Defining the threshold wind velocity for moistened sediments

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[1] The moisture of surface sediments is one of the most significant factors governing the initiation of particle movement by the wind and hence the aeolian transport rate. This paper develops an equation for the threshold shear velocity of moistened sediments based more soundly on physics by means of the moment balance method, taking account of the interparticle cohesive forces produced by moisture. The equation relates threshold shear velocity directly to moisture content and contains three simple coefficients that need be determined from experiments. The threshold equation for moistened sediments basically follows Bagnold's threshold equation for loose, dry sediments but with a proportionality coefficient that accounts for the effect of moisture. Previously published data on the threshold shear velocities of moistened sediments from wind tunnel tests are used to determine the coefficients contained in the threshold equation, and it proves that the new equation describes the threshold velocities of moistened sediments reasonably well. Comparing the threshold shear velocity predicted using the new equation with the results of Belly's and Hotta et al.'s empirical equations reveals that the predicted results differed greatly. These differences can be attributed to differences in the definition of threshold velocity and moisture content in the physical and chemical properties of the sediment samples and in the experimental methods. Further theoretical and experimental investigation is required to fully understand the effects of sediment moisture content on threshold wind velocity. We also suggest that methodological improvement itself is also a topic of future research.

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1. Introduction

[2] Predictions of sediment transport by the wind are required in the solution of numerous problems, such as the erosion of agricultural lands, the migration of sand dunes, and the influx of aerosols into the atmosphere over deserts [e.g., *Woodruff and Siddoway*, 1965; *Hagen*, 1996; *Fryrear et al.*, 1998]. To initiate particle motion, the driving force of the wind must overcome opposing forces that include gravity, cohesive forces, and adhesive forces [*Nickling*, 1988; *Pye and Tsoar*, 1990]. Sediment moisture is one of the most important bonding agents that affect the particle entrainment process. After moistening, moisture is retained on the sediment grains as a surface film, particularly at points of intergrain contact [*Pye and Tsoar*, 1990]. Through adhesion and capillary effects, the moisture film contributes strongly to the binding forces that keep sediment particles together [*McKenna-Neuman and Nickling*, 1989]. Thus, except under extremely arid conditions, it is not possible to accurately predict sediment transport by the wind unless the effect of surface moisture is adequately considered.

[3] The influences of surface sediment moisture on aeolian transport have received considerable attention for decades [*Namikas and Sherman*, 1995; *Cornelis and Gabriels*, 2003]. Although a few researchers have attempted to define the effects of moisture on transport rate [*Dong and Li*, 1996; *Chen et al.*, 1996], most have focused on the effect of moisture on the threshold wind velocity required to initiate particle movement because it is thought that sediment moisture influences transport rate through its effect on threshold wind velocity. Threshold wind velocity is usually expressed in terms of the wind velocity at a specific height or in terms of a shear velocity that characterizes the magnitude of shear stress. Although several empirical relations [e.g., *Chepil*, 1956; *Belly*, 1964; *Bisal and Hsieh*, 1966; *Azizov*, 1977; *Logie*, 1982; *Hotta et al.*, 1984; *Saleh and Fryrear*, 1995; *Chen et al.*, 1996; *Shao et al.*, 1996; *Van Dijk et al.*, 1996; *Dong et al.*, 2002a] and theoretical models [e.g., *Kawata and Tsuchiya*, 1976; *McKenna-Neuman and Nickling*, 1989; *Gregory and Darwish*, 1990; *Cornelis et al.*, 2004a] have been proposed to predict the effect of moisture on threshold wind velocity, none is generally accepted, suggesting that the effect of moisture is still not well understood [*Namikas and Sherman*, 1995; *Shao*, 2000; *Cornelis et al.*, 2004b].

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[4] Empirical relationships between threshold wind or shear velocity and the moisture content of the sediment have mainly been obtained from wind tunnel tests and field observations. *Chepil* [1956] conducted one of the earliest investigations on the influence of surface moisture on the erodibility by wind of four American soils, ranging from silty clay to dune sand, in a wind tunnel, and reported that the erodibility of soil was inversely proportional to the adsorbed moisture content. *Belly* [1964] conducted wind tunnel experiments to investigate the influence of surface moisture content on threshold shear velocity of 0.44-mm sand. He found a linear relationship for low surface moisture content (<0.5%) and a logarithmic relationship for higher moisture contents. *Bisal and Hsieh* [1966] did not attempt to fit a model to their wind tunnel data, but found that finer-textured soils required a higher moisture content to effectively prevent soil movement by the wind and that 4% moisture content could prevent the initiation of movement of particles in a fine sandy loam soil. *Azizov* [1977] conducted wind tunnel experiments on two loamy sand soils and found that below 4% moisture content, the effect of moisture was almost insignificant; above this level, the influence of moisture was significant. He suggested the use of an exponential function to express the effect of moisture on particle detachment. *Hotta et al.* [1984] developed their model based on data from wind tunnel experiments with 0.2, 0.5, and 0.8mm beach sand, and suggested a linear relationship. *Saleh and Fryrear* [1995] conducted their wind tunnel experiments using five American soils ranging from loamy fine sand to clay, and proposed a polynomial function. *Chen et al.* [1996] performed wind tunnel experiments on a loessial sandy loam soil and used a modified power function to describe the results. *Shao et al.* [1996] used five particle size groups ranging from 0.10 to 0.53 mm from Australian red soils in a wind tunnel experiment, and proposed an exponential equation.

