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FROM SCOUR TO DUNE MIGRATION: UNDERSTANDING AND PREDICTING SEABED MOBILITY NEAR OFFSHORE STRUCTURES AT DIFFERENT SPATIAL SCALES

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Abstract

Several offshore wind farms (OWF) are currently operating or being developed on a series of sand ridges on the Belgian continental shelf known as the Flemish Banks. In order to guarantee the stability of structures such as subsea cables and turbine foundations, the minimum and maximum projected bed level over the project lifespan should be known. Two applications are discussed in which sea bed dynamics are constrained to optimise the design of OWFs. The Jacket Scour Predictor (JaSP) model, a data –driven model of time-dependent scour depth development for jacket foundation, is presented. The model calibration allows to identify potential shortcomings of existing formulations. The estimated sea bed level (ESBL) methodology allows to define defendable bounding values of expected sea bed mobility in the absence of structures, based on a statistical analysis of dune migration rates.

Key words: morphodynamics, dunes, scour, measurements, modelling, offshore wind, offshore cable

1. Introduction

Several offshore wind farms are currently operating or being developed on a series of sand ridges on the Belgian continental shelf known as the Flemish Banks. In order to guarantee the stability of structures such as subsea cables and turbine foundations, the minimum and maximum projected bed level over the project lifespan should be known. The bed level evolves due to processes occurring at different spatial scales, including scour around the foundation structure, megaripple mobility [L ~ O(10 m)] and dune mobility [L ~ O(100 m)], while the sand ridges themselves appear to be stable over time spans of decades to centuries (Le Bot *et al.*, 2005).

Knowledge on sea bed dynamics is essential for several reasons. A lowering of the sea bed level around an offshore wind turbine, induced by scouring or by dune migration, increases the maximum bending moment of the pile, decreases the foundation bearing capacity, changes the eigenfrequency of the foundation and the resulting fatigue behavior, and may create free-spanning of the cables near their entry point into the turbine. Variations of the sea bed level around an offshore cable, on the other hand, may lead to exposure of the cable or to excessive burial. Exposure is now recognized to be a critical issue in offshore cable design due to the risk of accidental anchor dropping and dragging onto a cable. Cable claims represent over 40% of all claims in the offshore wind industry and account for more than 80% of all claim costs (Figure 1). On the other hand, excessive burial may lead to reduced thermal conductivity and overheating of the cable if it is not mitigated by a proper cable design. To prevent cable exposure in dune fields, it is common to pre-sweep the dunes and lay the cable under this pre-swept level. A precise definition of expected sea bed dynamics may help in finding a balance between pre-sweeping and operational maintenance. In addition to these design issues, contractors may also wish to anticipate field reality. The bathymetry used for the design basis may be different than the bathymetry measured during the in-survey just before construction starts.

In highly dynamic environments, a refined estimation of sea bed dynamics may hence lead to substantial savings and help make offshore wind a more competitive source of energy. This contribution

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presents two possible methods to achieve this. The first example illustrates the use of measurements and a data-driven model to predict scour evolution around a jacket foundation. The second example illustrates the use of high resolution bathymetry datasets to statistically analyse sea bed mobility.

