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Modelling the interaction of an offshore wind farm with a marine dune field: a case study in the southern North Sea

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ABSTRACT: By the end of 2020, around 5,400 offshore wind turbines had been installed or were under construction in European waters, and this number is set to rise steadily to meet net-zero energy targets. This study focuses on a 600 MW offshore wind project off the coast of Dunkirk in northern France, an area characterised by strong tidal currents and winds from the Atlantic Ocean and North Sea. The presence of marine dunes in the wind farm area is notable, with recurrent bathymetric surveys indicating dune migration rates of up to 30 metres per year.
A process-based numerical model was developed to examine the interactions between currents, winds, and sediment transport processes. The impact of the wind farm's fixed foundations on the dune field was studied over a two-year period. Situated in a complex environment, the wind farm is subject to spatial variations in flood and ebb flows, influenced by meteorological conditions, resulting in intricate sediment transport patterns and dune mobility. Turbines located in dynamic areas can influence regions more than a kilometre away, as their wake extends to adjacent turbines, which can have an impact on turbine siting strategies.

Keywords: marine dune; migration; fixed offshore wind turbine; wake effect; numerical modelling

1 INTRODUCTION

By the end of 2020, around 5,400 offshore wind turbines were either installed or under construction in European waters. As the number of offshore wind farms continues to grow to meet climate neutrality targets, it becomes increasingly important to understand how the fixed foundations of these wind turbines interact with their surroundings.

Marine dunes, also known as sand waves, are commonly found in the shallow shelf seas where offshore wind farms are located. These large, flow-transverse bedforms range from 1 to 5 metres in height and can span hundreds of metres in wavelength (Ashley, 1990). Notably, bedforms of this nature are highly mobile, migrating up to tens of metres per year (Knaapen, 2004).

Couldrey et al. (2020) observed that a crescent-shaped dune temporarily elongated as it passed a monopile, but this interaction did not result in lasting changes to the dune's morphology. Margalit (2017) suggested that monopiles can slow the migration of dunes. Further research is necessary to better understand the influence of monopiles on the marine dune fields they are installed in.

To address this, a process-based 3D model has been developed to simulate the migration of large marine dunes in the offshore area near Dunkirk, where a 600 MW wind farm project is in development. The study aims to investigate the impact of fixed foundations within a realistic layout consisting of 46 wind turbines (Durand et al. 2025b).

2 MATERIAL AND METHODS

2.1 Study area

Dunkirk, located near the French-Belgian border in the Southern Bight of the North Sea, was chosen for an offshore wind project due to its favourable conditions, including good wind resources, shallow water depths, and access to infrastructures (https://parc-eolien-en-mer-de-dunkerque.fr/presentation-du-projet). Comprehensive metocean and bathymetric surveys, over a 600-day period from November 2019 to July 2021, enabled a thorough characterisation of the site. The region is tidally dominated, with a spring tidal range of 5.5 m and peak flood currents of 1.25 m/s towards the northeast. The winds mainly come from the Channel, and from the North Sea in the spring. Bed levels less than 30 m below Mean Sea Level (MSL) extend up to 20 kilometres from the coastline. The seabed, primarily sandy (median sediment grain size d_{50} from 240 µm to 450 µm), supports marine dunes measuring 1-3 metres in height and 100-200 metres in length. These dunes migrate northeast at about 30 metres per year.

2.2 Numerical model set-up and validation

A three-dimensional coastal area model using the open**TELEMAC** system was developed to study the migration of this marine dune field over time. The TELEMAC-3D hydrodynamic module (Hervouet, 2007) was coupled with the GAIA sediment transport module (Tassi et al., 2023), focusing on tidal flows, weather, and bedload transport while excluding wave influence due to their secondary importance in water depths > 15 m MSL (Durand, 2024). The simulations are not accelerated with a morphological factor due to the non-linearity introduced by meteorological and other non-tidal processes.

The computational domain spans from Calais to Ostend, using a detailed unstructured mesh, discretised with triangular elements. The model is driven by tidal and meteorological inputs, calibrated and validated against site-specific field data. It effectively replicates marine dune migration (Durand et al., 2025a), providing valuable insights into coastal dynamics in the region.

