Estimation of marine dune migration using a three-dimensional numerical modelling

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ABSTRACT: A study using the dune Tracking method and based on bathymetric surveys performed over the Dunkirk future windfarm cable corridor area, show that dune migration is mostly eastward. However, during a month between March and April 2020, on the study area which comprise 6 dunes, 4 of the dunes move toward the west while two others follow the general eastward tendency. An estimation of the sediment fluxes using empirical formulation identify the influence of the current, waves and free-surface evolution and brings a first explanation on this inversion of migration direction. However, this study is made in 0D (calculations are made at a single point) and do not allow to understand the intra- or inter-dune variability as shown by the measured migration speeds. To overcome this limitation and start to investigate the dune migration, a fully non-linear three-dimensional numerical model was implemented using the CROCO modelling system, which included the sediment transport module developed by USGS. An idealized case was setup on a numerical domain covering the dune field (1000m x 500m) using bathymetric and sediment grain-size data as ground boundary and forced with idealized current and waves.

1 INTRODUCTION

In the next few years, an offshore wind farm (OWF) will be installed off the coast of Dunkirk on a large marine dune field. To ensure the safety criterium for the windfarm structures and to evaluate their impact on the seabed it is necessary to understand the dynamics of the underwater dunes. Eight bathymetric surveys were performed between November 2019 and July 2021 on a box located along the export cable corridor (Table 1). Morphometric parameters and migration rates was measured from the bathymetric data and the dynamic of these dunes was estimated through the associated sediment fluxes calculated using the Dune Tracking method (Bary et al., 2021). Results showed that the dunes migration is generally eastward and reaches up to several meters per month. However, between March and April 2020, based on the crest movements, most of them seem to have a westward propagation due to the presence of strong winds coming from the East-North-East. An estimation of sediment fluxes associated to the dune mobility was performed using a zero-dimensional (0D) model (Michelet et al., 2022). It brings a first explanation on this migration direction inversion by highlighting the major influence of the wave forcing. When there is no storm, the stronger flood currents than ebb currents result in an eastward dune migration. However, the synchronization of the low tide with the ebb current peak during some storm can generate a stronger current-wave bottom stress during the ebb period than during the flood. More sediment are thus mobilized and the bedload flux increases during the ebb compared to the flood, and results in an overall westward propagation. This calculation was however made in 0D and cannot explain the fact that during the same survey period, some dunes migrate eastwards and other westwards.

Table 1: Bathymetric surveys dates.

Survey name	Date
S1	16/11/2019
S2	17/03/2020
S3	16/04/2020
S4	31/08/2020
S5	05/12/2020
S6	22/01/2021
S7	27/05/2021
S8	03/07/2021

Using the second bathymetric survey (named S2) as the initial state of the bed, a three-dimensional simulation was setup with idealized forcing. The aim of the study is to understand the relative influence of the current and waves on the morphological changes and bring insight to understand the observed migration patterns.

2 DATA & METHOD

2.1 Study site

The numerical domain is based on an area (named B1) located off the Dunkirk coast along the windfarm export cable corridor (Figure 1). On this area, the bathymetric surveys show a dune field with, from west to east, two barchans, a sinuous one and three rectilinear dunes.

The area is macrotidal with a stronger maximum flood than ebb velocities (1.25 m/s against 0.75 m/s, Latapy, 2020). In term of wave forcing, the major part comes from the English Channel, from the west, while the other comes from the inside of the North Sea. Bonnefille et al. (1971) collected data and showed that the wave period is comprised between 5 and 12 s while the significant wave height is generally lower than 1.2 m and could reach 3 m during storm events (Latapy, 2020).

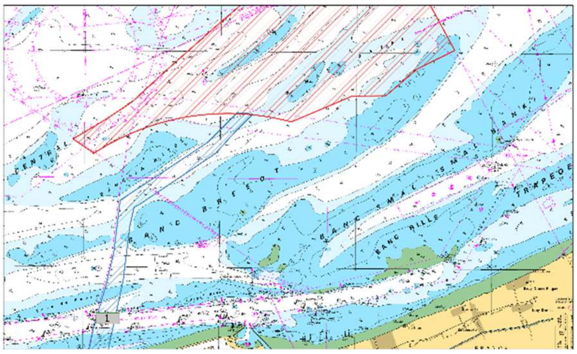

Figure 1. Location of Dunkirk windfarm area (red area) and the area of interest where bathymetric surveys were performed noted 1 on the figure.