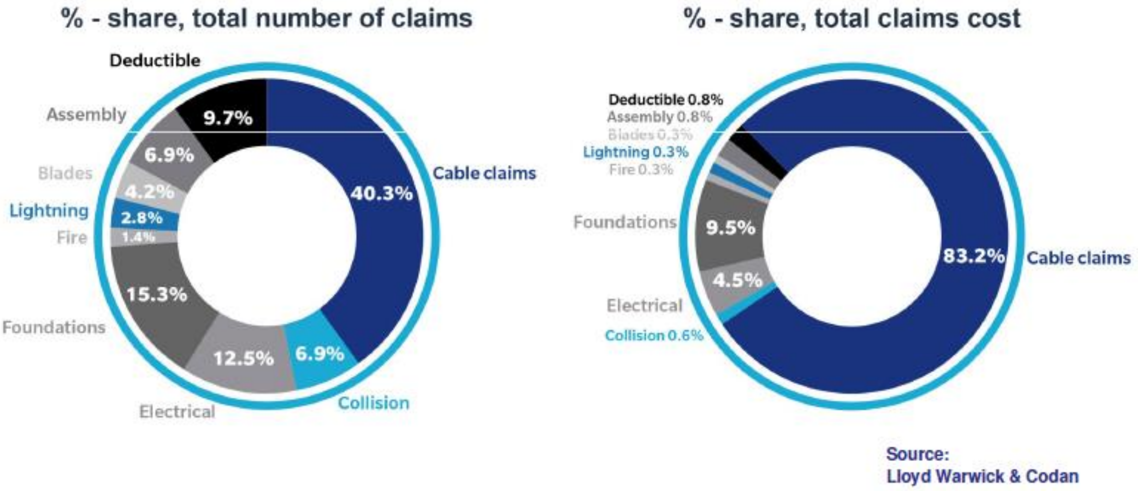

Figure 1: Statistics on offshore wind claims causes and costs (source: Lloyd Warwick & Codan, 2014)

2. Short Term Evolution: Scour around a Jacket Foundation.

2.1. *Context*

The C-Power offshore wind farm (OWF) is located on the Thornton Bank on the Belgian continental shelf at a distance of about 30 km from the coastline. In total 54 wind turbines were installed delivering a capacity of 325 MW, generating enough energy for the annual consumption of 300,000 families. Construction began in May 2007 and the installation of all turbines and cables was finalized early July 2013. In the first phase six turbines of 5 MW each were installed on gravity based foundations. The following two phases added another 48 turbines of 6.15 MW each to the wind farm and were installed on jacket foundations.

Monopiles are the most commonly used foundations in the offshore industry, representing 76% of installed foundations at the end of 2013 in Europe (EWEA, 2014). In large water depths, pile diameters increase accordingly – typically 6 to 10 m at typical depths of -25 to -40 m – creating larger and deeper scour holes. In comparison to monopiles, a jacket foundation offers the benefits of serial production and easier logistics. The jacket foundation is a steel structure with four legs connected to each other with braces. The legs are grouted to pinpiles. The latter are driven into the sea bed by means of pre-piling. Figure 2 illustrates a jacket foundation of the C-Power wind farm.

Contrary to monopiles, the smaller piles of the jacket foundation are not installed with a scour protection. For the Rentel OWF, the expected total scour depth, taking into account global scour around the entire jacket foundation and local scour around a single pile, is expected to reach 2.6 m, and the maximum total scour depth is expected to reach 4.1 m (Bolle et al., 2012). An alarm level, an intervention level and a critical level have been defined in the Operation and Maintenance program to take action based on monitoring results (Figure 3).

Figure 2: Jacket foundation (centre) and monopile foundation (left) on the C-Power OWF.

Local scour around one of the jacket foundation of the C-Power wind farm has been continuously monitored since November 2013. An in situ measurement setup was installed on one of the four piles of the jacket foundation, including a Nortek Scour Monitor that measures bed elevation at several points near the jacket pile, an Acoustic Doppler Current Profiler (ADCP), Acoustic Doppler Velocimeter (ADV), and an Acoustic Wave and Current Profiler (AWAC) to measure local hydrodynamic conditions. From the measurements, a multi-year time series of local scour depths, in relation to local wave and current conditions, was produced.