[5] Theoretical studies have attempted to develop the relationship between threshold velocity or threshold shear velocity and moisture content in terms of the interparticle cohesive forces produced by moisture. Sediment moisture can generate several kinds of interparticle cohesive forces, including adhesive and capillary forces, and explanations of their significance in the bonding of particles differ between authors [e.g., *McKenna-Neuman and Nickling*, 1989; *Fécan et al.*, 1999; *Cornelis et al.*, 2004a]. Different authors have used different equations, assumptions, and simplifications to relate these forces to moisture content. Consequently, different theoretical models have been developed [e.g., *Kawata and Tsuchiya*, 1976; *McKenna-Neuman and Nickling*, 1989; *Gregory and Darwish*, 1990; *Fécan et al.*, 1999; *Cornelis et al.*, 2004a].

[6] Theoretical models are usually more complex than empirical relationships and contain parameters that must be determined by means of experimentation. *Kawata and Tsuchiya* [1976] were the first authors to develop a theoretical model for the threshold shear velocity of moistened sand, based on the assumption that threshold shear velocity increased with increasing surface tension of the water contained in the pores and that the surface tension was a function of moisture content. The theoretical work of *McKenna-Neuman and Nickling* [1989] was based on the theory of *Haines* [1925] and *Fisher* [1926], who modeled the effect of low moisture contents on apparent cohesion (or capillary force) of equally sized spheres joined by an isolated wedge of water. By adding a term for the capillary forces associated with the presence of moisture to *Bagnold*'s [1941] equations, they developed expressions for threshold shear velocity of moistened sediments in open-packed and close-packed systems.

[7] In order to develop a model to predict threshold shear velocity under moistened conditions, *Gregory and Darwish* [1990] considered four different forces acting on moistened particles as the particles are exposed to the wind. In their model, the effect of moisture was included in the cohesive force associated with the water films that form around particles. Their model basically followed Bagnold's threshold equation, but modified by a correctional factor that accounts for moisture. In an attempt to model the increase in the threshold shear velocity due to surface soil moisture, *Fécan et al.* [1999] followed the same reasoning as *McKenna-Neuman and Nickling* [1989], but developed a relatively simpler equation. In *Cornelis et al.*'s [2004a] model, the interparticle cohesive forces due to moisture bonding include both capillary and adhesive forces. Their model contained three coefficients to be determined empirically. Two of these coefficients are incorporated in the term that applies to dry sediment. The third is incorporated in the term that applies to moistened sediment.

[8] It is apparent from this literature review that the effects of moisture content on the entrainment of particles by wind need be more fully investigated. In this paper, we describe the results of a theoretical analysis and its application to wind tunnel study. We attempted to develop a formula that would define the quantitative relationship between threshold shear velocity and the moisture content of sediments with different grain sizes in terms of fluid and particle parameters. Coefficients contained in the threshold equation for moistened sediments are determined by *Dong et al.*'s [2002a] published data on threshold shear velocity of moistened sediments. The predicted results by present equation are compared with those predicted by other empirical equations.

2. Threshold Equation for Moistened Sediments

[9] Threshold equation that relates threshold velocity or threshold shear velocity to factors influencing the initiation of sediment particle motion is usually developed by theoretical or empirical methods. Theoretical methods derive the threshold equation by examining the forces acting on individual particles at threshold. Wind blowing over a particle exerts a drag force and a lift force. Opposing these aerodynamic forces are the particle's weight and interparticle forces. For moistened sediments free of other bonding agents, the magnitude of interparticle forces is mainly related to moisture content.

