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MORPHOLOGY AND GRAIN DISPLACEMENTS OF TWO INTERACTING BARCHANS

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Abstract. *The crescent-shaped forms, known as barchan dunes, are formed in areas of unidirectional fluid flow and limited supply of granular material. Barchans are organized in dune fields, where occur interaction among dunes with similar or different speeds and sizes. In a previous study (Assis and Franklin (2020)), the short-range interactions occurring between two subaqueous barchans were experimentally investigated and five different patterns were identified. As a continuation, this work investigates the morphology and grain displacements occurring between two barchans with similar masses (called before as Chasing pattern). The experiment was conducted in a closed-conduit channel where a target dune was in a downstream position of a granular pile and a high-speed camera was used to track the interaction. The acquired images were treated using an image processing code. As results, we observed, through relations between width, length, and horns length of dunes, that the morphology of downstream dune is affected by the disturbance that the upstream dune causes in the fluid flow. In addition, particles exchanged between dunes were followed throughout the interaction and trajectories and velocities were calculated.*

Keywords: *Barchan dunes, morphology, interaction*

1. INTRODUCTION

The physics of dunes involves the interaction between fluid flow and granular material. Among the types of dunes observed in nature, the crescent-shaped, known as barchan dune, is formed in areas of unidirectional fluid flow and limited amount of granular material (Bagnold, 1941). In nature, they can be found in deserts, rivers, and the bottom of the oceans. In industry, they can be found inside oil pipelines.

Although barchans have been studied as isolated objects (Alvarez and Franklin, 2017), they belong to dune fields where they can be influenced by their neighbors with different sizes and speeds (Hersen *et al.*, 2004). Scientists, through observations in nature, have collected information about the dynamics and interaction between two or more barchans (Vermeesch, 2011) and (Hugenholtz and Barchyn, 2012). These observations, although important to trigger models to reproduce dunes behavior (Bo and Zheng, 2013), are incomplete due to the large time scale of aeolian cases (order of decades). An alternative is to reproduce subaqueous barchans in laboratory, reducing the interaction time from years to seconds.

Endo *et al.* (2004), through experiments with aligned subaqueous barchans, observed three interaction patterns using different mass ratios between dunes. Also, Hersen and Douady (2005) investigated the interaction of two dunes by modifying the transverse distances between them. Even with the previous experiments and observations, how the morphology and dynamics of barchans are affected during interaction are still open to be investigated.

Recently, Assis and Franklin (2020) investigated, experimentally the short-range interactions occurring between two subaqueous barchans. Varying the grain types (diameter, density, and roundness), pile masses, transverse distances, water flow rates, and initial conditions, five different patterns were identified for both aligned and off-centered configurations and interaction maps that depend basically on the ratio between the number of grains of each dune, Shields number, and alignment of barchans were proposed.

For a better understanding of dunes movement in a field, there is the need to understand the physics of its elementary components, which are the particles. Lajeunesse *et al.* (2010) carried out experiments filming moving particles on a flat bed. The grain trajectory was computed and it was observed that the distribution of longitudinal and transversal velocity of the particles follows exponential and Gaussian curves, respectively. Penteado and Franklin (2016) determined, experimentally, the displacement and velocity fields of the grains moving on flat bed-load. Wenzel and de Moraes Franklin (2019) investigated and experimentally followed the particles over a subaqueous barchan. By means of image processing, the authors determined the velocity field and particles trajectory. Higher speeds were found near the centroid of the dune and their trajectories to follow an intermittent path. Depending on the region over the dune, it was found that the velocity fields present values from 1% to 10% of the average fluid velocity in the cross section. Alvarez and Franklin (2019) studied the dynamics of grains that migrate to horns in subaqueous barchan. It has been shown that the trajectory of the particles that migrate to the horns comes from upstream regions of the bedform, exhibiting significant transversal displacements.

This work aims to investigate the morphology and grain displacements between two barchans with similar masses in aligned position (called chasing pattern in Assis and Franklin (2020)). To achieve this objective, the experiment was carried out and treated via image processing.

