verboven (2017) the complex numerical model Delft3D-4 was applied to predict the regeneration of dredged sand waves. In both studies the model contributed to the assessment of different dredging strategies in a qualitative manner. However, the results of both studies showed some differences with measurements. The equilibrium wave height from the 2DV model in De Koning (2017) was a factor 2-3 higher than the in-situ wave height of the considered area. This difference was attributed to model limitations and simplifications such as the exclusion of the lateral direction (De Koning, 2017). In Verboven (2017) large difference between the growth rates in the various model runs with a different initial bathymetries all based on in situ characteristics were found. Moreover, the migration rate of the sand waves was underestimated significantly (Verboven, 2017). These 2DV models are thus unsuitable for quantitative analysis, but could contribute in a qualitative sense.

In all studies the relation between the amount of dredged material and the recovery time was found to be nonlinear. For the peak removal strategy (see Subsection 5.1.1) the sand wave recovery was relatively fast, while when the full sand wave was removed the sand wave growth was slower. Furthermore, a slower initial growth rate was found for the total removal strategy in Verboven (2017) and De Koning (2017), similar to the adaptation period found in the data of Larsen et al. (2020). However, the study by Campmans et al. (2021) found a higher initial growth rate, which might be due to the partial swiping (i.e. cut&fill) of the sand wave, where in other studies the full sand wave was evened out.

Especially in case of local interventions, such as trenching or dredging a single sand wave in a field, the system response is hard to predict and may vary significantly over small areas. These problems cannot be simplified to a 2DV space, since the intervention is often not aligned with the sand wave crests and 3D processes, such as sideways filling of the sand wave, take place. This makes that 2DV models, which are often used in the field of sand wave modelling are inadequate to predict sand wave recovery in these situations. In case of full dredging a sand wave field, the seabed can be considered to be ’reset’ to an original situation without sand waves and the prediction of the future sand wave characteristics and the growth rate may prove to be less complicated. However, the comparison between model results and field data is often lacking or limited in extend in previous studies. The accuracy of these predictions is thus often unknown.

Knowledge gap:

How to accurately predict sand wave recovery after dredging?
And how do local parameters affect the recovery rate?

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6 CONCLUSIONS AND KNOWLEDGE GAPS

In this chapter the research question defined Chapter 1 are answered based on the literature desribed in the remaining chapters. For each question a short answer will be given, which summarises the findings in the related chapter. In the last section the discovered knowledge gaps are discussed.

6.1 Answers to research questions

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1. What are offshore sand waves?

Offshore sand waves are large-scale, rhythmic, dynamic bed forms, which can be found on the sandy seabed of shallow seas around the world. Sand waves are form as free instabilities of the seabed under tidal forcing (Hulscher, 1996). Due to complex interaction between this tidal current and bottom pertubations tide-averaged vertical circulation cells are formed, which support the growth of these features (Hulscher, 1996). The dimensions of sand waves in the North Sea are in the following ranges: length of 100-1000 m, height of 1-10 m and they migrate in this area with a rate of up to 10 m per year (Damen et al. (2018), Meijden (2021)). These dimensions and dynamics vary widely between the various areas where sand waves are found with for example sand wave height of up to 25 m at the Taiwan Shoal (Bao et al., 2014) and migration rates of up to 100 m per year in the Australian Banks Strait (Auguste et al., 2021). Despite this large variability sand wave features are often easily distinguished from other types of features based on size or orientation. Sand wave crest are oriented perpendicular to the main tidal current.

Sand waves have been observed in shallow seas throughout the world. Especially in the Dutch North Sea extensive bathymetry data-sets are available, with often a coverage of 3-4 distinct measurements (Meijden, 2021). This data has been processed and is publicly available.

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2. Which processes are drivers for offshore sand wave dynamics?

Through previous research various processes have been identified to be important for offshore sand wave dynamics. The tidal currents have been identified as the cause for sand wave formation (Hulscher, 1996), modulations of these tidal current are thus important drivers for sand wave dynamics. Besio et al. (2004) found that the addition of the M4 tide on top of the main M2 tide, could cause sand wave migration in either positive or negative direction depending on the relative phase of the constituents. The addition of a residual currents is also identified as a driver for sand wave migration (Van Gerwen et al., 2018). Campmans et al. (2018) found that although surface waves do not cause sand wave migration themselves, they are able to increase the migration rate. When underlying sand banks are present these are able to influence the sand wave migration rate and direction due to their influence on the major tidal currents (Leenders et al., 2021).

