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Numerical estimation of ORE export cables burial depth in a marine dune environment : the Dunkirk offshore wind farm study case

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ABSTRACT: Many Offshore Renewable Energy sites (offshore wind turbine farms and export cables) are constructed or planned in areas of high sediment mobility. Over such mobile sediment, it is frequent that large marine dunes (several meters high) develop and migrate (sometimes several meters per year). In presence of sandy substrates, submarine cables are generally buried at a depth of at least 1 meter below the (minimum) seabed level in order to ensure a sufficient protection. In case marine dunes migrate over the cable, bathymetric variations might reach several meters and cables might get over buried or exposed. Designing an adequate initial cable burial depth in such a dynamic environment is therefore particularly challenging. Here, we use a morphodynamic numerical model to assess the bathymetric variations over a planned cable route in an area of large active marine dunes. It focuses on an area located along the two export cables routes of the planned Dunkirk offshore wind farm (France), where multiple dunes ranging from 0.8 to 2.1 meters high and migrating up to 28.5 m per year are present. A configuration considering a morphological acceleration factor of 20 is setup over 4 months. A validity period is defined using multiple bathymetric surveys carried out prior to the cable installation. Using the maximum range of this period, the depth variations are studied along each cable route to provide estimations of both an appropriate burial depth and information for the cable design.

Keywords: Marine dunes; Numerical modelling; Export cables; Renewable Energy; Installation work

1 INTRODUCTION

Active bedforms with heights reaching 20-25% of the water depth are present in large parts of the English channel and continental shelf (Le Bot & Trenteseaux, 2004). These bedforms migrate at speeds of up to tens of metres per year. The active behaviour of the seabed is likely to pose specific challenges for the offshore wind farm industry, particularly concerning the electrical cables. Addressing this potential issue is therefore crucial. The estimation of an optimal cable route generally requires significant deviations of a straight direct routes to avoid areas with mobile sediment (Department for Business Enterprise & Regularoty Reform, 2008).

When the cable route needs to go through a zone of high mobility, seabed movement could expose the cable increasing the risk of damage (Whitehouse, et al., 2000). Therefore, a mitigation is to increase the burial depth to minimize the risk of exposure (Carbon Trust, 2015). However, when the crest of a dune passes over the cable, it can result in an increase of the sediment thickness, likely to cause an increase of the cable temperature (Quan, et al., 2019), directly associated with the cable ampacity, the maximum current carrying capacity of the cable (Duraisamy, et al., 2018). An understanding of the sediment layer variation during the wind farm lifetime is therefore vital. It influences the burial depth and the cable design which can both induce an increase of the cable and installation costs.

To contribute to France's renewable energy goals, an area off the coast of Dunkirk (France) in the southern part of the North Sea has been designated for the construction of an offshore wind farm. Using bathymetric surveys and a morphodynamic numerical model, this study aims to provide insights into the evolution of the sediment thickness above the cable in a specific area along the cable corridor. This provides information to determine an appropriate initial burial depth during installation phase which will ensure the cable will stay under a sufficient depth of sediment cover during the full operational phase. Additionnaly it gives insight into the duration for which the cable will remain under various depths of sediment which can affect the cable design.

2 *DATA & METHODS*

2.1 *Study area*

This study focuses on a domain referred to as B1 (Figure 1, inset), located along the export cable corridor of the future Dunkirk wind farm (Figure 1). Over this area, eight bathymetric surveys and numerous sediment samplings were conducted from November 2019 and July 2021 (Nexer, et al., 2024). In this study the bathymetry is expressed as the water depth with respect to the mean sea level (MSL). The area, with a bathymetry ranging from 15 to 20 m, is composed of six large dunes named D1 to D6. From west to east, they include two barchans, one sinuous dune and three rectilinear dunes (Figure 1, inset). Nexer et al. (2024) showed that dune height and crestline length are decreasing from west to east (Table 1). The two barchans D1 and D2 are the largest dunes with respectively average height of 2.12 and 2.03 m and crestline length of 510 m and 600 m. The area is highly dynamic, with an eastward migration of the dunes at an average rate of 28.5 m/year (Nexer, et al., 2024) due to the influence of tidal flow, characterised by a dominant flood period with currents directed towards N81°.

