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The flow over bedload sheets and sorted bedforms

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ABSTRACT

Field surveys show the existence of morphological patterns (named bed load sheets in fluvial enviroments and sorted bedforms in coastal environments) which consist of alternate bands of coarse and fine sediments and are characterized by a negligible spatial variation of the bottom elevation. Previous analyses show that these bottom patterns are self-organizing features which are originated by the interaction of poorly sorted sediments, fractional sediment transport and turbulence dynamics. Presently, we describe the results of an investigation of turbulence dynamics over a flat bottom but characterized by alternate bands of small and large roughness. Turbulence characteristics are obtained by means of the two-equation turbulence model of Saffman (1970) which is shown to provide a reliable description of turbulence structure both in steady and oscillatory flows, as those generated in coastal environments by surface wave propagation. Moreover, the turbulence model can describe both smooth and rough walls and provide fair results also at moderate values of the Reynolds number. The results are validated by comparing the predictions of the model with the experimental data of Jensen et al. (1989) and Fredsøe et al. (1993) who measured the velocity field and the bottom shear stress under a turbulent oscillatory flow over a plane bed with a uniform roughness and sudden spatial change of the roughness size, respectively. The measurements of Fredsøe et al. (1993) were simulated also by Fuhrman et al. (2011) by means of the k–ω turbulence model of Wilcox (2006, 2008) and an indirect comparison of the model results with the results of Fuhrman et al. (2011) can be made. The investigation shows that the streamwise advection of turbulence plays a significant role such that turbulence is more intense over the rough bottom than over the smooth bottom, if a region close to the bottom is considered. However, moving far from the bottom, an opposite trend is found. Moreover, the results clearly show that the streamwise variations of the horizontal velocity component induce a significant vertical component of the velocity which should be taken into account if an accurate description of transport phenomena is to be obtained.

1. Introduction

The transport of sediment mixtures in natural environments often gives rise to the appearance of bedforms of different length scales and, simultaneously, to phenomena of sediment sorting. A review of the most recent studies devoted to the investigations of the mechanisms which originate rhythmic morphological patterns in sedimentary environments characterized by the presence of sediment mixtures is provided by Seminara (1995) and Blondeaux (2012) for fluvial and coastal environments, respectively. Bedforms of small and intermediate spatial scales as well as large scale bedforms are considered. In particular, attention is focused on bed load sheets, sea ripples, sand ridges, fluvial and tidal dunes, fluvial bars, shoreface-connected ridges and sand banks. These morphological patterns give rise to sorting phenomena such that the fine/coarse sediments are found either in the troughs or at the crests of the bottom forms, depending on flow and sediment characteristics.

However, field surveys show also the existence of sorting phenomena which, apparently, are not driven by the existence of a bottom waviness. These morphological patterns are observed in both fluvial and coastal environments. For example, Whiting et al. (1988) carried out field observations along the Duck Creek (Wyoming) and observed bands of coarse sediments, orthogonal to the axis of the creek, which migrated downstream and were characterized by fronts which were only one or two grains high (bed load sheets). Similar observations were carried out by Iseya and Ikeda (1987) and Kunhle and Southard (1988) in laboratory flumes. Also in the coastal region, field surveys show the existence of morphological patterns which consist of alternate bands of coarse and fine grains. Sometimes these bands are associated with significant bottom forms but other times the bottom waviness is practically negligible, since the bands are hundreds of metres wide and just about one metre high (Cacchione et al., 1984).

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The key role played by the heterogeneous grain size distribution in the process which leads to the appearance of bed load sheets is described by Seminara et al. (1996). Seminara et al. (1996) showed that perturbations of the grain size distribution induce spatial variations of the bottom roughness which, in turn, induce spatial variations of the bottom shear stress and, then, of the sediment transport rate which tends to accumulate the coarse sediment in periodic bands. Similarly, Murray and Thieler (2004) and Coco et al. (2007a,b) showed that also in coastal environments the coarse bands, named sorted bedforms by Murray and Thieler (2004), are generated through a self-exciting mechanism where the bottom waviness has no role. In particular, Murray and Thieler (2004) developed an exploratory model with a spatially varying bottom roughness related to the sediment size. A larger bottom roughness induces a stronger turbulence which picks up the fine fraction from the bed, leading to a coarser bottom.

The different roles played by perturbations of the grain size distribution and perturbations of the bottom profile in the appearance of sorting phenomena have been recently investigated by Van Oyen et al. (2011) who determined the time development of perturbations of both the bottom profile and the grain size distribution superimposed to a flat sea bottom made up of a sediment mixture homogeneously distributed in the horizontal directions. The flow and sediment motions are driven by a constant shear stress applied to the free surface which is supposed to model a strong blowing wind. Assuming that the amplitude of the perturbations is small, Van Oyen et al. (2011) developed a linear analysis which predicts the growth/decay of the perturbations. The results obtained by Van Oyen et al. (2011) show the possible existence of two different modes which are both periodic and characterized by finite wavelengths. Van Oyen et al. (2011) named ‘topography driven mode’ the mode which is generated by the convergence of the sediment transport rate and is characterized by a significant bottom waviness. On the other hand, Van Oyen et al. (2011) named ‘roughness driven mode’ the mode which is mainly characterized by a periodic variation of the bottom composition with negligible variations of the bottom profile. The two modes have different characteristics and, in particular, the wavelength of the ‘topography driven mode’ is hundreds of metres long while the wavelength of the roughness driven mode’ is tens of metres long. Moreover, the coarse sediments are found in the troughs of the topography driven mode while the roughness driven mode is characterized by an up-current or a down-current shift of the coarse sediments with respect to the troughs of the bottom waviness, depending on the values of the parameters.