2. METHODOLOGY

2.1 Experimental Setup

The experimental setup consisted in a 5 m long closed-conduit channel with a rectangular cross-section (width α = 160 mm and height β = 50 mm). A water reservoir, two centrifugal pumps, a flow straightener, settling tank and return line are part of the equipment as well. A divergent-convergent nozzle with glass spheres of 3 mm in diameter was used, and its function is to homogenize the flow inside the channel. The test section is 1 m long and starts 40 hydraulic diameters downstream of the channel inlet. With the channel filled with water, the first amount of grains was poured in the test section, and after that, the channel was turned on to develop a barchan dune. In the following, the second amount of grains was placed upstream the barchan dune developed to start simulating interaction. Figure 1 represents the layout of the described experimental setup.

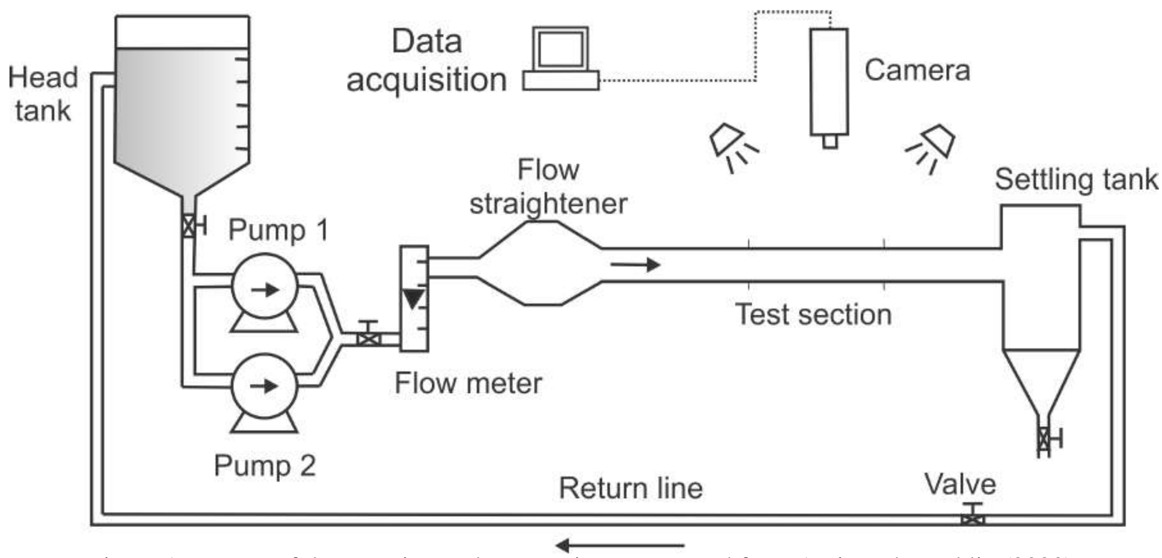


Figure 1: Layout of the experimental setup. Figure extracted from Assis and Franklin (2020).

Two kinds of tests were carried out: the first one, analyzing the dune morphology, round glass beads were used (ρ_s = 2500kg/m^3) with 0.15 mm $\leq$ d $\leq$ 0.25 mm. The mass of the initial heap, which forms the target dune, and the second heap, which forms the impact dune, were 3 g and 2.7 g, respectively; in the second one, analyzing the grain motion, round glass beads were used (ρ_s = 2500kg/m^3) with 0.40 mm $\leq$ d $\leq$ 0.60 mm, where ρ_s and d are density and diameter of the particles, respectively. The mass of both heaps was 10 g. To acquire the images, a camera was placed above the test section. For the first trial, the frequency used was 1 Hz and the *ROI* (region of interest) was fixed in 1920*px* x 481*px*. For the second trial, a speed camera with 200 Hz of frequency was used and the *ROI* (region of interest) was fixed in 2560*px* x 1200*px*. For both tests, the water flow was Q = 8 m^3/h which correspond to a cross-section mean velocity of $\overline{U}$ = 0.28 m/s and to Reynolds number based on channel height $Re = \rho\overline{U}\beta/\mu$ of $1.39 \cdot 10^{\,4}$, where ρ is the density and μ is the dynamic viscosity of the fluid.

