French marine sand dune project

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ABSTRACT: The objective of the work on sand dune dynamics, conducted by SHOM, is to predict the evolution of the morphology of the seafloor and to precisely determine the optimum recurrence for re-surveying. Attention focuses on the North Sea since the combination of frequent passages by super tankers and the presence of mobile dunes represents a serious threat for navigation safety. In 1998, a depth profile established during a survey by the Atlantic Hydrographic Mission on its way out and back to its base showed that while horizontal dune displacements in this area were undetectable in a one-week time interval and rather low over a period of 11 years (a few decimeters), by contrast vertical variations were quite sizeable. Depth variation had varied by one meter, that is a 15% deviation in a dune height in only one week. Therefore, a 10-year surveying strategy to measure the dynamics of such dunes is not optimum and to measure the most shallow sounding, the characteristics of the dune and the hydrodynamic conditions which prevailed before surveying must be taken into account.

1 INTRODUCTION

In sedimentary dynamics, weather and climate have a decisive role. Studying sand dunes should not be limited to instantaneous processes such as swell and tides but should also integrate event-related processes (storms). Thanks to the high resolution of multi-beam echo sounders, it has been possible to increase navigation safety. However the question is for how long (how many week, months or years) can the morphology of a dune be estimated as in conformity with the hydrographic survey? Is it possible to predict the evolution of bottom morphology or at least define the desirable frequency for survey recurrence so that nautical charts remain reliable? Can new dunes emerge between two successive hydrographic soundings? If so, for how long can we have the guarantee that no new dune will appear?

2 AN ASSESSMENT OF THE PRESENT KNOWLEDGE

Over a hundred researchers from some twenty countries participated in the «Workshops Marine Sandwave Dynamics» which took place in Lille (MSD2000) and Twente in the Netherlands (MARID2004). Lectures described case studies, parameterizing of structures, sea and river dune modeling using analytical, digital or physical techniques.

Issues concerning the structures and phenomena to be modeled are still at an early stage. What is the impact of grain size?, of depth? How do dunes and currents interact? Without answering all these questions, the two workshops were useful to further refine the knowledge and compare problems and progress in the various fields from acquisition to modeling. Why are we only at such an elementary stage in the domain of sub-aqueous sand dune modeling? First, because the localization of sedimentary structures on the sea floor until the eighties was not precise enough to enable scientists to measure displacements of the order of one meter or one to several decimeters. A second reason is that the data and studies on dunes were, and remain, still too scarce for realistic modeling to be feasible. As Stolk (2000) said "On the migration of sandwaves only a few datasets are available".

As far as observations were concerned, Le Bot and al. (2000) observe that gravel in the North Sea dunes are mobilized for several hours at each phase of tidal currents and that the currents generated by medium strength winds and storms modify the asymmetry of tidal currents to the extent they can reverse currents and the direction of dune progress. As remarked by Schüttenhelm (2000): "Sand waves in the southern North Sea are an enigmatic result of a dynamic equilibrium between sand, tidal currents and wave energy." and Mosher and al (2000) add: "The stability of the dune field remains unanswered. Repetitive multibeam bathymetric surveys and long term current flow monitoring are required to answer this question." For many authors, the sedimentary dynamics of dunes and their modeling are complex because they are poorly defined. Powell and al (2000) consider that "The formation and disappearance of sediment bedforms occurring under the action of waves and currents is the result of a complex interaction between the fluid and the underlying sediment; this is poorly understood, yet extremely important, in both physical and numerical models of coastal processes. Bedforms affect bottom roughness and shear stresses, wave attenuation, and sediment transport". Many questions remain unresolved "What are the physical mechanisms causing sand waves in shallow shelf seas to migrate and at what rate?". Thus these workshops emphasize the deficit of data and the limits of studies which are too local and instantaneous.

In 2001, SHOM conducted a survey for monitoring bottom morphology and variations in near-bottom current measurements in the Straits of Dover. This survey showed that the dune short term dynamics can be directly related to the dynamics of small superimposed structures. The displacement velocities recorded, fast for superimposed structures and slow for the dune, indicate that high resolution recurrent surveys are not the best answer to improve hydrographic knowledge. In order to warn navigators against dangerous shoal waters, it would be necessary to measure the surface area occupied by a dune and its peak envelope, and above all to keep a historical record of the dune and hydrodynamic conditions it was submitted to just before the hydrographic survey so as to determine its historical high point, modeling being used to calculate its theoretical height.

