MORPHODUNES, a new project dedicated to the 3D morphodynamics of sub-marine sand dunes for safety and maritime activities.

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ABSTRACT: Here is presented a new project, MORPHODUNES, dealing with the sub-marine sand dune morphodynamics. It is funded by Shom (French Navy) to develop a fully-coupled 3D hydro-morphodynamic model able to simulate the dune migration over the continental shelf according to the metocean forcings, sediment characteristics and seabed morphology. The first part of the project is related to the physical modelling of an idealized and realistic field of dunes at laboratory scale. The laboratory measurements of the flow characteristics and bed topography will be used to validate and calibrate the hydro-morphodynamic model for some specific processes (e.g. sur-imposed bedforms and impacts). The second part of the project is devoted to the analysis of field data. These data are recorded by Shom in Iroise/Celtic sea, near the Brest harbour during the project. Sedimentary fluxes, bed morphology and thickness of the mobile zone, sediment response of the hydrodynamic condition swill be determined from this analysis. The third part is dedicated to the set-up, validation, and calibration of the hydro-morphodynamic model for the study site thanks to the in-situ data and their analysis. This work will be based on several diagnoses for hydrodynamics and morphodynamics (e. g. flow characteristics, wavelength and height of dunes, asymmetry index, crest sinuosity). At the end, the model should be as much as possible independent of the site conditions to be used to simulate dune morphodynamics in 3D at another location in the world for the marine safety and navigation.

1 INTRODUCTION

Tidal sand dunes are mostly present in tidal channels or mouths (e.g. Kostaschuk & Best, 2015) as well as over the continental shelf in areas with a moderate mean depth and a tidal current, which is constrained by the site geometry or channelized (e. g. Le Bot and Trenteseaux, 2004; Ferret et al., 2010).Their characteristics (e. g. wavelength, height, shape, sediment vertical sorting) depend on many factors, including tidal range and tidal prism, ocean wave energy, sediment grain size, and the amount of mobile sediment (e. g. Fitzgerald, 1996).

Due to the generation of tidal sand dunes by a well-directed tidal flow, their dynamics have been often modelled in two-dimension vertical (e. g. Doré et al., 2016, 2018). In areas where the current varies little in the water column, two-dimension horizontal modelling (e.g. Ma et al., 2019) is usually performed. However, some cases require to use three-dimensional (3D) modelling for hydrodynamics when the hydrodynamic forcing is 3D or/and the dune morphology is 3D. For the moment, very few studies have been published in a realistic environment for the 3D case.

A pioneer study was initiated by Goll et al., (2016) for river dunes. The hydrodynamic model Telemac3D was used in combination with the Sisyphe module for morphodynamics (Villaret et al., 2013). They have simulated the movement of a sand dune field forced by a 3D flow in the Elbe River (Germany).

A recent study by Herrling et al., (2021), using Delft3D, simulated idealized 3D scenario for the sand dune dynamics in the Weser Estuary (Germany). They highlighted the need to consider dune-induced directional bed roughness in numerical models of estuarine and tidal environments.

From our knowledge and to date, no study exists for the 3D modelling of realistic sand dune fields on the continental shelf. The MORPHODUNES project, presented here, is dedicated to this.

In this context, this paper aims to explain the methodology forseen in MORPHODUNES to answer the following scientific questions and then provide a fully-coupled 3D hydro-morphodynamic model to the scientific community:

- How do the 3D hydrodynamics drive sediment transport and impact the sand dune morphology?
- When should 3D rather than 2D hydrodynamics be considered?
- What is the impact of winter storms on tidal dune dynamics?

After a short introduction in Section 1, physical modelling activities are presented in Section 2. The study site and field measurements are described in Section 3. The numerical modelling part, through the presentation of the numerical models and the calibration, validation steps, is detailed in Section 4. A brief conclusion is provided in Section 5.

2 PHYSICAL MODELLING

At a first step, some laboratory experiments will be conducted to identify key processes and assess the capability of the hydro-sedimentary model to simulate the sand dune morphodynamics. A first set of experiments will focus on the hydrodynamics above fixed concrete dunes of variable surface roughness. A second set will deal with the morphodynamics of sediment dunes in live-bed conditions. The experimental set-up and test cases are presented below.

2.1 Experimental set-up

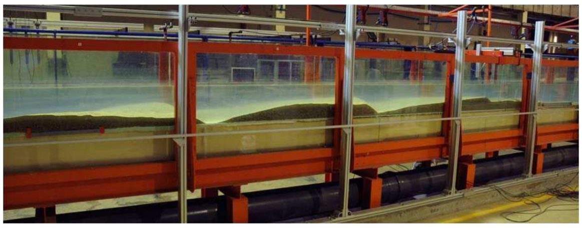

Figure 1. Wave-current flume of the University of Caen (M2C lab.)

