Dune dynamics: from field measurements to numerical modelling. Application to bathymetric survey frequency in the Calais-Dover Strait.

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INTRODUCTION

Submarine dunes, widespread on continental platforms, are known since the descriptions of Hider (1882). The knowledge on these sedimentary bodies is in constant progress thanks to the development in field survey methods - essentially acoustic like multibeam bathymetry and very high resolution seismic (Berné *et al*., 1988) - and in numerical modelling and theoretical studies (De Vriend, 1999 ; Hulscher, 1996 ; Blondeaux et al., 1999).

Dunes from the internal platform are in equilibrium with the present hydrodynamic regime (Berné, 1999). They are likely to migrate quickly as observed in the Southern North Sea by De Moor (1989) who recorded more than 150 m/yr. Although tide influence is documented, the processes responsible for dune displacements are not well understood.

These mobile features constitute obstructions for cable and pipeline networks and for navigation in shallow-marine environments. In France, the supervision of seaworthy zones is ensured by the Hydrographic and Oceanographic Service of the French Navy (SHOM) which performs regular surveys to detect the exact positions of dune crests. Among the supervised sectors, the Calais-Dover Strait is especially sensitive. A precise knowledge of dune dynamics would allow to optimize the survey frequency.

The final aim of this work is to improve our knowledge in the hydro-sedimentary processes responsible for dune migration in order to optimize the hydrographic surveys. Thanks to dune migration modelling, it would be possible to predict where and how dunes migrate. The following method is proposed: field studies will contribute to the design of a dune migration model.

In the field, only short (days) to long-term (few months) measurements, depending on the data type, can be realised. The collected data always correspond to a combination of all the mechanisms responsible for dune migration (eg several hydrodynamic agents acting at the same time). In that sense, field observations allow to display only hypotheses on the different processes and their quantification is not easy. Our field approach is essentially based on the definition of the hydrodynamic agents acting in dune displacements concerning their ability to mobilize sediment (in terms of dune migration rate and direction) and their time-scale.

There are different kinds of hydro-sedimentary models in tidal domain, but their aim is to calculate global sedimentary fluxes and not dune scale sedimentary structures evolution like dune migration. Indeed there is still lots of questions in short, medium or long term dune migration modelling, and the most appropriated model should include only the minimum complexity (De Vriend, 1999). Thus, to determine the most appropriated levels of dunes modelling complexity, we attempt to explore some physical and modelling questions.

In order to understand mechanisms of dune migration, we focalise the study on a dune field located in the Calais-Dover Strait (Southern North Sea) (figure 1).

I) FIELD RESULTS

a) Definition of the studied object and its environment

Sedimentary bedforms widely occur on continental platforms and especially on tide-swept dominated shallow marine environments (eg. Southern North Sea, figure 1a). This environment is characterized by tidal, wind-driven and wave-related currents, and show a complex pattern of water and sediment movement often seasonnaly dependant.

Subaqueous dunes are almost perpendicular to the major tidal axis. Their occurrence and evolution are controlled by numerous parameters: tidal current velocities, sand availability and sediment grain size (Stride, 1982), but also current asymetry and residual current characteristics (Allen, 1984). Dunes also interact with tidal currents

