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The effect of periodic changes in wind direction on the deformation and morphology of isolated sand dunes based on flume experiments and field data from the Western Sahara

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A R T I C L E I N F O

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A B S T R A C T

Sand dunes are shaped by the effect of wind on sand particles; consequently, their morphologies are strongly influenced by complex seasonal variations in wind direction. To improve our understanding of these effects we conducted flume experiments that generated periodically bidirectional and oblique flows, and found that dune topographies were controlled by two elements under these conditions. The most important factor was the angle between the two flow directions, which determined both the nature of change in the crest line following the change in flow direction, and the resultant topography. The second factor was the event duration ratio of the two flows, which influenced the curvature of the crest line. A new phase diagram of the morphological development of isolated dunes under bidirectional flow conditions is proposed, driven by differences in flow angle and duration. This diagram is in good agreement with data from a natural dune field in the Western Sahara where the wind regime is well understood.

1. Introduction

Sand dune morphology is controlled by the interaction of sand particles on the dune surface with the wind regime. Since Bagnold's pioneering study (Bagnold, 1941), many observational and experimental studies have been conducted to investigate the relationship between dune shape and environmental conditions. Wasson and Hyde (1983) summarized the conditions necessary for the formation of four types of unvegetated dune (star, transverse, longitudinal and barchan), in a phase diagram showing the relationship between wind complexity and the volume of sand available.

Knowledge of the conditions under which a dune formed makes it possible to use dunes as indicators of wind conditions where direct wind measurements are not possible, such as in extraterrestrial fields; e.g., Mars (Sagan et al., 1973; Breed et al., 1979b; Thomas and Veverka, 1979; Tsoar et al., 1979; Fenton et al., 2003), Venus (Greeley et al., 1992) and Titan (Greeley et al., 1992; Radebaugh et al., 2008; Rubin et al., 2009). While high resolution satellite images have contributed to such investigations by allowing comparison to typical dune types found on earth, unfamiliar sand dunes have also been discovered such as teardrop shaped dunes in Wirtz Crater on Mars (Edgett et al., 2003).

Although sand dunes formed by unidirectional wind (i.e. barchan and transverse dunes) have been used for estimation of dominant wind direction since 1970s, methods for estimation of complex wind conditions from the shape of sand dunes have not been established yet. There are two groups of candidates for indicators of complex wind conditions. One is sand dunes on a continuous sand sheet, such as longitudinal and star dunes. The other is atypical isolated dunes, including the unfamiliar sand dunes observed in extraterrestrial fields.

Among the first group of candidates, the formation of star dunes requires at least tri-directional wind. Since the wind condition is too complex, star dunes have not been used for wind estimation. Lancaster (1989) stated that a star dune with four radial arms was formed by tri-directional wind. A numerical simulation by Zhang et al. (2012) showed the shape of star dunes under multi-directional wind conditions (up to seven directions). Longitudinal dunes seem to form under oblique bidirectional wind and to lie along the averaged wind direction, but it is known that the dune orientation does not correspond to the directions of the averaged wind in the cases where the amounts of the sand transported in two wind directions are not even. Rubin and Hunter (1987) and Rubin and Ikeda (1990) conducted flume experiments on continuous sand topographies using bidirectional flows, which included oblique (non-180°) cases, and showed that the crest lines lay perpendicular to the direction of net sand transportation (transverse dune) in the cases where the angular variation was below 90°, but that crest lines became parallel (longitudinal dunes) or oblique (oblique dunes) when angular

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variations were above 90°. They concluded that such continuous dunes could only indicate whether or not the angular variation had exceeded 90°, and that it was not possible to reconstruct the detailed flow conditions from the crest orientation alone. Furthermore, crest orientations showed wide variability from run to run, even though the flow conditions were the same, and this was thought to be caused by the strong interaction of adjacent dunes. Moreover, Rubin et al. (2009) reported that longitudinal dunes can be formed under unidirectional wind in the area covered with cohesive sands.

In contrast with continuous dunes, the shape of isolated dunes exhibits high variety. Bourke and Goudie (2009) classified symmetric barchan dunes into four types depending on the ratio between the body length and the distance of two horns. Bourke (2010) showed a new classification of barchan dunes with asymmetric limbs, and she pointed out the necessity of further information on the range of application, because potential causes of these atypical dunes were not only bidirectional wind but also dune collision, surrounding topography and asymmetry of sand supply.

Previous theoretical works have studied dune collision and isolated dunes under bidirectional flows; e.g., Schwämmle and Herrmann (2003) and Katsuki et al. (2005) constructed models of the collision between two barchan dunes and reproduced three types of behavior, while Parteli and Herrmann (2007a,b) conducted numerical simulations under bidirectional flows to reproduce an unusual type of Martian isolated dune.

Physical experiments on isolated dunes have been conducted mainly in water flumes, rather than in wind tunnels, because the minimum size of aeolian barchan dunes is larger than subaqueous ones, and in small wind tunnels the necessarily small sand topographies are too easily eroded to allow long-term study of the deformation processes (Andreotti et al., 2002; Dauchot et al., 2002) due to the long saturation length l_s (Sauermann et al., 2001). In contrast, ripple-sized subaqueous barchans behave in the same manner as natural aeolian barchans; i.e., they migrate in the leeward direction while maintaining their crescentic shape (Niño and Barahona, 1997; Hersen et al., 2002; Kleinhans et al., 2002; Endo et al., 2004).

