How the Belgian wind farm business made us discover the challenging environment of marine sand dunes

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Abstract

During the last decade, it has become clear that sand dunes are important features in the Belgian wind farm concession area. Because they influence not only the design seabed levels, but also the hydrodynamic forcings and installation methods for both cable and foundations, the study of the seabed morhodynamics is essential for all wind farm projects.

This paper starts with an overview of the geographic and morphological setting of the Belgian wind farm concession areas and presents an overview of the key features of the bedforms in the different concessions.

Next the importance and impact of the sand dunes during the design and development of these wind farms is illustrated by exploring the different types of studies and investigations which have been performed in relation to seabed & morphology, the hydrodynamic loadings, the installation methods and the environmental impact assessments.

1. INTRODUCTION

Thanks to C-Power, the pioneers of the Belgian offshore wind energy sector, IMDC has had the opportunity to start to work on and to study the Belgian Part of the North Sea (BPNS) since 2003. During the following 10 years we did not only got to know the sand dunes on the Thornton Bank, but also the bed forms in the concession areas of Norther, Rentel, Northwind, SeaStar, Belwind, and Mermaid.

For the permits of these wind farms , the design of the wind turbine foundations and the cable laying not only the effect of the moving sand dunes on the structures is investigated, but also the influence of the constructions works and these artificial features should be scrutinized.

2. THE WIND FARMS

1.1. Geographical setting

In the KB (Koninklijk Besluit) of 17 May 2004 (and adapted by the KB of 3 February 2011) a preferential zone for the development of offshore wind farms has been indicated by law. This Belgian wind farm area is situated along the Northeastern boundary of the BPNS encloses the 7 concession areas. From shore towards the sea the concession areas are: Norther, C-Power, Rentel, Northwind, SeaStar, Belwind and Mermaid (see figure 1, end of paper).

The location of the concession zones ranges between 21 km (for the Norther wind farm) and 50 km (for Mermaid) offshore. Also water depth greatly varies: 12 m on top of the Thornton Bank, till 50 m far offshore (see table 1, end of paper).

The total installed capacity offshore wind energy in Belgium end 2012 was about 380 MW spread over 91 turbines, across two wind farms (C-Power and Belwind). This represents 7.6% of the total installed (offshore) capacity in Europe (EWEA, 2013).

1.2. Morphological setting

The bottom topography of the BPNS consists of a complex of sandbanks and swales, where the channels reach maximum depths of 30 to 40 m below LAT. The sandbanks are traditionally divided into four groups: the Coastal Banks, the

Flemish Banks, the Hinder Banks and the Zeeland Ridges. The Zeeland Ridges are roughly SW-NO oriented. From north to south they consist of the Lodewijkbank, the Thornton Bank, the Gootebank and the Akkaertbank. These banks are part from a group which is also situated on Dutch territory.

A fundamental process for the existence of the sandbanks is the presence of ebb and flood channels on both sides of the bank. This causes the circular sand movement over and around the bank which maintains the stability of the bank. Normally there exists an asymmetry in current velocity on both sides of the banks. This is because the sandbanks are positioned with a small angle relative to the tide, which makes that one side of the bank is more exposed to the flood current, while the other side is more exposed to the ebb current (Dyer en Huntley, 1999). The strongest current erodes most often one side of the bank and maintains in this way the steepest flank. The Zeeland Ridges have a steep eastern flank and the maximal current velocity is directed in the flood direction (NE) (Lanckneus et al., 2001). This points towards a circular sand movement around the Zeeland Ridges anti-clockwise, in contrast to the rest of the BPNS.

The occurrence and morphology of the sandbanks as a whole has generally not drastically changed over the last 200 years, despite of the very dynamic environment. Movements are only located within the area of sandbanks themselves and especially towards their summits. Generally sandbanks witness a major stability and this at least since 1800 (Le Bot et al., 2005; Van Lancker et al. 2009).

Throughout the area, the surface is covered with Holocene sea sand. This sand has a medium grain size between 250 and 500 μm and is generally coarser on the banks than in the swales. The sand on the banks can reach a total thickness of 20 m. In the swales possibly gravel and mud can be present.