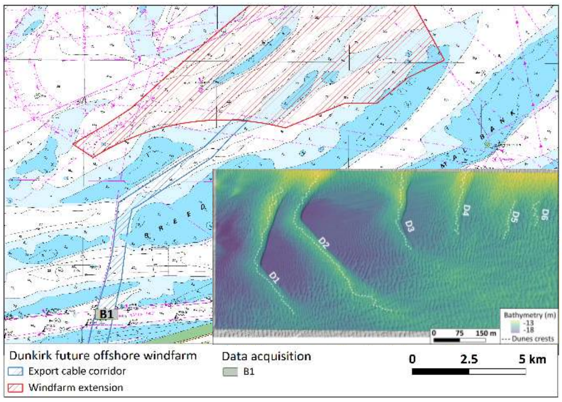

Figure 1. Location of Dunkirk wind farm area (in red), cable corridor (in blue) (data provided by SHOM – do not match the adopted cable corridor) and of the area of interest B1. (inset) Bathymetric data of B1 area collected on the first survey of November 17th, 2019. All six dunes are numbered on the figure (D1-D6) and their crestlines are represented by the white dash-lines.

Table 1. Heights, lengths and crestline lengths of the six dunes measured on November 17th, 2019 (Nexer, et al., 2024).

Dune name	Height (m)	Crestline length (m)
Dune 1	2.12	510
Dune 2	2.03	600
Dune 3	1.64	290
Dune 4	1.16	230
Dune 5	0.92	124
Dune 6	0.78	100

2.2 *Dune analysis*

The electricity generated by the Dunkirk wind farm is planned to be transported via two cables, deployed along the corridor (Figure 1). Both cables will traverse the B1 area to reach the shoreline. To assess the bathymetric changes over the cables location in the B1 area, the initial part of this study relies solely on bathymetric surveys. The present methodology was adapted from the method described to predict the seabed level changes of the Borssele wind farm (Deltares, 2015). First, all survey data were interpolated onto the numerical grid with a 5 m spatial resolution. Secondary bedforms were filtered out using a fourth order high-pass Butterworth filter to remove all bedforms with wavelength lower than 50 m before applying a focal average function with a window size of 45 m. Using the filtered bathymetries, the cross-correlation technique was applied to determine the migration direction of all dunes except D6. During the initial survey, this dune was found to be situated east of both cable positions. Consequently, its eastern migration suggests that it will move away from the cable, avoiding any interaction with it.

Following Duffy & Hughes-Clarke (2005), we use the cross-correlation technique to calculate migration vectors. For our purpose, the maximum correlation method was used. This technique was only applied on points located around the dune crests. Indeed, as described by Lefebvre et al. (2021), in an environment dominated by tidal currents, bedforms tend to have steeper slopes close to the crest, and flatter slopes close to the troughs. This facilitates crest identification, but makes trough identification difficult. In the current study, to apply the cross-correlation technique, we identified multiple points along the crestline of the five western dunes. To address boundary issues which might be caused by points leaving the domain during the two years observation period, points were extracted only within the range y = 100 m and y = 400 m (Figure 2).

The dune crest movements were extrapolated across the B1 area to determine an average migration direction and distance for all points. To predict the future bathymetries and the corresponding bed level changes over the cable positions, the final survey was artificially shifted following both direction and distance matrices with a timestep of 60 days. During the two years period covered by the eight bathymetric surveys, all dune heights stay relatively constant with variations of about 10% around an average value. For the purpose of this study, it is reasonable to assume that the dune height will remain constant while they are migrating. This statement will be discussed later. Consequently, no vertical changes are applied on the dunes while performing this seabed evolution prediction.