3. Which (modelling) methods exist to predict sand wave dynamics and what are their strengths and weaknesses?

Three commonly used methods for modelling and/or predicting sand wave dynamics have been identified, these are: stability analysis, complex numerical models and data-driven analysis. Because sand waves are formed as free instabilities of the seabed under tidal forcing stability analysis can be used to study these features (Hulscher, 1996). Due to the limited computation times stability analysis is very suitable for qualitative investigation of the sensitivity of sand wave characteristics and dynamics to various environmental influences. The amount of processes that can be included is however limited and the representation of the sand waves and hydrodynamics are simplified. Moreover, some processes have to be parameterized and to define correct forcing there is a dependence on the availability of hydrodynamic field data.

In recent years complex numerical models, such as Delft3D-4 have gained popularity in the field of sand wave modelling. These types of models allow for easy inclusion of various processes and are very flexible in terms of set-up. Due to this flexibility and the extended amount of physical processes which can be included very accurate representations of reality are possible. High levels of detail do however increase the needed computation time and due to their complexity these type of models can transform into a black box. Alike in stability analysis, parameterization of processes is necessary and there is a dependence on the available hydrodynamic data.

Finally, data-driven analysis is widely used to predict sand wave dynamics for engineering applications (e.g. Deltares (2020). In these type of analysis the historic sand wave dynamics are extrapolated to the future to predict future bed levels. These type of analysis are fast and quite reliable under stable conditions.

Significant influences of model settings on the simulated sand wave dynamics have been found. Turbulence formulation has been proven to be an important model setting and a more comprehensive model is thus necessary. Moreover bed roughness is found to be an important calibration coefficient. The sediment transport formulation should be considered, especially when comparing results, and some transport formulations have been identified as unsuitable for sand wave modelling. For the numerical settings also some important modelling choices have to be made, which include: horizontal and vertical grid sizes, time-step (or Courant number), boundary condition type and morphological scale factor. These choices are often best made in an iterative manner where the effect on the model outcomes is tested for various settings. Which boundary conditions are best suited for sand wave modelling (in 2DV and 3D setting) is something that has poorly been studied. This is especially the case for real-life sand wave studies.

4. Which potentially significant influences are missing in the current modelling methods?

Due to various simplifications some potentially significant influences have been left out of previous modelling efforts in the field of sand wave dynamics. These simplifcations have been made to either increase the modelling efficiency, or because the necessary data was unavailable. The most important simplification is that of a 2DV modelling domain, thus leaving out all influences, hydrodynamic and bathymetric, in the along crest direction. Since at many locations 3D sand wave features, such as bifurcations, changes in crest direction and along crest variations in amplitude have been observed, these influences could be quite significant. Moreover, the influence of sand banks cannot be included in these types of models, while a significant effect on sand wave migration has been discovered (Leenders et al., 2021).

Another influence often left out of consideration is the effect of a varying residual current. Especially due to meteorological influences the momentary residual current may be many times higher than the average current. This may results in significantly different migration rates of sand waves. Lastly, the influence of smaller bed forms is often left out of consideration.

5. What methods exist for increasing model efficiency?

The most commonly used method to speed up morphological simulations is the morphological scale factor (MF) (Lesser et al., 2004). In this method, which is based on the difference in typical timescale between the hyrdodynamic and morphological changes, the bed level changes are multiplied by a certain factor, speeding up the morphological development in the model (Ranasinghe et al., 2011). Input reduction is another method to reduce computation time. When applying input reduction a decision is made on which input is significant and which is not based on the desired model output, leading to a reduction of the model input an thus a reduction of the computation time (Li et al. (2018), Luijendijk et al. (2019)). Next to the input the complexity of the model itself can also be reduced, which is called model reduction. This can be done by simplifying the included processes, scales or dimensions (Li et al., 2018). By running models in parallel significant computational gains may be realised. This option can be used in multiple manners, such as dividing the model domain or the input over multiple computational cores (Luijendijk et al., 2019). In a communication process the output of the different cores is combined. Lastly for some types of hydrodynamic forcing it is possible to compress the timescale of the input. The factor with which the hydrodynamic timescale is compressed is than included as a morphological scale factor. Using these method significant gains in computational efficiency can be reached. According to Li et al. (2018) the possible efficiency gain factors for input reduction, model reduction and morphological scale factor are in the range of 10 - 10^3, 10 - 10^2 and 10 - 10^3 respectively. With time-scale compression the simulation can be accelerated by a factor 2 or 3 (see Li et al. (2018) and Luijendijk et al. (2019)) and parallel model running can lead to acceleration factors of the order 10 - 10^2. Disadvantages and limitations of the various methods can be found in Section 4.1.
Another way to gain efficiency in modelling studies is through the use of surrogate models, which are more efficient while results close to the original model can be reached. Two types of surrogate models are available: physical and data-driven surrogates. Using these surrogate models efficiency gains of up to 98% have been documented (Razavi et al., 2012).

