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The aerodynamic roughness with a blowing sand boundary layer (BSBL): A redefinition of the Owen effect

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[1] Attempt is made to define the aerodynamic roughness length with a blowing sand boundary layer. Two methods, the log curve-fit method and power curve-fit method, have been tried to determine the aerodynamic roughness length based on the measured wind profiles in a wind tunnel. The results suggest that a good linear relation exists between the aerodynamic roughness lengths obtained by the two methods. But the power curve-fit method yields greater aerodynamic roughness length for the same blowing sand boundary layer. The aerodynamic roughness tends to increase with sand transport rate. The relationship between the aerodynamic roughness length and shear velocity with a blowing sand cloud is much more complicated than that proposed by Owen and others due to the variation with height of the shear stress caused by the blown sand movement. *INDEX TERMS:* 1223 Geodesy and Gravity: Ocean/Earth/atmosphere interactions (3339); 3307 Meteorology and Atmospheric Dynamics: Boundary layer processes; 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 5415 Planetology: Solid Surface Planets: Erosion and weathering. **Citation:** Dong, Z., X. Liu, and H. Wang, The aerodynamic roughness with a blowing sand boundary layer (BSBL): A redefinition of the Owen effect, *Geophys. Res. Lett.*, *30*(2), 1047, doi:10.1029/2002GL016318, 2003.

1. Introduction

[2] In a blown sand transport system, wind provides the driving forces for the particle movement while the moving blown sand particles exert the opposite forces on the wind. The more than 2000 times difference between the density of quartz sand and that of air means that to keep a sand grain moving at the same speed as the wind, the wind must lose momentum equivalent to 2000 grain volumes of the air. The momentum extraction by the moving particles from the wind results in such great opposite forces to the air that the wind has to experience considerable reduction in velocity, which in turn reduces the sand-carrying capacity of the wind. This feedback between the blown sand movement and the near-surface wind has important implications for predicting sand transport [*Bagnold*, 1941; *Owen*, 1964; *Anderson and Haff*, 1991; *Raupach*, 1991; *Sherman*, 1992; *McEwan and Willetts*, 1993; *Gillette*, 1999].

[3] We define the very near-surface air layer re-adapted to blown sand movement as a Blowing Sand Boundary Layer (BSBL). Some pioneer researchers suggested that the aerodynamic roughness length characterized the BSBL [*Bagnold*, 1941; *Owen*, 1964; *Raupach*, 1991; *Gillette*, 1999]. The increased aerodynamic roughness with a blowing sand boundary layer is usually called the 'Owen effect' after the important theoretical work of *Paul Robert Owen* [1964]. The Owen effect has been of continuing significance in aeolian research since *Bagnold* [1941] founded the dynamics-oriented aeolian studies and stated, "the sand movement profoundly alters the state of wind" [*Bagnold*, 1941, p. 57]. Though great advances have been made, defining the aerodynamic roughness length of a BSBL is still open to argument. A central difficulty arises from the argument: Can the wind profile in the BSBL still be considered logarithmic? This depends on our understanding of the significance of the BSBL and decides the method we can use to derive the aerodynamic roughness length. The majority of previous researchers treated the wind profile in a BSBL as logarithmic though some disagreements arose [*Gerety*, 1985; *McKenna Neuman and Nickling*, 1994].

[4] The main objective of this study is, through detailed wind tunnel tests, to redefine the Owen effect; compare the aerodynamic roughness lengths of the BSBL derived by different methods; discuss the relationship between the aerodynamic roughness length and sand transport rate, wind velocity and friction wind velocity.

2. Methods

[5] The experiments were carried out in a wind tunnel at the Shapotou Desert Experimental Research Station, Chinese Academy of Sciences [*Dong et al.*, 2001].

