24th COBEM - 2017

24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-1893
FORMATION AND MORPHOLOGY OF SUBAQUEOUS BARCHAN DUNES

Carlos A. Alvarez
Erick M. Franklin
School of Mechanical Engineering, University of Campinas -UNICAMP, Campinas, SP, Brazil
calvarez@fem.unicamp.br, franklin@fem.unicamp.br

Abstract. *The present paper reports the formation of subaqueous barchan dunes by analyzing the temporal evolution of their main geometrical characteristics (width, length and horn lengths). The barchan dunes were formed from spherical glass and zirconium beads. An initial conical heap of beads was placed on a rectangular channel and it was entrained by a water turbulent flow. The evolution of the dunes was filmed with a CCD camera placed above the channel and mounted on a traveling system. Our results show that after a characteristic time the dune shape does not change and it travels with a roughly constant velocity.*

Keywords: *granular materials, transport of solid particles, bed-load, barchan dunes*

1. INTRODUCTION

The transport of solid particles entrained by a fluid flow is frequently found in both nature and industry. When shear stresses exerted by the fluid on the bed of particles are bounded to some limits, a mobile layer of particles known as bed-load takes place in which the particles stay in contact with the fixed bed. If it takes place over a non-erodible ground or with limited sediment supply from the bed, they form dunes showing a remarkable crescentic shape with horns pointing downstream (Herrmann and Sauermann, 2000). These dunes, known as barchan dunes, are commonly observed in deserts. However, field measurements suffer from the lack of control on meteorology conditions as well as the large length and time scales (100 m and 1 year) involved in the physics of dunes (Hersen *et al.*, 2002). The shape and size selection of dunes, their dynamics behavior, and even their stability remain as open issues (Hersen *et al.*, 2004). Creating dunes in a controlled way and using shorter scales could help to improve our knowledge about all these questions. Similar barchan dunes have also been observed under water flows (with much shorter lengths than in air). Barchan dunes under water have received much less attention than aeolian dunes, and important issues remain unanswered (Franklin and Charru, 2011). This work presents some experiments with glass and zirconium beads entrained by a turbulent water flow. Its objective is to investigate the formation, the morphology and velocity of barchan dunes.

2. EXPERIMENTAL DEVICE

The experimental device consisted of a water reservoir, two centrifugal pumps, a flow straightener, a 5 m long channel, a settling tank, and a return line. The flow straightener was a divergent-convergent nozzle filled with d = 3 mm glass spheres, the function of which was to homogenize the flow profile at the channel inlet. The channel had a rectangular cross-section (width = 160 mm and height 2δ = 50 mm) and was made of transparent material. Figure 1 shows the scheme of the experimental loop. The channel test section was 1 m long and started 40 hydraulic diameters (3 m) downstream of the channel inlet. The particles were placed in the channel test section, which was previously filled with water (the turbulent flow was completely developed in the test section). The grains settled in the water at rest and formed a conical heap. Next, a water flow was impossed in the channel, and the heap deformed into a barchan dune. The evolution of the dune shape was recorded with a CCD camera placed above the channel and mounted on a traveling system. With this procedure, each experiment concerns one single isolated dune.

In our experiments, the employed fluid was tap water at temperatures within 24 and 26 ^{o}C and the granular material was spherical beads: glass beads with density ρ_s = 2500 kg/m^3 with mean diameter d = 0.37 mm and heavier zirconium particles with density ρ_s = 4000 kg/m^3 and mean diameter d = 0.50 mm. The water flow rate was varied between 6.7 and 9.5 m^3/h. The fluid flow was measured with an electromagnetic flow meter and a 2D-PIV (two-dimensional particle image velocimetry) device. The flow velocity $\bar{U}$, defined as the ratio of the measured volumetric flow rate and the channel cross-section, was varied between 0.232 and 0.333 m/s. The shear velocities on the channel walls were computed from