[10] For spherical particles of diameter d, the drag force and lift force at threshold are given by

$$F_D = \alpha \rho_a u_{*_t}^2 d^2 \quad (1)$$

$$F_L = \beta \rho_a u_{*_t}^2 d^2 \quad (2)$$

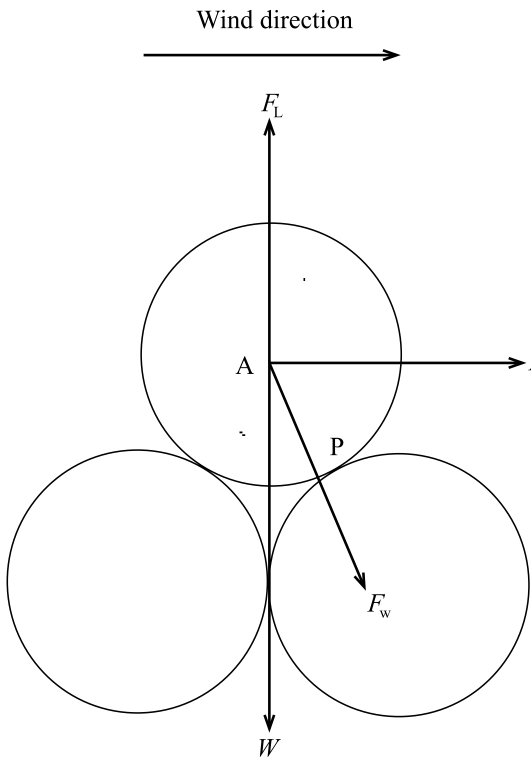

Figure 1. Sketch of the forces on a particle at the initiation threshold.

where F_D is the drag force, F_L is the lift force, ρ_a is the density of air, u_{*t} is the threshold shear velocity, d is the particle diameter, α and β are the proportional coefficients that depend on such factors as the wind turbulence and the relative position and proportion of drag per unit area experienced by the particle.

[11] The gravity is given by

$$W = B\left(\rho_p - \rho_a\right)gd^3 \tag{3}$$

where W is the gravity, ρ_p is density of the particle, g is the gravitational acceleration and B is a shape coefficient, for a sphere, $B = \pi/6$.

[12] The interparticle force resulting from sediment moisture is expressed as the function of moisture content.

$$F_w = f(w) \tag{4}$$

where F_w is the interparticle force due to moisture, and w is moisture content.

[13] The movement of particle A in Figure 1 is considered as a rotational movement around the point of contact that act as a pivot (P in Figure 1). The moment balance equation of particle A at initiation threshold is given by

$$F_D L_1 = (W - F_L)L_2 + F_w L_3 \tag{5}$$

where L_1, L_2 and L_3 are the arms of drag force, resultant force in the vertical direction and the interparticle force due to moisture.

[14] Substituting equations (1), (2), (3) and (4) into equation (5), and letting $L_1 = \alpha_1 d$, $L_2 = \alpha_2 d$ and $L_3 = \alpha_3 d$, we obtain

$$\alpha\rho_a u_{*_t}^2 d^2\alpha_1 d = Bd^3\left(\rho_p - \rho_a\right)g\alpha_2 d - \beta\rho_a u_{*_t}^2 d^2\alpha_2 d + f(w)\alpha_3 d \tag{6}$$

$$u_{*_t}^2 = \frac{\alpha_2 B}{\alpha_1\alpha + \alpha_2\beta}\frac{\left(\rho_p - \rho_a\right)gd}{\rho_a} + \frac{\alpha_3 f(w)}{(\alpha_1\alpha + \alpha_2\beta)\rho_a d^2} \tag{7}$$

Let $\gamma_1 = \frac{\alpha_2 B}{\alpha_1\alpha + \alpha_2\beta}$, $\gamma_2 = \frac{\alpha_3 B}{\alpha_1\alpha + \alpha_2\beta}$, then equation (7) is rewritten as

$$u_{*_t}^2 = \gamma_1\frac{\left(\rho_p - \rho_a\right)gd}{\rho_a} + \gamma_2\frac{f(w)}{\rho_a d^2} \tag{8}$$

$$u_{*_t} = \sqrt{\gamma_1\frac{\rho_p - \rho_a}{\rho_a}gd\left(1 + \frac{\gamma_2 f(w)}{\gamma_1\left(\rho_p - \rho_a\right)gd^3}\right)} \tag{9}$$

Let $\gamma = \sqrt{\gamma_1}$, $\lambda_2 = \frac{\gamma_2}{\gamma_1\left(\rho_p - \rho_a\right)g}$, then

$$u_{*_t} = \gamma\sqrt{\frac{\rho_p - \rho_a}{\rho_a}gd}\sqrt{1 + \frac{\lambda_2}{d^3}f(w)} \tag{10}$$

[15] Equation (10) illustrates that in general, granular media can be divided into two groups: noncohesive grains and cohesive grains. When coarse dry sand grains are considered to be noncohesive, the first term on the right-hand side of the equation is similar to *Bagnold*'s [1941] threshold equation. In the other word, the threshold equation for moistened sediments can be developed by adding a term responsible for the interparticle force due to moisture to the general threshold equation proposed by Bagnold for the dry loose sediments free of interparticle cohesive forces.