2.3 Numerical model

Modelling is conducted using the Coastal and Regional Ocean COmmunity (CROCO) model coupled with USGS sediment module. The computation is performed using a C-Arakawa grid of 5-m horizontal resolution that covers the B1 area. Over the vertical, 30 sigma layers are considered with thiner layers close to the seabed. Bedload transport is calculated using the Wu & Lin (2014) formulation. The bed evolution is calculated using the Exner equation. Following the results of in-situ measurements (Nexer, et al., 2024), in the domain, the sediment is represented as one 10 m layer of medium sand with d_{50} = 328 µm with a porosity set constant to 0.41. Initial bathymetry is interpolated from the first bathymetric survey conducted on November 17th, 2019.

Current and wave boundary conditions come from a regional simulation of CROCO and the wave model WaveWatch3. Validation (not shown here) is performed using data collected with measurements from an Acoustic Doppler Current Profiler (ADCP), a tide gauge and a wave buoy on the Dunkirk wind farm area. A morphodynamic simulation was performed over the B1 area. The validation is conducted over the B1 area over which the morphological accelerator parameter is set to 20. Comparison between model evolution and the fifth survey conducted about one year after the initial one (December 5th, 2020) are made using the Brier Skill Score (BSS) on both the water depth and crest positions to find respective values of 0.5 and 0.74.

3 RESULTS

3.1 Bathymetric evolution

Figure 2 represents the results of the cross-correlation technique applied on the five western dunes. All crests consistently migrate toward the east or north-east covering an approximate distance of 100 m within the two years period. The migration pattern seems consistent across all dunes: the northern points align with the tidal residual current direction (N81°), while the southern points face north. Bedforms are generally assumed to migrate in the direction of the steeper slope (Knaapen, 2005). This seems to be verified in our case for the southern part of both barchans and the sinuous dune. For the western dunes D1 and D2, the points located north of the dune horns migrate aligned with the tidal residual current direction. Around the dune horns and south of it, in accordance with the steeper slope direction, the direction turns to north until it reaches almost N20° for the southernmost point.

Regarding dune D3, the migration direction also shifts northward along its southern part. Notably, like the two rectilinear eastern dunes (D4 and D5), the shape of D3 cannot fully explain this change in migration direction. The southern points of these three dunes lie near the large plain in the southeastern part of the B1 area, where the total residual current – comprising tidal-, wind- and wave-induced currents – tend to flow northward. This northward flow, combined with the direction of the steeper slope of each dune, provides a first explanation for the B1 area configuration. The southern part of each large dune migrates northeastward and "avoids" the southeastern part of the area, where, consequently, only a flat surface with small bedforms on it is observed.

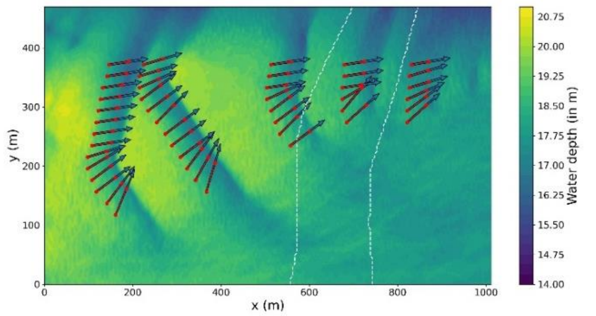

Figure 2. Results of the cross-correlation technique with initial and final positions over the crests (red dots). The arrows represent the estimated directions, while the colormap corresponds to the bathymetric data surveyed in July 2021. The white dash lines represent possible routes for the export cables.

Starting from the last survey conducted in July 2021, the direction and distance migration matrix estimated through the cross-correlation technique are applied to predict the bathymetric evolution by performing an extrapolation of seabed mobility based solely on the survey data. Since no additional data are added within the domain, the boundaries also shift with the migration, resulting in a reduction of the available data. Following this methodology, predictions cannot be made for more than 15.6 years. After that, the southern and western boundaries have been shifted across the domain.