2.2 CROCO model description

CROCO is a three-dimensional, free-surface numerical model that solves finite-difference approximation of the Reynolds-Averaged Navier Stokes (RANS) equation using the hydrostatic and Boussinesq approximations. The flow is assumed to be turbulent over a rough bottom allowing the existence of a logarithmic profile. The computation is performed using a C-Arakawa

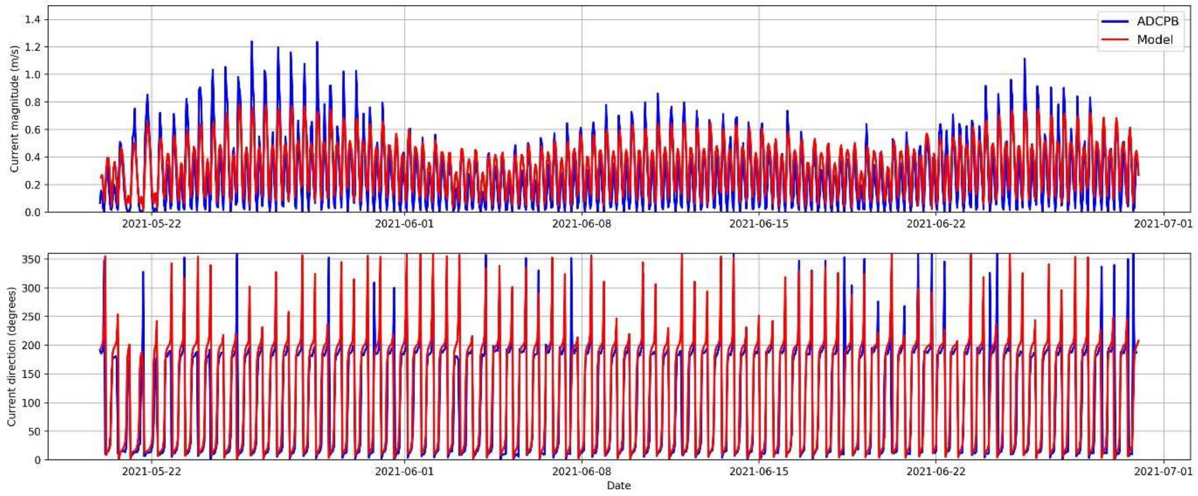

Figure 2. Current magnitude and direction comparison between regional simulation and Acoustic Doppler Current Profiler (ADCP) on B1 area.

grid over horizontal dimensions and a terrain following σ coordinate along the vertical dimension.

2.3 Sediment module

Like the water column, the sediment is represented as a constant number of layers that extend under the horizontal water cells (Warner et al., 2005). Each layer is initialized with a thickness, sediment-class distribution, porosity and age. The in-situ analysis showed that the sediment is homogeneous over the area so that a medium sand with $d_{50} = 328\ \mu m$ is considered in the class distribution. The porosity is also set constant (0.41). Since no suspended sediment is considered, the sediment age is left to 0 the default value. To initiate the morphodynamic study, only the bedload transport was considered. The formulation of Meyer-Peter Muller (1948) is used. Therefore, the bedload flux depends on the skin-friction component of bottom stress which is calculated with the maximum wave-current combined stress. The bed evolution is calculated using the Exner equation. Since the suspended sediment transport is not considered, no erosion or sedimentation is included in the equation which is then written as follow:

$$\frac{\partial z_b}{\partial t} = -\frac{f_{mor}}{1-p}\left(\frac{\partial q_b}{\partial x}\right) \qquad (1)$$

The height of the bed z_b is then function of the bedload flux q_b, the sediment porosity p and the morphological acceleration factor f_{mor}, here set to 10.