3. Interparticle Cohesive Forces due to Moisture

[16] In equation (10), the influence of sediment moisture on the threshold shear velocity is accounted for by the interparticle cohesive force. An expression for $f(w)$ is required to relate the threshold shear velocity to moisture content. The cohesive forces between two moistened particles result from capillary forces and adhesion forces. When considering the model of *Fisher* [1926] and the well-known Young-Laplace equation, the capillary force F_c can be written as [*Cornelis et al.*, 2004a]

$$F_c = \frac{G_c\sigma^2}{|\psi_c|}d^2 \tag{11}$$

where G_c is a parameter that accounts for sand and fluid properties, σ is the surface tension of the liquid (N m^{-1}), which is a constant at a given temperature that equals 7.39 × 10^{-2} N m^{-1} at 15°C, and ψ_c is the capillary potential, which is the negative of the suction force (MPa).

[17] The overlapping of the adsorbed layers of neighboring particles creates the adhesion force. Its strength is proportional to the tensile strength of the adsorbed film and the area of contact. Since the contribution of adsorbed-layer bonding to the attraction between two particles increases with increasing moisture content and as the area of contact increases, the force associated with adsorbed-layer bonding (F_a) is assumed to equal the tensile strength of the film of water. As moisture content increases, the width of the waist of the water wedge between adjacent particles increases. *Cornelis et al.* [2004a] assumed F_a to be inversely proportional to the suction within the adsorption films. Since F_a depends on the contact area between the water films, it is proportional to the square of the particle diameter, and the adhesion force F_a can be written as [*Cornelis et al.*, 2004a]:

$$F_a = \frac{G_a \sigma^2}{|\psi_a|} d^2 \tag{12}$$

where G_a is a proportionality factor that accounts for sediment and fluid properties (m^{-2}), and ψ_a is the potential in the adsorbed layers (MPa).

[18] Summing up equations (11) and (12), the interparticle cohesive force F_w due to moisture bonding can be written as [*Cornelis et al.*, 2004a]:

$$F_w = \frac{G \sigma^2}{|\psi_m|} d^2 \tag{13}$$

where G is a proportionality coefficient that accounts for sediment and fluid properties and that combines G_c and G_a (m^{-2}), and ψ_m is the matric potential (MPa), which combines ψ_a and ψ_c.

[19] Equation (13) is a simplified representation of the interparticle force due to moisture bonding because it assumes the effect of capillary and adsorptive forces to be equal, but it is believed to be sufficiently realistic for the prediction of sand transport rates [*Cornelis et al.*, 2004a].

[20] Equation (13) shows that it is the matric potential (ψ_m) that will determine the magnitude of the interparticle force (F_w) between particles of a moistened sediment. However, the requirement for data on matric potential forms a key limitation from a practical perspective [*Namikas and Sherman*, 1995]. Standard equipment used for measuring matric potential, such as tensiometers, is unable to record this potential in the uppermost millimeters of the sand bed that are exposed to the wind, where the matric potential can be far beyond the tensiometer's measuring range. Yet it is the water's condition at low (very negative) potentials in the uppermost layer of the sediment that is most important in our analysis. Therefore, matric potential should be related to moisture content, a parameter that can be determined with much higher precision in the sand bed and at low water contents using techniques such as the gravimetric method (drying and weighing), radio spectrometry, infrared photography, microwave techniques, or through modeling of sediment water transport as a function of meteorological parameters and sediment type [*Cornelis et al.*, 2004a].

[21] In the literature, many functions have been given to relate the matric potential to the sediment's moisture content, such as the well-recognized models of *Brooks and Corey* [1964] and *Campell* [1974]. These models are intended to describe the water retention curve over the whole range of water contents, but often give poor results at low moisture contents. In this paper, we use *Gardner*'s [1970] equation to convert the matric potential in equation (13) into a moisture content:

$$\psi_m = k_1 w^{-k} \tag{14}$$

where k_1 and k_2 are coefficients that depend on the sediment's grain size (k_1 in Pa, k is dimensionless), and w is the gravimetric moisture content.