[6] The aerodynamic roughness length was derived from the measured wind profiles that were measured by a wind profiler made by the Shaanxi Air Instrument Company [*Dong et al.*, 2001]. A computer that acquired one reading every second recorded the wind velocity measurement and output the average. The sand transport rate was measured by a segmented sand sampler [*Dong et al.*, 2003]. In the experiment, the sampler and wind profiler were set 0.1 m apart, 16 m downwind from the entrance of the working section of the wind tunnel. The bottom of the lowest opening of the sampler was set flush with the tunnel floor. A sand tray was placed 8m upwind from the sand sampler and wind profiler. The 8 m gap between the sand tray and wind profiler minimized the influence of the changing sandy surface on the wind measurement during sand transport. The sand tray was 4 m long, 0.8 m wide and 0.025 m deep. The chosen length of the tray ensured a significant development of the saltation cloud. Natural sand from the field was screened into nine size groups: 0.10–0.15, 0.15–0.20, 0.20–0.25, 0.25–0.40, 0.40–0.50, 0.50–0.56, 0.56–0.63, 0.63–0.80, and 0.80–1.00 mm, and their threshold shear velocities are listed in Table 1. The prepared sand samples were put in the sand tray, the surface flattened and

0094-8276/03/2002GL016318

Table 1. The Threshold Shear Velocity of Different Size Group of the Tested Sands

D (mm)	0.10–0.15	0.15–0.20	0.20–0.25	0.25–0.40	0.40–0.50	0.50–0.56	0.56–0.63	0.63–0.80	0.80–1.00
U_{*t}(m s^{-1})	0.51	0.50	0.49	0.47	0.45	0.40	0.39	0.31	0.27

leveled to the tunnel floor, and then blown by the required free-stream wind velocity (measured at the centerline, 0.6 m above the tunnel floor) above the initiation threshold. An automatic sliding lid covered the sand tray. When the required equilibrium free-stream wind velocity was reached, the sliding lid was lifted rapidly to the top wall of the tunnel. About 15 seconds later, the velocity profile of the wind re-adapted to the blowing sand cloud was recorded. For each sample at each free-stream wind velocity, three repetitions were made to get the mean values.

3. Results and Discussion

[7] Both a logarithmic function (Equation (1)) and a power function (Equation (2)) fitted the measured wind profiles with blowing sand cloud reasonably well. Equation (2) fitted the experimental data a little better than Equation (1). The greater the sand transport rate, the better the Equation (2) fitted the wind profile than the Equation (1), implying that the wind profile deviated more from the logarithmic wind profile with increasing sand transport. Table 2 lists some typical curve-fit results. Equation (1) defines a wind profile with a constant air shear and aerodynamic roughness length throughout the boundary layer while Equation (2) defines a wind profile with the air shear and hence aerodynamic roughness lengths that vary with height.

$$U_Z = a_1 + b_1 \ln Z \tag{1}$$

$$U_Z = a_2 Z^{b_2} \tag{2}$$

where, U_Z is the horizontal wind velocity at height Z, a_1, b_1, a_2 and b_2 are regression coefficients.

[8] Both Equation (1) (The log curve-fit method) and Equation (2) (The power curve-fit method) have their advantages in determining the aerodynamic roughness length. The log curve-fit method is more direct while the power curve-fit method is more appropriate theoretically. If the measured wind profile is fitted by Equation (1), the aerodynamic roughness length can be derived directly by:

$$Z_0 = \exp(-a_1/b_1) \tag{3}$$

If the measured wind profile is fitted by Equation (2), the aerodynamic roughness length should be derived from the air stress that determines the wind profile. The presence of blown sand movement results in the grain-borne stress, and hence the air stress that varies with height. The air stress is calculated by:

$$\tau_a(Z) = \rho K^2 Z^2 \left(\frac{dU_z}{dZ}\right)^2 \tag{4}$$

where, $\tau_a(Z)$ is the air stress at height Z, ρ is density of the air, K is the *Karman*'s constant. So,

$$\tau_a(Z) = \rho K^2 Z^{2b_2} a_2^2 b_2^2 \tag{5}$$

The aerodynamic roughness length can be calculated by:

$$Z_0(Z) = Z/\exp\left(\frac{KU_Z}{U_*(Z)}\right), U_*(Z) = \sqrt{\frac{\tau_a(Z)}{\rho}} \tag{6}$$

where, $Z_0(Z)$ and $U_*(Z)$ is the aerodynamic roughness length and shear velocity at height Z respectively.

[9] The aerodynamic roughness length derived by Equation (3) is the average throughout the boundary layer while that derived by Equation (6) can describe the variation with height of the aerodynamic roughness length, which is the case for a blowing sand boundary layer.