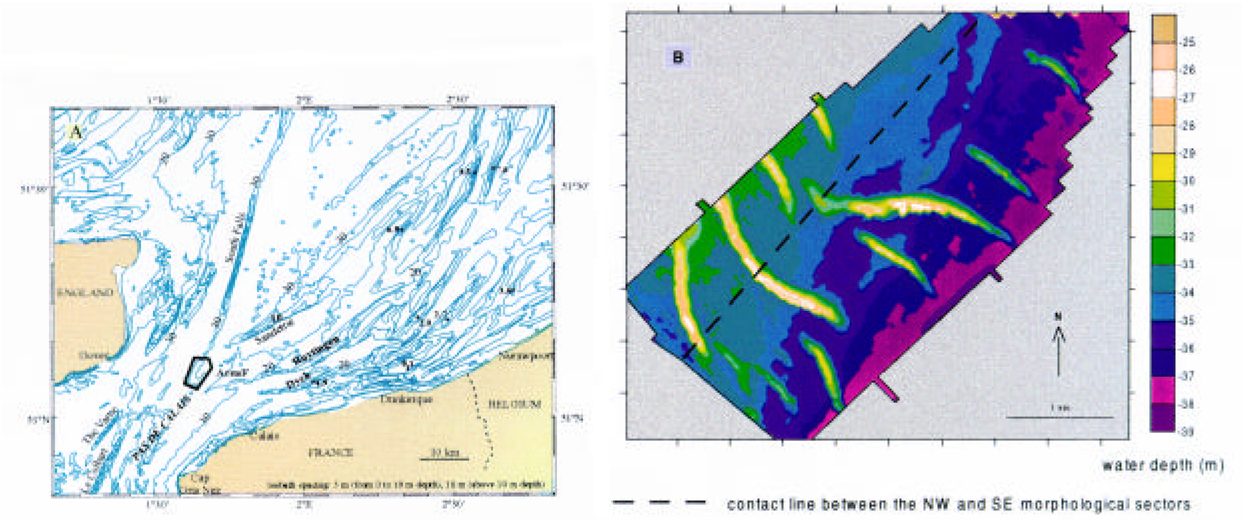

Figure 1. Bathymetric map of, a: the Southern North Sea and the Calais-Dover Strait (excerpt from map n° 6735, SHOM), and, b: the studied F area (1992)

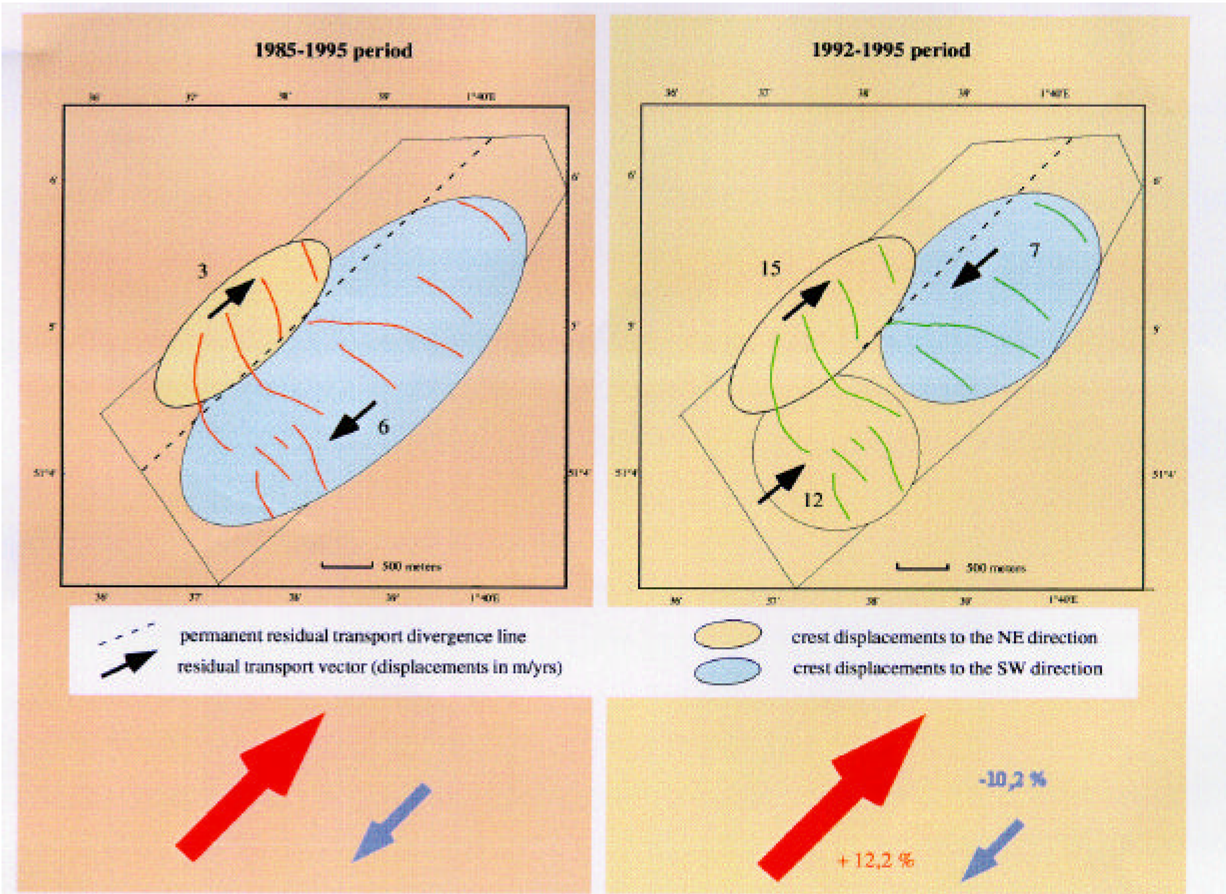

Figure 2. Migration scheme of dune crests from the studied area over, a: the1985-1995 period, and, b: the 1992-1995 period (after Herman, 1996). Corresponding frequency variations of SW winds (N200°-N220°) and NE winds (N20°-N40°) referenced to the 1985-1995 period.