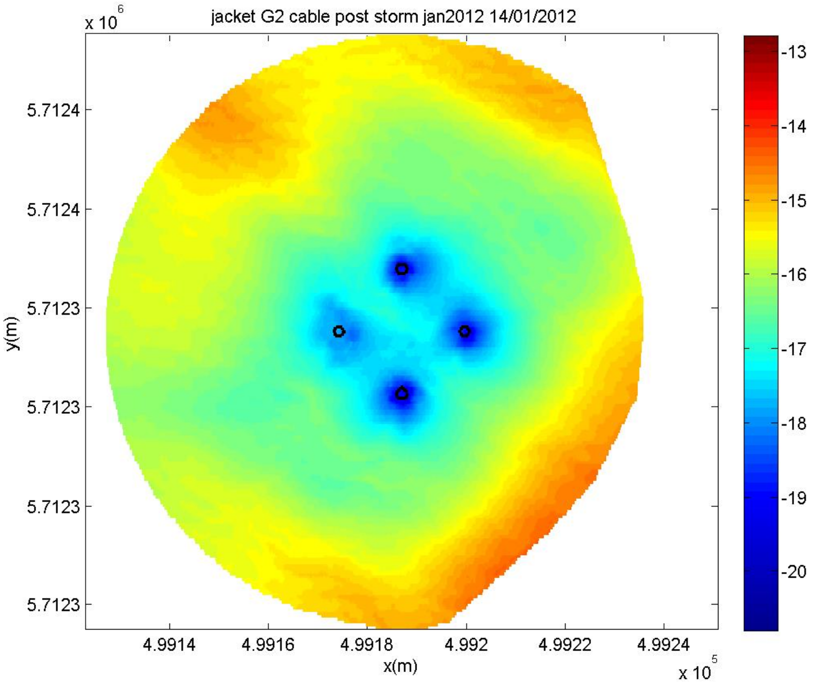

Figure 3: Measured scour around a jacket foundation of the C-Power OWF, from a bathymetry survey (Bolle et al. 2012)

2.2. *Predicting scour development*

Scour has been studied extensively during the past 20 years (Hoffmans & Verheij, 1997, Whitehouse, 1998 and Sumer & Fredsøe, 2002). Extensive research work carried out on scour phenomena in offshore wind farms with monopile foundations, has led to different formulations to predict the maximum scour depth and maximum scour extent in the vicinity of the pile. Studies on scour development around jacket foundations is sparser since only 5%, or 130 units, of all offshore wind turbines were installed on jackets at the end of 2013 (EWEA, 2014).

The time dependency of the scour development has been less well studied (Dixen, Dixen, Pedersen, & Dahl, 2012). Nevertheless the STEP model of (Harris, Whitehouse, & Benson, 2010), the WiTuS model of (Nielsen & Hansen, 2007), and the work of Raaijmakers & Rudolph (2008) enabled scour depth development over larger periods of time to be assessed for monopiles.

The time series obtained from the monitoring campaign at the C-Power wind farm were used to develop a model for time-dependent scour depth at jacket foundations: the JaSP (Jacket Scour Predictor) model. The scour hole development in the JaSP model is based on the formulations of the WiTuS model. The formulation of the WiTuS model of Nielsen and Hansen (2007) is taken:

$$S_n = S_{eq,n} + \left(S_{n-1} - S_{eq,n}\right)\exp\left(-\frac{dt}{T}\right)$$

in which the scour depth S_n at time t is determined by the scour depth at the previous time step S_{n-1}, the time step dt, the instantaneous equilibrium scour depth $S_{eq,n}$ and development time scale T towards the equilibrium depth (both for scouring and backfilling).

The equilibrium scour depth is calculated with different models depending on the flow type: dominated by the current, waves or by combined waves and current. The flow type is determined with the current-velocity-to-wave-velocity ratio Ucw as in Nielsen and Hansen (2007):

$$U_{cw} = \frac{U_{c,b}}{U_{c,b} + U_{w,b}}$$

in which Uc,b is the current velocity measured at the bottom of the seabed and Uw,b is the maximum wave induced orbital velocity at the bottom of the seabed calculated with Stokes 2nd order theory (Soulsby, 1997). When Ucw is larger than 0.8 the flow is assumed to be dominated by the current. The following equation is used to calculate the equilibrium scour depth in case of a current-dominated environment, Se,current, which is a combination of Sumer et al. (1992) and Whitehouse (1998):

$$S_{eq,current} = \begin{cases} 0.95D & \theta \geq \theta_{cr} \\ 0.95D\left[2\sqrt{\dfrac{\theta}{\theta_{cr}}} - 1\right] & \dfrac{\theta_{cr}}{4} \leq \theta < \theta_{cr} \\ 0 & \theta < \dfrac{\theta_{cr}}{4} \end{cases}$$