1.3. Bedforms

An important phenomenon on top of the sandbanks and in the gullies in between are the sand dunes. Sand dunes are significantly smaller than sandbanks (a couple of meters high), but are more dynamic and, as the tidal banks, prominent in the Belgian part of the North Sea (BPNS). Usually they are perpendicular to the direction of the net present flow. Like the tidal banks they incurred due to an unstable seabed area subject to tidal currents. In general the highest sand dunes occur on the northern end of the Flemish Banks (up to 8 m) and in the northern part of the Hinder Banks (up to 11 m) (Deleu, 2001).

Dunes can strongly migrate (e.g. more than 50 m in 1.5 year for the dunes on the Westhinder bank) (Deleu et al., 2004), although sometimes with an oscillating movement. Sand dunes are oriented perpendicular to the main current direction, on both sides of the bank they are often oriented towards the crest of the bank.

The dunes are usually covered with smaller dunes and (mega)ripples, which dimensions change at a short time scale (tidal cycle). The size of ripples is controlled by water depth and grain size (O'Conner, 1992). Ashley (1990) has classified the bed forms according to amplitude and wave length into ripples, small, medium, large and very large dunes (see table 2).

Table 2: Classification of bed forms according to Ashley (1990)

Bed form	Amplitude [m]	Wave length [m]
Ripples	< 0,075	< 0,6
Small dunes	0,075 - 0,4	0,6 - 5
Medium dunes	0,4 - 0,75	5-10
Large dunes	0,75 – 5	10 – 100
Very large dunes	> 5	> 100

In the Belgian wind farm area, a variation of bed forms has been observed (see table 3, end of paper). On top of the sandbanks quite often large to very large sand dunes are present with heights from 2 to 7 m and wave lengths of 150 – 500 m (Haerens et al. 2008). Superposed on these sand dunes smaller bed forms, such as ripples, can be present. Quite often, in the gullies in between the sandbanks, bed forms are less important (e.g. Norther), although for example in the Rentel area also there large dunes are present.

3. DESIGN OF WIND TURBINE FOUNDATIONS

During the design, bed forms have an influence on the selection of the foundation type, the foundation level, and the scour protection type. Three

foundation types are currently present in the BPNS: monopile, jacket and gravity based foundations (GBF) (see figure 2 and 3). To be able to make a smart choice for one of these foundation types, amongst others long term predictions of the dune mobility and possible seabed levels are required.
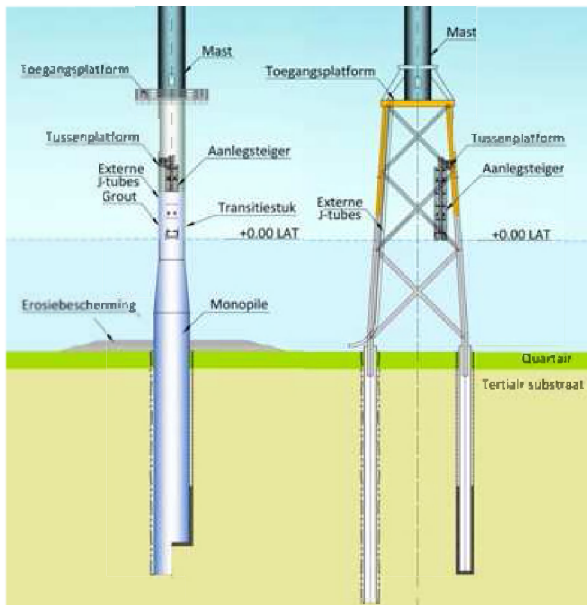