3 DUNE FORMATION AND CLASSIFICATION

In order to characterize the dynamics of dunes, high-quality long-term data must be available on the velocity and direction of migration, crest shape and evolution, and grain size of the sediments. Because of the lack of data on dune formation and development, dune formation time is obtained by modeling. Such dune formation models (Blondeaux and al. MSD2000), still do not provide relevant results in complex sectors such as the North Sea (Idier, 2002).

Dunes are sedimentary ripples, often periodical, featuring a crest, a gentle slope and a steep slope. The orientation of their crests is generally perpendicular to the main direction of currents, but angular variations reaching up to 20° are frequently observed (Le Bot, 2001). When the current cannot set in motion all sedimentary particles or when there is a sand deficit, dunes are barchanoid-shaped, whereas they have a linear shape when the current is saturated with sediments. By their shape, dunes therefore reflect hydrodynamic conditions.

Ripples, which are structures of some centimeters having the same shape as dunes, are ubiquitous. Lenôtre (1977) observes that ripples photographed in the ocean, at a depth of 7,535 m, are identical to ripples observed on the foreshore. The ubiquity of dunes is established, they exist from rivers to the basis of the continental slope and in deserts and similar shapes seem detectable in deep ocean environment and on Mars

4 DUNE SHAPE, NATURE AND MOVEMENTS

According to several authors, dunes with linear crest have the slowest migration velocity. On the other hand, barchanoid dunes are characterized by high velocities, and can reach an annual mean displacement of 70m/year (Berné and al (1989). Dune shape is strongly correlated to their nature. Flemming (2000) gives, for medium grain sediments D, the characteristic values of dune Maximum Height (H_{max}) and wavelength (λ). For instance, for very fine sediments, D = 0.063 mm, $H_{max} \approx 0.028$ m and $\lambda \approx 0.14$ m; whereas for coarse sediments with D = 0.5 mm, $H_{max} \approx 24.0$ m and $\lambda \approx$ 380 m.

The compilation of the descriptive parameters of 1,500 dunes from various environments in every seas of the world, enabled Flemming to establish a continuous statistical model ranging from ripples to giant dunes, with the following characteristics:

- Dune height comprised between 0.001 and 20 meters,
- Wavelength ranging from 0.01-1000 m
- The equation of the height of dunes with respect to their spacing $H_{mean} = 0.0677\ \lambda^{0.8098}$
- The equation of the maximum height of dunes is $H_{Max} = 0.16\ \lambda^{0.84}$

However, as indicated by Bartholdy and al. (2004), the mere existence of superimposed dunes contradicts the dune size – depth relation also proposed by Flemming.

The classification proposed by Ashley (1990), widely accepted today (see Table), concerns the sand structures generated by unidirectional currents, bidirectional currents and the combination of both. Dunes are defined by their wavelength. The H_{mean} of the Flemming diagram allows obtaining the height of the corresponding dunes.

Such models constitute a very important basis for digital modeling. But Flemming has observed that four repetitive surveys performed along the coasts of South Africa, yielded different H/L models according to hydrodynamic conditions.

Classes	Wavelength (λ)	Height calculated with H_{mean}
Small dunes	0.6 m < λ < 5 m	0.075 m<H<0.4 m
Medium dunes	5 m < λ < 10 m	0.4 m < H <0.75 m
Large dunes	10 m< λ < 100 m	0.75m< H < 5 m
Very large dunes	λ > 100 m	H>5 m

Up to about 1995, dune studies, due to technological limitations, dealt only with large and giant dunes. With the resolution of the MES it is now possible to map medium size dunes with accuracy and to trace their evolution. This generated many recent studies on these small structures and their detection (Kleinhans and al; Idier and Astruc in MARID2004).