Figure 3 represents the maximum water depth predicted over both cable course compared to the initial bathymetry (last survey data). Results express

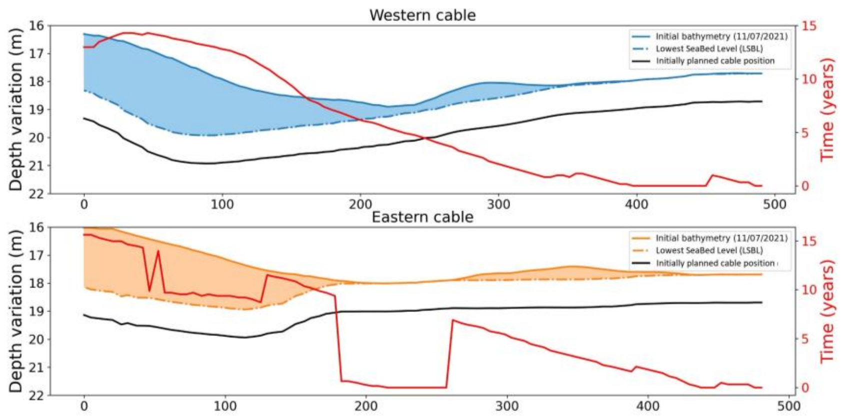

Figure 3. Lowest SeaBed Level (LSBL) estimated over both cable routes using bathymetric survey data. The difference with the initial bathymetry (considered as the last survey data) is represented by the coloured area. The initially planned cable position is displayed as the dark line on both plots. The time of occurrence of each maximum water depth is represented on both plot (red line).

water depth as a function of the distance from the northernmost points of each cable (referred to as D_w and D_e respectively for the western and eastern cables). For each maximum, the corresponding time of occurrence is represented as a red line.

As described before, the southern boundary moves up north and provides no data for the southern points after a few timesteps. As a result, maximum water depth is estimated within the first 3-4 years for the southern part of each cable ($D_w > 300$ m and $D_e > 400$ m). On the northern part of each cable, significant variations in water depth were estimated, in accordance with the presence of the dunes. For the western cable, the maximum depth fluctuates between 18 and 20 m along its route. The time of occurrence of these values linearly decreases as the distance from the northernmost point increases, starting from 15 years ($D_w \approx 20$ m) and reaching zero for the southernmost point. This occurrence timeline provides insights into the origin of the maximum values. Here only 15.6 years of prediction are available. As a result, the boundaries of B1 would take 15.6 years to cross the domain to reach the cable locations and leading to no data available. Therefore, the maximum water depth estimated for $D_w < 150$ m, with a time of occurence of 15 years, originates from values originally located close to the boundaries of B1 area. In this case, the values matches with the western trough area of the D1 dune.

Regarding the eastern cable, the same pattern is predicted compared to the western cable, albeit with lower variations. The water depth estimated for the first 180 m south of the northernmost point of this cable range from 18 to 19 m. Contrary to the western cable, the maximum values show an occurrence time that rapidly fluctuates. These rapid variations are the consequence of small difference in the water depth between the different troughs leading to different location of the maximum and consequently an important variation of the time of occurence.

3.2 Lowest SeaBed Level (LSBL)

To address the methodological limitation of an extrapolation based on bathymetric data, we use the morphodynamic model results to estimate the seabed evolution and predict its evolution after the last survey. The initial survey data is used as initial bathymetry for the model which runs for 4 months. A morphological accelerator factor of 20 is applied so that 1 day of modelling using the morphological factor is corresponding to 20. The model accuracy was assessed by calculating the Root Mean Square Error (RMSE) between the survey data and estimated water depths along the cable routes. The model is considered valid until the error reaches 0.5 m, which represents half of the initial burial depth of 1 m. Using this methodology, the validity periods of the model for the western and eastern cables are estimated to 42 and 64 days, respectively. Considering the morphological factor, this corresponds to a validity of approximately 2.3 and 3.5 years.

