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Numerical study of shear stress distribution at sand ripple surface in wind tunnel flow

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ABSTRACT

The mechanism responsible for the formation and sustainability of sand ripples sheared by a uniform air flow is not well understood, despite the significant attention that has been given to it ever since the pioneering studies of Bagnold (1941). In this study we explore ANSYS Fluent simulations of fine-scale turbulent flow structure in the vicinity of 2D sand ripples with particular emphasis on shear stress distribution at the sand bed. The flow parameters in the simulations were pertinent to the wind tunnel experiments for studying sand ripples formation. The simulations show that the shear stress at the crest is about 2.5 times larger than the shear stress at the trough and that in most of the simulations a separation bubble has been developed at the lee slope. In contrast to wind tunnel experiments the simulations show that ripples will be flattened at wind speed of 9 m/s as shear stress at the ripples surface exceeds the fluid threshold. This discrepancy between the calculations and real wind tunnel measurements are due to the important role of the saltation layer on the decrease of the shear stress at the surface. Without this effect ripples cannot grow higher and will be diminished at quite moderate winds.

1. Introduction

One of the open questions in aeolian geomorphology concerns the formation of aeolian sand ripples in the desert or in sand beaches. Although this problem has been investigated by many researchers in the past (e.g. Bagnold, 1941; Sharp, 1963; Anderson, 1987; Yizhaq et al., 2004; Durán et al., 2014; Rasmussen et al., 2015) there are still a number of unresolved or insufficiently explored aspects of sand ripples formation: (i) combined effect of saltation, reptation, suspension and splashing on ripple formation (see e.g. Manukyan and Progozhin (2009) and Kok et al. (2012); for discussions); (ii) effect of electric forces in sand ripple formation (see e.g. Kok (2008)); (iii) influence of grain size distribution on the formation of ripples (Anderson and Bunas, 1993); (iv) mechanism for ripples merging (see Prigozhin (1999)); (v) effect of temperature gradient in the vicinity of the sand bed on ripple formation; (vi) mechanism that limits sand ripples growth; (vii) mechanism which determines the ripples wavelength (Durán et al., 2014).

Clearly, detachment of sand particles depends strongly on their diameter, adhesion forces, soil wetness, flow parameters such as pressure, temperature and velocity and fluid parameters such as viscosity and molecular structure. One simple characterization of the flow and the fluid parameters is the shear velocity at the surface u_* defined as $u_* = \sqrt{\tau/\rho}$, where τ is the local shear stress and ρ is the local fluid density. According to Shao and Lu (2000) the critical threshold shear velocity for the initiation of motion for static grains is given by the following relation:

$$u_{*t} = \sqrt{0.0123\left(sgd + \frac{3.0 \cdot 10^{-4}}{\rho \cdot d}\right)}, \tag{1}$$

where s is the ratio between the sediment density and the fluid density, g is the acceleration due to gravity and d is the grain diameter. Similar equation that is still used in the literature was suggested by Bagnold (1941):

$$u_{*t} = A\sqrt{\frac{\rho_s - \rho}{\rho} gd}, \tag{2}$$

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where ρ_s is the grain density and ρ is the air density, and A is a coefficient ($A \approx 0.1$) that depends on the grain Reynolds number (Wiggs, 1997). It must be noted that Eq. (2) does not take into account the cohesion between small particles. A comprehensive analysis of formula (2) for critical threshold velocity that accounts for the variability of the coefficient A was conducted by Li et al. (2014).

For any particular sand bed there exists a threshold value of shear velocity beyond which grain detachment begins. This critical velocity is known as the fluid threshold. The shear stress τ is proportional to the velocity gradient and equal to $\mu \frac{\partial u}{\partial y}\Big|_{y=0}$, where μ is the local dynamic viscosity of the fluid, u is the fluid velocity which is parallel to the surface and y is the axis locally normal to the surface with its origin at the surface. The goal of this work is to study the wind flow in a wind tunnel over ripples bedform using the commercial CFD (Computational Fluid Dynamics) software ANSYS Fluent. Whereas few such studies of flows over dunes topography have been conducted in the past (Parsons et al., 2004; Herrmann et al., 2005; Schatz and Herrmann, 2006) and their potential for dune research have been discussed (Livingstone et al., 2007), to the best of our knowledge none has been done for sand ripples.

Wind tunnel experiments are one of the common methods to study the evolution of ripples and their characteristics (see review in Rasmussen et al. (2015)), but the details of the wind flow over the ripples are still unexplored. In the present study we address this issue by using two-dimensional simulations of the flow without sand flux in the wind tunnel of the Aeolian Simulation Laboratory of the Ben-Gurion University. Despite the fact that in most aeolian situations the air flow will interact with the sand flux (see Kok et al. (2012)), our results will help to understand the pattern of the flow over the ripples and the initial response of the bedform to different wind velocities.