2.3 Scenarios

To assess the impact of turbine fixed foundations on marine dune migration, a baseline simulation initially modelled natural hydrodynamic and sediment transport processes offshore Dunkirk without monopiles over a two-year period. This duration was chosen to be sufficiently long to provide meaningful results, yet short enough to be completed in a timely manner, considering that no acceleration factor was used. The simulation was then repeated, including an array of 46 monopiles within the projected footprint of the Dunkirk offshore wind farm (the most conservative project scenario). The turbines are located a minimum of 10 km from the coastline and spaced approximately 1 km apart (Figure 1). Additional scenarios with half the number of turbines were simulated to specifically investigate the implications of wind turbine placement.

The turbine fixed foundations are explicitly represented in the model by removing triangular elements from the computational mesh (one per monopile) as supported by Rivier et al. (2016). At the horizontal mesh resolution, this implies a monopile diameter of approximately 10 m, which aligns with the project technical specifications (diameter between 7 and 11.5 m).

3 RESULTS

3.1 Natural state

The baseline simulation reveals natural spatial variations in sediment transport patterns across the

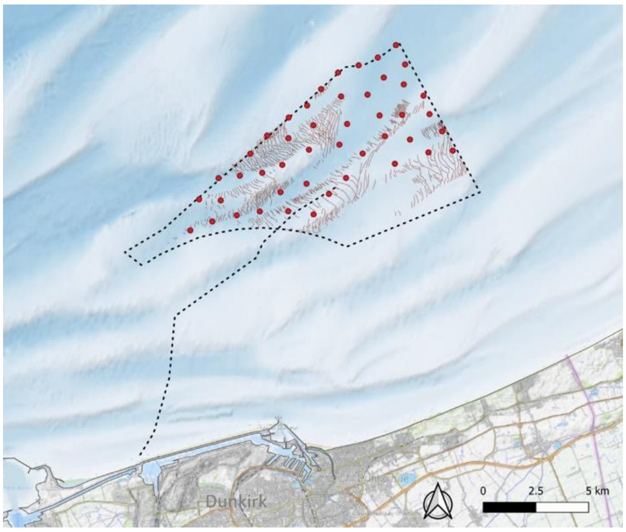

Figure 1. Proposed layout for the Dunkirk OWF, also showing marine dunes inventoried by Shom (2017) represented by sinuous brown lines.

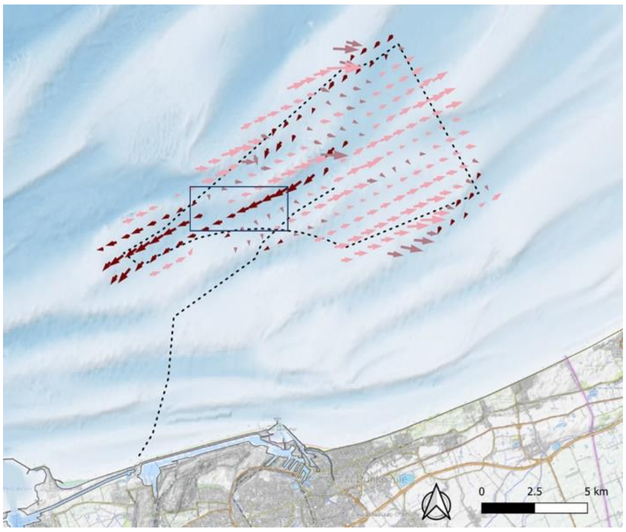

Figure 2. Predicted sediment transport in the natural state, coloured by directional quadrant for clarity, also showing the zone of interest as a rectangle.

offshore wind farm footprint (Figure 2). These variations are attributed to differences in tidal currents, influenced by wind conditions (Durand et al., 2025a), with bedload transport roughly proportional to the cube of the current speed. Figure 1 shows that dunes are not uniformly distributed throughout the offshore wind farm footprint. Durand et al. (2025b) identified three morphological behaviour zones: 1) in the gully between sandbanks, where marine dunes migrate southwest, contrary to the general trend, 2) on the slopes of the sandbanks, and 3) in a relatively flat and featureless area in the northern corner. In the following analysis, the focus is on the morphological zone outlined by a rectangle in Figure 2, located in a natural gully featuring marine dunes. The wind turbines there are aligned along the sediment transport pathway.