Figure 2: Monopile (left) and jacket foundation (right) (source: Technum-IMDC)
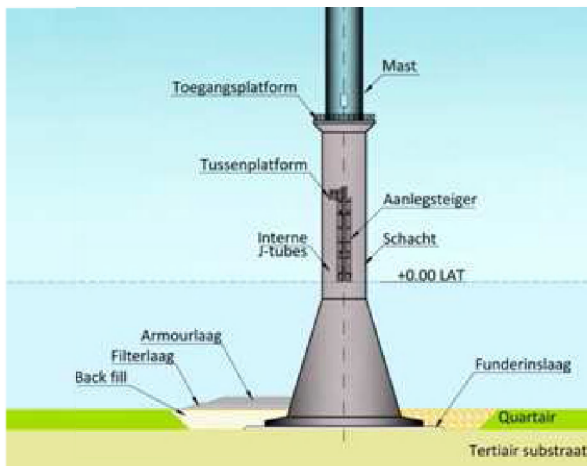

Figure 3: Gravity Based Foundation (GBF) (source: Technum-IMDC)

Depending on the foundation type, changing seabed levels around the foundation can easier be dealt with (e.g. jacket foundations) or should be prevented by the placement of an adequate scour protection (e.g. GBFs and most monopole

foundations). Whereas for GBFs a constant seabed level is a firm condition for the design and construction, an interaction exists between the variation of the seabed level during the lifetime of the foundation and the design of the steel structures: varying levels might change the eigen frequencies and influence the fatigue behaviour of the structure.

Also for the scour protection different options can be considered: the so called "static" or "dynamic" scour protections. Whereas the first type cannot deal with dropping seabed levels, the second type is designed to remain functional. In the BPNS currently the static scour protection has been chosen for the GBFs (C-Power) and monopiles (Belwind). For the jackets structures of C-Power, it has been chosen to leave the seabed unprotected, and thus to allow the scour of the seabed due to the presence of the structures.

Not only for the selection of the foundation type, but also for the actual design of the foundation, sand dunes and their mobility remain important. The passing of a sand dune introduces changes in the hydrodynamic loadings on the foundation, not only in terms of water depth, but also the wave characteristics might change. Steep slopes in shallow areas introduce different types of wave breaking, each having their own influence on the loading (e.g. IMDC 2009a & 2012a).

Construction and installation methods are influenced as well by the presence of sand dunes. Gravity based foundations for example require a perfect horizontal foundation surface and thus quite some seabed preparation. For the GBFs a foundation pit has been dredged, and a horizontal gravel bed has been installed to provide a solid base for the foundations (Bolle et al., 2010 & 2012). Also for the jacket foundations some seabed preparation was necessary: the seabed had to be (locally) flattened (or dredged) in order to be able to position the installation frame for the pin piles of the jacket foundation (Bolle et al., 2012).

During the lifetime of the project cables can become exposed as a consequence of mobile sand dunes. Therefore enough coverage of the cables will be aimed for during installation. But on the other side, cable installation (e.g. by means of a plough) is hindered if dune slopes are too steep, which might result in insufficient burial and a higher risk of cable exposure later on.

But let's not forget the other way around as well, namely the influence these rigid structures might have on the dynamic, sandy surroundings. The environmental impact assessment (EIA) procedures force us to investigate, describe and predict these changing environments and the possible impacts in the best possible way for both the short and the long term (e.g. IMDC, 2012b & c). Typically the expected effects during construction of the foundations, during operation of the farm and in case of dismantling are described. Regarding morphology, a slightly bigger effect is expected during construction of the GBFs, compared to the installation of monopiles or jackets due to the more important seabed preparations (IMDC, 2012d).

4. STUDY OF DESIGN PARAMETERS AND FUTURE CHALLENGES

For all these studies numerous tools and models are applied and further developed: historic data and brand new high-resolution measurements are analysed and numerical models are put in place to predict waves, currents and the morphodynamics of the seabed.

The type and detail of the studies depend not only from the amount and quality of the data available, but also from the aim of the study. Whereas during feasibility and preliminary design studies, a more general approach will be followed (because a choice for a foundation type still has to be made, or because only limited data are available at that stage), for the detailed design one should be much more precise in order to limit the variation of all parameters to be taken into account in the design.

An overview of the current practice and some of the evolutions over the past 10 years follows below.