in which θ and θcr are respectively the Shields parameter and the critical Shields parameter, calculated according to Soulsby (1997), and D is the pile diameter (2.028 m including biofouling). The value of 0.95D was chosen since this was the maximum observed relative scour depth during current dominated flow. When Ucw is smaller than 0.7 the flow is assumed to be dominated by combined waves and current. The equilibrium scour depth formulation proposed by Rudolph and Bos (2006) is used:

$$S_{eq,comb} = S_{e,current}\left[1 - e^{\{-A(KC-B)\}} \cdot \{1 - U_{cw}\}^{C}\right];\, KC \geq B$$

$$KC = \frac{U_{w,b} T_p}{D}$$

$$A = 0.03 + 1.5U_{cw}^4$$

$$B = 6e^{-5U_{cw}}$$

$$C = 0.1$$

because it fits the data better for low KC numbers (1 < KC < 10) than the formulation of Sumer and Fredsøe (2002). When Ucw is between 0.7 and 0.8 linear interpolation is performed.

The development time scale for scouring Ts is taken from Sumer et al. (1992). It is related to the non-dimensional time scale T* by the following relationship:

$$T_s = \frac{D^2}{\sqrt{g(s-1)d_s^3}} T^*_{combined}$$

in which g is the gravitational constant, s the specific gravity of the sediment (2.59), ds is the grain size diameter (300 µm for the Thorntonbank) of the bed material and $T^*_{combined}$ the non-dimensional time scale for combined waves and current, adopted from Nielsen and Hansen (2007) and Sumer et al. (1992). $T^*_{combined}$ is defined as:

$$T^*_{combined} = T^*_{current} U_{cw} + T^*_{waves}(1 - U_{cw})$$

$$T^*_{current} = \frac{1}{2000} \frac{h}{D} \theta^{-2.2}$$

$$T^*_{waves} = 10^{-6} \left(\frac{KC}{\theta}\right)^3$$

$$T_b^* = 8 \cdot T^*_{combined}$$

The development time scale for backfilling is defined in a similar way, with a multiplication factor calibrated based on data to account for the observation by Nielsen and Hansen (2007) that in general backfilling occurs much slower than scouring.

Scour can only occur when the Shields parameter is large enough to mobilize sediment (θ > θcr/4) and when the scour hole depth is smaller than the equilibrium scour depth. Backfilling can only occur when the live-bed regime is fulfilled (θ > θcr) and when the scour hole depth is larger than the equilibrium scour depth. When the Shields parameter is too low (θ < θcr/4), neither scour nor backfilling can occur and the scour hole will remain at the same depth.

The WiTuS model of Nielsen and Hansen (2007) also includes an additional threshold for scour and backfilling, which can only occur if KC is large enough (KC>6). In the JaSP model as well, such a threshold is implemented. Existing studies do not address the case of low KC values.

2.3. *Model calibration and validation*

The model described in the previous section is not calibrated yet. The analysis of measurement data during the events which were not captured by the JaSP model allowed to identify the physical conditions and processes for which corrections were needed. The data were analysed by making a distinction between slow scouring, fast scouring, slow backfilling and fast backfilling events. The Shields parameter was calculated to estimate which events correspond to clear water scour or live-bed scour.

Clear water scour corresponds to the situation in which the bed material far from the obstacle is at rest (shear stress lower than critical shear stress for motion). Live-bed scour corresponds to the situation in which the bed material far from the obstacle is mobile (shear stress larger than the critical shear stress).

Several important site-specific correction factors were necessary to match long-term observations (Figure 4). The base model did not properly capture several scouring and backfilling events, in particular under strong wave-dominated conditions, with waves both parallel and perpendicular to the dominant current direction. The backfilling time scale had to be strongly shortened compared to the recommendation of Nielsen and Hansen (2007). The computed equilibrium scour depth under combined waves and current was also found to be too small. This can be improved by introducing correction factors, as suggested by Devolder (2012). Finally deviations between model and data were observed at very low KC numbers.

