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On the formation of periodic sandy mounds

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A B S T R A C T

Le Bot and Trentesaux (Marine Geology 211, 2004) surveyed the periodic morphological patterns which are present in the English Channel close to the strait of Calais-Dover, where the shortage of sand does not allow the formation of typical sand waves (tidal dunes). The field observations show that, for similar hydrodynamic and morphodynamic conditions, the crest-to-crest distance of the observed sandy mounds is larger than the wavelength of the sand waves which form where sand is abundant.

The present contribution describes an idealized model able to predict the hydrodynamics and the morphodynamics of the interaction of tidal currents with large scale bedforms such as sand waves and sandy mounds in sand-starved environments. Indeed, when the availability of sand is limited, classical morphodynamic stability analyses cannot be applied for two main reasons. First, part of the rigid substratum becomes bared when bedforms appear and the bed profile is no longer sinusoidal. Second, the formulae commonly used to quantify sand transport are no longer valid when sandy mounds alternate with a rigid substratum.

In accordance with the field observations, the analysis shows that the bedforms which appear when the rigid substratum is bared (sandy mounds) are longer than those which form in a rich sand environment (sand waves).

1. Introduction

In the marine environment, field observations show the existence of different sedimentary patterns ranging from small scale ripples to large scale sand banks. Ripples play an important role in the sediment transport and the mixing processes taking place close to the sea bottom. Indeed the flow separates at their crests and vortices are generated, which increase mass and momentum transfer and sediment transport. For practical purposes, the effect that ripples have on large scale phenomena can be modeled by assimilating the ripples to a roughness of appropriate size. Sand banks, named also tidal ridges, have wavelengths of the order of kilometres, and the temporal scale of their time development is of the order of hundreds of years. Since these bedforms evolve on very long time-scales the design of coastal structure and human interventions is made considering a steady sea bottom configuration and attention is focused on the long term effects that the structures and interventions have on the surrounding environment. On the other hand sand waves, also named tidal dunes, have significant interactions with human activities because of their migration. The displacement of sand waves, which can be of the order of tens of metres per year, may cause the exposure and buckling of pipelines and/or cables, may reduce the local water depth up to the minimum value required for navigation and may be a risk for the stability of oil platforms and windmill farms.

The field observations of Trentesaux and Le Bot (1998a, b); Le Bot and Trentesaux (1999); Le Bot et al. (2000); Le Bot (2001); Le Bot and Trentesaux (2004), which were carried out in the English Channel at the southern end of the sand bank named 'South Falls' (central part of the Dover Strait), report sand waves characterized by different geometries and migration rates, depending on tide characteristics, wind regime and sediment properties. The observations were carried out in an area where the tidal current accelerates because of the geometrical constraint of the channel and the high velocities prevent the uniform deposition of the sediments. Hence, in some parts of the area the pavement is mainly composed of relict pebble lags, which were deposited before the postglacial sea level rise (Houbolt, 1968; Jelgersma, 1979) and mobile sediments are present only in the form of periodic sand and gravel mounds (James et al., 2002). Moreover, the field data show that, in sand-starved environments, the sandy deposits are mainly concentrated in bedforms with geometric and kinematic characteristics different from those of the sand waves that form in zones where the sand is abundant. In particular, Le Bot and Trentesaux (2004) divided the area into two sectors, named sector A and sector B. In sector A, the sediment, which mainly originates from the South Falls and Sandettie sand banks (Smith and Rijkswaterstaat, 1988), is a mixture of sand and gravel and totally covers a pebble lag which could not be mobilized by the tidal currents. In the northern part of the sector, the mean grain size is equal to 0.35 mm while in the southern part the sediment is

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characterized by a larger mean grain size. In this sector, the sand waves are typical of an environment rich of sand and characterized by low energy hydrodynamics. The rate and direction of the migration of the bottom forms depend on the wind regime and on the time scale of the observations.

In sector *B*, a sequence of isolated mounds, of finite extent in the transverse direction, was observed. The mounds are made up of coarse heterogeneous sediment with grain sizes ranging between 2.5 mm and 10 mm at the crests, while the flanks were covered with a bimodal mixture of coarse sediment and medium sand (grain size equal to 0.35 mm). In this sector the bottom forms migrated towards the South-West. Moreover, the field observations indicate that the crest-to-crest distance of the bottom forms is longer than the wavelength of the sand waves generated where the sand is abundant. Since both the hydrodynamics and the characteristics of the mobile sediment are the same for site A and site B, a possible explanation for the observed differences in the bedforms is sand availability.

The goal of the present analysis is to explain the mechanism of formation of the sequences of mounds and to provide a detailed evaluation of the flow field generated by the interaction of an oscillatory tidal current with periodic sandy mounds superimposed on pebble lags. Indeed the idealized predictive models for the formation of sand waves in environments with sand abundance Besio et al. (2006); Hulscher (1996); Németh et al. (2002) cannot be applied to areas with sand scarcity.