[10] The measured wind profiles with a blowing sand cloud didn't show the focus as *Bagnold* [1941] suggested. Both methods were tried for the blowing sand boundary layer to compare their differences. We denote the aerodynamic roughness length derived by the log curve-fit method as Z_{0S1}, and that by the power curve-fit method as Z_{0S2}. The aerodynamic length roughness of the tunnel surface free of sand movement, Z_{0N} found to decrease with the free-stream wind velocity. All the measured wind profiles were fitted by Equation (1) and Equation (2) to obtain the regression coefficients a_1, b_1, a_2 and b_2 required in calculating the aerodynamic roughness length. In the power curve-fit method we specify the top of the boundary layer as the height that has an aerodynamic roughness representative of the saltation layer (Z = 0.5 m in Equation (6)). Outside the boundary layer, the wind profile with a blowing sand cloud gets close to the clean wind profile (without blown sand), similar to *McKenna Newman and Nickling*'s [1994] wind tunnel results.

[11] Figure 1 shows that the aerodynamic roughness lengths derived by the two methods are linearly related, but that derived by the power curve-fit method is about 18 times that derived by the log curve-fit method. This implies that both methods can produce meaningful aerodynamic roughness length characterizing the influence of a blowing sand cloud on the wind. Both Z_{0S1} and Z_{0S2} indicate the blown sand movement increases the aerodynamic roughness length. Z_{0S1} is 3 to 140 times of Z_{0N}, and Z_{0S2} is 50 to 2300 times of Z_{0N}. The following discussion will focus on Z_{0S2} because it represents the aerodynamic roughness length of the whole blowing sand boundary layer.

Table 2. The Comparison of the Typical Curve-Fit Results of the Measured Wind Profiles (for 0.40–0.50 mm Sand) by the Two Methods[a]

	Log curve-fit method			Power curve-fit method		
U (m s^{-1})	a_1	b_1	r^2	a_2	b_2	r^2
10	6.69	0.86	0.99	11.0284	0.1096	1.00
12	7.99	1.04	0.98	13.2387	0.1108	0.99
14	9.25	1.20	0.98	15.3636	0.1117	0.99
16	10.34	1.35	0.97	17.2170	0.1121	0.99
18	11.42	1.61	0.97	19.6360	0.1194	0.98
20	12.72	1.74	0.95	21.6166	0.1170	0.98
22	13.94	1.88	0.94	23.6320	0.1167	0.97

[a] r^2 is the correlation coefficient at 0.05 significance level.

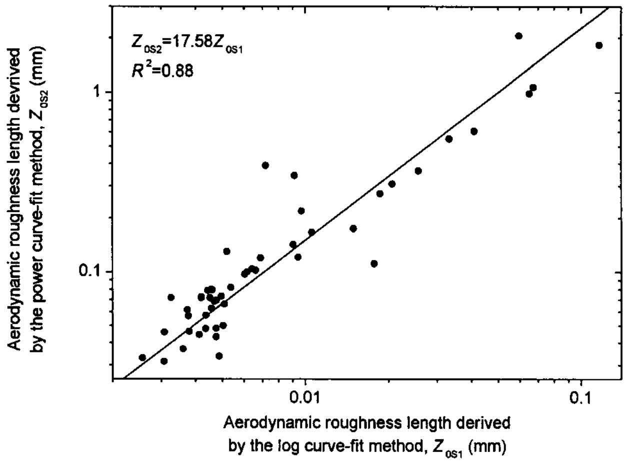

Figure 1. Comparison of the aerodynamic roughness lengths derived by the two methods.

[12] Unlike the simple relationship without sand movement where Z_{0N} decreases with increasing free-stream wind velocity (Table 3). Z_{0S2} does not have the tendency to decrease with the free-stream wind velocity because the sand transport rate increases with wind velocity (Figure 2). Except for the 0.63–0.80 mm and 0.80–1.00 mm sands that have less transport rate, Z_{0S2} shows the tendency to increase with free-stream wind velocity. The finer the grain size, the more obvious is the increase of Z_{0S2} with free-stream wind velocity due to the greater sand transport rate. The influence of sand transport rate and free-stream wind velocity on aerodynamic roughness length can be expressed by (Figure 3):

$$Z_{0S2} = 0.055 + 6.99 \times 10^{-10} \exp(826.76Q^{0.28}/U) \qquad (7)$$

where, Q is sand transport rate in g mm^{-1} s^{-1}, U is free-stream wind velocity in m s^{-1}.