5 THE NATURE OF SAND DUNES

Our analyses of North Sea dune sediments show grain sizes which are rarely homogenous on a dune scale. In this regard, the following examples are taken from the presentations of the Lille and Twente workshops:

- On the sand dunes of the North Sea, the stronger currents in the vicinity of the crest generally yield coarser and better sorted sediments, but this becomes more complex in the presence of megaripples superimposed on the dune (Flemming, 2000)
- Ernsten et al. (2004) note that barchanoid dunes exhibit coarse sediments and a maximum height in their centers whereas on their sides the grain sizes and the height of the dune decrease.
- Kleinhans et al (2004) indicate that the relationship between the grain size and the dimension of sand structures can be observed even for small dunes such as hummocks.
- Passchier et Kleinhans (2004) show that the bioturbation of the Lanice conchilega polychete may be the cause of the decreasing grain size in the surface sediment and non-uniform grading, lowering down the size of sand structures with respect to neighboring sectors without such worm tubes.
- Bartholdy et al (2004), for medium to large dunes, superimposed on large and very large dunes near Denmark, establish a relationship between the height and wavelength of superimposed dunes as a function of the mean grain size (H: depth (m), MG: mean grain diameter (Phi unit), λ: wavelength (m)): H = 0.17 MG1,68 and λ = 7.90 MG0,68.

6 DUNE DISPLACEMENT

In a desert environment, barchan dunes migrate by only a few meters per year, but their shape may change within days after a storm, and ripples may appear within hours (Michaut, 2003). Similar observations are made in a maritime environment, but, because of the variability of hydrodynamic factors, there are no general data or statistical laws on the displacement velocity of sedimentary structures. However, the knowledge of near-bottom velocities is essential in order to validate digital models. Velocity integrates the depth, the slope, the nature of sediments and the hydrodynamic factors (tidal currents and waves). Bibliographic syntheses such as the synthesis carried out by Wever (2004), come up against difficulties: having all the parameters at the origin of displacement at one's disposal is not easy and the number of publications on displacements is small. In addition, it appears that dune displacements vary in the course of time. Thus Le Bot (2001) observes, for a series of dunes in the North Sea that the average annual displacement is 7 m, 17 m and 472 m when the time intervals between surveys is respectively 10 years, 1 year and 7 days. Therefore, the shorter the time interval between mapping surveys, the more intense the dynamics appear to be. At the present time no robust formulation of dune dynamics is available. The annual rate of displacement of a dune based on hydrographic surveys spaced out in time can then mask movements having bigger amplitude.

Le Bot et al. (2001) explain this phenomenon by an analysis of environmental variations:

- on a scale of several months to several years, migration varies as a function of storms and to a lesser degree as a function of average winds. Both factors strengthen, slow or reverse migrations of tidal origin;
- on a decade scale, the migration controlled by a residual tidal current is constant. This is due to the periodicity of 8 to 11 years of the number of the relatively stable number of storms during the last two decades.

In available literature, migration rates vary from one to several tens of meters/year for large dunes and giant dunes and rates of several tens to several hundred of meters/year for small and medium-size dunes. The actual dynamics of dunes is thus much more intense than that perceived by comparative studies of mapping surveys over a time interval of a few years.

7 MODELING OF SAND DUNE DYNAMICS

As shown by Le Bot et al. (2000a), predicting morphological dune changes requires a good knowledge of hydrodynamic agents and of their capacity to reset sediments in motion, and using the finest possible integration factor for space and time scales.

The measurements of near-bottom currents carried out in the south of the North Sea showed that wind was the prevailing factor over swell and pressure, capable of modifying currents over the entire sea layer from surface to bottom, even capable of preventing tidal current reverse and that the velocity of currents was still affected by a dune at a 150-m distance away from it. Hennings et al. (2000) emphasize that the velocity of currents is higher above dunes, and that the wave direction variation and the tidal current changes of directions must be taken into account for modeling hydrodynamic factors. These factors and a quality DEM (digital elevation model) are therefore necessary to be able to model dune dynamics.