6. How do human interventions influence sand wave dynamics and how fast do sand waves recover?

Various types of human interventions take place in marine environments were sand waves are present. These interventions can be categorized as dredging interventions and other interventions. Interventions that do not include dredging may have (lasting) effects on sand waves, such as increased turbulence in the wake of structures, but these are often difficult to measure. In case of dredging interventions the sand wave recovery is often observed, although the rate and extend of the recovery varies widely over small areas. In some areas sand waves have observed to be (almost) fully recovered in only 5 months after cable trenching, while in other areas no recovery can be distinguished in this time period (Orsted, 2018). Generally sand waves are expected to recover within a time period in the order of years, up to a decade (Larsen et al. (2020), Campmans et al. (2021)). This recovery speed may vary widely and is dependent on both environmental conditions and the type of intervention. In areas with a high seabed mobility the sand waves are expected to recover more quickly (Orsted, 2018). In case of trenching the alignment of the trench with the sand wave crest is found to be of importance as well as the dredging volume (Orsted, 2018). When a sand wave field is dredged, lower recovery rates are found when the bed is equalized, compared to when part of the sand wave structure is still present (Campmans et al. (2021), De Koning (2017), Verboven (2017)). Various models have been developed for or applied to predict this recovery speed, but due to limited synthesis with field data the accuracy of the results and/or the applicability to other locations is largely unknown. Especially in case of local dredging, such as cable trenching, the recovery seems highly dependent on its immediate surrounding and the sand wave might not recover to its original shape (Campmans et al. (2021), Larsen et al. (2020)).

6.2 Knowledge gaps

From the literature search various gaps in the present knowledge have been identified, which are discussed in this section. The knowledge gaps found and their respective sections are shown in Table 6.1. In these sections more background information about the knowledge gaps can be found.

Firstly it is observed that most of the influences on sand wave dynamics, listed in Section 2.4 are derived using idealized models. The parameters in these models are chosen in such a way that they represent a certain area (such as the North Sea), but quite some simplifications are made, which lead to differences with the real situation. Examples of such simplifications are: the use of flat underlying beds, sinusoidal sand waves and simplification of the tidal current. These models are suitable for qualitative assessment of the influence of various processes, for which sensitivity analysis are performed. However, translating this to quantitative effects on sand wave dynamics is rather difficult. Moreover, in most cases the comparison with field data is limited or even omitted. More realistic model studies could provide more insight into the relative importance of various processes on real sand waves. Moreover, this would allow for quantitative assessment of the predictive capacities of these numerical models.

Due to the widespread use of idealized models, knowledge on how to accurately represent real hydrodynamics in sand wave areas is lacking. The boundary conditions used in these studies do not produce a propagating tidal wave, such as the tidal wave in the North Sea area. Moreover, since the boundaries of these models are located at a significant distance from the sand wave area, applying the local conditions at the boundaries might not lead to accurate hydrodynamics in the sand wave area. An in depth study on how to recreate these hydrodynamics in both 2DV and 3D sand wave studies is missing.

In the extensive idealized model studies, some influences have been omitted. These influences are mentioned in Section 3.3 and are related to model simplifications. Most importantly the lateral sand wave direction (along the crest) is often left out of modelling studies. This simplification is implemented based on the assumption of little variation in this direction and will significantly reduce computation times of the simulations. While this might be valid in some areas, at many locations sand waves are observed to be far from straight and long crested as is assumed in these models. In these areas 3D sand wave structures, such as bifurcations, changes in crest direction and along crest changes in amplitude are observed. Due to the lack of 3D models, much is unknown about the development of these 3D sand wave structures. Moreover, their influence on local sand wave dynamics has not yet been investigated.