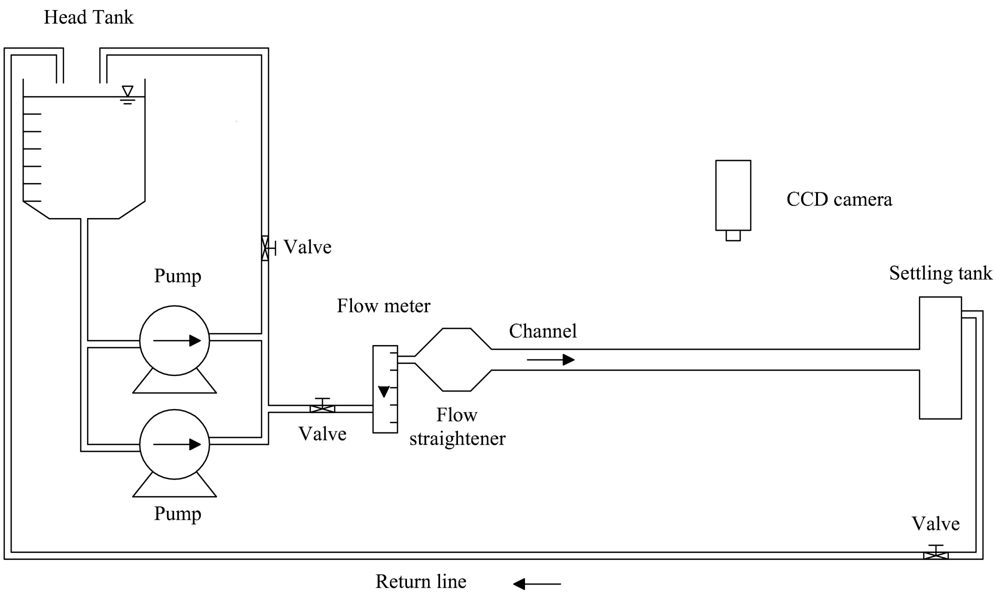


Figure 1. Schematic of the experimental loop.

the velocity profiles acquired by the PIV device and were found to follow the Blasius correlation (Schlichting (2000)). They correspond to 0.0143 and 0.0195 m/s for the employed flow rate range. The corresponding Reynolds number, with ν as the kinematic viscosity, was calculated using the Eq. 1

$$Re = \frac{\bar{U} 2\delta}{\nu} \tag{1}$$

and it was in the range $11600 - 16700$.

3. DUNE MORPHOLOGY

Once a conical heap of grains is formed in the channel, the flow is imposed at a constant rate. Before being displaced over a measurable distance, the pile is deformed and adopts a "croissant" shape as shown in Fig. 2. The initial heaps were formed with 10.5 g of glass beads, and with 16.5 and 10.5 g of zirconium beads.

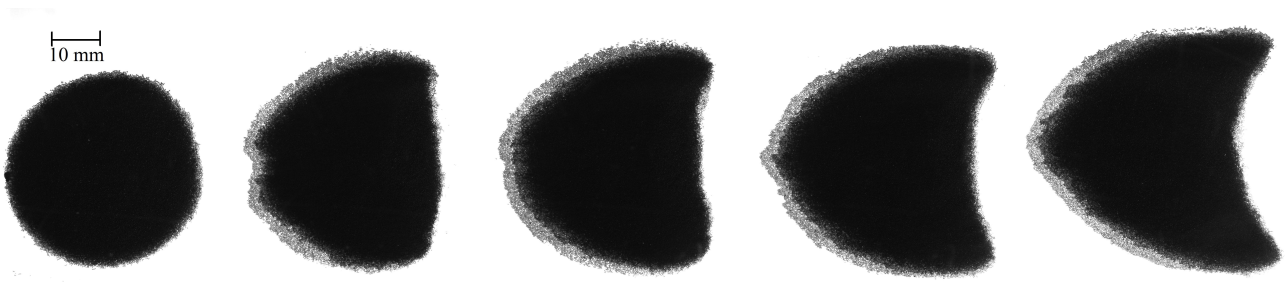


Figure 2. Top views of an initially conical heap settled on the channel test section and deformed by the water flow at different times. The flow, with Re = 12150, is from left to right. The particles used were black glass beads with mean diameter of 0.37 mm.