After calibration, the maximum difference in predicted scour depth over the 9 months period was 0.10 m. The validation results highlighted some additional limitations. Nevertheless the maximum difference in predicted scour depth over a 3 months validation period was 0.15 m. Details of the JaSP model, data analysis and calibration procedure can be found in Kimpe (2016).

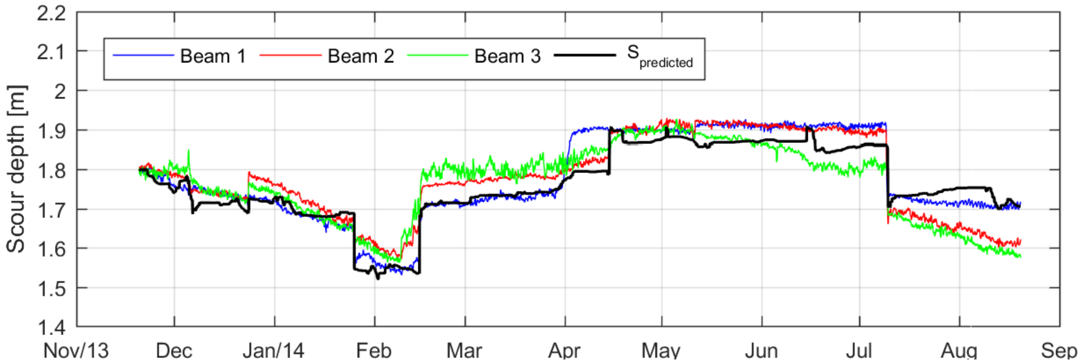

Figure 4: Modelled (black line) and measured (blue: beam 1, red: beam 2, green: beam 3) scour at the jacket foundation.

These corrections highlights the difficulty to schematize a highly non-linear scouring and backfilling process with simple formulations. It is however by combining such schematic models with data analysis that the limitations of the present formulations will be highlighted. Once longer datasets are available, the predictive capability of the JaSP model and the relevance of the corrections proposed can be assessed to derive a more general formulation.

3. Long Term Evolution: Large-scale Dune Migration and Megaripples

3.1. *Context*

The nv Rentel is developing an offshore wind farm (OWF) concession located on the Belgian Continental Shelf, in between the Thornton Sandbank (C-Power OWF concession) and the Lodewijkbank (Northwind OWF concession). In accordance with the concession permit, at least 288 MW of wind turbine capacity has to be developed. The offshore wind farm Rentel is located in a large dune field. The sea bed in the concession area is mostly situated between -25 m to -35 m LAT.

Multibeam bathymetry surveys available for 2003, 2012, 2013, 2015 and 2016 were analysed to determine dune characteristics. Underwater dunes generally have a height between 1 m and 5 m and a length between 100 m and 400 m. Megaripples and smaller dunes characterised by wavelength of 20 m and heights of up to 1.5 m superimposed on the large dunes were also observed. The average long term dune migration rate is estimated to be in the order of 0 to 2 m/year towards the South-West depending on their location. However some dunes have occasionally been observed to migrate in the opposite direction during shorter periods.

The dunes are subject to the combined forcing of tide and waves. Astronomical tidal forcing is continuous and deterministic, while wave forcing is mostly episodic and stochastic, with a seasonal pattern showing more pronounced storm activity in the winter. In the project area, tidal forcing tends to increase the dune amplitude and residual tidal current pushes the dunes to migrate towards the South-West. Storm waves on the other hand tend to flatten the dunes and push the dunes to migrate towards the South-West or the North-East depending on the wave characteristics. Morphological analysis also showed that dune asymmetry is a fairly good predictor of dune migration rates and direction.

3.2. *Predicting sea bed dynamics*

It is possible to use numerical morphological modelling to get insight into sea bed dynamics. However due to the qualitative nature of the morphological results obtained and the long computation time, the use of numerical models is not standard industry practice yet. The large number of bathymetry datasets can be used to constrain the expected sea bed dynamics. By analysing the movement of each dune for each combination of two bathymetry datasets, a large number of migration rates can be estimated. If data is sufficient, subzones may be defined to account for physical differences. A cumulative probability distribution of the migration rates can subsequently be derived (Figure 5).