3.2 Influence of the fixed foundations

The effect of fixed foundation turbines on dune migration has been documented in Durand et al. (2025b) in a tidally dominated environment, with strong directionality of the currents. It was demonstrated that the monopiles act as morphodynamic magnets, causing the dune sections on the tidal axis to converge towards them. This is attributed to a velocity deficit, hence a sediment transport deficit, downcurrent for each phase of the tide (Figure 3), a mechanism referred to as the 'wake effect'. It follows that a wider tidal ellipse results in a more diffuse impact of the monopile, and the impact becomes less pronounced with increased distance from the monopile (Durand et al., 2025b).

This effect is illustrated in Figure 4 showing the predicted seabed changes two years after installing the array of turbines. The changes are calculated as the difference between seabed levels with the monopiles and without the monopiles (baseline simulation), highlighting the impact of the fixed foundations rather than natural migration. Shades of blue indicate a lowering of the seabed (erosion) compared to baseline, while shades of brown indicate a rising of the seabed (accretion), after two years. In general, light colours indicate minor changes. The colour scale is designed to emphasise changes in marine dune propagation. As such, local effects in the immediate vicinity of the monopiles may exceed these limits (to be considered with caution). It is important to note that the physical processes related to scour (e.g., Melville, 1988) require much finer horizontal and vertical resolution than what was used to model the large-scale migration of marine dunes. Therefore, scouring might not be adequately represented in this model.

While the spatial extent of the seabed changes stabilises after an initial period of 6 to 9 months (not shown), their magnitude increases over time. In the zone of interest, the wind turbines are placed in a gully between sandbanks. The currents are channelled and linear. The area is dynamic, and the rhythmic succession of erosion and accretion patterns demonstrates the impact on the marine dunes (Figure 4). The largest predicted variations in seabed level (on the tidal axis of monopile M2, beyond 4 pile diameters) are -2.5/+5.1 m west of M2 and -0.9/+2.6 m east of M2, for example, in the simulation with all the monopiles. Variations of this magnitude indicate a significant difference in dune positions with and without the monopiles, given that dunes in this area reach heights of 3 to 4 m. This difference is attributed to the deformation of the dune plan shape due to the 'wake effect'.

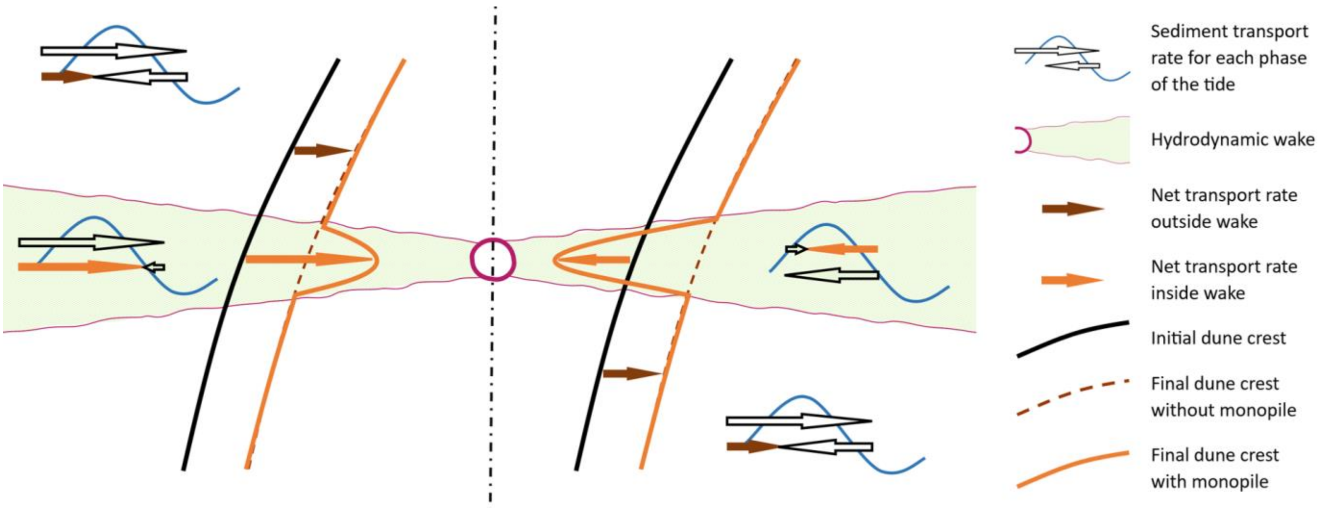

Figure 3. Schematic representation of the influence of a monopile on net sediment transport rates (filled arrows) and marine dune migration (lines). The predominant flow direction is from left to right (Durand et al., 2025b).