[22] Substituting equations (14) into equation (13) and considering equation (4), we can obtain:

$$F_w = f(w) = \frac{G\sigma^2}{k_1} d^2 w^k \tag{15}$$

[23] Substituting equation (15) into equation (10) produces

$$u_{*_t} = \gamma \sqrt{\frac{\rho_p - \rho_a}{\rho_a} gd} \sqrt{1 + \frac{\lambda_2 G \sigma}{k_1 d} w^k} \tag{16}$$

Let $\lambda = \frac{\lambda_2 G \sigma^2}{k_1 d}$, which is a dimensionless number. Equation (16) can be rewritten as

$$u_{*_t} = \gamma \sqrt{\frac{\rho_p - \rho_a}{\rho_a} gd} \sqrt{1 + \lambda w^k} = \gamma \sqrt{\frac{\rho_p - \rho_a}{\rho_a} gd} \sqrt{1 + f_1(\lambda, w)} \tag{17}$$

where $f_1(\lambda, w) = \lambda w^k$. $f_1(\lambda, 0) = 0$ for $w = 0\%$. For low moisture content such as this in present study, $\sqrt{1 + f_1(\lambda, w)}$ for $f_1(\lambda, w)$ can be rewritten through Taylor expansion as

$$\sqrt{1 + f_1(\lambda, w)} = 1 + \frac{1}{2} f_1(\lambda, w) - \frac{1}{4} f_1^2(\lambda, w) + \cdots \tag{18}$$

[24] Substituting equation (18) into equation (17), we have

$$u_{*_t} = \gamma \sqrt{\frac{\rho_p - \rho_a}{\rho_a} gd} \left(1 + \frac{1}{2} f_1(\lambda, w) - \frac{1}{4} f_2^1(\lambda, w) + \cdots \right) \tag{19}$$

[25] For low moisture content, reserving only the linear term in equation (19) is also a good approximation. Then

$$u_{*_t} = \gamma \sqrt{\frac{\rho_p - \rho_a}{\rho_a} gd} \left(1 + \frac{1}{2} f_1(\lambda, w) \right) = \gamma \sqrt{\frac{\rho_p - \rho_a}{\rho_a} gd} \left(1 + \frac{\lambda}{2} w^k \right) \tag{20}$$

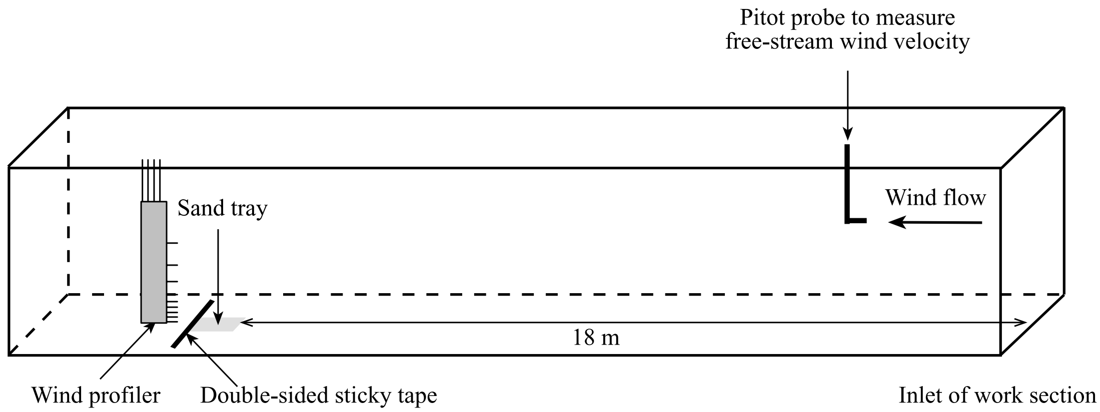

Figure 2. Layout for the experiments.

[26] So, the threshold equation for moistened sediments can be rewritten as

$$u_{*_t} = u_{*_{to}}\left(1 + 0.5\lambda w^k\right) \quad (21)$$

where $u_{*to} = \gamma\sqrt{\frac{\rho_p - \rho_a}{\rho_a}gd}$ is the threshold shear velocity for the sediments at dry state.

4. Wind Tunnel Experiments

[27] Equation (21) has three dimensionless parameters (γ, λ and k) that need to be determined. In an attempt to validate the theoretical model developed in this paper, experimental data from wind tunnel were used. The experiments were carried out in the wind tunnel at the Shapotou Desert Experimental Research Station, Key Laboratory of Desert and Desertification, Chinese Academy of Sciences. The wind tunnel is a noncirculating blow type with a 21-m-long, 1.2-m-high by 1.2-m-wide working section [*Dong et al.*, 2002b]. The thickness of the boundary layer can reach 0.40 to 0.50 m in the working section. Details of the wind tunnel experiments are described to show the reliability of experimental data.