2.4 Model setup

Current and free-surface elevation were defined following the results of a preliminary regional simulation performed on an area covering the Eastern part of the English Channel and the southern part of the Northern Sea. This simulation was validated against tidal gauge (not shown here) and Acoustic Doppler Current Profilers data (ADCP). The mean averaged error for the barotropic current magnitude is 0.11 m/s (Figure 2).

Based on these results, an idealized mean spring tidal cycle were created accounting for the asymmetrical features regime in this area. The current direction was extracted at each peak and are respectively N70° and N250° during flood and ebb periods. In the same way, an idealised free-surface elevation was created which accounts for the synchronisation of the low tide with the ebb peak and the high tide with the flood peak (Figure 3).

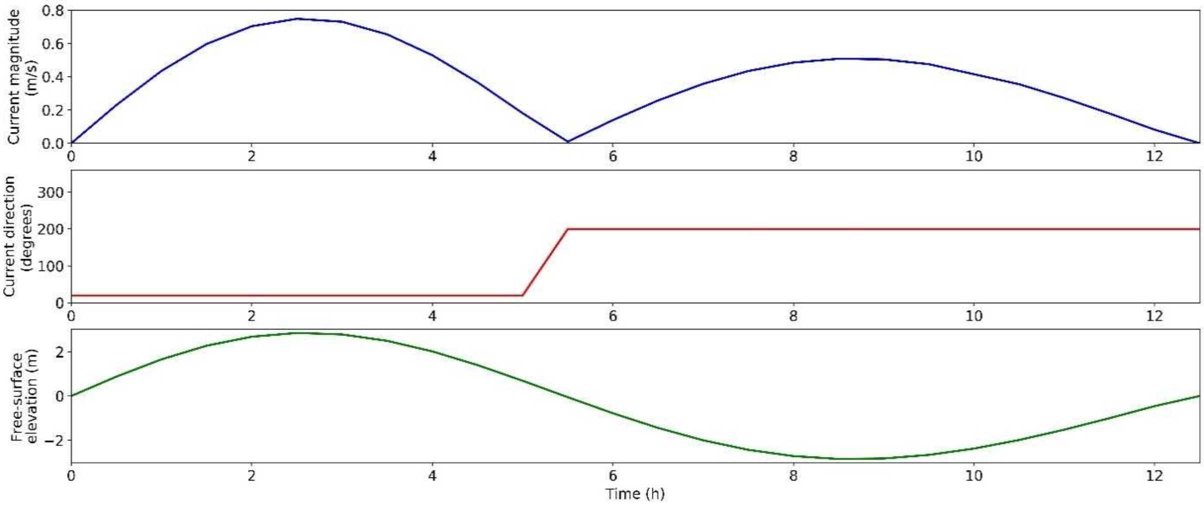

Figure 3. Current magnitude, current direction and free-surface elevation idealized forcing.

Two cases were setup and run over 4 days with a morphological acceleration factor of 10. In both cases current and free-surface elevation conditions described above are repeated in loop. On the Case 1, no wave forcing is accounting while on Case 2, constant wave conditions were considered and fixed to the maximum significant wave height observed during the period between S2 and S3 (Table 1). It is then fixed to Hs = 2 m with a peak period of Tp = 6 s. Wave direction is also set this way to come from the East-North-East (N33.75°).

3 RESULTS AND DISCUSSION

3.1 Effect of tidal currents

The following figure 4 represents the difference between the initial and final bathymetry after a simulation without waves. The current induces an important sediment transport over the dunes with the stronger bathymetric difference on the two barchans varying between 0.5 and 1 m depending on the position on the dune. This difference indicates that the stronger sediment transport is located over the higher dunes. Since the current forcing is the same over the entire area, these higher values are due to the dune morphology and especially to the shallow depth of their crests. The shallower the dune crest, the stronger the bathymetric variations. Indeed, the barchans have a mean height of 2.04 m and 1.95 m while the third dune is 1.61 m height. The variation of this last one is lower than those of the barchans with values comprised between 0.25 and 0.75 m. Variations are strongly reduced for the three rectilinear dunes located to the east in accordance with their mean heights of 1.08 m, 0.85 m and 0.69 m, from west to east respectively.