2.2 Image Processing

A numerical code was developed to treat and process the images acquired with the setup described in subsection 2.1. For the first test performed, for each image, the code identifies reference points to measure the dune width (W), length (L), and horn length (L_h). Also, the distances between dunes centroids in y (η) and x (ζ) directions are computed as well. For the second test performed, the particles were identified and the centroid value of each one was followed over 1500 images (representing about 7.5 s of interaction). Figures 2 (a) and (b) show the raw image acquired for test 1 and treated image with measurements taken, respectively. Figures 2 (c) and (d) show the raw image at grain scale and particles identification.

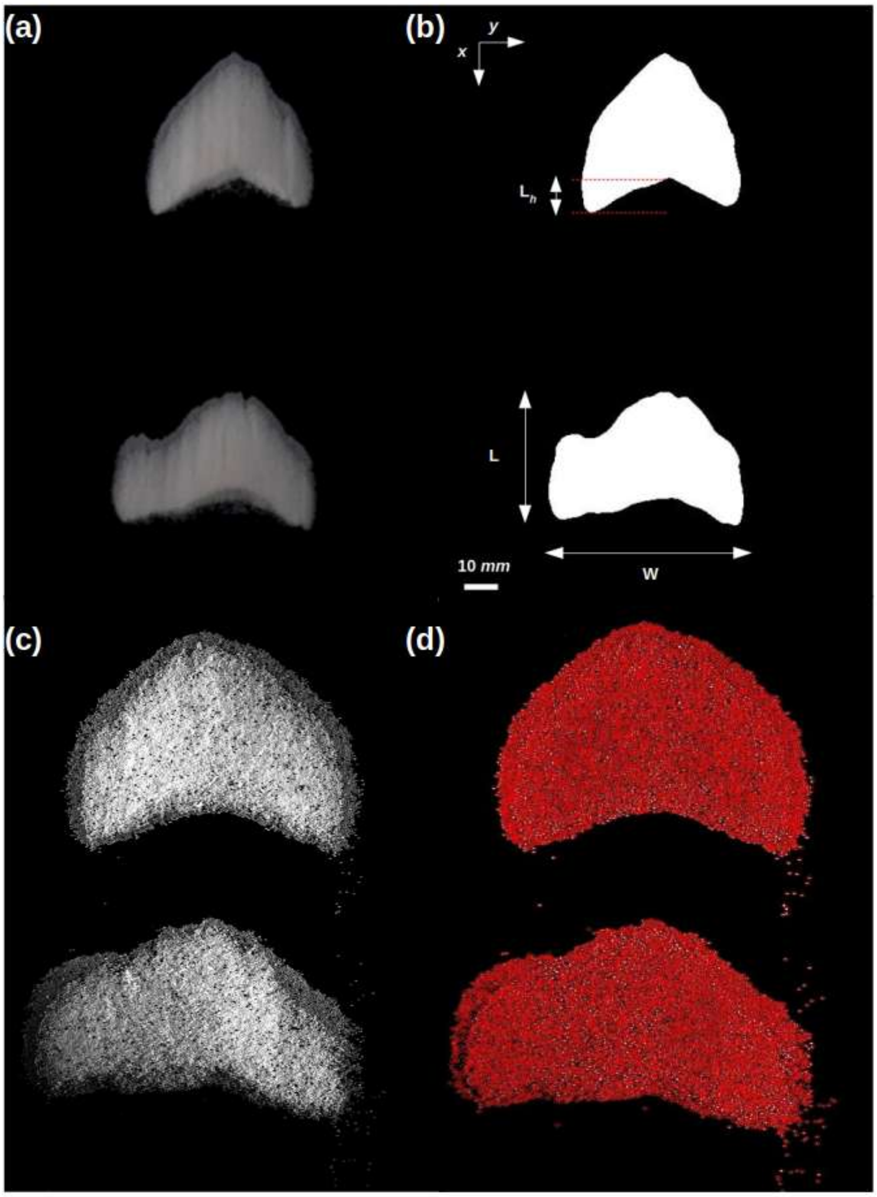


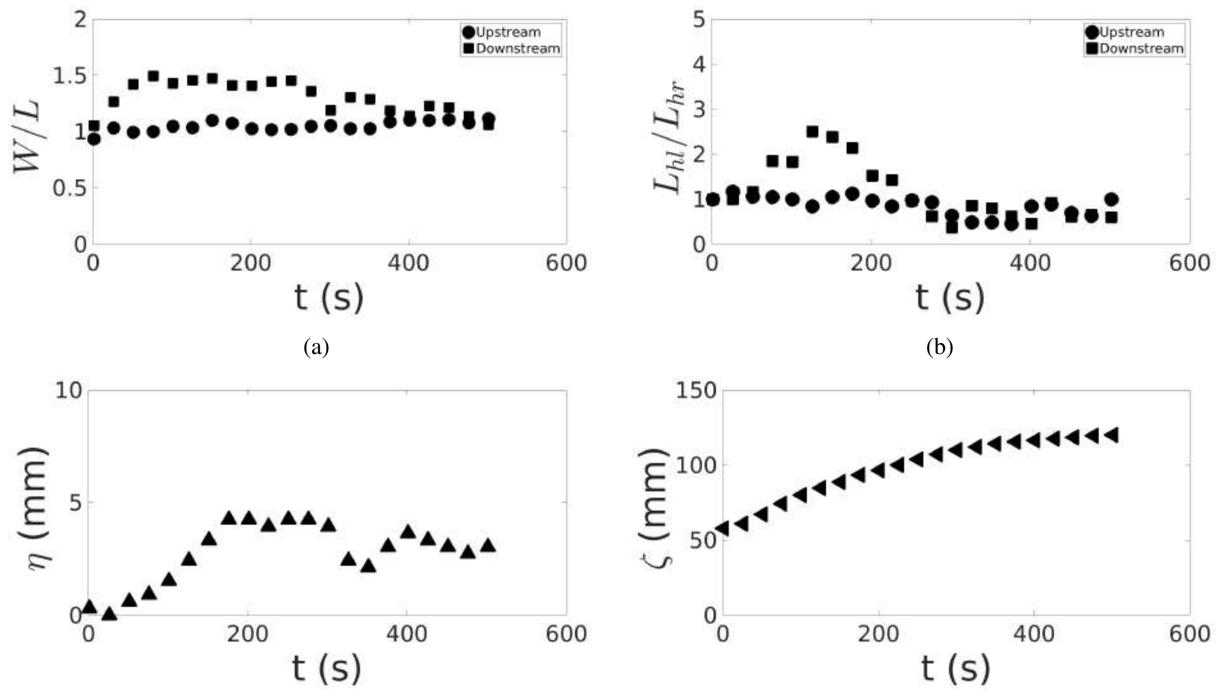
Figure 2: Interaction between two barchans. (a) Raw image at dune scale; (b) treated image with measurements analyzed; (c) raw image at grain scale; (d) treated image with particles identified in red circles.

3. PRELIMINARY RESULTS

3.1 Morphology of two interacting barchans

As preliminary results, we can observe in Fig. 3(a) that the morphology of downstream dune is affected by the disturbance that the upstream dune causes in the fluid flow (Bristow *et al.*, 2018). In Fig. 3(b) we computed the ratio between left (L_{hl}) and right (L_{hr}) horns, according to the fluid direction. Asymmetry in the downstream dune occurs, mainly at the beginning of the test, where the longitudinal distance of dunes is considered still short.

Figures 3 (c) and (d) show the distance between dunes in x and y directions, respectively. We can observe that there is an erosion process in the downstream dune, being displaced transversely. Besides, even if downstream one has a larger mass and receives grains throughout the process, it moves faster than the upstream dune, with no collision during the test. Another point observed is that after a certain time of interaction (in this case, about 300 seconds), the downstream dune behaves with no more interaction with upstream dune, returning to symmetry and morphology similar to an isolated body.