[28] The purpose of this study is mainly to examine the effects of moisture on threshold velocity. The sediment samples used in wind tunnel tests are required to be free of other interparticle bonding agents except moisture. The interparticle cohesive forces may be produced by organic matter, soluble salts and the presence of fine particles such as clay. Clean particles free of any cohesive agents greater than 0.1mm in diameter are usually considered to be cohesionless except being moistened. Hence, to minimize the number of bonding agents and ensure that the interparticle cohesive forces are predominantly produced by moisture when they are moistened, well-sorted sediments with a range of particle sizes were sampled from the southeast of the Tengger Desert, China. The sediment samples contained no organic matter and insignificant quantity of soluble salts.

[29] Before test, the sediment samples were sifted into several size populations. The sediments of all size populations were predominantly composed of quartz. Experimental results of six size populations over 0.1mm were selected: 0.100–0.135, 0.135–0.150, 0.150–0.200, 0.200–0.250, 0.250–0.400 and 0.400–0.500 mm. For all tests, the sifted sediments were placed in thin-walled test trays (50 cm long by 20 cm wide by 1 cm deep). During the tests, trays filled with the sediment samples were placed 18 m downwind from the inlet of the working section and the surface was leveled to the tunnel floor. Figure 2 shows the layout of the experimentation. Wind velocity was gradually increased until initiation of sediment particle movement occurred. The wind profile above the floor of the tunnel was then recorded to derive the threshold shear velocity, and the moisture content of the sediment was measured.

[30] The initiation of sediment particle movement was observed following a procedure used by previous researchers [e.g., *Musick et al.*, 1996]. Strips of double-sided sticky tape were placed flat on the bed surface near the downwind end of the test tray and capture of moving grains by the tape was visually observed. Three repetitions by different observers were made to get the average. Wind speeds at 10 heights (3, 6, 10, 15, 30, 60, 120, 250, 350, and 500 mm above the tunnel floor) were monitored simultaneously using a wind profiler [*Dong et al.*, 2002b] consisting of 10 fine pitot static probes connected to a computerized data acquisition system. The wind profiler was made by the Shaanxi Air Instrument Company and was calibrated using standard pitot tubes before use. The computer recorded wind speeds every second for a least 1 minute and averaged the wind speed data. Shear velocities were derived from measured wind profiles using a curve-fitting method. The measured wind speeds at the 10 heights were fitted using the following equation:

$$u(z) = g_1 + g_2 \ln z \quad (22)$$

where $u(z)$ is the wind speed at height z, and g_1 and g_2 are regression constants. Shear velocity (u_{*t}, for dry sediment, $u_{*t} = u_{*to}$) was obtained using the following equation:

$$u_{*_t} = kg_2 \quad (23)$$

where k is von Karman's constant, and equals 0.4.

[31] To moisten the sediment samples, the bottoms of the test trays were made of 35-mesh stainless steel screens on which filter paper was spread to hold the sediment in the tray. A test tray full of sediments was half immersed in

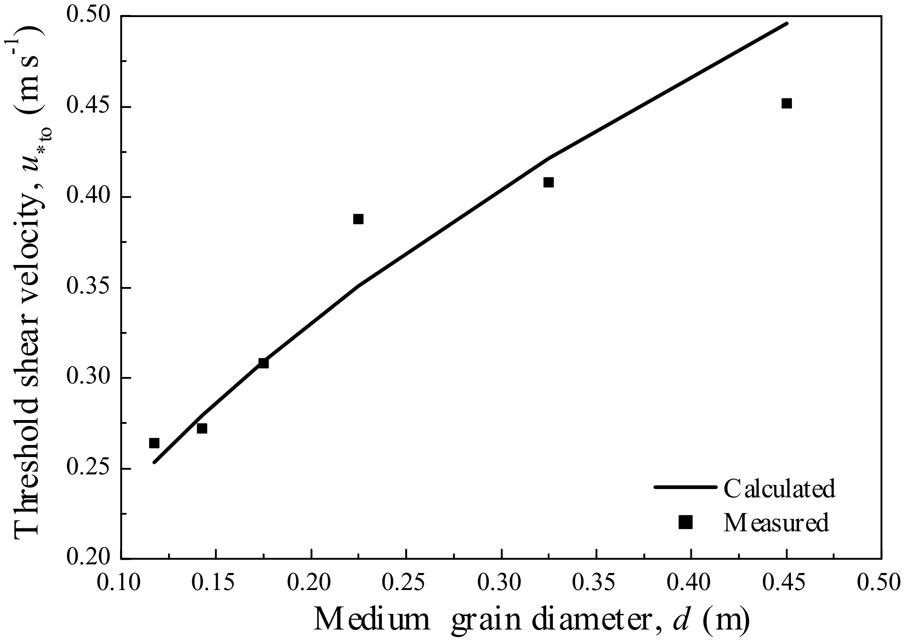

Figure 3. Threshold shear velocity of dry sand (u_{*to}) versus particle size (d). Wind tunnel results are compared against the model derived in this study.