[13] Although it is only significant when sand movement occurs, Equation (7) implies that when the sand transport rate is very small, the influence of U on Z_{0S2} is predominant, and Z_{0S2} decreases with increasing U. But when the sand transport rate is great enough, the influence of Q is predominant; Z_{0S2} increases with Q and hence wind velocity.

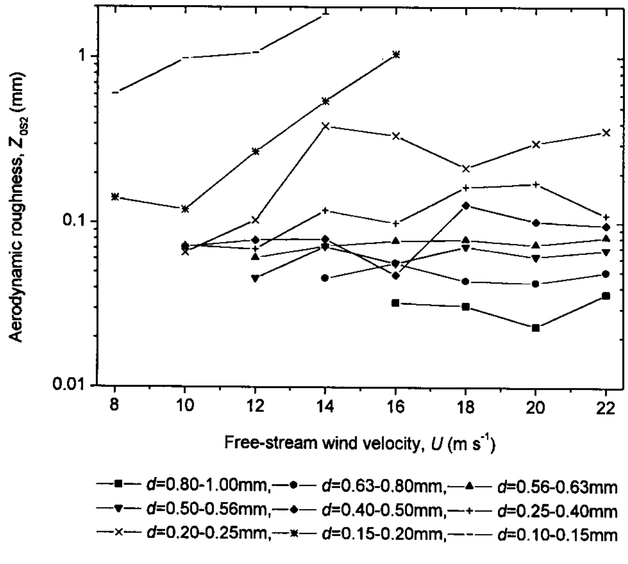

Figure 2. The aerodynamic roughness of the blowing sand cloud with different grain size at different free-stream wind velocity.

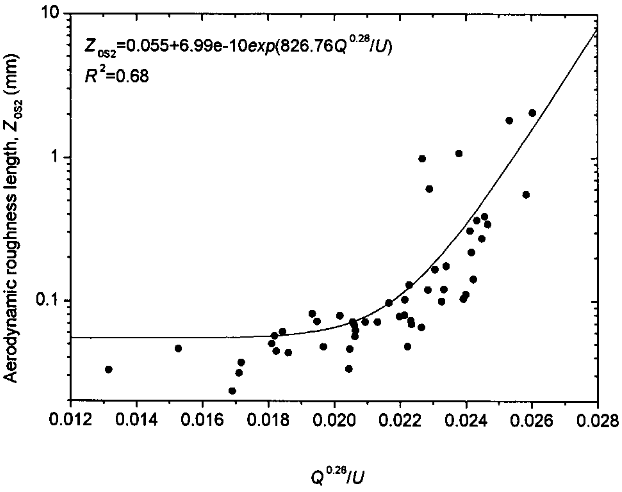

Figure 3. Z_{0S2} versus $Q^{0.28}/U$.

[14] When defining the Owen effect, *Owen* [1964] suggested that the relationship between aerodynamic roughness length and shear velocity with a blowing sand cloud be expressed by the *Charnock*'s [1955] equation:

$$Z_{0S} = \frac{\alpha U_{*S}}{g} \qquad (8)$$

where, Z_{0S} and U_{*S} are the aerodynamic roughness length and shear velocity with a blowing sand cloud, g is the gravitational acceleration, α is the proportionality coefficient, 0.02. By Equation (8)

$$\alpha = gZ_{0S2}/U_{*S2}{}^2 \qquad (9)$$

[15] Z_{0S2} and U_{*S} are the aerodynamic roughness length and shear velocity derived by Equation (6). The α value obtained here is not a constant as that proposed by *Owen* [1964], but varies widely from 0.00036 to 0.026, averaging 0.004. Some pioneer researchers [*Charnock*, 1955; *Owen*, 1964; *Wu*, 1969; *Hicks*, 1972; *Chamberlain*, 1983] suggested that the Equation (8) be valid for mobile water, snow and sandy surface. In fact, although they are flexible surfaces, the mobile sandy surface and water surface are different. On water surface the waves still act as a fixed bed with changing roughness in response to wind action and the over-flowing boundary layer has a constant air shear so that the wind profile still keeps logarithmic. However, the boundary layer over a sandy surface is much more complicated by the involvement of moving sand particles in the air in addition to the changing surface roughness such as sand ripples. *Raupach* [1991] and *Gillette* [1999] suggested the Equation (10) as a modification to Equation (8) to estimate, the Owen effect:

$$Z_{0S} = \left(\frac{\alpha U_{*S}}{g}\right)^{1-R} Z_{0N} \qquad (10)$$

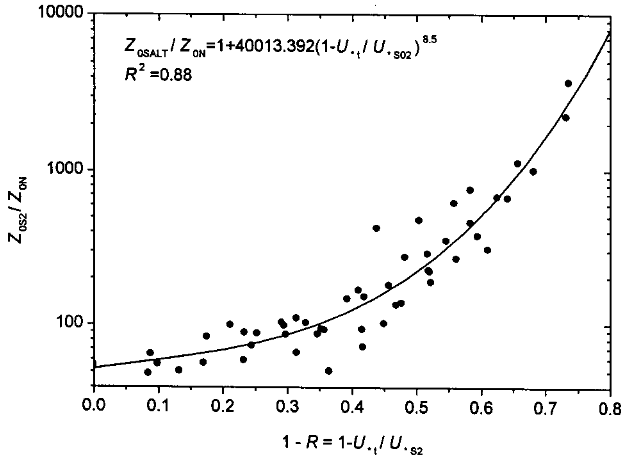

Figure 4. Z_{0S2}/Z_{0N} versus 1-R.

where, Z_{0S}, and U_{*S} are the aerodynamic roughness length and shear velocity of a BSBL, Z_{0N} is the aerodynamic roughness length without sand movement.

[16] In our test the 8 m distance between the measurement position of wind profile and the upwind sand tray basically eliminated the effect of changing surface on the aerodynamic roughness length. The difference between the aerodynamic roughness length of a blowing sand boundary layer and that of sand-free wind mainly resulted from the blown particle movement in the air. The coefficient α in Equation (7) obtained here varies widely. We define the ratio Z_{0S2}/Z_{0N} for a given free-stream wind velocity as the relative aerodynamic roughness. It is revealed that the relative aerodynamic roughness is related to the shear velocity in accordance with:

$$\begin{aligned} Z_{0S2}/Z_{0N} &= 1 + 40013.39(1-R)^{8.5}, \text{ or} \\ Z_{0S2} &= \left[1 + 40013.39(1-R)^{8.5}\right] Z_{0N}, \qquad R = U_{*_t}/U_{*_{S2}} \end{aligned} \tag{11}$$

where, U_{*t} is the threshold shear velocity of the sand grain, R is the ratio of threshold shear velocity U_{*t} to shear velocity U_{*S2}. Figure 4 shows the correlation is reasonably good.

4. Conclusions

[17] The aerodynamic roughness with a blowing sand boundary layer was studied by means of wind tunnel tests, and two methods for deriving the aerodynamic roughness length were suggested. Both methods produced meaningful aerodynamic roughness length characterizing the so-called Owen Effect. The power curve-fit method that yielded greater aerodynamic roughness length was recommended because it took account of the alternation of air stress by blown sand movement and re-adaptation of the wind profile to the blowing sand cloud. With a blowing sand cloud, the aerodynamic roughness length was closely related to the sand transport rate. A mobile sandy surface is different from a water surface in that the involvement of moving sand particles in the air makes a blowing sand boundary layer a non-constant air shear layer while the boundary layer over a water surface is a constant air shear layer with changing aerodynamic roughness length in response to wind action. Applying the *Charnock*'s equation that is valid for a water surface to the Owen effect must take account of the complication of the air stress caused by blown particle movement in the air.

[18] **Acknowledgments.** We gratefully acknowledge the funding from the Knowledge Innovation Project of the Chinese Academy of Sciences (KZCX1-10-06, KZCX3-SW-324), and National Science Fund for Distinguished Young Scholars of the National Natural Science Foundation of China.

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