(a) (b) (c) (d)

Figure 3: (a) Ratio between width and length of dunes. (b) The ratio between left and right horn lengths of both dunes. Finally, (c) and (d) represent the variation of transversal and longitudinal distances between dunes during interaction.

Although the results are preliminar, they can lead to a better understanding of the dynamics in a dune field. Barchans with similar masses interact with each other with no collision during the process. After a certain time and length of interaction (to be determined), the dunes return to behaving as isolated objects. More investigation needs to be done to confirm the physical aspects described in this work.

3.2 Grain displacement between barchans

Another aspect investigated in this work is the dynamics of the particles exchanged between the dunes. The first analysis was performed qualitatively and appears in the figures 4 (a) and (b), where red and blue lines mean particles trajectory leaving the upstream and downstream dune, respectively. Figures 4 (a) and (b) represent the initial and final instant of the interactions between the two dunes. The full view of the chasing pattern with aligned dunes can be found in the article Assis and Franklin (2020).

At the beginning of the interaction (figure 4(a)), a total number of 180 particles were computed leaving the upstream dune. Over this total, 59.4% of them remain on the downstrem dune (only 1.1% enters the recirculation region; the remainder enters laterally and in the upstream region of the downstream dune) and the rest of them do not interact. Grains from downstream dune and leaving it were computed and 162 particles were found. Although the dunes have the same mass, the total number of grains that the downstream dune receives is less than the amount of grains it loses, leaving a total balance of 55 particles lost during the filmed interaction. Comparatively, the total balance of the upstream dune was 180 particles lost during the process.

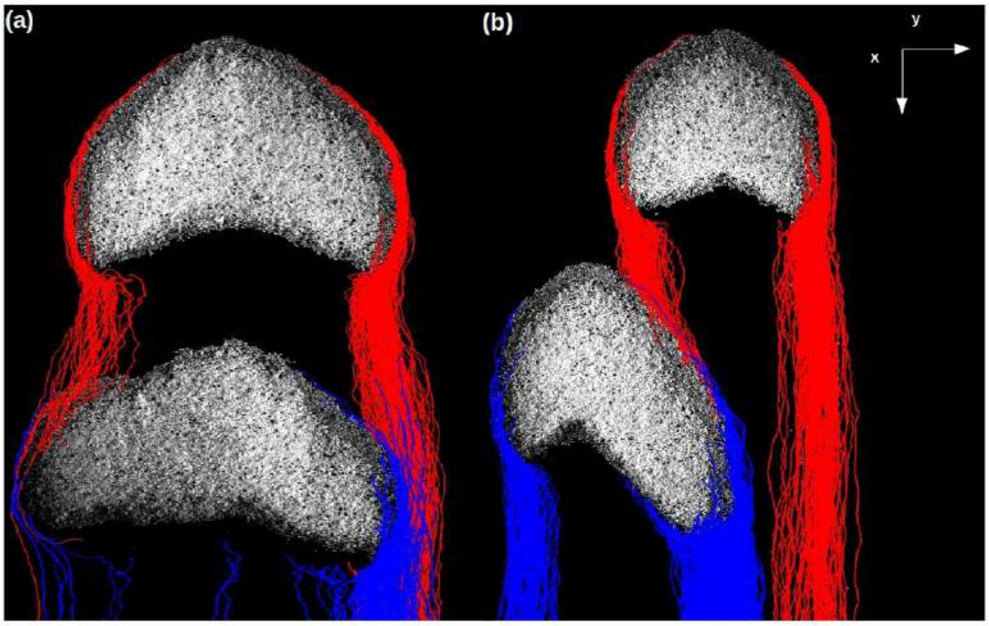
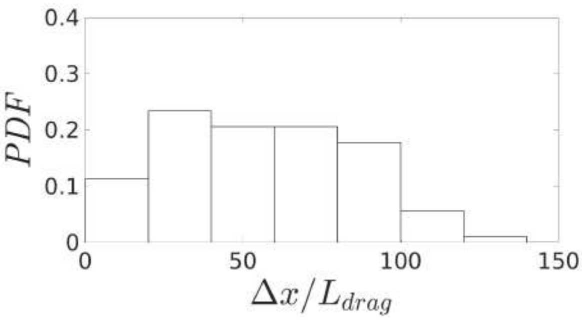
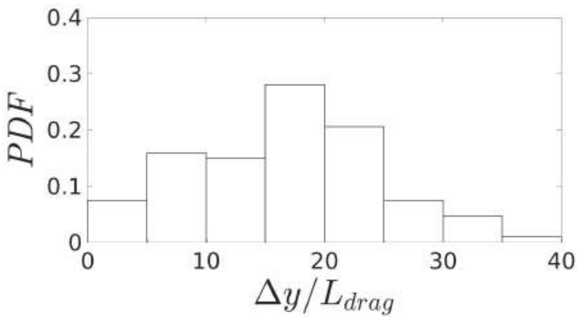