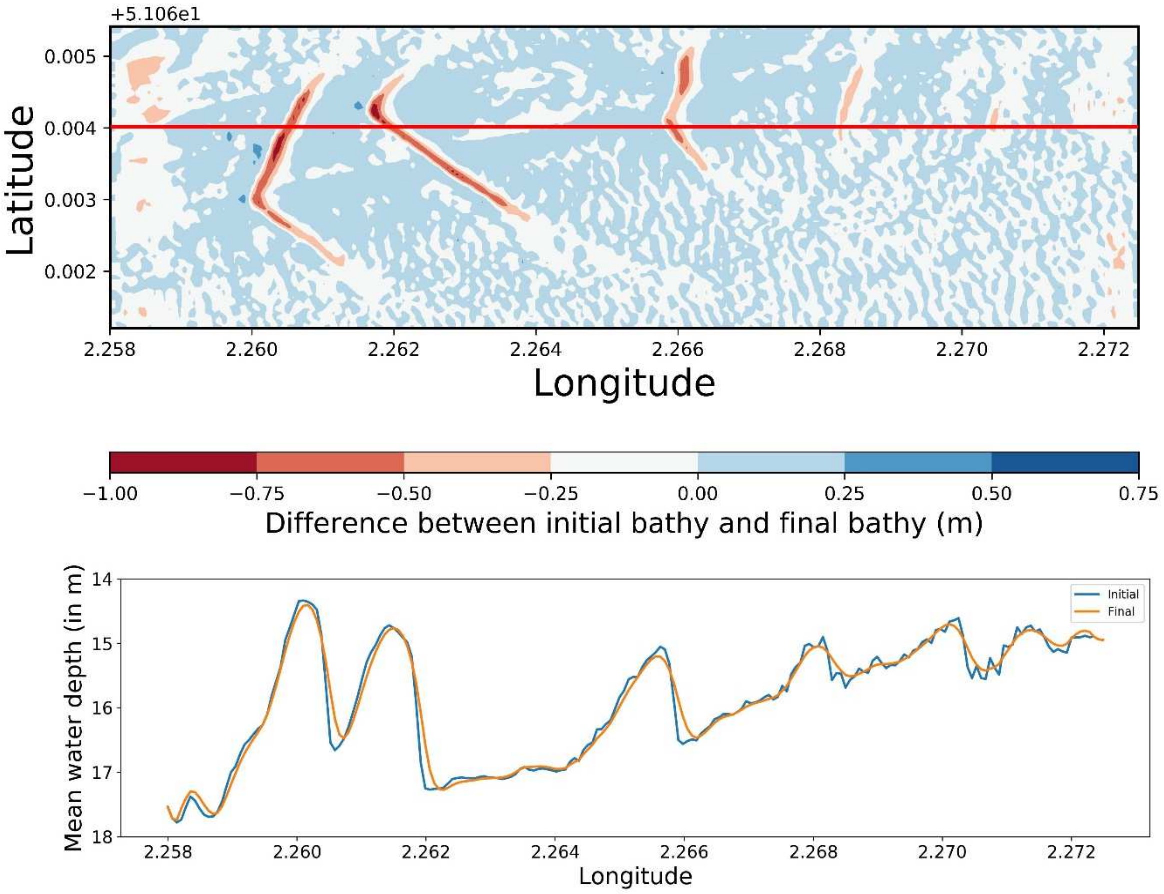

Figure 4: Top Difference between initial and final bathymetry for the case without wave forcing. The red line shows the location of the longitudinal profile displayed on the lower panel. Bottom. Initial (blue) and final (orange) longitudinal profiles from the case without wave forcing.