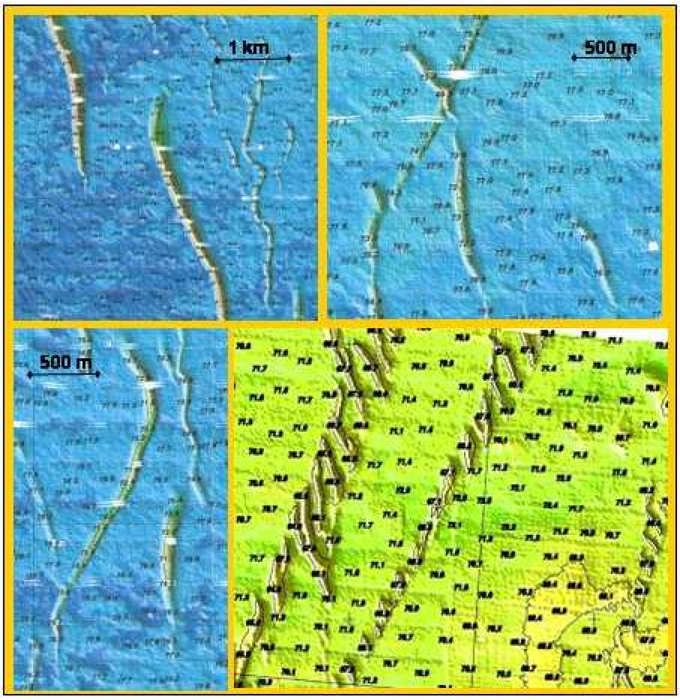

Figure 1 Original sand dunes in the north of Brittany

One of the problems met when modeling dunes is the role played by avalanches and suspensions; thus the dynamics of certain dunes would be governed by the bed load while others would be governed by suspension transports, generating different morphologies (Van den Berg et Van Gelder (1998)).

8 SAND STRUCTURES TOO COMPLEX TO BE MODELED

All dunes do not exhibit a simple morphology; it is true that "conventional" dunes are the majority but recent surveys carried out by SHOM led to the discovery of frequent exceptions (Garlan, 2004, 2007):

- Hexagonal structures having a diameter of a few decimeters which had been described until now in ancient geological formations and analyzed as symptomatic of the impact of storms on sediments have been filmed at 50-m depths close to Punta Spano (Corsica).
- During hydrographic surveys carried out between 1998 and 2006 in the north of Brittany at depths ranging from 70 to 80 meters, SHOM evidenced meridian crested dunes having heights of 1 to 13 meters and lengths which could exceed 10 km. Among these hundreds of dunes, some are overlapping sometimes bayonet-shaped and even intersecting crosswise, which seems to reflect a double hydrodynamic mode. Figure 7d displays the most original stage with a structure transversally cut in a series of hectometer sigmoid dunes at an angle of some 30 degrees to the structure centre line; the latter could form where currents separate in two directions.

The very poor H/λ correlation, and the distance between dunes characterize a deficit in sediment being carried down. The shape and dimensions of these dunes seem to show that they can be active. While only one hydrographic survey is sufficient to map their distribution, near-bottom current measurements alone associated with modeling would enable researchers to know their dynamics.

- Dune alignment in Trégor (North Brittany): The surveying of an unexplained morphological structure in the SHOM Bathymetric data base (see Figure 2) and confirmed by former bathymetric data, showed a series of dunes in skein-like alignment close to northern Brittany coastline.

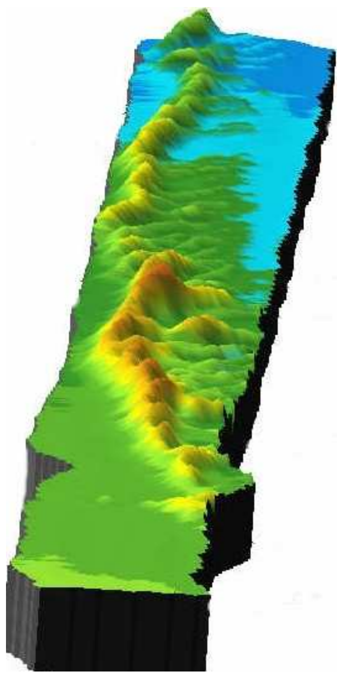

Figure 2. Seif marine dunes of Trégor (north Brittany)

This 5-m high structure at depths ranging from 60 to 70 meters, close to 11 kilometers in length is comparable to the "Seif dunes", described in desert environments McKee (1979) and on the planet Mars. All sand structures in deserts have much bigger dimensions (up to 10 times) than marine counterparts. This holds true for Saharan Seifs averaging heights of 100 meters and whose lengths can reach 100 kilometers. Saharan Seifs are active linear dunes formed under the action of winds of variable directions as opposed to barchans and dunes submitted to the action of winds blowing in only one direction. Seifs dunes are on the limit between transverse dunes and star-shaped dunes. Until then, the star-shaped dunes and Seif dunes were the only structures which had not been observed in the marine domain. It now seems that star-like dunes are the only category in McKee's classification which does not correspond to any description in the marine domain.