Figure 4: Trajectory of the particles exchanged between barchans. Red and blue lines mean trajectories of the particles leaving upstream and downstream dune, respectively.

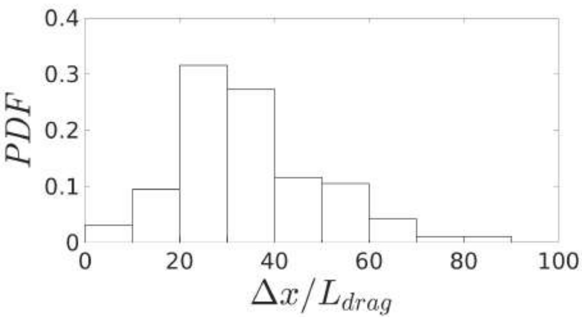
From figure 4(b) the downstream dune lost 534 particles and the upstream one lost 306 particles. Of this total of 306, 95 of them ended up on the downstream dune (representing 31.04%) and the location was mainly at the upstream and left side (according to the fluid flow) of the downstream dune. This results can prove that the erosion process is larger in the downstream dune due the wake of the upstream dune, which increases turbulent levels and creates channeling (Bristow *et al.* (2018)).



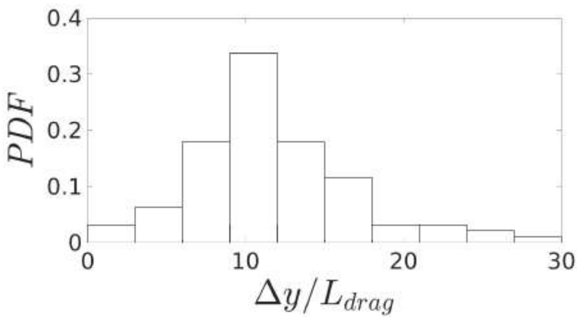
(a)



(b)



(c)



(d)

Figure 5: PDFs of longitudinal (Δx) and transversal (Δy) traveled length of the particles that leave the upstream dune and arrive at the downstream one parameterized by inertial length L_{drag}. Figures 5(a),(b) and (c),(d) show longitudinal and transversal length of the particles analyzed from Figure 4(a) and (b), respectively.

The second analysis was to compute the trajectories and velocities of the particles which are leaving the upstream dune and arriving the downstream one. Figure 5 shows probability density functions (PDFs) for the longitudinal (Δx) and transversal (Δy) traveled length of the particles that leave the upstream dune and arrive at the downstream one parameterized by inertial length L_{drag} = (ρ_s/ρ)d, which it is proportional to the saturation length L_{sat} and it is the length necessary for the sand flux to reach equilibrium conditions (Andreotti *et al.* (2002)). The mean value of longitudinal and transversal distances were calculated by computing the total distance traveled by each particle and taking the arithmetic mean. Results of 56.3 and 16.7 (figures 5(a) and (b) for the beginning of the interaction) and 34.6 and 11.5 (Figures 5(c) and (d) for the end of the interaction) were obtained. The results obtained until here are similar with results from (Alvarez and Franklin, 2019), which investigated the dynamics of grains moving to horns.