First, since previous models of large scale morphological patterns in tidal environments show that both sand waves (tidal dunes) and sand banks (tidal ridges) appear because the sediment is dragged towards the crests of the bottom forms by the steady velocity component (Hulscher, 1996; Huthnance, 1982), attention is focused on the steady velocity component which is generated by the interaction of the oscillatory tidal flow with the bottom profile. Then, the bottom shear stress is determined, along with the sediment transport rate. Finally, the dynamics of the bottom forms which appear in a sand-starved marine environment, is evaluated and the characteristics of the bottom forms are predicted. The analysis is similar to that described in Blondeaux et al. (2016) who studied the formation of ripples under surface-gravity waves when only a thin layer of sediment covers a rigid substratum. Presently, the approach of Blondeaux et al. (2016) is used to quantify sediment transport when sandy patches alternate with rigid bottom areas. However, the present analysis differs from that of Blondeaux et al. (2016) because the oscillatory flow induced by tide propagation is turbulent and vorticity pervades the whole water column.

The next section is devoted to the description of the model. Then the results of the flow field and sediment transport rate over a sequence of sandy mounds are shown and discussed. The predictions provided by the model are discussed also by comparing them with those obtained by means of models devised for environments with abundance of sand. The fourth section is devoted to a discussion of the model and its results. The fourth section contains also an application of the model to the site in the English Channel where the measurements by Le Bot (2001) and Le Bot and Trentesaux (2004) are available. The last section is devoted to the conclusions.

2. The model

The model is made up of two modules: the hydrodynamic module and the morphodynamic module. In the first subsection, we determine the effects that a sequence of sandy mounds has on the tidal current, generated by the propagation of different tidal constituents. In particular, the characteristics of the steady recirculating cells originated by the presence of the bedforms are evaluated. In the second subsection, the morphodynamic module of the model is described and the approach used to determine the time development of the bottom profile is made explicit.

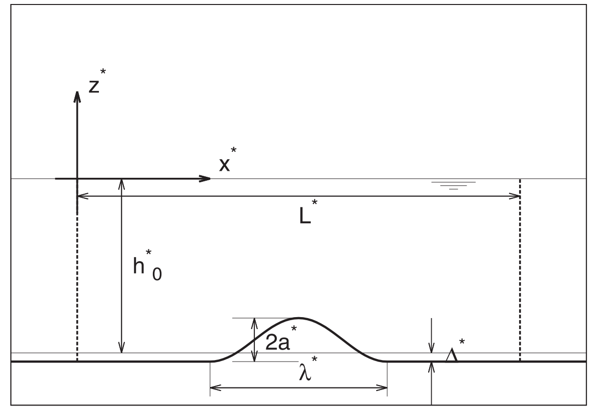

Fig. 1. Sketch of the bottom profile.

2.1. The hydrodynamic module

We consider the flow field generated by the propagation of a tidal wave over a horizontal sandy bottom and we introduce a local Cartesian coordinate system (x^*, y^*, z^*) with the x^*-axis aligned with the direction of the tidal current, the z^*-axis vertical and pointing upwards and the origin at the free surface (see Fig. 1). Hereinafter a star is used to denote dimensional quantities.

Even though, in the English Channel, the semidiurnal constituent provides the largest contribution and is sufficient for a fair description of the flow field, here the current is assumed to be bidirectional and generated by the propagation of a tidal wave composed of the M2, M4 and Z0 tide constituents. The M4 and Z0 constituents are added to show the different mechanisms which cause the migration of the bottom forms.

It follows that the velocity profile induced by tide propagation over a horizontal bottom is described by:

$$u^*(z^*, t^*) = \left[\frac{U^*_{M2}(z^*)}{2}\exp(i\omega^* t^*) + c.\,c.\right] + \left[\frac{U^*_{M4}(z^*)}{2}\exp(2i\omega^* t^*) + c.\,c.\right] + U^*_{Z0}(z^*). \quad (1)$$

where ω^* is the angular frequency of the M2 tidal constituent. In (1) the dependence of U^*_{M4}, U^*_{M2} and U^*_{Z0} on x^* is neglected because the area of interest has the size of the sandy mounds and turns out to be much smaller than the tidal wavelength.

Now, let us consider the interaction of the tidal current with a periodic sequence of sandy mounds, with a spatial periodicity L^*. The crests of the bottom forms are assumed to be orthogonal to the direction of the tidal current and interspersed by flat areas made up of relict pebble lags. Considering a spatially periodic flow domain of extent L^* in the x^* direction, the bottom profile can be modeled as (see Fig. 1):

$$z^* = -h_0^* - \Delta^* \ \text{for}\ 0 < x^* < \frac{L^* - \lambda^*}{2} \ \text{and}\ \frac{L^* + \lambda^*}{2} < x^* < L^*$$
$$z^* = -h_0^* - \Delta^* + a^*\mathscr{F}(x^*) \quad \text{for} \quad \frac{L^* - \lambda^*}{2} \le x \le \frac{L^* + \lambda^*}{2} \quad (2)$$

where L^*, λ^* and Δ^* are free parameters. Moreover, in (2) $\mathscr{F}(x^*)$ indicates a function that describes the bottom profile at the considered time and assumes values of order one. At this stage the exact form of $\mathscr{F}(x^*)$ is not relevant. In the model, similarly to Roos et al. (2005), a Fourier decomposition of (2) is used, which allows any bottom profile to be considered. Presently, to discuss the influence of sandy mounds on the tidal current only, we consider:

$$\mathscr{F}(x^*) = \left[1 + \cos\left(\frac{2\pi(x^* - L^*/2)}{\lambda^*}\right)\right],$$

which is a fair approximation of the profile of the sandy mounds.