distilled water to thoroughly moisten the sand sample. The test trays full of moistened sediments were then air dried for different lengths of time until their threshold shear velocities could be measured in the wind tunnel. The relative humidity and temperature of the air were around 40% and 28°C during the whole tests though they varied a little with time. This means that the moistened samples were not in equilibrium with the ambient atmosphere and there was continuous drying of the surface sample during the test that lasted for 1 to 5 min depending on moisture content and wind velocity. In the tests, we attempted to measure the surface moisture content of the sediments at the moment when the initiation of particle motion occurred because only the surface particles were initiated at threshold. Hence, when the initiation of sand movement was observed, the tunnel was turned off and the top 1 mm of the sediments were scraped away using a sharp knife so that we could measure the moisture content by oven drying. The moisture content in the top 1 mm of the sediments was considered to represent the surface moisture content. However, it must be emphasized that getting a representative moist sample is an open question. For example, for the coarsest sediments (0.400–0.500 mm) in the present experiments, the top 1 mm would sample two grains thick, while it would sample nine grains thick for the finest (0.100–0.150 mm) sediments. Sampling method for such study is a topic of future improvement.

5. Results and Discussion

[32] According to experiment data of the threshold shear velocities for the different sediment samples in a dry state (six size populations: 0.100–0.135, 0.135–0.150, 0.150–0.200, 0.200–0.250, 0.250–0.400 and 0.400–0.500 mm, dried in an oven at 105°C for 8 hours), the values of parameter γ in equation (20) derived for the six size populations are found to be 0.167, 0.157, 0.160, 0.178, 0.156, and 0.146 respectively (The air density ρ_a = 1.227 kg m^{-3} at 15°C, particle density ρ_p = 2650 kg m^{-3} and gravitational acceleration g = 9.8 m s^{-2}). The mean value is 0.16, within the range of γ values proposed by previous researchers. *Bagnold*'s [1941], *Zingg*'s [1953], and *Lyles and Krauss*'s [1971] results for sand, *Chepil*'s [1945] results for sediments ranging from clay loam to sand, and *Fletcher*'s [1976] results for large glass spheres gave γ values of 0.10, 0.09–0.11, 0.12, 0.17–0.20 and 0.13 respectively. Figure 3 shows the threshold shear velocities of the sediments at dry state. Hence the threshold equation for moistened sediments is

$$u_{*_t} = 0.16\sqrt{\frac{\rho_\mathrm{p} - \rho_\mathrm{a}}{\rho_\mathrm{a}} gd}\left(1 + \frac{\lambda}{2} w^k\right) \tag{24}$$

[33] The coefficients λ and k in equation (24) are associated with the effect of surface moisture on threshold shear velocity. Equation (24) can be rewritten as

$$\ln\left(\frac{u_{*_t}}{u_{*_{to}}} - 1\right) = \ln\frac{\lambda}{2} + k \ln w \tag{25}$$

On the basis of equation (25), the coefficients λ and k are determined from the measured threshold velocities of moistened sediments by means of the least squares curve-fitting method. The results are: λ = 478.20 ($\ln\frac{\lambda}{2}$ = 6.17) and k = 1.52, with a squared correlation coefficient R^2 = 0.83. The high correlation coefficient suggests that the dimensionless proportionality coefficient λ does not change obviously with the grain size. Now, it is possible to predict the threshold shear velocity of moistened sediments of given grain size by equation (26).

$$u_{*_t} = 0.16\sqrt{\frac{\rho_p - \rho_a}{\rho_a} gd}\left(1 + 478.20 w^{1.52}\right) \tag{26}$$