(bathymetric effects). Malikides (1989) shows that flow over dunes is three-dimensional: a shift in flow direction between dune crest and trough is observed like over sandbanks. When dune slopes are large (more than 10°) and current asymetry is strong, the phenomena of separated flow appears (Allen, 1984).

According to Ashley (1990), dunes can be definde by heights and wave lengths respectively superior to 6 and 60 cm. These morphological parameters are interdependant: $H = 0{,}0677.L^{0{,}8098}$ (Flemming, 1988) and dependant of water depth (D): $H = 0{,}167.D$, $L = 6.D$ (Yalin, 1964).

The studied area is a dune field located in the central part of the Calais-Dover Strait where the South Falls and Sandettié sandbanks converge (figures 1a and b). The sea-floor gently slopes from 32 m (NW) to 39 m (SE) and is covered with large dunes which are organised in two morphologically contrasted sectors. NW dunes are oriented N150°, asymetric to the NE and present average height and wave length respectively of 7 m and 350 m ; SE dunes, oriented N120°and asymetric to the SW, are larger with average height and wave length of 10 m and 500 m. The boundary is underlined by symetric dunes and oriented N45° (figure 1b), which is the orientation of the major tidal axis. Dune steep slopes range from 1° to 35° (average about 10°).

b) Processes responsible for dune migration

In order to define the hydrodynamic agents responsible for dune migration, we study them at different time-scales (decennial, pluriannual and event scale). This allow us to analyse especially the effects of tides and storms (Le Bot et al., 2000).

Influence of tide and "long-term" dynamics

In the Calais-Dover Strait, formation and mobility of large dunes are essentially related to the periodic phenomena of tides. The strait is submitted to a semi-diurnal macrotidal regime. Tidal currents are very strong ; peak surface currents reach 105 cm/s and 185 cm/s respectively during neap and spring tides. They show a strong alternative character probably enhanced by the strait configuration. In the studied area, the ebb, oriented to the SW, is dominant compared to flood, flowing to the NE: ebb lasts one hour longer than flood, ebb peak velocities are superior to those of flood of 15 cm/s and 20 cm/s respectively during neap and spring tides.

Dunes are composed of a medium sand of 0.3 mm whose mobility threshold corresponds to a bottom friction velocity of 1,5 cm/s (Dyer, 1986). Using the von Karman-Prandtl equation, the corresponding sea-surface velocities range between 35 and 50 cm/s. Such velocities are reached during several hours of each ebb and flood tidal phases, for both neap and spring tides. In others words, dune sediment is quite permanently mobilised by tidal currents and preferentially by the SW oriented ebb.

Over a decade (example of the 1985-1995 period), dune migration imitates the tidal scheme (figure 2a). SE isolated dunes undergo the direct influence of the dominant ebb and show SW migrations at the rate of 1 to 12 m/yr. NW dunes migrate slowly in the opposite direction, i.e. NE, at an average rate of 3 m/yr. These dunes, which constitute the SW extreme prolongation of the South Falls sandbank, show the same morphological characteritics as those observed on this sandbank. They seem to be protected from ebb influence by the sandbank and preferentially react to the superimposed sand bank circulation (Kenyon et al., 1981 ; Smith, 1988).

Very high resolution seismic data (3.5 kHz) confirm these long-term sedimentary transport directions. They reveal internal reflectors sloping almost all to the SW in the SE sector and to the NE in the NW sector.

Influence of storm and "short-term" dynamics

During some storms crossing the Southern North Sea (septembre 1995 and 1999), winds and residual current characteristics show a direct and quasi synchronous correlation over the whole water column. NE winds strengthen the ebb dominant action to the SW. SW winds reduce it or inverse it to the NE according to wind velocity and tidal range (i.e. current velocities). As well, at the "storm event" time-scale, in shallow marine environments, winds are able to strongly modify the water circulation related to tidal currents over all the water column and affect the sedimentary transport characteristics. Heathershaw (1982) noticed a persistant modification of the residual current direction on the sea-bed until 20 days after a storm.

Seismic data reveal sporadic irregularities in dune construction. In some dune sections, sub-horizontal reflectors truncate the seismic units located beneath, and are, sometimes, followed by a dune rebuilding in the opposite direction (figure 3). An estimation of the eroded volumes displays amounts of sediment (about 100 m^3/linear meter of dune) that are too large to be transported only by tidal currents. Only high energetic processes such as storms or strong winds are able to induce a major current inversion and to modify the sedimentary transport so far as to erode dune crests and reverse the dune progradation sense.