The experiments will be conducted in a 16 m-long, 0.5 m-wide and 0.5 m-deep current flume, equipped with a centrifugal pump for water recirculation (Fig. 1). In order to ensure the uniformity of the flow, a honeycomb will be installed at the entrance of the flume, followed by a 1 m-long pebble bed to ensure the fast development of a turbulent boundary layer. For live-bed experiments, a sediment trap will be installed at the end of the flume to collect the bedload sediment, to be reloaded regularly upstream. The topography of the sediment bed will be surveyed every 15 minutes along 5 parallel longitudinal transects, using a laser distance-meter mounted on a carriage. The longitudinal profiles will then be interpolated to obtain maps of the bottom topography. Flow measurements under live-bed conditions will be monitored using the UBERTONE acoustic Doppler velocity profiles UB-Lab 2C. The probe will be placed downward-looking at a fixed position, with the dunes migrating underneath. It will provide two-dimensional flow velocity profiles (u,w) at a spatial resolution of 2-3 mm, and a sampling rate between 20 and 50 Hz. The suspended sediment concentration will be estimated from the intensity of the backscattered signal (Thorne and Hurther, 2014), after calibration with the appropriate sediment. The flow dynamics over the fixed concrete dunes will be investigated using PIV at a sampling frequency of 200 Hz.

2.2 Test cases

2-D fixed dunes (scaled in situ topography) will be built in smooth concrete panels. Local change of the micro roughness will be insured by rough bands (parallel to dune crests) of glued sand. Similitude scaling will be focused on reproducing the main flow features, including turbulence, at the seabed. Velocity profiles, vorticity and turbulence features will be quantified thanks to high frame rate PIV system. Spatial equivalent roughness will be then determined along the varying macro and micro morphology and will be correlated with the dynamic of the flow.

Experiments in live-bed conditions will be performed using a bimodal quartz sand. The dunes morphology will evolve naturally from an initial 10 cm-thick flat bed, under stationary flow conditions, until a dynamic equilibrium is reached. Several flow velocities will be tested within the field of stability of dunes, in order to quantify the dune morphology variability in response to hydrodynamic forcing. A qualitative analysis of segregation of the bi-modal sediment will be performed thanks to sidewall photographies and cross-sections.

3 STUDY SITE AND FIELD MEASUREMENTS

3.1 Study site

The study site is in the exit channel of the Bay of Brest in Iroise Sea (western-most part of Brittany, NW France; Fig. 2).

Tidal regime is semi-diurnal with macrotidal conditions (average tidal range of 4.7 m). Tidal currents are constrained by the bathymetry of channel and reach 2.3 m/s during the ebb (SW orientation) and 2 m/s during the flood (NE orientation). This part can be also dominated by the swell mostly during south-west storm events (Grégoire, 2016).

The study area consists in two fields of medium to large dunes, composed of gravelly shelly fine to coarse sands (Grégoire et al., 2016) for a total area of 2,3 km^2. The water depth is comprised between 25 and 40m (LAT). Bedload transport is important during spring tides (around 1.10-6 m^3/m/s) with residual fluxes oriented towards the W-SW, direction of the tidal ebb-dominated residual current (Grégoire et al., 2016). Dune migration rates are estimated from their asymmetry index (Xu et al., 2008) to be around 4-6 m/yr (Grégoire et al., 2016).

3.2 Field campaigns and future analysis

Bathymetric data are acquired since 2022 every one to two weeks to describe the dune short-term morphodynamics. Bathymetric DEMs and DODs will be produced. The data will be analyzed with GIS tools to quantify dune morphometric parameters and migration rates. Sediment fluxes will be estimated using empirical formulas for sediment transport (e.g. van Rijn, 1984), « dune tracking » formula (e.g. Simons et al., 1965; Schmitt and Mitchell, 2014) and through the quantification of displaced sediment volumes between two bathymetric surveys (e.g. Claude et al., 2012).

Grain-size and seismic data will allow to characterize dune sedimentary environment and analyze the internal architecture of dunes (erosion-deposition structures) and the thickness of the active layer. Acquisition of current velocity and wave data during the bathymetric monitoring will allow to try to put forward relations between hydrodynamics and dune morphodynamics.