Even though the generation of turbulence by the roughness of the bottom and both the advection and the diffusion of turbulence certainly play a fundamental role in the mechanism which gives rise to bed load sheets and sorted bedforms, the theoretical models developed in the past use a simplified description of turbulence dynamics, which implies a local equilibrium between production and dissipation of turbulence. Hence, these models can explain qualitatively the process through which the morphological patterns appear but they do not provide accurate quantitative results on the conditions leading to the appearance of the bedforms and on their geometrical characteristics (e.g. wavelength).

In the present study, to increase our understanding of turbulence dynamics and possibly to improve the actual models, we investigate turbulence dynamics over periodic alternate bands of coarse and fine sediments over a flat bottom by using a two-equation turbulence model. The model can describe the turbulence structure in the outer layer, the log-law region, the buffer layer and it provides the flow even in the viscous sublayer (if present). Moreover, the turbulence model can handle both smooth and rough walls and it was successfully applied to study oscillatory boundary layers characterized by the presence of relaminarization phenomena (Blondeaux, 1987; Blondeaux and Vittori, 1999) and steady streaming generated by nonlinear effects (Vittori and Blondeaux, 1996; Blondeaux et al., 2012), even though phenomena as receptivity (Blondeaux and Vittori, 1994) and appearance of turbulent spots and coherent vortex structures (Costamagna et al., 2003; Carstensen et al., 2010; Mazzuoli et al., 2011; Carstensen et al., 2012) cannot be described.

Hence, the use of this model allows the investigation of turbulence production and dissipation and its transport by the local flow both in fluvial and coastal environments.

In the next section, the problem of studying turbulence dynamics over bed load sheets and sorted bedforms is formulated. The numerical approach employed to determine the solution is described in Section 3 while the results are presented and discussed in Section 4. Finally, Section 5 is devoted to the conclusions and the description of the possible developments of the analysis.

2. The problem formulation

As pointed out in the introduction, both bed load sheets in rivers and sorted bedforms in the coastal region are characterized by a periodic distribution of the mean grain size along the flow direction and by a negligible bottom waviness. Hence, following earlier models, we consider a steady current or an oscillatory fluid motion flowing over a rough bottom made up of a mixture of two sands of grain sizes d_1^* and d_2^* (hereinafter a star denotes dimensional quantities while the same symbols without a star denote the dimensionless counterparts which are defined later). Although only two grain sizes are considered, the analysis can be easily extended to consider N sediment classes and even a continuous grain size distribution. The bottom is assumed to be flat but characterized by a heterogeneous grain size distribution which can be described by giving the probabilities of occurrence p_1 and p_2 of the two sand classes. Moreover, since the morphological patterns which we want to model have crests that are orthogonal to the flow direction, the grain size distribution is assumed to be periodic in the x^*-direction and uniform in the z^*-direction, such that $p_1=p_1(x^*,t^*), p_2=p_2(x^*,t^*)$, where (x^*,y^*,z^*) are Cartesian coordinates with the x^*- and z^*-axes lying on the bottom, the x^*-axis pointing in the flow direction and the y^*-axis vertical and pointing upwards. The reader should be aware that, even though the values of p_1 and p_2 can vary in space and in time because of the action of the flowing water, their values are subject to the constraint:

$$p_1+p_2=1 \tag{1}$$

Hence, the grain size distribution is known when just the value of p_1 is known. Since, the aim of the present paper is the evaluation of turbulence dynamics over a time independent grain size distribution, p_1 is assumed to be a given function of x^* only.

The problem of flow determination is posed by continuity and momentum equations. Let us introduce the following dimensionless quantities:

$$(x,y,z)=\frac{(x^*,y^*,z^*)}{\ell^*}, \quad t=\frac{t^*\mathcal{U}^*}{\ell^*}, \quad (u,v,w)=\frac{(u^*,v^*,w^*)}{\mathcal{U}^*}, \quad p=\frac{p^*}{\rho^*(\mathcal{U}^*)^2} \tag{2}$$

where ρ^* is the water density, t^* is the time, (u^*,v^*,w^*) are the velocity components along the (x^*,y^*,z^*)-axes, respectively, ℓ^* and $\mathcal{U}^*$ are the characteristic length and velocity scales, respectively, which are defined later. Moreover, the pressure p^* is the actual value P^* of the pressure minus the hydrostatic contribution given by $-\rho^*g^*y^*$, g^* being the gravity acceleration. Such definition of p^*