Taniguchi and Endo (2007) showed that deformed barchan topographies depended on the drift potential ratio, through flume experiments under bidirectional flow conditions where the intensity of the two flows was varied, although the angular variation was fixed at 180°. Reffet et al. (2010) and Taniguchi et al. (2011) independently studied isolated sand dune morphology using even-intensity bidirectional flows running obliquely, but each starting with different initial states; the former adopted a conical sand pile, a transverse ridge, and a longitudinal ridge, while the latter used a conical sand pile only. Taniguchi et al. (2011) found three types of isolated dune morphologies that were related to changes in the angular variation of the bidirectional flow, which suggests that these three morphologies, as well as barchans, can be used as indicators of angular variation in wind direction at the time of dune formation. However, further study is required to determine more precisely the critical threshold of angular variation for each type of dune. Reffet et al. (2010) report similar results to Taniguchi et al. (2011) despite different initial conditions.

In this paper we aim to: 1) determine the critical angular variations of several dune-deformation processes, and the resultant sand topographies, through detailed flume experiments using 15 increments in angular variation; 2) quantify the effect of the event duration ratio of two flows under bidirectional conditions where the durations of the two flows are different; 3) propose a new phase diagram for isolated sand dune morphology that relates the angular variation θ to the event duration ratio α, in contrast to previous models that relied upon RDP/DP that is the ratio between absolute value of the Resultant Drift Potential (RDP) and the sum of the Drift Potentials (DP) (Wasson and Hyde, 1983); and 4) test the applicability of the new phase diagram against data from a dune field in the Western Sahara where the wind regime is well understood.

2. Materials and methods

2.1. Apparatus

Experiments were carried out using a water flume (Fig. 1(a)) that consisted of an open channel (width: 50 cm, length: 5.6 m, and depth:

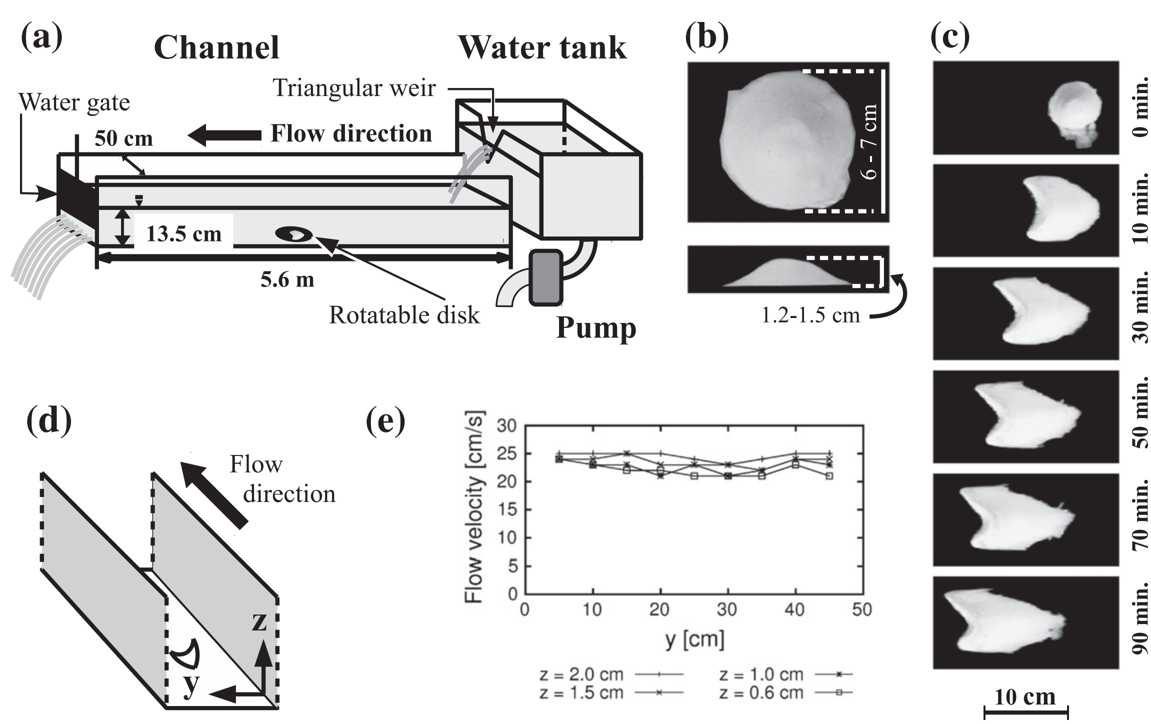

Fig. 1. The water flume, initial topography, and flow conditions. (a) The water flume. (b) The initial topography of the sand pile used in the experiments. (c) Photographs showing the migration of the topography. The flow direction is from bottom to top. (d) Definitions of *y* and *z*. (e) Profile of flow velocity in the flume.