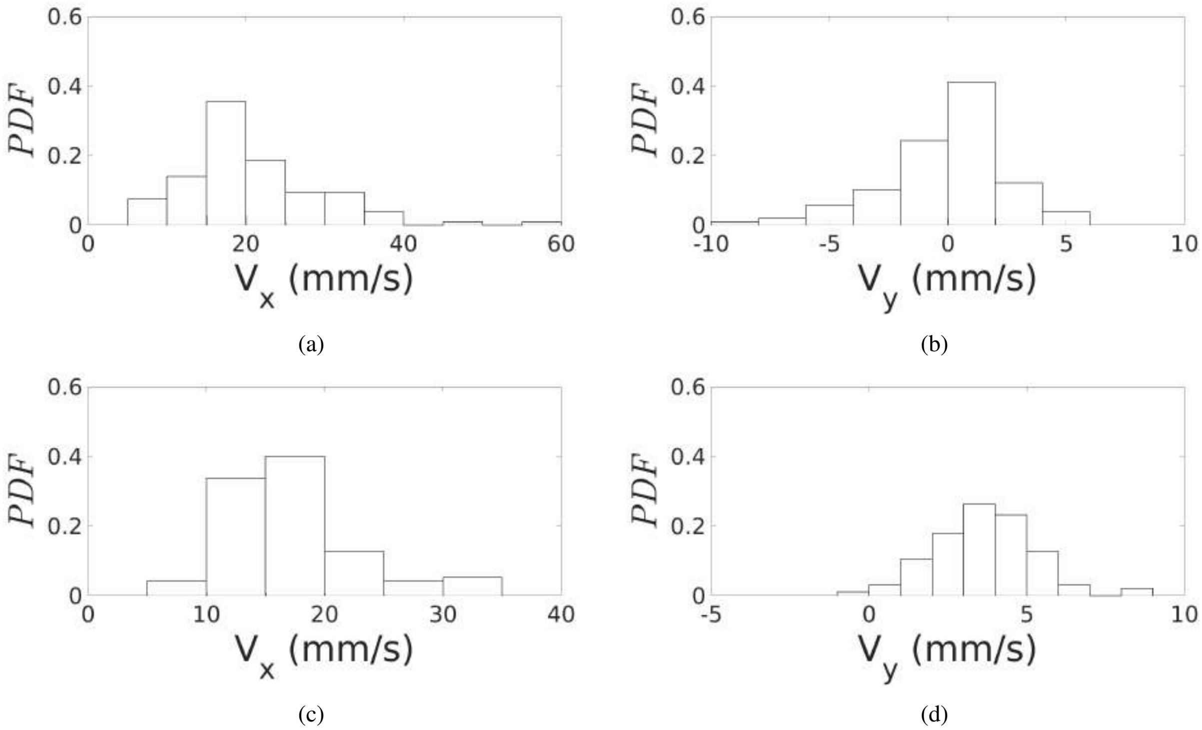


Figure 6: PDFs of longitudinal (V_x) and transversal (V_y) velocities of the particles that leave the upstream dune and arrive at the downstream one. Figures 6(a),(b) and (c),(d) show longitudinal and transversal velocities of the particles analyzed from Figure 4(a) and (b), respectively.

Finally, longitudinal (V_x) and transversal (V_y) velocities were calculated for each condition analyzed and PDFs are also plotted. Figures 6(a) and (c) show similar longitudinal velocity for both inital and final condition of interaction. Figure 6(d) shows higher values of V_y comparing with Figure 6(b) because the grains that arrive at the downstream dune in the final condition of interaction (Figure 4 (b)) come from just one horn from upstream one. Although preliminary, these analyzes may clarify the understanding of dynamics of barchans in a dune field.

4. ACKNOWLEDGEMENTS

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