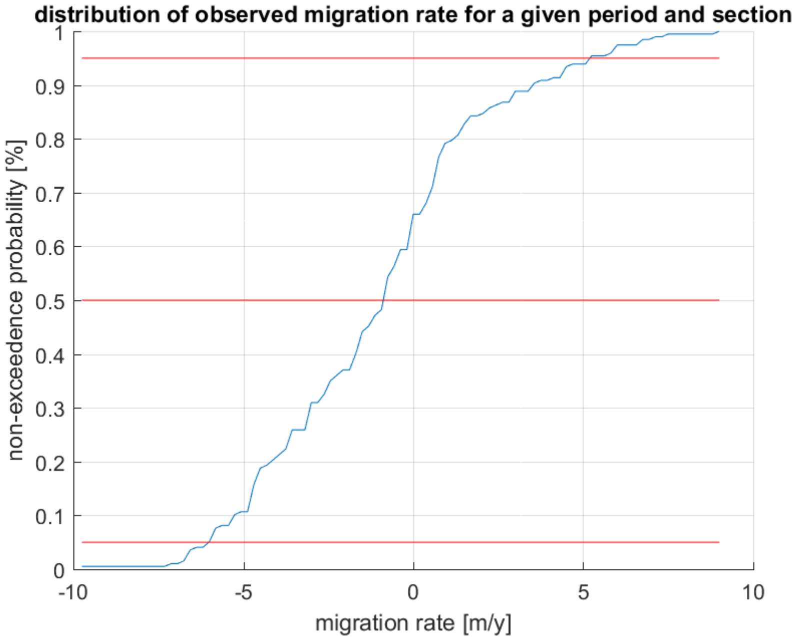

Figure 5: Example of cumulative probability distribution of migration rates over time intervals of less than 5 years. Positive values correspond to a migration towards the North-East, negative values towards the South-West.

Establishing such distributions for different spatial areas or different temporal horizons enables us to gain quantitative insight into past sea bed dynamics. Figure 5 illustrates the cumulative probability distribution of migration rates when only short time intervals are considered (in the present case 2012-2013, 2012-2015 and 2013-2015). It shows a median migration rate of about 0.9 m/year towards the South-West, and a great variability of the migration of individual dunes around the median value. The 5% and 95% confidence interval values are respectively 6.0 m/year towards the South-West and 5.2 m/year towards the North-East. When a similar distribution on a long time interval is considered (2003-2015), the median value does not change much (1.4 m/year towards the South-West), but the 5% and 95% values become much closer to the median value (respectively 3.0 m/year towards the South-West and 0.6 m/year towards the North-East). This suggests that over the short term the effect of individual storms and natural variability dominates, with dunes migrating in both directions. Over the long term this variability is overshadowed by the constant migration trend due to the tide.

Migration rates can then be used to predict the sea bed level for a given time horizon. A quick estimate can be obtained by simply shifting the present day bathymetry with the mean migration rate (assuming a horizontal migration of the dunes and no amplitude variation). This yields a best estimate but no bounding values of the bed level at each location. For offshore cables, it allows to estimate the cumulative length of cable which is expected to become exposed or excessively buried at a given time. A better estimate taking into account the stochastic nature of the sea bed dynamics, can be obtained by using the 5% and 95% confidence interval values to derive the bounding values of the expected sea bed level at each location. Shifting the bathymetry with different migration rates is the same as looking for the bed level values within a certain search window around that point. By defining a search window of specified dimensions around a given point (i.e. a turbine or cable position) equal to the 5% and 95% migration rates times the desired time horizon, the minimum and maximum estimated sea bed level occurring during or after the time horizon of interest can be derived. The minimum sea bed level at each point may be used for foundation design of turbines or to define the pre-sweeping level of cables. Figure 6 illustrates a cable for which even after 30 years, the worst case scenario requires less dredging than if sea bed dynamics had not been studied and a complete pre-sweeping of the dunes had been executed.