A schematic view dune of a barchan dune is shown in Fig. 3, which defines its dimensions. L is the distance, in the symmetry plane, from the front to the rear of the dune, not taking into consideration the horns. W is the dune width, L_h is the horns length and H is the dune height. An image processing code, written as a Matlab script, was developed during this work to automatically treat the adcquired images. The code tracks the dunes along the images and computes its W, L and the centroid position; from the latter the dune velocity V_d is computed.

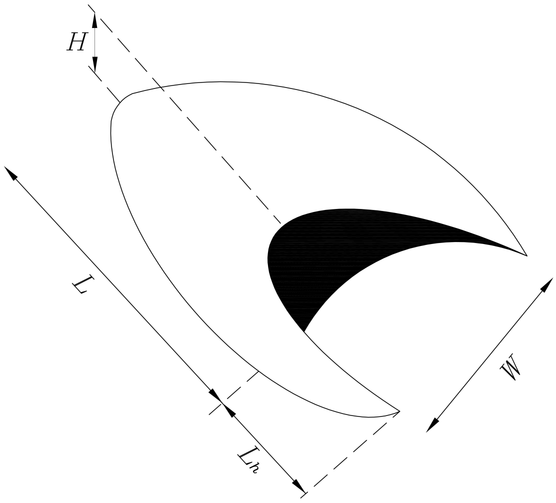


Figure 3. Scheme of a barchan dune showing its dimensions.

4. RESULTS AND DISCUSSION

The evolution of barchan dunes is analyzed. It is considered as initial state a conical heap of grains. As soon as the water flow begins, the heap deforms and to adopt a "croissant" shape. Our results show the evolution of some geometrical parameters of dunes along the time. Figures 4 and 5 show the formation of barchan dunes, through L and W, respectively, considering the initial state at time equals to zero. The symbols used in the figures are explained in the key. From the Fig. 4, we observed different behaviors from the initial piles, with the heaps consisting of heavier zirconium beads decreasing in the time while that of glass beads maintaining roughly constant along the time. In the case of W, Fig. 5 shows that the dunes maintain roughly the same width of the initial pile, attaining an equilibrium width around 150 s for the zirconium beads and around 50 s for the glass beads. Considering these dune-feature variations, it could be stated that the length and width of barchans are not good indicators of the formation and evolution of barchan dunes.

As shown in Fig. 6, which presents the time evolution of W/L, the dunes consisting of zirconium beads have W/L values around 1.5 times the values presented by dunes formed with glass beads. Figure 7 shows the dune velocity V_d, which is computed using the dune's centroid position along the time. For the same Reynolds numbers, it is evident that dunes formed from glass beads are faster than these of zirconium dunes; and as it would be expected, dunes under highest Reynolds numbers have the highets velocities. In addition, the Fig. 7 shows that dunes formed from glass beads attains a roughly constant velocity at 30 s and the zirconium dunes at 150 s, the same behavior as observed in the Fig. 6.

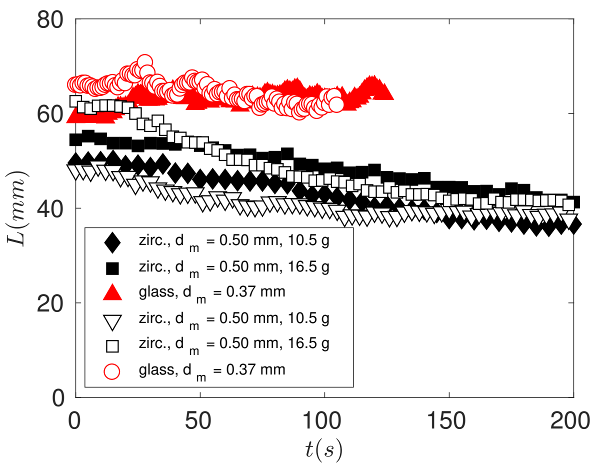


Figure 4. Evolution of dune length L along the time. The black diamonds and inverted triangles correspond to zirconium beads with d = 0.50 mm and 10.5 g of initial mass, the black squares and white squares correspond to zirconium beads with d = 0.50 mm and 16.5 g of initial mass, and the red triangles and circles correspond to glass beads with d = 0.37 mm. The solid symbols correspond to Re = 14700 and the empty ones to Re = 16700.

