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Experimental and numerical study of Sharp's shadow zone hypothesis on sand ripple wavelength

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ABSTRACT

Despite advances in understanding processes of sand transport by saltation and reptation, which are involved in the formation of sand ripples, the mechanisms that determine the linear dependence of ripple spacing on wind speed and their relative importance are yet unknown. In a pivotal study, Sharp (1963) proposed that this linear dependence arises from the scaling of the ripples' shadow zone – the part of the ripple devoid of particle impacts – with the wind speed. Here, we test this hypothesis by integrating wind tunnel experiments with numerical simulations of saltation. Specifically, we measured the effective shadow zone by using sand traps designed for this purpose and found a linear relationship between the shadow zone and the wind shear velocity, consistent with Sharp's hypothesis. However, contrary to what Sharp assumed, we found that the shadow zone is not completely screened from particle impacts, which as indicated by numerical simulations is due to the wide distribution of impact angles. Nonetheless, the shadow zone can be one of the major mechanisms contributing to the linear increase of the ripple wavelength with wind speed at the nonlinear growth stage of the ripples where merging events between small ripples take place. However, for the initial stage of ripple development, when the ripple dimension is small, other mechanisms can be dominant, such as the recently suggested resonant saltation trajectory (Durán et al., 2014).

1. Introduction

Sand ripples are the smallest aeolian bedform (<30 cm) created in sand, characterized by an asymmetric ridge perpendicular to the prevailing wind direction, usually transverse stable (Yizhaq et al., 2012), and with a unimodal sand size distribution (Fig. 1). The ripple height (*H*) is defined as the vertical distance between the bottom of the trough to the top of the ridge, and the ripple wavelength (λ) is the distance between one ridge crest to the next. The ripple index (*RI*) is the ratio between λ and *H* ($RI = \lambda/H$) (Bagnold, 1941; Sharp, 1963).

As the wind speed exceeds a certain threshold, sand grains begin to move, mostly through saltation and reptation (Kok et al., 2012) to create ripples. The motion of grains transported by saltation is composed of a series of asymmetric ballistic trajectories which are accelerated by the wind and upon hitting the bed they eject low energy grains. These grains move in small jumps close to the surface through a mode of transport known as reptation (Anderson, 1987; Durán et al., 2014; Warren, 2014).

The ripple dimensions (height and wavelength) grow in time until reaching an equilibrium where the growing ceases and the ripples only drift downwind with a velocity (celerity) which is linearly depended on wind speed (Andreotti et al., 2006; Rasmussen et al., 2015). Their steady state dimension depends on the wind velocity and on grain diameter (Bagnold, 1941; Sharp, 1963; Seppälä and Lindé, 1978; Anderson, 1987; Andreotti et al., 2006; Durán et al., 2014) as shown in Fig. 2.

The basic symmetry-breaking mechanism behind the formation of normal sand ripples is commonly described as a screening instability (Andreotti et al., 2006). When the high energy saltation grains collide with the bed, they eject grains of smaller energy, termed reptons. The windward slope of a small bump is subject to more impacts than the lee slope, so that the flux of reptation particles is higher uphill than downhill, thereby enlarging the bump. Although normal ripples were extensively studied and their

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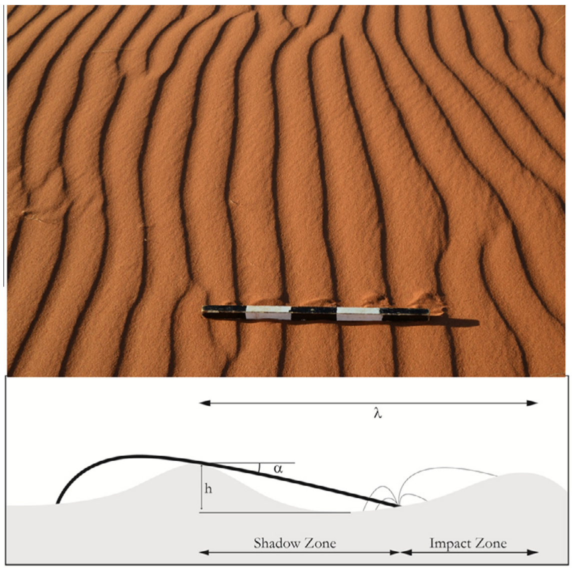

Fig. 1. (a) Ripples at NamibRand Nature Reserve (Namibia) with wavelength of 10 cm. The prevailing wind is from left to right (indicated by the white arrow). The divisions on the scale bar are of 10 cm. (b) Schematic illustration of the Sharp (1963) impact zone hypothesis. The impact angle of the saltation particle is denoted by α. The shadow zone is the region in the lee side of the ripple that is protected from bombardment by saltation particles.