▪ Dunes in the English Channel central trench: At depths of some 100 m on the edge of the English Channel deep, an alignment of symmetrical dunes was found; their length is of the order of 1 kilometer and their height from 5 to 6 meters. The absence of dunes on the northern slope of this trench could be related to the circulation of currents, but because of the absence of measurements on currents in the trench and adjacent shelf, researchers cannot establish the intensity of dynamics and the origin of the morphological dissymmetry. Here again, the morphological characteristics and the location of dunes seem to indicate that these dunes are currently subject to active dynamics.

▪ The Schôle bank, located between the Channel Islands is a 7-km long x 1-km wide x 35-m high structure lying at depths of some 40 meters, exhibiting a gentle slope, made of very large dunes migrating southward and a western abrupt and smooth flank at the foot of which a complex system of chevrons and V-shaped ripples can be observed, pointing to a northward displacement (see figure 3). This bank structured by a vortex of some 10 kilometers centered on the northern tip of the bank; consequently it does not feature the typical angle between banks and currents. As in the case of Calais gullies (Garlan, 2004), we observe here the rotation of sand dunes over the flanks of a bank which remains stable.

▪ Another examples on the French continental shelf is presented on the figure 4, which show superimposed sand dunes on the banner bank of Lézardrieux; always in the north of Brittany (SHOM, 2007).

