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Aeolian sand transport over gobi with different gravel coverages under limited sand supply: A mobile wind tunnel investigation

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ABSTRACT

Transport is one of the important aeolian processes on earth. Here we report results of systematic tests using a mobile wind tunnel to examine aeolian sand transport over different gravel beds and at different wind speeds. The gravel beds differ in terms of gravel size and spacing. The results reveal that the blown sand flux profile over gravel beds is non-monotonic such that sand transport increases with height above the surface for the first 5–8 cm before exponentially decreasing. The height at which the maximum sand transport rate occurs tends to increase with increasing both the experimental wind velocity and gravel coverage. Furthermore, the total sand transport rate in the upper exponentially decreasing zone of the sand flux profile scales as $u_*^2 - u_{*t}^2$. However, sand transport over gravel beds with different coverages within the 0–20 cm layer can be well expressed by an Owen-type saltation equation: $q = g(C)\frac{\rho}{g}u_*(u_*^2 - u_{*t}^2)$ where q is the total sand transport rate, u_* is the friction velocity, u_{*_t} is the threshold friction velocity, g is the gravitational acceleration, ρ is the air density, $g(C)$ is a cubic polynomial equation of gravel coverage C. In addition, gravel beds can obviously reduce sand transport compared with the same surface without the tested gravels, and the increase in gravel size benefits the reduction in sand transport.

1. Introduction

Aeolian sand transport is one of the important geomorphic processes operating in arid regions (Nickling and McKenna Neuman, 2009). It creates various problems, such as obscuring the sun, impeding traffic, damaging crops and electrical switches, abrading paint, has a negative impact on human health and can cause degradation of valuable and nonrenewable soil resources (Fryrear and Saleh, 1993). The problems caused by blown sand are related to both the amount transported and the vertical distribution of the transported material (Dong et al., 2002). Sand particles are mainly transported in the near-surface layer, and the mass flux decreases with increasing the height above the surface (e.g., Chepil, 1945; Sharp, 1964; Wu, 1987). Such a vertical distribution has implications for the design of sand control measures such as fences: they need not be set too high (Wu, 1987).

The Gobi Desert is a very important type of landform in arid regions of China. "Gobi" is actually a regional name of desert pavement in Asia from Mongolian. This kind of surface is also present in other arid regions of the world, where it is known variously as gibber, reg or hamada, and comprises a single surface layer of coarse clasts in various sizes from gravel to boulder underlain by fine silts and sands with very few coarse particles (Cooke and Warren, 1973). The density of the coarse surface layer of these surfaces varies quite widely, and for example, the density is over 80% in Negev Desert of southern Israel (Matmon et al., 2009) and over 60% in most Gobi Deserts of China (Qu et al., 1997). Such surfaces are common in deserts on Earth and even more on Mars (Lancaster et al., 2010).

Aeolian sand transport over gobi surfaces is different from that over sandy surfaces because of the presence of non-erodible roughness elements such as gravels or cobbles. The difference is mainly caused by the partitioning of shear stress between the roughness elements and the surface (Gillies et al., 2007). With reference to surfaces covered by non-erodible roughness elements, the total force of wind acting on these surfaces can be divided into two parts: the force on the roughness elements and that on the intervening surfaces between them (Schlicting, 1936). Therefore, the roughness elements can protect the underlining surface by absorbing the wind momentum, thus increasing the threshold velocity for sand movement on the intervening surface. In addition, the presence of non-erodible roughness elements has an impact on the grain-bed interaction. The collision between sand particles and non-erodible roughness elements is almost elastic, and sand particles can lift off with higher wind velocity and larger angles.

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However, compared with sandy surfaces, fewer attempts have been made to describe the blown sand flux profile over gobi surfaces (Dong et al., 2004). Besides, few models have been established to predict sand transport rates over these surfaces. The difficulty of assessing sand transport rates on rough surfaces mainly lies in the lack of the empirical models integrating surface features, airflow and sand transport (Greeley et al., 2006; Lancaster et al., 2010).

Recent research has shown that most natural eroding surfaces including gravel surfaces tend to be supply limited (Nickling and McKenna Neuman, 2009). Hence, in this study, under limited sand supply, systematic wind tunnel tests were conducted to attempt to define the blown sand flux profiles over gravel beds with different coverages and sizes of gravels, to establish the equation of sand transport over these surfaces and to determine the influence of gravel coverage and size on sand transport.