The stationary wind tunnel in the Aeolian Simulation Laboratory in the Ben-Gurion University (BGU) is described in Pye and Tsoar (2009) and Katra et al. (2014). The BGU wind tunnel is an open circuit wind tunnel composed of three sections: an entrance cone, a test section and a diffuser (see Fig. 1). The tunnel is configured for air suction mode whereby air is fed into the tunnel through the bell-shaped entrance by a fan located at the end of the diffuser. The maximum air flow speed measured at the central section of a tunnel at a distance of 0.15 m from the inlet is 25 m/s. The cross sectional area of a tunnel is $0.7 \times 0.7\ \text{m}^2$ and the working length is 12 m (7 m of test section) test section. Insets A and B in Fig. 1 show different overall views of the wind tunnel and arrow indicates the flow direction. The wind tunnel has a feeder (seen at the upper left corner of inset B) for controlling the saltation flux in the test section. This is a medium wind tunnel according to the classification of Rasmussen et al. (2015).

Fig. 1. Wind tunnel of the Aeolian Simulation Laboratory (Ben-Gurion University of the Negev) with sand bed covered by ripples.

2. Numerical model

For this numerical study we use ANSYS Fluent (see ANSYS Manual, http://www.ansys.com/Support/Documentation). The details of the implementation of the numerical code are elaborated in the following subsections.

2.1. Geometry and meshing

We considered a two-dimensional (2D) rectangular control volume whose height corresponds to the wind tunnel experiment and equals 0.7 m. The width of the control volume (i.e. the length in the dimension parallel to the shearing flow) of 1.063 m was chosen such that it is short enough to be numerically efficient with reasonably fine mesh while long enough to ensure that the mean flow and the small-scale flow features in the vicinity of the ripples do not change appreciably along the direction of the flow. The upper boundary of the control volume is a non-moving smooth wall, while the bottom is a non-moving wavy wall shaped by a periodic pattern of ripples. The basic form of a ripple is asymmetric and shown in Fig. 2a and b and its shape was taken from a previous wind tunnel study (Schmerler et al., 2015, see Table 1 which summarizes the ripples morphology in the experiments). The inlet boundary condition is posed at the left boundary of the control volume while the outlet boundary condition is posed at the right boundary of the control volume.

In constructing the mesh we used an adaptive mesh which is refined in the vicinity of the wavy wall in order to capture fine features of the flow (see Fig. 2c). General view of the control volume geometry and the mesh are shown in Fig. 3.

2.2. Setup and solution

We use a steady-state density-based 2-D solver. The operating conditions are pressure of 1 atm and a temperature of 300 K at

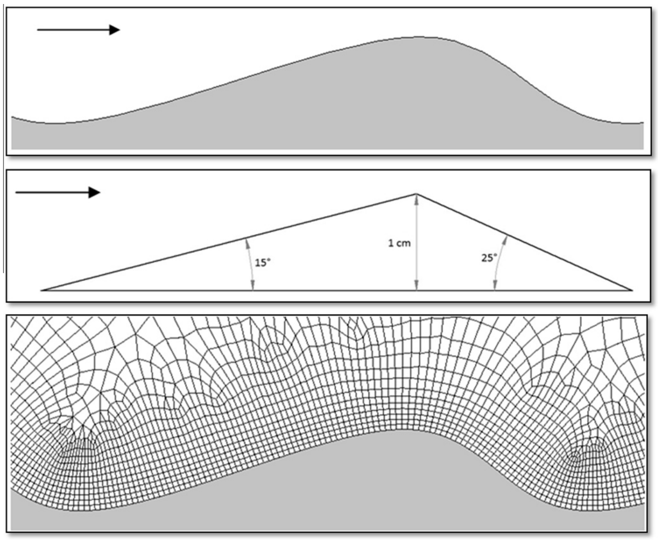

Fig. 2. (a) Ripple profile. The shape of the ripple was approximated by splines passing through the measured topography of the ripples formed in the wind tunnel. The arrow in the top left indicates the direction of the shearing mean flow. The skeleton and scaling are given in Fig. 2b. (b) Skeleton of a ripple is based on measured topography of the ripples formed in the wind tunnel. The arrow in the top left indicates the direction of the shearing mean flow. The length of the bottom edge is fully determined by the rest of the parameters and it is approximately 5.877 cm.