The influence of the monopiles extends over more than 1 km to adjacent wind turbines, as observed when only half the number of turbines is considered (see the 2nd and 3rd panels in Figure 4). These effects combine, with each monopile in the array pulling sections of the dunes towards them. This is most noticeable in the seabed changes around monopile M2 and southwest of monopile M4. An alternative scenario has been proposed for Dunkirk offshore wind project, contingent on the technology available at the time of implementation. Although this scenario was not modelled, it is anticipated that the larger turbine sizes, spaced further apart (approximately at a 1.4 ratio), may limit the impact, even though the monopiles remain aligned.

Validation is crucial in any modelling exercise to ensure accurate representation of the system and the processes controlling it. It is important to recognise that, in this case, it is not possible to compare the model predictions of seabed evolution with *in situ* data because construction has not yet begun. To the authors' knowledge, there are no known extensive and recurrent bathymetric surveys of existing offshore wind farms with similar environmental conditions (sandy seabed, water depths around 20 m MSL, linear currents up to 1.25 m/s) and technical characteristics (monopile foundations). Understandably, post-construction surveys primarily focus on potential risks, such as scour at the base of the foundation (Couldrey et al., 2020) and/or cable exposure or free spanning along the cable corridor. Additionally, some data are available to support current research efforts on the regeneration of partially dredged marine dunes (Larsen et al., 2019; Roulund et al., 2023). However, these surveys are limited in scope and do not provide information about the influence of fixed foundations on the propagation of marine dunes.

4 APPLICATION TO DESIGN

In the growing field of offshore wind energy, the strategic placement of turbines should consider not only energy efficiency but also environmental harmony. Wind turbine placement is the result of several considerations, including wind resource, geological / technical constraints, benthic habitats, infrastructure and cost.

The observed modifications in dune transport due to turbine installation necessitate careful consideration of sediment dynamics. Recognising and mitigating these changes is essential to maintain ecological balance and minimise disruption.

Moreover, the placement of turbines has been identified as an important factor influencing seabed dune movement. This insight is valuable for the design phase of offshore wind projects, as it highlights a crucial factor for sustainable development.

Additionally, considering the dunes' extra height resulting from the installation of turbines is critical in the design of cables. The cable's thermal resistance correlates with the thickness of sediment it is buried under, thus, integrating these data into the early stages of cable design is advisable.

By incorporating these findings into the design process as early as possible, a harmonious balance between energy generation and environmental stewardship can be achieved, ensuring that offshore wind farms are both efficient and sustainable.

5 CONCLUSIONS

The movement of the seabed offshore Dunkirk is dominated by marine dunes. Understanding these movements is crucial for the project and the Offshore Wind industry at large. Equally important is understanding how these movements change after the implementation of the wind farm. This study indicates that the fixed foundations of wind turbines can influence the propagation of marine dunes over distances ranging from several hundred metres to kilometres, primarily in the direction of the current.

The results presented in this paper are limited to a two-year period. Running long-term simulations for the entire life cycle of an offshore wind farm project is challenging with complex 3D models due to the extensive computational resources required and the reduced predictive capability over time. While the findings of this study contribute to understanding the interactions between monopiles and marine dunes, there is a need for efficient long-term forecasting strategies. Furthermore, the current lack of field data underscores the importance of continued monitoring post-construction to ensure the reliability of model predictions.

It is worth noting that while this research considered large-scale processes relevant for refining design seabed levels and assisting in cable laying, integrating knowledge gained from numerical and physical experiments at the scale of a single monopile would address further technical challenges related to scour protection measures.