2. Materials and methods

The experiments were carried out using a mobile wind tunnel on the sandy gobi surface atop the Mogao Grottoes at latitude 40.05°N, longitude 94.80°E. This wind tunnel, made of hard aluminum alloy panels, has a total length of 11.4 m and a 6.0-m-long working section with a cross-sectional area 0.6 m × 0.6 m. It is powered by a 13 kilowatt gasoline engine and the centerline wind speed can be changed continuously from 0 to 14 m s^{-1} (Fig. 1). The axial pressure of the working section is almost constant and the wind tunnel walls have minimal influence on the wind field, so the airflow in the working section is assumed to the characteristics of airflow near the Earth's surface. The depth of the boundary layer in the wind tunnel is approximately 20 cm.

Three kinds of gravel, with the average respective length, width and height of 2 × 1.5 × 1, 3 × 2 × 2, 5.5 × 3.5 × 4 cm^3 were used in the experiment and were chosen from gravels of the Yumen rock formations which are widely distributed atop the Mogao Grottoes. All the gravels used in the experiment were sieved to get gravels in the same size. The coverage of each gravel bed (C), that is, the ratio of total gravel coverage area to the area of the tested tunnel floor was controlled by changing the number of gravel clasts in the test area. The experimental gravel coverages ranged from 10% to 70% (at 10% intervals). The area of the working surface is constant, and thus gravel coverage such as 30% was calculated by evenly paving the gravels of the same size such as 3 cm on a graph paper with the same area (30% of the working surface area), and then these gravels were those used in the experiment of 30% coverage for 3 cm gravels. All the clasts were arranged in rhombus patterns. Each gravel bed was composed of clasts of the same size and the total gravel bed 4.8 m in length. The underlying surface of the wind tunnel floor is the sandy gobi (Fig. 2). It is mainly composed of gravels with sizes mainly ranging from 0.3 to 1.0 cm underlain by silts (Table 1). Before the experiment, loose sediments on the working surface area were blown away to minimize their influence on sand transport.

Experimental wind velocities are 6, 8, 10, 12 and 14 m s^{-1} measured using a pitot-static probe placed in the centre of the wind tunnel at the height of 30 cm above the ground, and a wind profiler was placed at 0.6 m from the downwind edge of the gravel bed to measure the centerline wind velocity at the heights of 0.5, 0.9, 1.5, 2.2, 4.3, 8.3, 16.3, 20.2, 24.2 cm. Sand used in the experiment is natural mixed sand ranging in size from 0.08 to 0.5 mm with a mean grain size of 0.25 mm. Sand was introduced to the tunnel using a 0.6 × 0.5 m^2 tray containing 16 kg of sand weighing and put evenly on the 1.2-m-long sand bed upwind of the working section during each run of the experiment. The chosen length of the sand bed ensured the full development of the saltating cloud before blowing over gravel beds. The lengths of each experiment decreased with the increase of the experimental wind velocity, and were 20, 10, 6, 5 and 3 min for wind speeds of 6, 8, 10, 12 and 14 m s^{-1}, respectively. Three replicate simulations were made for each gravel coverage at each experimental wind velocity to get the mean value of the blown sand flux and the three replications were performed under the same condition of sand supply and experimental time.

The step-like sand traps, whose total height and width were 20 and 2 cm, respectively, were used to measure the blown sand flux (Fig. 3). Despite its limited observation height, this kind of trap is widely used owing to its compactness, portability, and convenience in data processing (Zhang et al., 2008). Two sand traps were laid in the central line the wind tunnel. No. 1 sand trap was located about 0.7 m from the upwind edge of gravel bed and mainly applied to measure the initial wind-blown sand flux conditions. The No. 2 trap was located about 0.6 m from the downwind edge of gravel bed and mainly used to measure the conditions of sand transport over gravel beds when the wind-blown sand flux had developed fully after passing over about 4 m long gravel bed and thus provides the more important data set for this study. The experimental layout is showed in Fig. 4.

3. Results and discussion

3.1. The blown sand flux profiles

The relationship between horizontal sand flux and height above the surface for different gravel bed configurations and wind

Fig. 1. The mobile wind tunnel.

Fig. 2. The underlying surface of the wind tunnel floor.