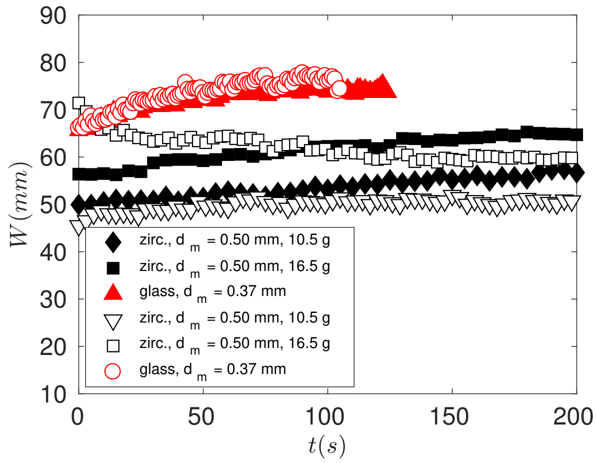


Figure 5. Evolution of dune width W along the time for different flow conditions and solid particles. The symbols are the same as in Fig. 5.

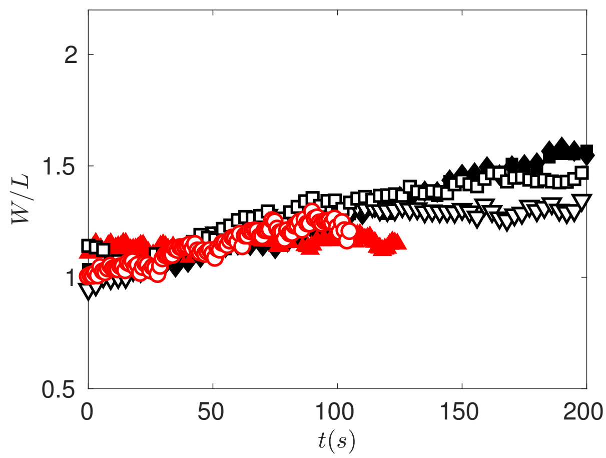


Figure 6. Evolution of W normalized by the dune length L for the same grains as in Fig. 4.

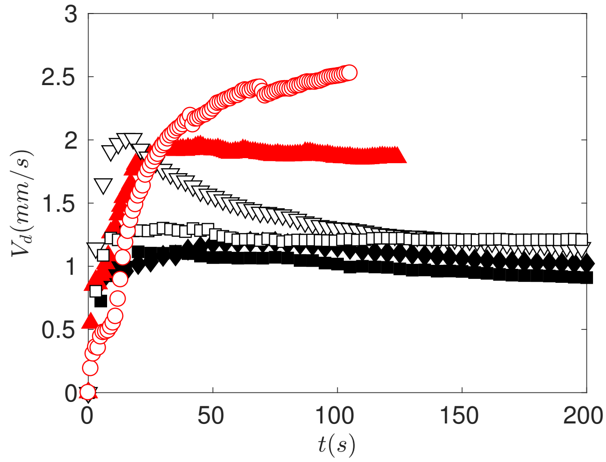
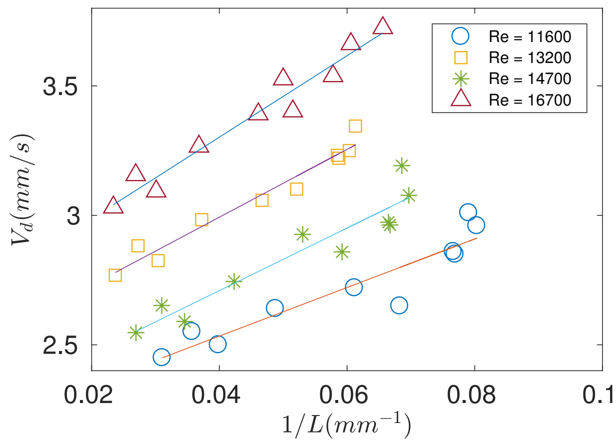


Figure 7. Dune velocity V_d versus time t. The symbols are the same as in Fig. 4.