1.4. Seabed & morphology

A basic bathymetry will provide a first idea of the expected water depths. However, since the seabed level is an important design parameter, foundation designers do not only want to know the present seabed level, but also the level throughout the lifetime of the foundation and the variations which can occur.

Although ideally several detailed bathymetries (e.g. full coverage multibeam surveys) are needed to assess the seabed stability, quite often and almost certainly for the first orienting studies, one has to deal with less dense datasets (e.g. single beam surveys with a large spacing).

To give the designers the data they need, typically the following studies are performed. When only one dataset is available, the studies are limited to the observations which can be made: the presence of sand dunes and bed forms, the amplitudes and wave lengths and the orientation of their slopes, which give already a first indication of the seabed mobility (see table 3 for estimates for the different concession areas). In this case, literature remains a very important source to compare with earlier studies.

If more detailed datasets are available, difference maps can reveal an erosion or sedimentation trend, and the migration rate of the bed forms over the years can be determined. The combination of all this information allows to predict the minimum and maximum seabed levels which can be expected during the lifetime of the foundation due to the autonomous evolution (Haerens et al. 2008).

Of course it is still a bit more complex than this: migration rates are often roughly estimated without any link to the hydrodynamics. Last decade some successful attempts were reported to model these sand dune migration with numeric models (e.g. Hulscher & Van Den Brink, 2001; Roos & Hulscher, 2003; van den Berg & van Damme, 2004; Borsje, 2011) and to model several of this processes or impacts separately (e.g. Knaapen & Hulscher, 2002). But still a lot of the interactions between sand dunes and different foundation types are not very clear yet. How do sand dunes influence the scour holes and depths around jacket foundations without scour protection? How do sand dunes influence the scour protection around monopiles and GBFs? And what's the effect of seabed preparation or dredging, which lowers the seabed around the foundation below the surrounding levels? Studies are still ongoing and hopefully field data from existing wind farms can give us more insight in the future.

1.5. Hydrodynamic loading

The hydrodynamic forcing on a foundation is a combination of the water levels, the currents and

the waves. Not only the regular conditions, but especially the extreme conditions will influence the design. Typical values with a return period of 50 or 100 years are taken as design values.

In the Belgian part of the North Sea, the "Meetnet Vlaamse Banken" (2012) has collected over the years a valuable data set which allows us to determine these extreme values. However, when the first wind farm was designed, no site specific data were available yet, so measurements had to be performed on the Thornton Bank. A wave rider buoy has been installed and through tide measurements have been performed to capture the current distributions on top and around the sandbanks (Technum, IMDC & Elsam, 2006). Another option is to perform numerical modeling both for the currents and the waves. But also then, these new datasets are very useful, to validate the models.

If we focus a bit more on the waves, there has been an evolution in the type of models which are applied. The spectral models (e.g. SWAN) are typically used to determine the wave climate on a large scale and are already a long time part of the current practice. Extreme values can be calculated, and maximum wave heights and locations with wave breaking are typically determined according to rules of thumb.

For some locations however, for example the sandbanks and locations with sand dunes, non-linear interactions become important and spectral models cannot give an answer anymore. A combination with Boussinesq type models (e.g. MIKE21BW) can offer a solution, since all processes and non-linear interactions are included so the effects of the seabed can be better predicted. Indeed, some sandbanks and sand dunes can influence (also increase!) the local wave heights, or can introduce wave breaking (IMDC, 2009b and 2012a).

Even one step further, we can determine the loading of one single wave on a foundation with CFD models (Christensen et al., 2011). These models allow also taking into account a specific bathymetry and can provide the designer with time series of the pressure distribution on the foundation and the conditions for wave breaking (DHI, 2009a & b). This type of modeling is certainly useful for all foundations with a particular shape (e.g. GBFs).

1.6. Installation techniques

Also installation techniques depend on the water depth and the seabed morphology. Although for the installation itself, mainly information about the actual state is needed, which can be provided with a multi-beam survey, for some aspects also the bed evolution has to be considered.