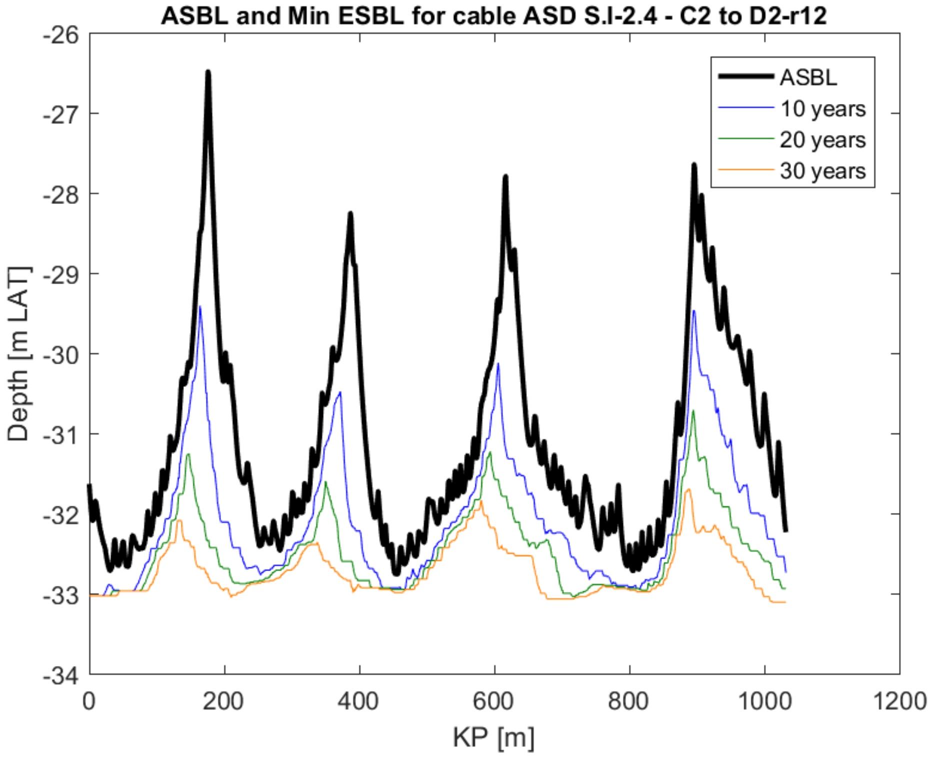

Figure 6: Example of present day bathymetry (black) and minimum estimated sea bed level over the next 10 (blue), 20 (green) and 30 years (yellow) along a cable route in a dune field in the Rentel OWF concession.

Applications of this simple method will vary depending on the initial bathymetry, prediction time horizon, selected migration rates (short term or long term), dimensionality (0D, 1D, 2D) and whether sea bed mobility should be estimated *during* or *after* the prediction time horizon. The time horizon may typically be the lifetime of the turbines or cables, the maintenance interval, or the time until the start of construction. The initial bathymetry may be called the actual sea bed level (ASBL), the best estimate sea bed level after the prediction time horizon the estimated sea bed level (ESBL) and the bounding values the maximum and minimum ESBL (Max ESBL and Min ESBL).

To illustrate the added value and relevance of this method, a validation was done based on the 2016 bathymetry dataset. The 2015 bathymetry (ASBL 2015) was used as starting point, the time horizon was chosen such as to reach the date of the 2016 bathymetry survey, and short term migration rates were selected in view of the short time horizon. Overall, all measured bed levels of 2016 (ASBL 2016) at the 42 turbine positions of the Rentel OWF fall within the 5%-95% predicted bounding values (Min ESBL and Max ESBL 2016). The difference between the best estimates (ESBL 2016) and measured values varies from -0.6 m to +0.5 m with an average of 0.1 m. The range between the bounding values after a year varied between 0.5 m and 1.3 m with an average of 0.8m.