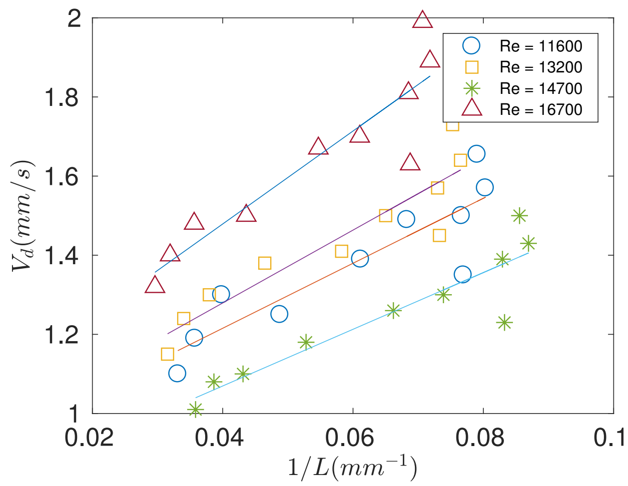
We analized the relation between the dune velocity and the dune length. The V_d was calculated once the dunes had reached their equilibrium shape, i.e., after they had traveled a distance of the order of the size of the initial heap (Franklin and Charru, 2009).

Figure 8 displays the velocity V_d as a function of the inverse dune length ($1/L$), for four different Reynold numbers, and for the two types of beads employed in this study. It is possible to identify that for a given Reynolds number, the dune velocity scales with the inverse length, $V_d \propto 1/L$. Furthermore, in Fig. 8 it is clearly visible that given a dune length, the dune velocity increases with the Reynolds number.

The results obtained once the dunes had reached their equilibrium shape, i.e., the dune velocity V_d as a function of the inverse dune length L^{-1} (Fig. 8) are in good agreement with previously reported results (Hersen *et al.*, 2002; Franklin and Charru, 2011).



(a)



(b)

Figure 8. Dune velocity V_d versus the inverse length $1/L$ for four different Reynolds number. (a) Black glass beads with mean diameter d = 0.37 mm. (b) Zirconium beads with d = 0.50 mm and 10.5 g. The continuous lines emphasize the linear dependence $V_d \propto 1/L$ for given flow conditions.

5. CONCLUSIONS

This experimental work reported the evolution of a conical heap of grains entrained by a turbulent flow that evolved to a barchan dune. The grains were formed from glass and zirconium beads. The formation of the dunes was filmed with a CCD camera. An image processing code was developed to identify the dunes, follow them along the images, and to calculate some geometrical parameters that define their morphology. Our results showed that after a characteristic time the dune shape does not change, and it travels with a roughly constant velocity.

The velocity scales with the inverse dune length, and for the two grain types used the dune velocity increases with the Reynolds number for a given dune length. An important issue to future works is the formation of barchan dunes employing grains with different characteristics, for instance, using beads with irregular shapes. Other important task is to measure the evolution of barchan dunes consisting of grains of two different specific masses.

6. ACKNOWLEDGEMENTS

Carlos A. Alvarez is grateful to the Ecuadorian government foundation SENESCYT for the scholarship grant (no. 2013-AR2Q2850) and to CNPq (grant no. 140773/2016-9). Erick M. Franklin is grateful to FAPESP (grant nos. 2012/19562-6 and 2016/13474-9), to CNPq (grant no. 400284/2016-2) and to FAEPEX/UNICAMP (grant no. 2210/17) for the financial support provided.

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