The water depth is the main factor which influences the choice of the vessels. Also to place a frame on the seabed and to install the pin piles for C-Power's jacket foundations, a minimum water depth was required, which implied (limited) local dredging on top of the sandbank, in the shallowest locations.

For the cable however, both bed forms and bottom type impact the installation. Whereas the bottom type determines the installation technique (plough, jetting, ...), the seabed erosion and the migrating bed forms will influence the burial depth. This depth has to be chosen sufficiently large to prevent cable exposure during the wind farm's lifetime, but putting the cable too deep will make installation too expensive (if even possible). Also the steep slopes on some dunes might cause problems during cable installation. So typically a profound analysis of the cable trajectory is advisable before starting any works.

1.7. Environmental impact assessment

Last but not least, the seabed is one of the topics that has to be addressed in the EIAs which are performed to obtain the concession.

Although this study has to be made in a very preliminary stage of the project, and often the choice between different foundation options and lay-outs is still to be made, all possible impacts from the structures and the works have to be identified (IMDC, 2012d). For these studies typically all the available information from literature or previous projects is collected. In some cases, numerical modelling is performed though, to estimate for example the local sediment transport (IMDC, 2012b), or the sediment plumes during the dredging operations more accurately (IMDC, 2012c).

For the first wind farms, information was fairly limited, but every year more and more information becomes available from the wind farms in operation. Long term monitoring and analysis of these data will certainly improve the insight in the

system (e.g. Degraer, & Brabant, 2009; Degraer et al., 2011, 2012).

5. CONCLUSIONS

Sand dunes are important features in the Belgian wind farm concession area, as has been illustrated in this paper. Not only they are evidence for the dynamic environment of the sandbanks, they can certainly not be neglected during the design and installation of the wind turbine foundations and electrical cables.

Since 2003, studies have been performed to qualify and quantify their temporal evolution, to determine their impact on the design bottom levels for the foundations and their impact on the hydrodynamic forcing and installation methods. Over the past years not only the amount of available information has drastically increased, but also the quality of the data has been improved as a result of the important investments the wind farm industry has done into research. In the framework of this search towards better defined boundary conditions and design values, consultants have been pushed towards more performant numerical models.

Also scientists have been focusing on this research, trying to understand the physics behind all these processes and to capturing these processes in often complicated and time consuming models. Monitoring on the other hand remains essential to improve the understanding of the processes, and to validate the developed models.

One of the major challenges for the future will be to build a bridge between scientists and engineers, to be able to use this knowledge for new projects, within the often short time frames available for these studies.

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Table 1: Basic characteristics of the 7 wind farm concession areas.

Wind farm	Distance from shore [km]	Water depth [m]	Location	Surface [km²]	Number of turbines	Total capacity [MW]
1. Norther	21	14-30	Rabs bank and Gootebank	44	47-100	420
2. C-Power	27	12-27	Thorntonbank	18	54	300
3. Rentel	31	22-28	Zuidwest-Schaar	27	47-78	289-468
4. Northwind	37	16-29	Lodewijkbank (Bank zonder naam)	14.5	72	216
5. SeaStar	41	20-25		18	41	246
6. Belwind	42	15-37	Bligh Bank	35	55	330 (2x165)
7. Mermaid	50	25-50		28	75	450

Table 3: Morphologic characteristics of the 7 wind farm concession areas.

| Wind farm	Water depth [m]	Location	Height sand dunes [m]	Spacing sand dunes [m]	Classification (Ashley, 1990)	migration rate [m/year]
1. Norther	14-30	Rabs bank	3.4-5.7	200-340	Large and very large dunes	2.4-7
		Gootebank	1.5-3.9	170-320		1-7
		gully between Rabs & Thornthonbank	<0.5	10-20	Small to medium dunes	stable
2. C-Power	12-27	Thorntonbank	2-7	100-500	Large to very large dunes	1-3
3. Rentel	22-28	Zuidwest-Schaar	2-7	200-500	Large to very large dunes	
4. Northwind	16-29	Lodewijkbank (Bank zonder naam)	3.7-7.5	170-350	Large to very large dunes	2.5-3.3
5. SeaStar	20-25		2-4	?	Large dunes	?
6. Belwind	15-37	Bligh Bank	3-4 °	150- 225	Large dunes	1 -2.5
7. Mermaid	25-50		2-4	?	Large dunes	?