Within these validity periods, the numerical results were interpolated over both cable routes for each calculation timestep. The Lowest SeaBed Level (LSBL), which refer to the maximum water depth estimated from the combination of the previous section results and numerical modelling predictions, was extracted. If the model-estimated water depth was higher than the value estimated from survey data, the LSBL was updated to use the model data. As a result, the maximum water depth estimated over the northern portion of both cable routes (distance from northernmost point lower than 200 m) remains unchanged from the previous section. These values are

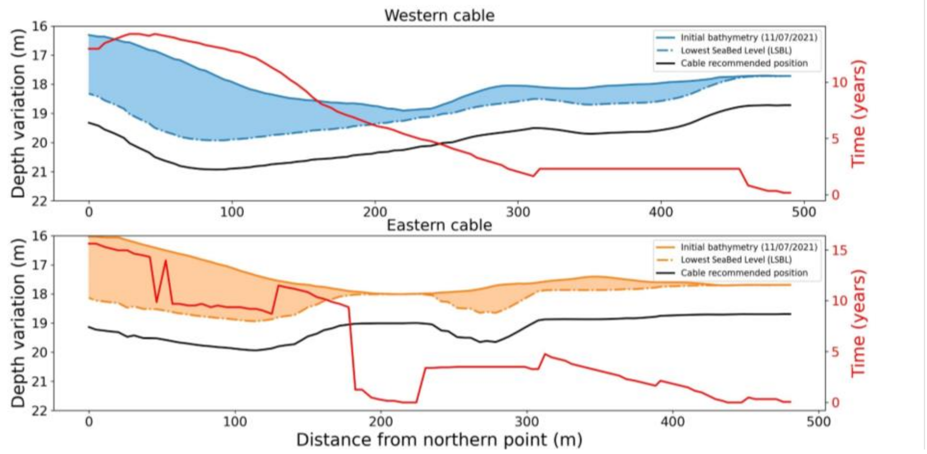

Figure 4. Lowest Seabed Level (LSBL) estimated over both cable routes using bathymetric survey data and numerical modelling. The difference with the initial bathymetry (considered as the last survey data) is represented by the coloured area. The recommended cable position is displayed as the dark line on both plots. The time of occurrence of each maximum water depth is represented on both plot (red line).

anticipated to manifest 15 years after the last survey. However, due to the short validity periods, D1 and D2 did not have sufficient time to reach the cable locations. Consequently, the updated values only pertain to the southern portion of the cable route.

On the western cable, the LSBL is increased by 1 m along the southern section of the cable route ($D_w >$ 300 m). Regarding the eastern cable, the LSBL exhibits fewer changes, with only a 1 m increase for 220 m $< D_e <$ 320 m. However, south to these points, the LSBL remains unchanged, as no dune passes over those locations within the validity period.

3.3 *Maximum SeaBed Level (MSBL)*

If the installation works follows the recommended burial depth (LSBL), it may result in the cable being buried beneath a significant sediment layer when a dune crest passes over it. As defined by Duraisamy et al. (2018), the cable internal temperature could therefore be increased. Depending on the sediment layer width, the cable design might need an adaptation to maintain its integrity while also ensuring that ampacity is not significantly impacted. Given that the cable design remains consistent throughout its length, the following results pertain to the maximum values estimated across the different locations and over time (Table 2).

For both cables, the time spent under a layer of sediment decreases as the sediment layer thickness increases, reflecting seabed variations. The maximum prediction time under a 1 m sediment layer is 15.6 years for both cables. The western cable starts by being buried under 2.5-3 m of sand, with the thickness of the sediment layer reducing due to dune migration patterns. The eastern cable, initially buried less deeply, shows similar patterns but with shorter consecutive time periods under sediment layers.

Despite the similarity in the thicknesses of the lower sediment layers, a significant difference exists between the cables. The eastern cable could be buried under a 4-m sediment layer for a consecutive period of 0.38 years, while the eastern cable may never experience this.

Table 2. Consecutive time (in years) spent by western and eastern cables under various sediment layer width.

Burial depth (m)	Time for western cable (years)	Time for eastern cable (years)
1	15.61	15.61
1.5	11.83	8.87
2	8.71	7.56
2.5	3.45	3.12
3	2.14	1.86
3.5	1.31	0.49
4	0	0.38

4 LIMITATIONS

4.1 *Limitations*

The methodology described in this study allows to provide estimations for cable installation but contains sources of uncertainty.