Another influence which is yet to be investigated, is that of a varying current. In previous research an average current is applied to the sand wave system, while large variations in its strength are observed in reality. Including these variations might significantly alter the model results.

In Chapter 4 various ways to increase model efficiency are mentioned. Since sand wave modelling requires high resolution models, the associated computation times are long and these type of methods could prove to be very useful. Some of these methods have been used in sand wave modelling applications, but for others the possible gains and limitations are yet to be discovered. Moreover, an in depth assessment of the acceptable level of model/input simplification or model acceleration is often lacking. This has a.o. resulted in large differences between the values for the morphological scale factors which are deemed to be acceptable in different sand wave modelling studies (see Subsection 3.2.3).

The interaction between human activities and sand wave systems poses further challenges. Especially in case of local dredging interventions the system response is hard to predict and varies widely over small areas. For these kind of problems the commonly used 2DV set-up is inadequate. This is because 3D processes are taking place, such as sideways filling of the dredged area, and the intervention is often not aligned with the sand wave crest. These type of models have been applied to cases were full sand wave areas were dredged, but the synthesis with field data is limited. This makes that the accuracy and the dependency on local parameters of the model results are unknown. In order to be able to predict the response of sand waves to these kind of dredging interventions more realistic modelling studies have to be set up. Moreover, the comparison with field data, preferably with high temporal resolution, has to be made in order to evaluate the model performance.

Table 6.1: Knowledge gaps found in this literature review

Knowledge gap	Section
What is the importance of various environmental influences on sand wave dynamics in real life cases? And how does this differ from idealized cases?	2.4
How to realistically represent the difference in bed roughness between sand wave crests and troughs?	3.2.1
How to accurately reproduce local hydrodynamics in a 2DV sand wave model?	3.2.2
How to accurately and efficiently couple a 3D sand wave model to a large scale hydrodynamic model?	3.2.2
What is the influence of a time varying residual current on sand wave dynamics?	3.3
What is the influence of 3D forcing and bathymetry on sand wave dynamics? And how significant are these effects?	3.3
How can upscaling techniques and surrogate models contribute in sand wave cases and what is the order of the possible computation time reduction?	4
What is the influence of subtle, but lasting changes in hydrodynamics, due to offshore constructions, on sand wave characteristics and dynamics?	5.1
Why does the response of sand waves to dredging activities vary widely within small areas?	5.2.1
How to accurately predict sand wave recovery after dredging? And how do local parameters affect the recovery rate?	5.2.2

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A DIFFERENCES DELFT3D-4 AND DELFT3D FM

In this appendix first a short description of the Delft3D model is given. Then some of the main differences between Delft3D FM and its predecessor Delft3D-4, as indicated in Deltares (2021b), are discussed.

A.1 Short description of Delft3D

Delft3D is a process based model developed by Deltares. The model can be used for both 2D and 3D modelling of coastal, river and estuarine areas. The model is able to simulate flows, sediment transports, waves, water quality, morphological developments and ecology (Deltares, 2021a). Through online coupling, the main (flow) module is able to interact with other modules for simulations of for example waves or sediment. With Delft3D as base, Delft3D Flexible Mesh (FM) is developed to include differently shaped, unstructured grids as shown in Figure A.1. These unstructured grids allow for smooth transition to finer or coarser grid cells in certain areas. This difference in grid shapes has extensive implications for the numerical computations that need to be carried out.