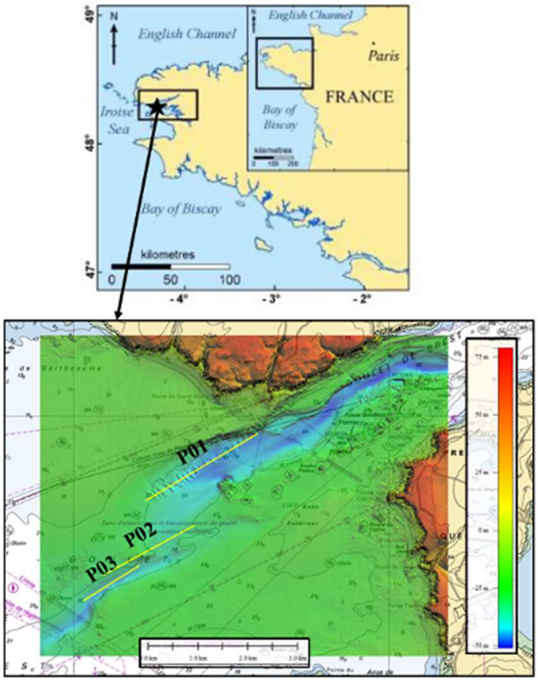

Figure 2. Location (top) and bathymetry (bottom) of the study area. P01 to P03 are the bathymetric profiles surveyed every 1 or 2 weeks.

4 NUMERICAL MODELLING

In this section, the fully-coupled 3D hydro-morphodynamic model is described through all its component models. Then, the methodology for improving, calibrating, and validating the coupled model thanks to the laboratory and in-situ measurements is presented.

4.1 Hydrodynamic model

This study uses the hydrodynamic model, CROCO, which is currently developed by IRD, Ifremer, INRIA, Shom and CNRS (https://www.croco-ocean.org). It solves the primitive equations of the ocean under the Boussinesq assumptions and with/without hydrostatic assumption. It computes the coastal dynamics at different scales in time and space. CROCO is also in capacity to simulate air-sea, sea-bottom and sea-ice interactions by its coupling with atmospheric, morphodynamic or ice numerical models (e.g. Pianezze et al., 2018). This coupling is managed by the automatic coupler OASIS (Valcke et al., 2015).

In a cartesian framework (x,y,z), the governing equations for horizontal momentums are:

$$\frac{\partial u}{\partial t} + \vec{\nabla}.\left(\vec{\mathbf{v}}u\right) - fv = -\frac{\partial \phi}{\partial x} + \mathcal{F}_u + \mathcal{D}_u$$

$$\frac{\partial v}{\partial t} + \vec{\nabla}.\left(\vec{\mathbf{v}}v\right) + fu = -\frac{\partial \phi}{\partial y} + \mathcal{F}_v + \mathcal{D}_v$$

and the continuity equation is:

$$\vec{\nabla}.\vec{\mathbf{v}} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

Where $\vec{\mathbf{v}}=(u,v,w)$ is the 3D flow velocity vector. The vertical velocity (w) is computed thanks to the continuity equation. f is the Coriolis parameter, $\mathcal{D}_u$ and $\mathcal{D}_v$ are the diffusive terms, $\mathcal{F}_u$ and $\mathcal{F}_v$ are the forcing terms, g is the gravity acceleration, ϕ is the dynamic pressure (more details about CROCO in Jullien et al., 2022).

The time-evolution of passive tracers (e.g. temperature, salinity) is governed by:

$$\frac{\partial C}{\partial t} + \vec{\nabla}.\left(\vec{\mathbf{v}}C\right) = \mathcal{F}_C + \mathcal{D}_C$$

where C is the tracer concentration. $\mathcal{F}_C$ and $\mathcal{D}_C$ are the source and diffuse terms, respectively.

The non-hydrostatic solver will be used in particular at local scale to simulate the flow separation downstream the dune crest.

CROCO will be coupled to WAVEWATCH-III (WAVEWATCH-III, 2019), a spectral wave model, and to MUSTANG (Le Hir et al., 2011), a sediment and morphodynamic module. This allows to understand how the sub-marine dunes move according to the metocean conditions.

4.2 Spectral wave model

The spectral wave model, WAVEWATCH-III, developed by NOAA/NCEP and Ifremer, is coupled to

CROCO to simulate the wave-induced circulation, changes in bottom friction and impacts on sediment transport.

This model computes the generation, propagation, and dissipation of ocean waves at the ocean surface for a phase-averaged flow. It solves the equation of conservation of the wave action (N) such that:

$$\frac{\mathrm{D}N}{\mathrm{D}t} = \frac{S}{\sigma}$$

where σ is the intrinsic wave frequency and S contains all the physics required to represent ocean wave behavior (more details in WAVEWATCH-III, 2019). Here, the most significant source terms will be those for wave-atmosphere interactions (particularly for studying storm effects on dune morphodynamics), wave breaking, wave-bottom interactions, scattering of waves by bottom features.

4.3 Sediment and morphodynamic model

The sediment and morphodynamic model, named MUSTANG and developed by Ifremer (e.g. Le Hir et al., 2011), is used here. It computes the sediment concentration in the water column, which is modulated by the hydrodynamic forcing. An update of the bottom morphology is done at each time step.

