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Field observations of wind profiles and sand fluxes above the windward slope of a sand dune before and after the establishment of semi-buried straw checkerboard barriers

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ABSTRACT

Straw checkerboard barriers are effective and widely used measures to control near-surface sand flow. The present study measured the wind profiles and sand mass flux above the windward slope of a transverse dune before and after the establishment of semi-buried straw checkerboards. The 0.2 m high checkerboards enhanced the aerodynamic roughness length to larger than 0.02 m, which was two to three orders of magnitude higher than that of the bare sand. The modified Charnock model predicted the roughness length of the sand bed during saltation well, with $C_m = 0.138 \pm 0.003$. For the checkerboards, z_0 increased slowly to a level around 0.037 m with increasing wind velocity and the rate of increase tended to slow down in strong wind. The barriers reduced sand flux and altered its vertical distribution. The total height-integrated dimensionless mass flux of saltating particles (q_0) above bare sand followed the relationship $\ln q_0 = a + b(u_{*t}/u_*) + c(u_{*t}/u_*)^2$, with a peak at $u_*/u_{*t} \approx 2$, whereas a possible peak appeared at $u_*/u_{*t} \approx 1.5$ above 1 m × 1 m straw checkerboards. The vertical distribution of mass flux above these barriers resembled an "elephant trunk", with maximum mass flux at 0.05–0.2 m above the bed, in contrast with the continuously and rapidly decreasing mass flux with increasing height above the bare sand. The influences of the barriers on the wind and sand flow prevent dune movement and alter the evolution of dune morphology.

1. Introduction

Straw checkerboard barriers are an inexpensive, convenient, effective, and widely used measure to control near-surface sand flow (Zheng, 2009). The barriers have been successfully used in the protective system of the Baotou–Lanzhou railway line where it crosses the Tengger Desert and in the protective system of the Taklamakan Desert Highway in western China, as well as in other desert regions of China. Checkerboard barriers can be constructed from the straw of wheat, rice, reeds, or other plants. In practice, the straw is arranged in the shape of a checkerboard and half is buried in the sand and the other half is left exposed (Fig. 1). The barriers are generally installed at a size of 1 m × 1 m or a little larger and typically have 0.2 m of straw height above the surface. The barriers disrupt the flow of wind and thereby change the structures, direction, and intensity of the near-surface wind–sand flow above mobile sands, reducing erosion and facilitating surface stability. This plays an important role in fixing sand by preventing surface sand from encroachment and causing sand in transport to settle in place. This technique has now been introduced in Ghana, Egypt, and Iran (Zheng, 2009).

Much research has been done on understanding the mechanisms by which the straw checkerboard barriers control sand flow, including studies of the principles that govern the control of blowing sand, the size of the barriers, and their effectiveness (Buckley, 1987; Wolfe and Nickling, 1993; Arens et al., 2001; Qu et al., 2007). It is generally accepted that the barriers increase the roughness of the underlying surface, reduce the wind velocity and sand transport intensity (Gao et al., 2004; Qiu et al., 2004), and create a stable, concave surface inside the grid created by the barriers (Ling, 1991; Wang and Zheng, 2002). Work has also been done on the remarkable ecosystem effects of the barriers, which can promote the formation of biological soil crusts and the restoration of habitat and species diversity (Li et al., 2004, 2006b). Previous research

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Fig. 1. Semi-buried straw checkerboard barriers.

focused mainly on wind tunnel simulations (Liu, 1988) or theoretical deductions (Wang and Zheng, 2002), and there have been few field observations (e.g., Qu et al., 2007). To improve our comprehension of how the barriers affect the near-surface wind and sand flow, field observations of the near-bed wind behavior and particle transport are needed.

The near-bed behavior of wind above bare mobile sand in the presence of a particle flow has been well studied (Owen, 1964; Williams, 1964; Anderson and Haff, 1988, 1991; Sørensen, 1991, 2004; White and Mounla, 1991; Rasmussen et al., 1996; McKenna Neuman and Maljaars, 1997; Iversen and Rasmussen, 1999; Namikas, 2003). Owen (1964) first described the apparent saltation-induced aerodynamic roughness length, which depends on the shear velocity:

$$z_0' = Cu_*^2/2g \tag{1}$$

where z_0' is the apparent saltation-induced aerodynamic roughness length (m), C is a proportionality constant, u_* is the shear velocity (m s^{-1}), and g is the acceleration due to gravity (m s^{-2}). Since then, several models have been proposed to relate the aerodynamic roughness length during saltation to the shear velocity (Raupach, 1991; Sherman, 1992; Butterfield, 1993; Farrell, 1999; Sherman and Farrell, 2008). However, the most physically plausible relationship is the modified Charnock relationship (Sherman, 1992; Sherman and Farrell, 2008):