The lower panel of figure 4 represents the longitudinal profile of the initial and final bathymetry for the simulation without waves. The initial profile show that the six primary dunes are superimposed with smaller secondary dunes and ripples. These structures are smoothed by the model which does not consider their migration. It thus estimates a stronger erosion over the four dunes on the east compared to the 2 barchans on the west. This model does not consider the migration of these smaller structures and since their presence should favour the migration of the primary dunes (Idier et al., 2002), the influence of the current here might be underestimated.

The migration of the primary dunes is however in accordance with the forcing. The difference between the two profiles, shows that the highest bathymetric variations are located on the troughs and the crestal parts of the dunes. This movement is in accordance with the flood dominant current which then induce a sediments transport from the crests to the eastern troughs.

3.2 Effect of the waves

On Case 2, the forcings were tidal current and wave. This wave climate is homogeneous and constant over the whole period which means that its influence on the sediment transport is then related to the bathymetric differences. The combination of current-wave bed shear stress is naturally higher and then induce stronger sediment transport than in Case 1 with current alone. Le Bot & Trenteseaux (2004) have noted that the influence of strong waves formed by a storm can reduce, cancel, or even inverse dune migration direction. Here, the results are in accordance with their observation. The stress induced by the wave is stronger during the ebb period due to the synchronization with the low water level. The difference of bed shear stress between flood and ebb period is then weakened. Over the tidal cycle, the residual transport is then lower which could result in a migration reduction.

This influence is well represented over the second dune with an increase of its height. Indeed, as described by Tonnon et al. (2007), as long as the bedload transport is dominant, a symmetrical tidal current will result in the increase of the dune height. Here, the difference between the bed shear stress at ebb and flood current peaks is reduced but still slightly stronger during flood period. Therefore, the influence of this forcing is closer to a symmetrical tidal current. In could then explain that in Case 2 (contrary to Case 1) the second dune crest depth is reduced while at the same time its trough is moving eastward.

Over the two barchans on the west, the forcing induces either an increase of the dune height for the second dune or only a weak change of the crest for the first dune. However, on the following dunes, the most notable changes concern their morphology. In the case of the third dune, the difference between the initial and final bathymetry shows a reduction of the horizontal asymmetry of this dune. Its morphology adapts to the forcing and its crest is then moving toward the west while the eastern trough is following the general tendency.

This difference of migration direction between crests and troughs brings more insight on the migration inversion observed between surveys S2 and S3. Indeed, the Dune Tracking method was applied on a short period of 30 days (March – April 2020). The dune migration speed and direction were estimated following the difference of the crest's positions between these two surveys. However, during this period, the influence of a storm and the waves coming from the East-North-East could then induce a temporary reduction of its asymmetry or the movement of a secondary dune (at the crest) to the west. It could then let think that it is moving toward the west. Figure 5 also displays the migration direction of the crests and troughs. As we can see, all troughs are moving toward the east in accordance with what is expected. However, the crests of the dunes 3, 4 and 5 show an opposite movement. Here on the dune 4, the smoothing of the secondary dunes artificially moves the crest to the west but for dune 3 and 5, the westward movement of the sediment induce a clear reduction of the asymmetry.

By estimating the migration with the crest positions difference for the Dune Tracking, the results would then show an inter-dune variability with multiple dunes moving