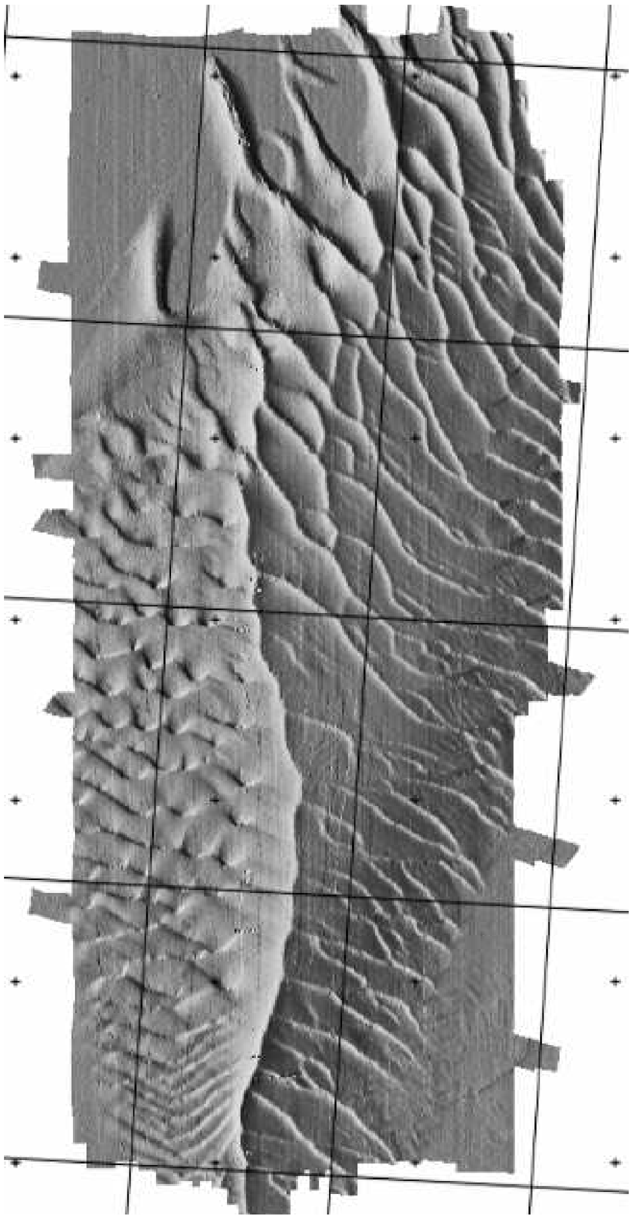

Figure 3. The Schôle bank, located between the Channel Islands

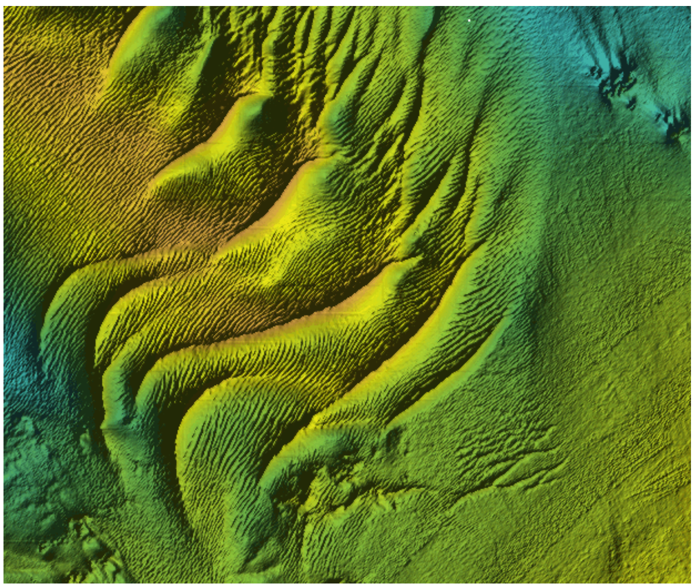

Figure 4, The Lézardrieux banner bank

9 CONCLUSION

Dunes are effectively controlled by the velocity and the direction of tidal currents, but are also affected by many other factors such as the availability and grain size of sediments, currents associated with swells and storms, locally raised relief both natural and anthropic as well as the slope and roughness of sediments and small morphological structures. By a retroaction phenomenon, currents are also affected by the nature of sediments and the morphology of sedimentary structures. Thus dunes can generate upwelling currents which can be strong enough to modify surface currents, even when the dune crest lies at depths exceeding 10 meters (Hennings and al, 2000).

The analysis and modeling of sand dunes in the southern sector of the North Sea allowed the acquisition of a large amount of results requiring validation on other dunes and in other environments; some results are pertinent for hydrographic purposes or detection of burying objects, helping to establish a minimum recurrence for surveys:

- the saturation height of a dune is of the order of 35% of depth,
- the time for dunes to form seem to be of the order of 25 years,
- isolated dunes in the North Sea move 1.5 times faster than dunes grouped in dune fields,
- storms have a major role in the displacement of dunes, speeding up or slowing their migration depending on whether they add up to the prevailing current or oppose it,
- dune displacement is relatively constant on a decade scale and allows researchers to predict evolutions provided if the number of storms does not change.
- dune appearance and disappearance are not observed in the scope of our study and the question of a possible cyclic nature of North Sea dune dynamics emerges. Indeed such phenomena seem to exist on the Schôle bank, in the Gironde estuary (Mallet, 1998) and in the approaches close to Arcachon Basin (Michel, 1997), causing sizeable dynamics on dune scale and also a form of stability of the regional system in the long term.

In order to answer such questions and define the displacement of more complex dunes, the use of models would be necessary because in the absence of comparative surveys and near-bottom current measurements, it is not possible to determine whether dunes are relicts or active. But the execution of such models necessitates being in possession of an excellent knowledge of sediments and near-bottom currents. Therefore scientific advances on dune migration hinge on looping the loop between hydrographic data acquisition and the development of appropriate models.

The original aspect of studying marine sand dune dynamics is that it relies only on a very high resolution bathymetry and on the measurement of near-bottom currents. Thus this sedimentary domain depends on acquisition systems and technological progress in hydrology instead of the conventional systems used earlier in sedimentology. To these technological aspects, should be added the impact of exceptional events (storms, hurricanes, extreme tidal conditions) which had been disregarded so far in studies and had not been taken into account in digital models. The sedimentary dynamics cannot be defined by simply comparing survey values; results need to rely on long range time series integrating variable acquisition time intervals representative of the various meteorological conditions or on precise and exhaustive batches of data perfectly describing the phenomenon and used as basis for digital models. This is why the French hydrographic service is making up a data base on dunes of the French continental shelf.

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