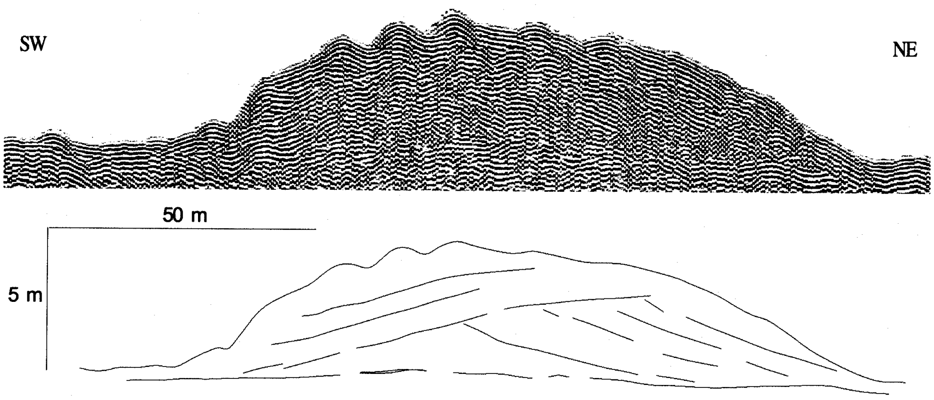

Figure 3. Dune internal structure from the studied area showing the impact of an instantaneous high-energetic erosive event, like a storm (a seismic transversal profile and its interpretation).

Influence of winds and " medium-term " dynamics

At a pluriannual time-scale (example of the 1992-1995 period), dune dynamics is different from the one observed on the "long-term " (figure 2b). The tide only cannot explain the residual sedimentary transport scheme. Frequent occurrence of strong winds, especially in preferential directions (i.e. ebb and flood directions) conduct to residual sand transport modifications by strengthening, slowlying or even reversing tidal current action. Harris (1991) and Thauront *et al.* (1996) suggests wind-induced seasonnal modifications of currents which conduct to asymetry inversion of large dunes.

In the studied area, the morphological boundary (see I-a) coincides with the permanent divergence line of the sedimentary residual transport (see figure 2). The presence of large sedimentary bodies (eg sandbanks) in the surrounding of dune fields, so, generate bathymetric effects on the tidal wave propagation which have to be taken into account.

In shallow-marine environments, dune morphodynamics strongly depends on the hydrodynamic context. It essentially results from the interplay between tide and strong winds. According to the considered time-scale, the one or the other influence prevails.

II) MODELLING

Problems of modelling

From a general point of view, the principle of hydro-sedimentary modelling (De Vriend, 1987) is based on : an hydrodynamic model coupled with a sedimentary model using a transport formula (bed or/and suspended load). There are several kinds of hydrodynamic models (2DH depth integrated, fully 3D, 2DH depth integrated + 1D vertical model) which describe effects of tides, surface waves, wind stresses. In the same way, several kinds of sediment transport parametrization could be used in sedimentary models (empirical, statistical, etc) which describe bed load or suspended sediment transport, and which take into account the effect of surface wave or not, of bed-form slope, etc. Among these models, the most refined would not always be the better. It follows the concept of appropriate modelling and predictability cascade (De Vriend, 1999) : the most appropriate will be as complicated as necessary, and as simple as possible. An important key of this problem is the modelling of interactions between processes. Indeed, enough accurate processes models computed together are not sufficient to describe well bed-hydrodynamic interactions, and so dune migration (De Vriend, 1987). In this paper, we attempt to explore several physical and modelling questions.

A nominal system : dune - tide

Although the experimental results suggest that the system is not purely a " dune – tide " system, but a system characterised also by local effects (wind, surface wave, pressure, etc), we could first consider that the interactions between tidal currents and dunes constitutes a kind of nominal system which could be studied through modelling. This nominal case could be basic in a first stage and use only bed-load transport. Indeed, several stability studies using bed-load transport only succeed in predicting dunes generation (Hulscher, 1996). This transport mode could be, so, sufficient in first stage of this work. In the description of the interactions between a dune and the flow stands the fundamental question of the kind of flow responsible for this migration : 2D or 3D. According to field studies (see I-a), already existing dunes show 3D bathymetric effects on the spatial distribution of tidal currents : flow separation and shift in flow direction. In term of dune migration modelling, is it necessary to describe these phenomena ? Some authors (Hulscher et al., 1993 ; Hulscher, 1996 ; Komarova et al., 1998 ; Blondeaux et al., 1999) show that a 3D described flow is necessary to model the generation of sand wave. But is the 3D description necessary for modelling migration of already existing dunes ?

