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Characteristics of Drifting Sand Flux over Gobi Surface: A Wind Tunnel Simulation

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Abstract: Through simulation studies on characteristics of drifting sand flux over Gobi surface in wind tunnel, this paper aims to inquire how the environmental parameters of Gobi surface affect the turbulence of air current, the structure of drifting sand flux and the velocity profile within the boundary layers so that it can provide a theoretical basis for the engineering design of sand-control in Gobi region. The experiment showed that the drifting sand activities mainly focus within 20 cm over the Gobi surface, and there is a good relationship between sand concentration and corresponding wind velocity. However, the distribution pattern of sand concentration takes on a shape like elephant nose over Gobi surface and it does not follow the logarithmic law as it does on sand-bed. This phenomenon mainly results from grain-to-gravel collision over the Gobi surface. By combining the sand concentration with the distribution function of wind velocity, the function of energy distribution within sand-laden layer could be drawn.

Key words: Sand-laden layer, structure of sand flux, wind tunnel simulation, wind velocity profile.

Sand flow, two-phase fluid of sand-laden air, takes a leading role in the subject concerning wind-sand issues. It is not only the core of blown-sand physics, but also one of the basic theories in both aeolian geomorphology and sand-control engineering. The most effective measure for controlling sand damages in a sandy terrain is to abate or to weaken the intensity of drifting sand flux. There is a vast literature available on aeolian saltation (Bagnold, 1941; Owen, 1964; Willetts and Rice, 1986; Ungar and Haff, 1987; Werner and Haff, 1988; Anderson and Haff, 1991; McEwan *et al.*, 1992; Nalpanis *et al.*, 1993; Foucault and Stanislas, 1997; Remigius, 2003). From the viewpoint of fluid mechanics, Bagnold (1941) researched drifting sand flux in both wind tunnel and field. Chepil (1945a,b) inquired wind-blown sand more completely from the standpoint of wind erosion. Other major researches on drifting sand discusses energy distribution, trajectories of saltation grain, vertical concentration distribution in sand-laden layers and the electric effect of grains (Yang *et al.*, 1996, 1999; Zou *et al.*, 1995, 1999; Dong and Liu, 1997; Huang and Zheng, 2000). The landscape of Gobi in north-west China is characterized by barren surfaces and strong wind. The drifting sand from the Gobi causes widespread damages to agricultural infrastructure, and is the most serious natural disaster in north-west China (Li and Ni, 1998; Wu, 1987).

The characteristics of wind blown sand over Gobi surface was simulated in a wind tunnel, using natural mixed sand grains from 0.063 mm to 0.80 mm. The experiment provided data on saltation and wind profile within the boundary layers. The objective of the study was to gather sufficient data to analyze how the environmental parameters of Gobi surface affect the characteristics of wind blown sand.

Materials and Methods

The experiment was conducted in a wind tunnel at Shapotou, the key laboratory of Desert and Desertification, Chinese Academy of Sciences. The wind tunnel has a working section of 21 m length and cross-section of 1.2 x 1.2 m. Based on air pressure and temperature, the inlet wind velocity can be adjusted through a digital micrometeorograph system. Wind velocities were measured with Pitot tube at eight heights (1.0, 1.5, 3.0, 6.0, 12.0, 20.0, 35.0, 50.0 cm) above the surface. Measurements were conducted both when the wind speed was less than the threshold value to initiate grain motion and when the wind speed was high enough for motion to occur. For the experiment, we chose wind velocities of 8, 12, 16, and 20 m s^{-1}. Vertical distribution of sand transport was measured by a vertical-arrayed trap, which had a height of 60 cm and inlet section with 0.5 cm wide x 1.0 cm height. In order to simulate Gobi surface, the working section of wind tunnel was covered with small gravels. Pitot tube was located 5 m downwind from the furthest edge of Gobi surface. To ensure full development of wind-sand stream, a 9 m sand-bed before the edge of Gobi was retained. The sand mass was sufficient for the experiment.