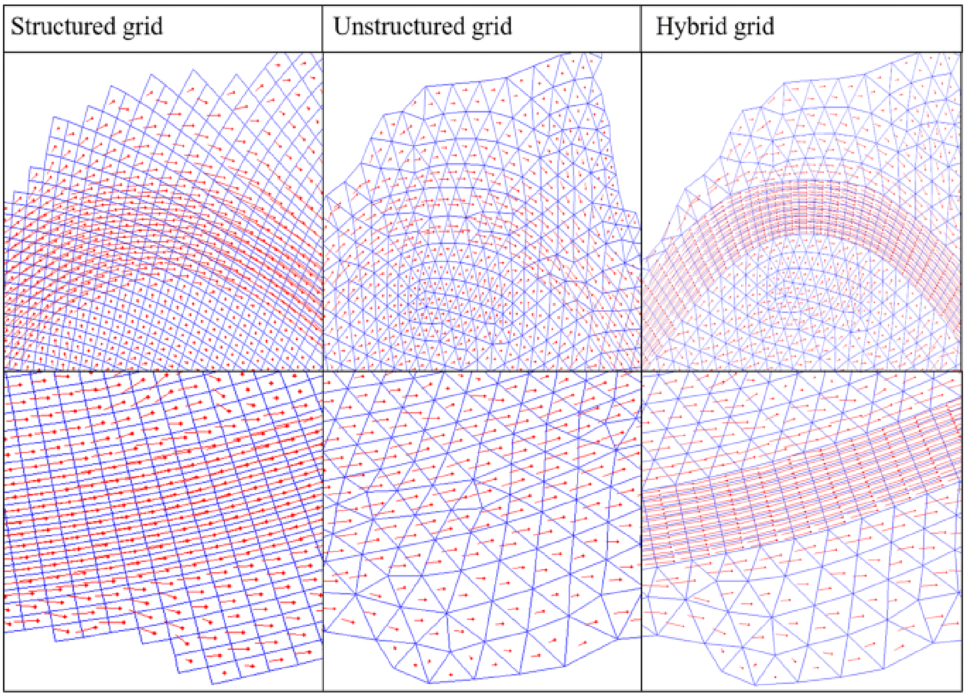

Figure A.1: Example of structured, unstructured and hybrid grids (Bomers et al., 2019b)

A.2 Main differences between Delft3D-4 and Delft3D FM

The main differences between the two model versions are summarized in Table A.1. For the specifics in terms of numerics reference is made to the manual: Deltares (2021b). The most important difference between the models is the possibility to use unstructured grids in Delft3D FM. Where in Delft3D-4 only (deformed) square grid cells could be used, the Delft3D FM model also allows for triangles, pentagons and hexagons. This increased freedom makes coupling between coarser and finer grids much easier and smoother. Furthermore the strict definitions of rows and columns used in Delft3D-4 are removed. This also means that grid points can no longer be indicated with indices (indicating row and column) and thus cartesian or spherical coordinates are used.

Table A.1: Main differences between Delft3D-4 and Delft3D FM

Description	**Delft3D-4**	**Delft3D FM**
Grid types	Structured	Structured, unstructured & hybrid
Grid shapes	Rectangular or curvilinear	Rectangular, curvilinear, triangles, pentagons & hexagons
Cell definition	Based on rows and columns	Based on coordinates
Spatial derivative	Finite differences*	Finite volumes
Time integration	Implicit, explicit (ADI)	Implicit, explicit advection term
Time-step implementation	User defined	Automatic
Time-step limitation	No strict Courant limitation	Courant limited

These differences in grid have a significant impact on the computational side of the model. Due to the regularity of the grid, Delft3D-4 is able to solve the hydrodynamic equations using Finite Differences Methods. In Delft3D FM Finite Volume Methods are used, as they are better capable of dealing with complex geometries. In Delft3D-4 the time integration of the shallow water equations is solved using an Alternating Direction Implicit (ADI) method, which alternates explicit and implicit solving methods between the both directions (of the rows and columns). Because this concept of rows and columns is not implemented in Delft3D FM this solver cannot be used in this model. Instead the continuity equation is solved in a single combined implicit system for both directions. The advection term uses an explicit time integration method and the resulting dynamic time step limitation, based on the Courant number, is set automatically, where Delft3D-4 uses a user defined time step. Lastly the Delft3D FM model has the possibility of parallel model runs, where the domain is divided into partitions which are run simultaneously. All above differences impact the computational performance of the models. The Finite Volume Method is less efficient than the Finite Differences Method. Combined with the time step limitation this increases the computation times in Delft3D FM relative to Delft3D-4. It is however believed that this is compensated for due to the smooth refinement of models in Delft3D FM using unstructured grids, which allows for increased accuracy in areas of interest and coarsening in other areas. This coarsening outside of the area of interest will decrease computational effort and thus computation time. Moreover further computational gains are reached through other means such as parallel running. In addition, the code efficiency of Delft3D FM is improved relative to Delft3D-4.