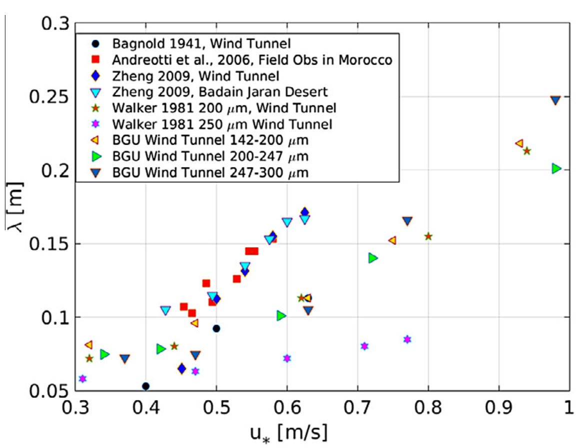

Fig. 2. Summary of wind tunnel and field measurements of ripple wavelength (λ) against shear velocity u_*. In most of the measurements the ripple wavelength increases linearly with shear velocity.

instability mechanism was captured by many mathematical models (e.g. Anderson, 1987; Yizhaq et al., 2004; Manukyan and Prigozhin, 2009), there are still open questions regarding their formation. The most challenging one is the dependence of the wavelength on wind speed (Andreotti et al., 2013). Experimental (Rioual et al., 2000), numerical, and theoretical results (Kok et al., 2012; Lämmel et al., 2012; Yizhaq et al., 2014) indicate that the mean reptation length does not depend on the wind shear velocity. Thus, the models based on Anderson's model (Anderson, 1987) that assume that the initial wavelength of the ripple is ~6 times the mean reptation length, failed to explain the wavelength dependence on wind speed. This indicates that something is still missing in the current models of sand ripples and in our understanding of sand transport processes. The basic physical mechanism which dictates the ripple wavelength is still in debate after more than 100 years of research since the work of Cornish (1914).

Bagnold claimed that λ is determined by the mean characteristic path of a saltation grain (Bagnold, 1941), which increases with wind velocity. Later works (Sharp, 1963; Walker, 1981; Anderson, 1990) showed no relation between these two factors and that ripples start as small bumps that grow in time, their final wavelength not directly related to the mean saltation path. Bagnold's theory was first challenged by Sharp (1963) who argued that the ripple wavelength depends on the ripple height and on the impact angle α – at which the saltation grains approach the surface. Thus, the ripple wavelength is mainly dictated by the size of a shadow zone s (Fig. 3) that is sheltered from a significant sand grain impact. Since the impact angle is inversely related to the wind velocity, stronger winds will produce longer wavelengths since the shadow zone length becomes larger (Cooke and Warren, 1973). According to Sharp (1963), the length of the impact zone i decreases with wind velocity and increases with grain size and ripple height (see also Pye and Tsoar, 2009). The ripple wavelength can be approximated by $\lambda = i + s$; thus, if λ increases with wind velocity, the increase in s should exceed the decrease in i. Thus, the ratio i/s which is a measure of the ripple asymmetry should increase with grain size and decrease with wind velocity.

According to numerical simulations and wind tunnel experiments, most of the saltating grains impact the surface at angles between 10° and 15° (Anderson, 1987; Nalpanis et al., 1993). Most experiments found that the impact angle decreases with shear velocity u_*, and increases with grain size (Jensen and Sørensen, 1986; Willetts and Rice, 1989; Rice et al., 1995; Fu et al., 2013), due to the larger vertical component of the terminal velocity of the coarse grains (it scales as the square root of the grain diameter).

However, in wind tunnel experiments Fu et al. (2013) found a much wider distribution of incident angles (0–180°) than most accepted ranges reported in previous works, probably due to the experimental difficulty to discern between saltation and reptation particles.

Sharp (1963) found a relation between λ and shear velocity u_* but not with the mean grain diameter (Walker, 1981). A linear relation between λ and h was obtained for steady state equilibrium wind tunnel ripples (Andreotti et al., 2006). Recently it was suggested by direct numerical simulations of grains (45,000) interacting with a wind flow (Durán et al., 2014) that the instability is driven by resonant grain trajectories with a distance that is close to the initial ripple wavelength. The initial wavelength increased linearly with the wind velocity, but the relation to the final wavelength was not clear in this study. Durán et al. (2014) argued that the screening instability predicts a wavelength which is independent of the shear velocity, and that spatial modulation of the saltating flux, which was assumed uniform in Anderson's model (1987), is needed to explain their new hypothesis.

It is important to note that according to the gravity waves theory for ripple formation, ripples are initiated by Helmholtz instability between the dense saltation layer and the air above it, treating them as two fluids (Brugmans, 1983; Milana, 2009). The prediction of this theory is that the wavelength scales the square of the wind speed, which contradicts wind tunnel experiments and field observations (see Fig. 2).

Uncertainties remain in characterizing the physical mechanisms that control the relations between wind velocities and ripple wavelength and height. We suggest that Sharp's shadow zone theory can be one of the mechanisms contributing to the linear dependence between the ripple wavelength and wind velocity. This mechanism was explored directly for the first time in this study, by combining experiments in a boundary-layer wind tunnel and numerical models of saltation.