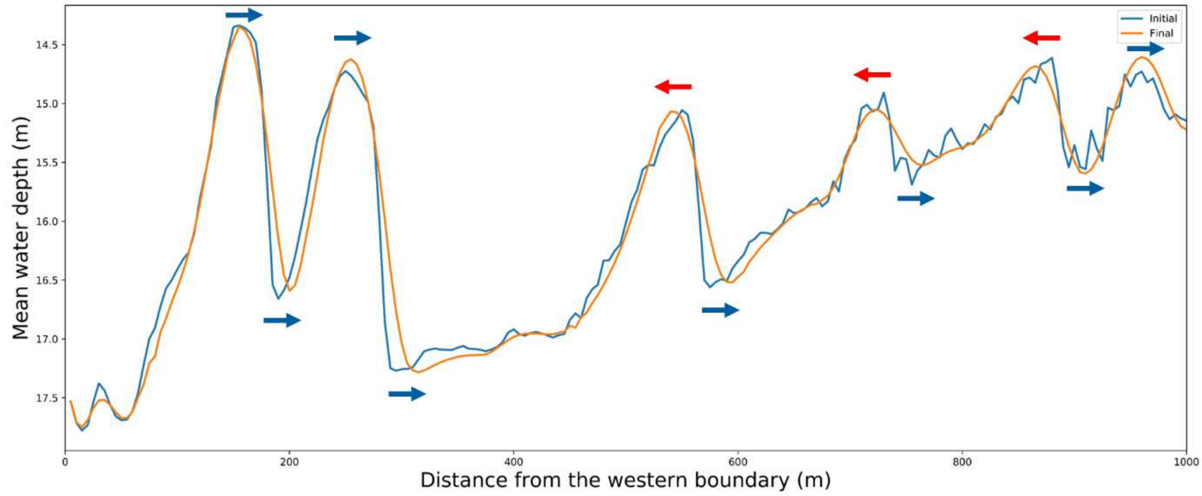

Figure 5. Initial and final longitudinal profiles from the case accounting the wave forcing along the red line displayed on the top panel of Figure 4. Blue and red arrows respectively show the eastern and western migration of the crests and troughs.

toward the west and some towards the east. However, over this short period, by only considering the crest position, it is difficult to assess if we are looking at the crest movement or the entire dune movement. In order to avoid this potential bias creating by dune crest movement, Ernstsen et al. (2006), recommend applying this method by considering the troughs positions. They also suggest to perform it on surveys conducted at similar times during the tidal period. That is because they saw some strong variations of the crest position during a tidal period. Our results show a modification of some dunes morphology which are created by wave activity. In this case, the influence of the waves is much stronger than in reality since it is considered constant during 4 days. However, it illustrates some modifications that could appears during a short period of time and should be considered when analysing bathymetric surveys.

This limitation on the estimation of the migrations parameters is however limited to small migration distances. For the other surveys that have shown movement of tens of meters for each dune, the movement of the crest or the change of its horizontal asymmetry would not induce any difference on the migration direction. Therefore, to make sure that the dune migration was affected between surveys S2 and S3, the migration speed and direction estimation used in the Dune Tracking method should also be performed on the trough. Moreover, it could be interesting to apply the method proposed by Knaapen (2005) which used either the movement of the crests and troughs to determine the dune migration. A comparison of the results of both methods would then give more information on the dune movement during this short period.

4 CONCLUSION

An idealized three-dimensional model including the morphodynamics was implemented to understand the migration direction observed between two bathymetric surveys performed off the Dunkirk coast. The bathymetry initialized in the model come from an in-situ survey (March 2020) while idealized hydrodynamic forcings were setup with and without waves. Two simulations were run with idealised boundary conditions, the first with the influence of the tides only, the second with tides and waves. On both simulations, the model smoothed the secondary dunes, and results can only be used to consider the primary dune morphodynamic.

Submitted to a (eastward) flood dominant current, all dunes follow an eastern migration. An erosion is predicted on the crest and deposition is observed at the foot of the dune steep side, in the trough, inducing its movement to the east. Sediment transport is stronger over the shallower crests than over the deeper ones. Including the influence of idealised waves (representing a storm impact) change this migration and equilibrate the bottom shear stress between flood and ebb periods. Some dune movement is then closer to morphodynamic observed in a symmetrical tidal environment. The height of the symmetrical dunes is increasing while the horizontal asymmetry is reduced for others.

These results show that the movement of a dune is then not homogeneous. The movement of the crest may not represent the migration of the whole dune. Indeed, beside its migration, a dune morphology could also change. In particular cases like between S2 and S3, the migration might then be misunderstood if only the displacement of the dune and not its morphological evolution is considered. A combination of the modification of the crests and troughs positions should then be applied to avoid accounting for short-term processes and/or morphology evolution in the study of the global migration of these forms. A perspective of this study would be then to estimate the migration speed and direction using this combination and a classical method and compare the different information that could be extracted using both.

5 ACKNOWLEDGEMENT

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