Additionally, marine dunes are ecologically important areas that support unique marine life adapted to their mobility. More research is needed to

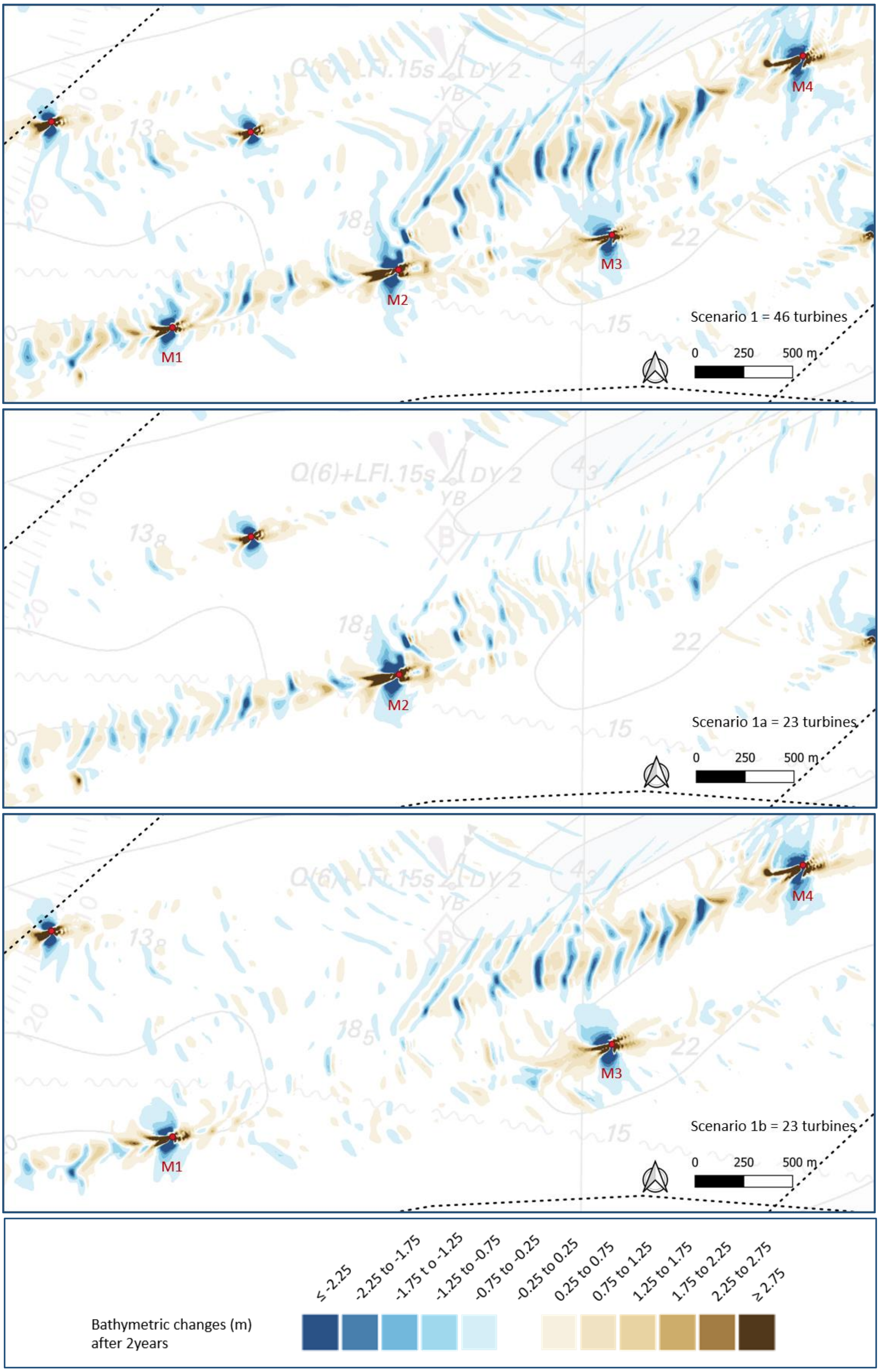

Figure 4. Predicted bathymetric changes two years after the implementation of wind turbines (foundations = filled red circles), calculated as the difference between model-predicted seabed levels and baseline levels (without monopiles), both after two years. (Source of the background data: Shom nautical chart 7214).

understand the ecological impacts of human activities, such as offshore wind farms, to minimise negative effects on marine life while promoting the transition to renewable energy.

AUTHOR CONTRIBUTION STATEMENT

Noémie Durand: Methodology, Software, Formal Analysis, Investigation, Visualization, Writing-Original draft. **Walid Chaabouni**: Writing- Original draft. **Pablo Tassi**: Supervision, Writing- Reviewing and Editing.

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