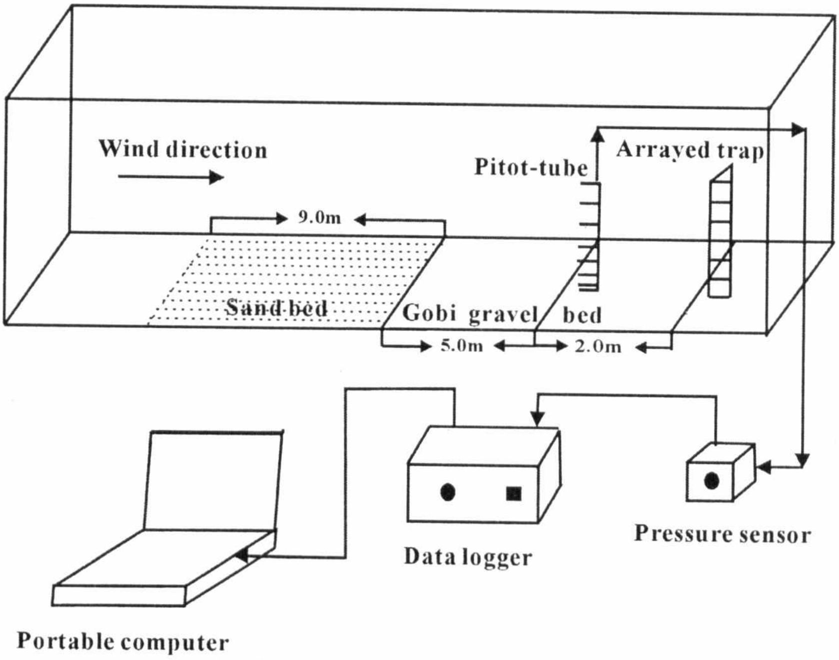

Fig. 1. Schematic diagram of the experimental layout.

A vertical-arrayed trap was installed 2 m behind Pitot tube in the middle of wind tunnel (Fig. 1).

Results and Discussion

Structure of wind-sand stream over Gobi surface

The structure of drifting sand flux can be defined as vertical distribution of sand transport in sand-laden layers, produced by the interplay of wind and underlying surface. Different kinds of surfaces influence wind velocity, saltation height and energy attenuation of sand grain differently. Figure 2 shows the detailed effect of Gobi surface on wind-sand stream. It can be seen that up to 20 cm height above the surface, amount of transported sand is increased with wind velocity, while above 20 cm, the amount of sand grain keeps an equilibrium state. Moreover, the height of sand-laden column increased with wind velocity. The most sand-content heights were 2, 4, 5 and 6 cm when the velocity reached 8, 12, 16 and 20 m s^{-1}, respectively. With increasing velocity, surface-creeping grains gain more kinetic energy. Therefore, those in collision with gravels on Gobi surface bounce higher and higher, and the height of sand-column increases. We can call it as the effect of trunk visuality. It also illustrates that the energy loss is very little in the course of sand grains colliding with gravel and the grains can obtain a greater bounce angle when wind velocity is more than the threshold speed. The distribution of sand fitted well with height for a certain wind velocity (Fig. 2) and the function curve can be expressed by the equation (1):

$$m = \frac{a + cz + ez^2 + gz^3 + iz^4}{1 + bz + dz^2 + fz^3 + hz^4 + jz^5} \qquad \text{...(1)}$$

where, m is sand transport at different heights and z is height from 0 to 60 cm; a,b,c...j are different fitting parameters and listed in Table 1.

In terms of Fig. 2, the structure of drifting sand flux manifests different characteristics at different heights. It is in a linearly-increased layer near the surface, and enters a saturated layer as the height increases, and transporting capacity of sand-driving

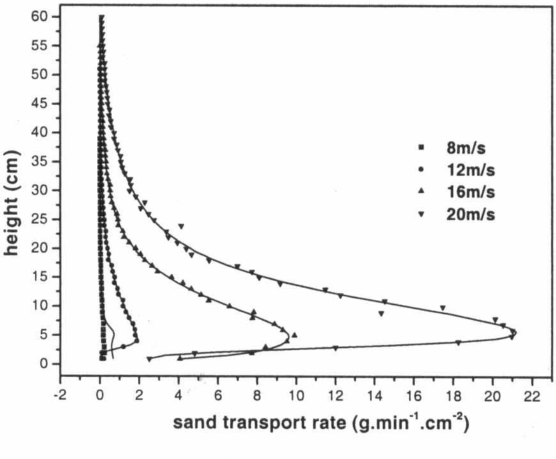

Fig. 2. Structure of drifting sand flux over Gobi surface.