Modelling of relative local effects highlighted by field experiments

Then the problem is to determine the relative effect and scales of each factors of migration. The field study put forward some hypothesis, and we attempt to explore these, thanks to simplified models in order to distinguish the different processes.

First, concerning the hypothesis of the local spatial effects (bathymetric effect on tidal currents), the influence of the South Falls and Sandettié sand banks could be explored through simplified bottom topography : two bathymetric singularities on a flat bed (figure 4). This study will highlight the characteristics of circulations due to these bathymetric singularities which could explain opposite sand wave migration in the studied area. Such kind of study would concern only the nominal system " dune – tide ".

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Figure 4. Residual currents due to sand banks. The directions of residual circulations are based on Smith (1988), Kelf and Hart (1998), Kenyon et al. (1981).

Storm constitutes a local temporal effect on dune migration as its influence lasts over a short period. Two aspects could be studied through modelling: the storm acts through wind waves and wind shear stresses and is linked to extreme water levels. Which of these processes are most important in dune migration? What is the relative influence of storm superimposed on tidal currents, compared to the effect of tidal currents alone (nominal system) ? In this way, we could determine the threshold (between storm strength and tide) above which the effect of storm is not anymore negligible.

Short- and long-term modelling

At last, the aim of this project is to build a modelling method able to predict dune migration, and so to optimise the hydrographic surveys. The morphological time-scale is much larger than the hydrodynamic one. So, describing all the processes would be too time consuming and it is necessary to use or to create specific long-term methods which give bathymetric evolutions over years. Indeed, there are some informations that this kind of model can not provide, like dune positions just after an exceptional storm for instance. So, two types of models could be necessary and, in these two models, no doubt that we do not have to take into account neither the same processes (storms, tidal currents, surface waves ...), nor in the same way. Several techniques exists to reduce computer, but all of these techniques have some limits time (Latteux, 1995 ; Latteux et al., 1998).So we must check if some of these techniques allow the description of long-term migration dunes in a tidal environment like the Dover Strait.

III) APPLICATION TO BATHYMETRIC SURVEYS

The final aim of this work is to provide a tool for navigation security in shallow-marine environment. The dune migration modelling we propose would allow to predict the spatial and temporal resolution needed for bathymetric surveys (figure 5). Here, it is only a scheme of the informations we want to obtain thanks to modelling. It doesn't foresee the feasibility out of.

Figure 5. Modelling application to hydrographic survey.

First, a critical migration threshold should be defined above which a marine map has to be redrawn. The modelling would give the time at which dune migration would exceed the critical treshold (see A and C) and would require a bathymetric survey. In case of exceptional meteorological event, the short-term model computation would give the corresponding migration (see B) which would be integrated in the following long-term computation (see C).

Furthermore, it would be interesting to compare (every year for instance) the meteorological data (i.e. wind and wave data) used in the long-term computation to the real data. In case of important differences, the long-term model should be run with the real meterological spectrum, and if the differences of dune migration between these both computations are too important, then the last results with real spectrum have to be taken into account.

CONCLUSION

The combination of field results and modelling is a good methodology to improve knowledge in dune migration. The field study allow to exhibit hypotheses on the governing processes and may contribute to the design of a model which would allow to predict dune migration.

In shallow-marine environments, and in particular in the Calais-Dover Strait, dune migration scheme depends on the relative predominance of some hydrodynamic agents varying either in time or in space : on the short-term, storms modify the tidal signature of dune migration scheme observed on the long-term ; the bathymetric singularities (dunes themselves, sand banks, slopes) spatially control dune migration via the current refraction.

For modelling purposes, today, there is no available morpho-sedimentary model able to predict the migration of already existing dunes. Our approach will be, so, progressive. First, we will attempt to reproduce dune migration in simple cases taking into account bed-load transport and tidal currents. Storm effects (surface waves, shear stresses…) could be explored on such simple cases. The ability of long-term techniques to describe long-term dune migration will be checked. The problem consists, so, in the selection of the processes to describe and the way to integrate them, with regard to chosen prediction time-scales .

As a final and applied aim, the modelling would constitute a good tool for navigation security in shallow-marine environments. It would contribute to the optimization of the spatial and temporal resolution needed for bathymetric surveys.

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