In a cartesian framework (x,y,z), it solves the advection-diffusion equation:

$$\frac{\partial C}{\partial t} + \nabla(\mathbf{u}\, C) = \frac{\partial}{\partial x}\left(D_H \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_H \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_V \frac{\partial C}{\partial z}\right) + \frac{\partial w_s C}{\partial z}$$

where C is the sediment concentration and w_s is the vertical settling velocity.

This module computes the erosion (E) and deposive (D) fluxes such that:

$$\begin{aligned} E &= E_0 \left(1 - \frac{\tau}{\tau_{ce}}\right)^n & \text{if } \tau > \tau_{ce} \\ &= 0 & \text{if } \tau < \tau_{ce} \end{aligned}$$

and

$$D = w_s C^b,$$

where τ is the bottom shear stress, τ_{ce} is the critical shear stress and n is a constant set to 1.5. C_b is the concentration at the bottom (calculated from a Rouse profile).

The bottom shear stress and the settling velocity are estimated using Soulsby and Whitehouse (1997) and Soulsby (1997).

This module is able to generate sand dunes and their movement as shown in Rivier et al. (2016).

4.4 Validation and calibration

The hydro-sedimentary model will be first tested against laboratory measurements for the test cases described in section 2. Then, the model will be used to simulate the dynamics at the study site scale.

4.4.1 Simulations at the laboratory scale

At this scale, two different versions of CROCO will be set-up, a non-hydrostatic and hydrostatic version. These versions allow us to represent different vertical hydrodynamics. For a strong vertical velocity, the vertical acceleration of the flow becomes non-negligible and therefore the hydrostatic assumption is broken. The turbulent activity will be parameterized with classical turbulent closures for RANS modelling (e.g. k-ε or k-ω). In addition, DNS simulations will be tested to try to simulate all the turbulent structures with a characteristic length-scale greater than the mesh size. Indeed, the turbulent activity near the bottom, particularly in the bottom boundary layer, is a key factor for the dune dynamics and it is therefore important to represent it as accurately as possible

For experiments using a rigid bottom, purely hydrodynamic simulations will be performed using only CROCO. Because of the water is mainly oriented towards the longitudinal direction, the model will be run in 2DV (two-dimension vertical). The bottom rugosities will be considered in the simulations by using parameterizations or they will be solved explicitly thanks to their integration in the bathymetry file.

For experiments using a mobile bed, MUSTANG will be coupled to CROCO. The bed load being the key process in the dune dynamics, it will be studied in-depth using the works of Rivier et al., 2017 and Mengual et Le Hir, 2018. 2DV and 3D (if necessary) simulations with CROCO-MUSTANG will be set-up and run for a bi-modal sediment.

Numerical results will be analyzed and compared to measurements for the flow velocity at different points (on and off the dunes), sea surface height, and near-bottom turbulence characteristics. In case of mobile bed, the time evolution of the bed, the bed thickness and the flow velocity near the bed will be also analyzed.

According to the comparison results, the model could be improved to represent significant processes like the near-bed turbulence and its impact on sediment transport, for example.

4.4.2 Simulations at the study site scale

Based on the previous work at the laboratory scale, a realistic configuration of CROCO-WWIII-MUSTANG will be set-up and applied to the dune fields located at the entrance of the Brest Harbour (Fig. 2).

The impact of the metocean forcings (e.g. tide, wind, wave) on the hydro-sedimentary environment will be assessed as well as the influence of the extreme events (e.g. winter storms) on the sediment transport. Different boundary fields from European and American databases (e.g. Copernicus or CFSR) will be tested.

Cross-comparisons with existing datasets (CANDHYS for waves, MAREL for sea water level or others) and with new data (e.g. flow velocity, bed topography, granulometry and sediment sorting) recorded during the project (more details in section 3) will be carried out to estimate the capability of the model to reproduce the dynamics induced by tide (e.g. flood and ebb flow, tide asymetry), ocean waves (e.g. Stokes drift, wave orbital velocity) and turbulence (e.g. horizontal and vertical mixing) and coupling effects (e.g. wave-induced current, wave-enhancement of the bottom stress). Then, tide, wave, turbulence and coupling effects on sediment transport and bed morphology will be assessed for: i) wavelength and height of dunes, ii) location of the dune crests, iii) dune asymmetry index, iv) length and slope of the dune sides, v) sinuosity of the dune crestline.

The main novelty here is to consider 3D computed hydrodynamics in interaction with a realistic 3D dune field. The modification of the flow in all the directions by the sand dunes could be simulated as well as the effects of 3D hydrodynamic processes.

5 CONCLUSIONS

In this project, thanks to an exceptional dataset, particularly for the bottom topography, we could be able to identify the driving mechanisms of the sand dune dynamics and their internal structure. Moreover, an innovative fully-coupled 3D hydro-morphodynamic model will be developed and assessed, which can be deployed in the future by the scientific community to study other sand dune fields around the world and preserve marine safety and navigation.

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