° Wiertsema & Partners (2008)
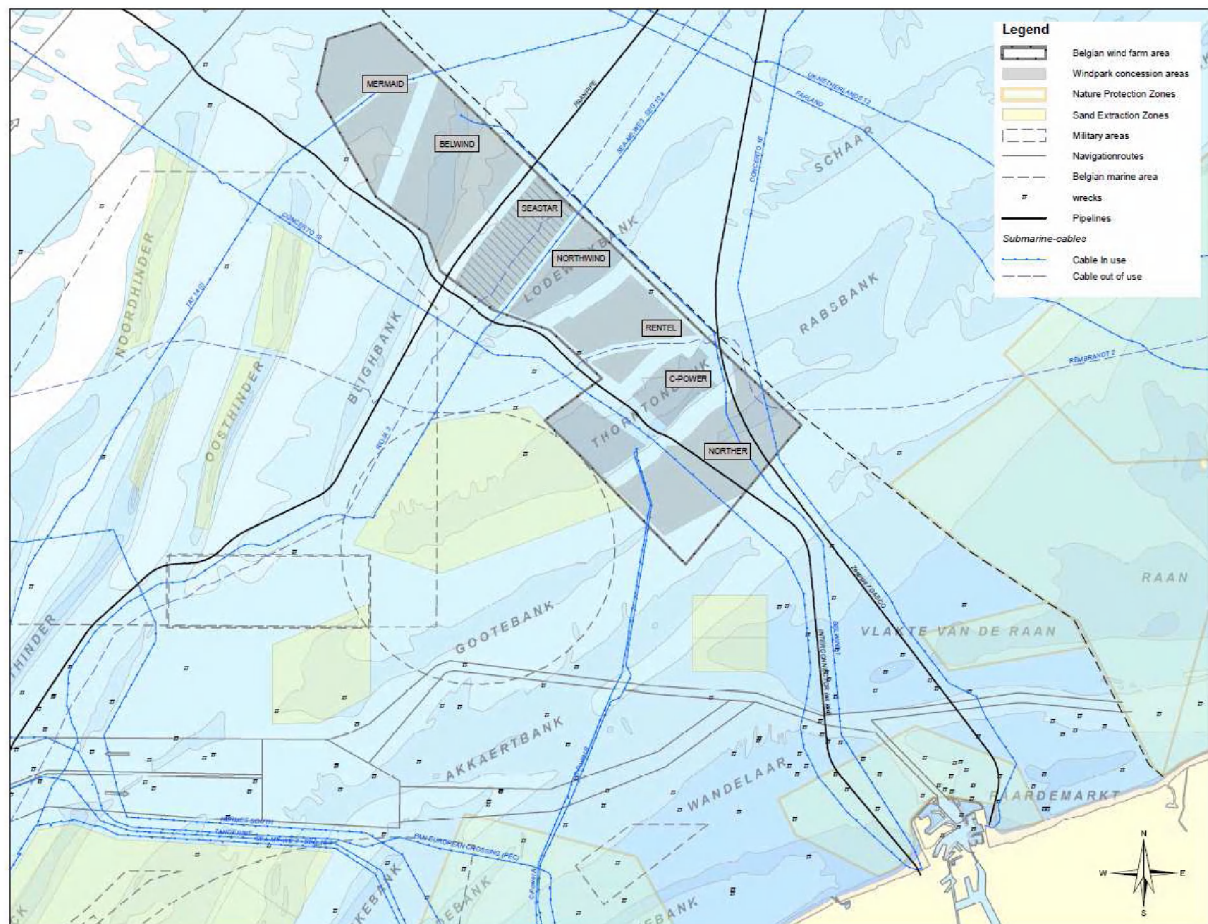
Figure 2. Concession zones in the Belgian wind farm area.