$$g(z_0' - z_0) = C_m(u_* - u_{*t})^2 \tag{2}$$

where z_0 is the aerodynamic roughness length in the absence of saltation (m), C_m is the modified Charnock constant, and u_{*t} is the impact threshold (m s^{-1}). Sherman and Farrell (2008) used a compilation of 137 wind profiles from field measurements and determined the value of the modified Charnock constant to be 0.132 ± 0.080. The best-fit value of the modified Charnock constant from a comprehensive numerical model of steady-state saltation (COMSALT) by Kok and Renno (2009) was 0.118, which is close to the empirical value obtained by Sherman and Farrell (2008).

Sand flow caused by wind above sand dunes represents a fundamental geomorphological process. Bagnold (1936) was the first researcher to relate the sand transport rate to u_*, but in the past century, many aeolian sand-transport models have been developed (Bagnold, 1937; Kawamura, 1951; Zingg, 1953; Owen, 1964; Kadib, 1965; Hsu, 1971; Lettau and Lettau, 1978; White, 1979; Sørensen, 2004; Kok and Renno, 2009). These models are able to predict the observed maximum total mass flux to different degrees of accuracy (Sherman and Li, 2012; Sterk et al., 2012). This important progress has reiterated the necessity to obtain reliable predictions of mass flux for verification of sediment transport models and the calibration of theoretically derived flux equations.

Studies of the near-bed behavior of wind within the saltation layer and of the movement of sediments caused by wind have clarified the properties of this air flow and sediment transport, though some of the theories still need verification with field observations. Above the sand surface covered by straw checkerboard barriers, the near-bed air flow and particle movement tend to be more complex than in their absence. Although wind tunnel observations and theoretical simulations have been carried out to explore these phenomena, there have been few field observations examining the difference in aeolian transport characteristics above these barriers compared with that above bare sand (e.g., Zhou et al., 2014).

Given these limits of our knowledge, we designed a field study to provide additional information to increase our understanding of the effect of checkerboard roughness on saltation processes. Based on comparative field observations above the same windward slope of a sand dune, we (i) compared the vertical wind profiles above bare sand and two sizes of straw checkerboard barrier; (ii) explored the vertical distribution of sediment flow above the three surfaces; (iii) examined the applicability of the modified Charnock model (Sherman, 1992) for describing near-bed wind profiles; and (iv) analyzed the relationship between the sand transport rate and the wind shear velocity above the windward slope of sand dunes.

2. Materials and methods

2.1. Study site

The Shapotou section of the Baotou–Lanzhou railway is located southeast of China's Tengger Desert (37°27′N, 104°59′E), where network dunes, barchan dunes, and barchan chains are the main dune types (Fig. 2). The prevailing wind direction is from the NW and WNW; ENE is an important secondary wind direction.

The railway protective system in the Shapotou area consists of four parts: an upright sand fence farthest upwind, a belt of straw checkerboards and vegetation without irrigation, an irrigated vegetation zone, and a gravel platform for sand transport with no settlement. The protective system has continued to work well since its establishment in 1956. The straw checkerboards and the vegetation belt without irrigation are the main parts of the protective system. At the upwind edge of the protective system, straw checkerboard barriers have been installed on the upper parts of the windward slopes of sand dunes to create the first barrier against blown sand, and have been crucial not only in fixing the mobile sand and retarding the migration of sand dunes, but also in altering the evolution of dune geomorphology and affecting the near-bed air flow in downwind areas (Zhang et al., 2007).

Our experiments were carried out on the windward slope of a mobile transverse dune immediately upwind of the railway protective system (Fig. 2a). The topography of the dune was measured using a Trimble 4700 global positioning system (GPS) receiver with real-time differential correction that provided planimetric and altimetric precision of 0.01 m and 0.02 m, respectively (Fig. 2b). The dune was 4.8 m tall measured from the toe of the leeward slope and 13.7 m tall measured from the toe of the windward slope, and had a 68.8-m-long windward slope (Fig. 2c). The total windward slope was about 10.5°, but the slope was variable from the toe to the top. The fixed site of the wind and sand flux measurements was located on the upper windward slope of the dune (Fig. 2c), where the surface slope is 5.6°.

The local sediments were predominantly well-sorted, fine to medium quartz sands; coarser surface lags were also present, particularly in association with larger ripples. Zhang et al. (2007) reported a mean grain size of 0.129 mm (2.95 Φ) and a sorting coefficient of 0.29 Φ calculated using the formulas of Folk and Ward (1957) at this site.