(i) The first source of uncertainty lies in the assumption that no vertical alterations were applied during the bathymetric shift. As previously noted, no clear variation was observed during the two years covered by the eight bathymetric surveys. All dune heights exhibited a consistent variation of approximately 10% of their height around an average value. Consequently, assuming no vertical changes during the cable lifetime seems reasonable. However, it might introduce an error that could reach 20 cm (10 % of the dune height). Assessing whether this error renders the LSBL conservative or not is difficult but should be addressed.

(ii) When the bathymetric shift is applied, the southern and western boundaries of the B1 area are also moved. This implies a reduction of the available data and limits the estimation for a large part of the cable route. In the current case, it limits estimations over the southern part of the cable. Since this part is in a large plain area, no important variations are expected. However, this limitation could also lead to an underestimation of the consecutive time as described in section 3.3. The dunes are expected to traverse the cable route, with D2 taking approximately 10 years and D1 about 15 years to go over the cables. Consequently, due to the bathymetric shifts, this consecutive time only refers to the northernmost points of the cable route. It might miss a part of the route which could be buried underneath a 4 m sand layer for a longer consecutive time. An adaptation of the bathymetric survey extension can be a solution to reduce this limitation and lead to accurate estimations. Additionally, the installation works are not considered here. The morphodynamic changes that could induced to the surrounding marine dunes could also have an impact on the estimations of section 3.3 and should be considered on a later study.

(iii) Another limitation of this methodology is that the average dune migration is determined using two surveys conducted two years apart. This makes it difficult to account for the various variabilities that could occur on both small and large temporal scales. On a small scale, the tidal cycle should be carefully considered, as it could either minimise or maximise the estimated average migration. In the present case both surveys were made during a mean tidal cycle which might be a way to avoid issues. On a larger temporal scale, inter-annual variability is not accounted for here. Storm conditions can vary between years (especially when considering the effects of climate change) and, as described by Lewis et al. (2015), could significantly impact the morphology.

4.2 (iv) A final limitation is the lack of consideration for anthropogenic activities, such as dredging. Although these activities could significantly impact the morphology, it is challenging to incorporate them into this methodology. Therefore, the results presented here should be interpreted with caution regarding those activities.*Application to design*

In a sand dune environment, LSBL could be used to define the minimum burial depth ensuring proper protection from hazards, especially when a dune trough goes over the cable and risk to expose the cable (worst case scenario). MSBL could be considered for cable cross-section selection, as a conservative approach. The sand dune dynamic are likely to be an important design factor. Being able to predict dune dynamics allows for some cross-section optimizations by considering the thermal inertia of the cable, as it takes several days/weeks to reach the thermal threshold leading to internal damage.

5 CONCLUSION

Cable burial is necessary for protection against physical aggression events. The deeper the burial, the better the protection. However, increased burial depth can reduce the power transmission capacity of the cable due to a less effective heat dissipation through the environment. This study shows a simple methodology to perform a first estimation of both the recommended burial depth and the maximum thickness sediment layer that could pass over the cables in a marine dune region. The number of surveys could be reduced to two, considering only the initial and final ones. In the present study, this change would shorten the validity period of the numerical model. This could impact the estimation of the Maximum Seabed Level (which depends solely on the modelling) but would not cause significant differences in the estimation of the Lower Seabed Level, as the influence of the modelling is confined to the southern part of the study area. Despite this limitation, the LSBL estimation could therefore be conducted using fewer in-situ data, thereby reducing costs of such study.

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AUTHORS‘ CONTRIBUTIONS

N. Michelet : Software, Formal Analysis, Writting – Original Draft, Writting – Review & Editing **W. Chaabouni, F. Boukrouche :** Writting – Original Draft, Writting – Review & Editing **J. Charvet, S. Rochwerger, E. Arteaga :** Data Curation, Writting – Review & Editing **A. Lefebvre :** Supervision, Writting – Review & Editing

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