Table 1. Parameters concerning distribution function of sand transport at different wind velocities

Velocity m s^{-1}	a	b	c	d	e	f	g	h	i	j	R^2
8	-22.78	46.86	37.03	-8.10	-11.68	-0.31	1.23	-0.04	-0.03	0.02	0.997
12	0.53	-0.69	0.17	0.20	-0.01	-0.01	0.0	0.00	0.00	0.00	0.998
16	-24.41	4.53	48.11	-0.77	-3.91	0.10	0.14	0.00	0.00	0.00	0.998
20	3.87	1.30	0.84	-0.89	-1.95	0.25	1.28	-0.02	0.02	0.00	0.993

wind reaches maximum value. When height exceeds saturated sand-laden layer, it comes into an attenuated layer and sand transport declines with height by a rule of negative exponent. In order to inquire the relationship between environmental parameters affecting turbulence of airflow and sand transport, the relationship of transported sand quantity in different wind velocities over Gobi surface was also computed. Because velocity of 8 m s^{-1} is small and the height of sand-laden layer is relatively low, we accounted for three other velocities (Table 2).

Table 2. Relationship of sand transport with different wind velocities

	12 m s^{-1}	16 m s^{-1}	20 m s^{-1}
12 m s^{-1}	1	0.929	0.986
16 m s^{-1}	–	1	0.936
20 m s^{-1}	–	–	1

Data show that under different velocities, sand transport at different heights differs as per the underlying surface, due to the influence of the underlying surface on turbulence of air current, which then affects the structure of sand-driving wind. The result also suggests that characteristics of drifting sand flux depends upon airflow turbulence, which also lies on environmental parameters of underlying surface. Therefore, for adopting proper measure for blown sand control, environmental parameters of underlying surface have to be modified.

Wind profile

Wind velocity in the boundary layer is logarithmic with height. Because of the effects of underlying surface on turbulence of airflow, energy distribution of sand grains shows large variation and leads to a general increase in concentration with wind velocity.

The wind velocity increases sharply up to 20 cm height. In the range of 20 to 35 cm, wind velocity changes very slowly with height. Above 35 cm wind velocity begins to increase again with height. Comparing wind velocity changes in these sections and sand grain concentration at corresponding height, it can be found that in the range of 0 to 20 cm a simple linear relationship between sand transport and wind velocity does not exist. Energy distribution of sand-laden air varies greatly with wind speed in this height range, and influences wind profile within the boundary layers. In the range of 20 to 35 cm, sand grain movement mainly refers to some suspended particles with smaller diameter, and therefore, does not produce much effect on wind velocity. Above 35 cm, changes in wind velocity with height are higher because there is a lower content of sand grains in these layers, and wind velocity is similar to that on stable sand-bed.

Energy distribution function of sand grains in the sand-laden layers

Wind velocity profile near the surface is logarithmic with height, which has been interpreted by hydro-mechanical theory. The slope of the logarithmic wind profile is defined by the Prandtl-von Karman equation:

$$u = \frac{u_*}{k} \ln \frac{z}{z_0} \qquad ...(2)$$

where, u is the wind velocity measured at a height z above ground; u_* is the drag velocity, and related to shear stress (i) exerted by the wind on the bed and to the density of air (p) by the expression (equation 3).

$$u_* = \sqrt{\frac{i}{P}} \qquad ...(3)$$

Both u_* and i increase as the wind velocity (u) increases; k is the von Karman constant which varies with temperature gradient, but is usually taken as 0.4; z_0 is the height at which the velocity is zero.

From Prandtl-von Karman wind profile equation, we can gain a fitted function as follows (equation 4):

$$u = a + b \ln z \qquad ...(4)$$

where, a and b are parameters, and can be calculated through the data of many sets of velocity and corresponding heights from experimental simulation in the wind tunnel.

Energy in the sand-laden layers refers to the total of kinetic energy and potential energy when sand-drifting flux is in a stable state. According to time-averaged velocity, using the sand quantity distribution function (Eq. 1) and Prandtl-von Karman wind profile equation (Eq. 4), we can obtain energy distribution equation (5):

$$E = \frac{1}{2} mu^2 + mgz \qquad ...(5)$$

where, E is energy in sand-laden layers; m is sand quantity in different heights; g is acceleration due to gravity.

Conclusions

Due to collision of sand grains with gravels over Gobi surface, concentration distribution of sand grains with height does not decrease in a logarithmic rule, and the height of its maximum value increases as the wind velocity increases. Concentration of sand grains in different sand-laden layers has a good relationship with corresponding velocity. Amount of sand grain below 20 cm increases with wind velocity, while above 20 cm, the amount of sand grain is in a tranquilized state. In other words, energy distribution of sand grains over Gobi focuses on the range within 20 cm above surface.

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