3.3. *Limitations and recommendations*

The method presented in section 3.2 is very simple. The difficulty lies in having sufficient data, in the data analysis and the interpretation of the results. It is important to understand upon which data the analysis of migration rates is based. In the most extreme case if only two bathymetry datasets are available, the probability distribution will only be based upon spatial data, i.e. migration rates of different dunes over the same time interval. It is very well possible, especially for short time intervals that dunes globally behaved in a particular way because of a particular storm climate. This will reflect in skewed bounding values of the migration rates and possibly wrong predictions. Similarly, it will make no sense to predict short term sea bed dynamics based on long term migration rates which do not capture natural short-term variability. The method hence relies on temporal data availability and is no substitute for expert engineering judgement. A validation is strongly recommended.

The method also does not take into account variations in dune amplitude and secondary spatial scales. An initial bathymetry at the end of the summer may be more conservative than at the end of the winter, when successive storms may have flattened the dunes. Smaller bed forms may also be present on top of the dunes (Figure 7). These megaripples or small dunes, having a shorter wavelength, migrate much faster than the large dunes and their trough and crest levels should be taken into account. Larger bed forms (sand ridges) may also impact predictions when a slope is present, because shifting the bathymetry is not the same as shifting the dunes along the sand bank. To account for these other spatial scales the sea bed level may be separated in different components (sand ridges, dunes, megaripples), similar to a harmonic analysis, with low-pass filters. The method presented may then be applied to the different components, which are then recombined.

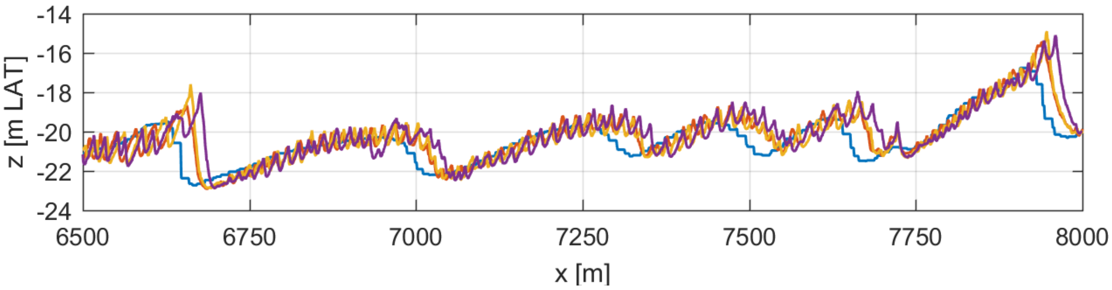

Figure 7: Transect of bottom level, in SW-NE direction (perpendicular to dune crests) in the Norther OWF concession, showing the superposition of bed forms. Blue: 2001. Red: 2010. Orange: 2011. Purple: 2015.

Finally the method applied should remain practical enough to keep its added value. It does not seem sensible to want to refine the predicted sea bed level to more than 0.1 m accuracy, as other considerations will be more important. Local scour (which may become very significant) will develop around the foundation of the wind turbine, and will certainly locally affect the dune field. The presence of a shallow consolidated clay layer may physically limit sea bed dynamics and pose important limitations to dredging techniques. Turbine location may be constrained by wind efficiency considerations. Sea bed slopes may impose cable rerouting due to trencher operability limits, UXOs and wrecks may require cable rerouting if they cannot be removed.

4. Conclusions

As more data is being gathered regarding bed evolution near offshore wind farm structures, our knowledge of short term and long term sea bed dynamics improves. In this paper, time-dependent local scour around a jacket structure was modelled using a new Jacket Scour Predictor (JaSP) model, and bed level change due to large-scale dune and mega-ripple migrations were predicted based on measured dune migration rates.

The JaSP model showed that our understanding of scour development under combined waves and current around jacket structures is still incomplete. Data collection and analysis efforts should continue in order to generalise existing formulations.

A simple statistical analysis of dune migration rates showed a great spatial and temporal variability of dune movements at Belgian offshore wind farms. A combination of 5% and 95% confidence interval values of migration rates, scale separation between megaripples to sand banks, and expert judgement provide adequate bounding values of sea bed mobility for the design of wind turbine foundations and cable burial.

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