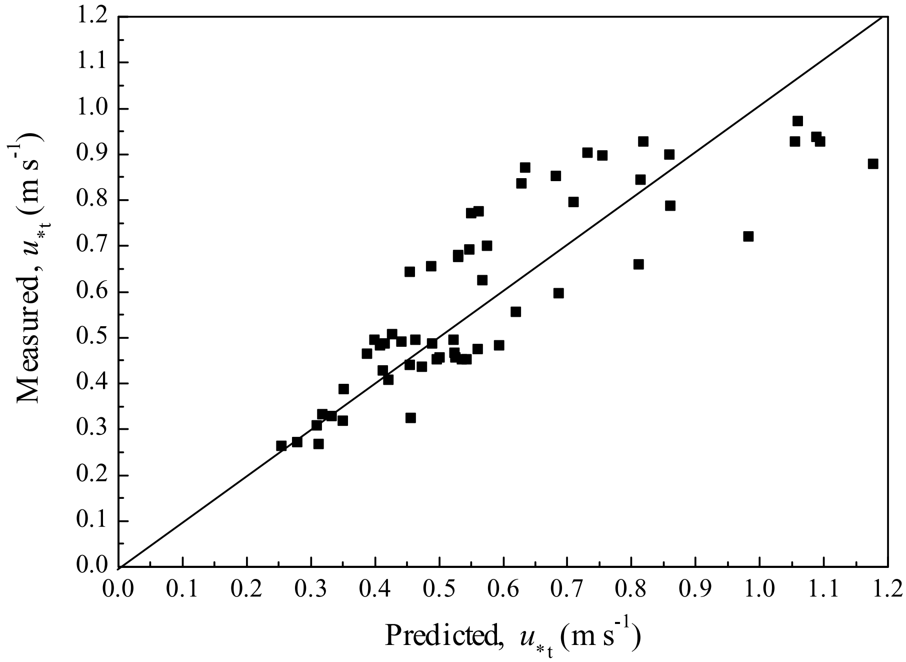

Figure 4. Comparison of the measured threshold shear velocity with the threshold shear velocities predicted using equation (26).

Therefore, the equation for the threshold shear velocity of moistened sediments follows Bagnold's threshold equation for loose dry sands, but with a proportionality coefficient added to account for the soil moisture content. Figure 4 shows that equation (26) is a good predictor of the threshold shear velocity of moistened sediments.

[34] We compared equation (26) with *Belly*'s [1964] and *Hotta et al.*'s [1984] well-known equations that have been proposed to define the threshold shear velocity of moistened sediments. Although several models are often referred to, such as those of *Chepil* [1956], *McKenna-Neuman and Nickling* [1989], *Gregory and Darwish* [1990], *Saleh and Fryrear* [1995], and *Cornelis et al.* [2004a], we have not compared these models with equation (26) because a moisture retention curve must be used to provide the value of $w_{1.5}$, the moisture content at $\psi_m = -1.5$ MPa, and to convert the capillary potential into a moisture content. The behavior of their models would thus depend intrinsically on the model chosen for the moisture retention curve.

[35] *Belly*'s [1964] empirical equation was developed on the basis of wind tunnel tests of well-sorted 0.44-mm sand, but he considered his relationship to be applicable to sands with different particle sizes. This equation takes the following form:

$$u_{*_{tw}} = u_{*_{to}}\left(1.8 + 0.6\log w_*\right) \tag{27}$$

where u_{*to} is the threshold shear velocity in the dry state and w_* is the surface gravimetric moisture content (%).

[36] *Hotta et al.*'s [1984] empirical equation was based on the wind tunnel data of *Tanaka et al.* [1954], and takes the following form:

$$u_{*_{tw}} = u_{*_{td}} + 7.5w_*/100 \tag{28}$$

where w_* is also the surface gravimetric moisture content (%).

[37] To compare the present threshold equation (equation (26)) with Belly's and Hotta et al.'s threshold equations (equations (27) and (28)), all threshold shear velocities u_{*to} at dry state in the three threshold equations are calculated by $u_{*to} = 0.16\sqrt{\frac{\rho_p - \rho_a}{\rho_a}gd}$ derived in present study. Figure 5 compares the threshold shear velocities predicted by *Belly*'s [1964] and *Hotta et al.*'s [1984] equations with the results of equation (26) for 0.100–0.135, 0.135–0.150, 0.150–0.200, 0.200–0.250, 0.250–0.400 and 0.400–0.500 mm sediments. The measured threshold shear velocities in the wind tunnel are also shown. We found that Belly's equation and the present equation fit the experimental results better while Hotta et al.'s equation generally yields lower threshold shear velocities especially when the moisture content is over 0.4%. However, Belly's equation and that in present study characterize curves with different change trends (Figure 5) and their differences enlarge rapidly when the moisture content is lower than 0.25% and over 2%. The former is more sensitive to the increase in moisture content at lower moisture condition while the latter is more sensitive to the increase in moisture content at higher moisture condition. The equation in present study is advantageous over Belly's equation in predicting the threshold shear velocities of low moisture sediments because the latter produces unacceptably low or negative threshold shear velocities because of the log term it contains.

[38] The disparities between the predicted threshold shear velocities for the moistened sediments can be attributed to the following reasons. First, reviewing the published results shows that different definitions of threshold shear velocity were used. For example, *Belly* [1964] defined threshold velocity as the point at which grain movement was fully sustained (corresponding to a sediment transport rate of 4 g m^{-1} s^{-1} in his study), whereas *McKenna-Neuman and Nickling* [1989] defined the threshold at the point when

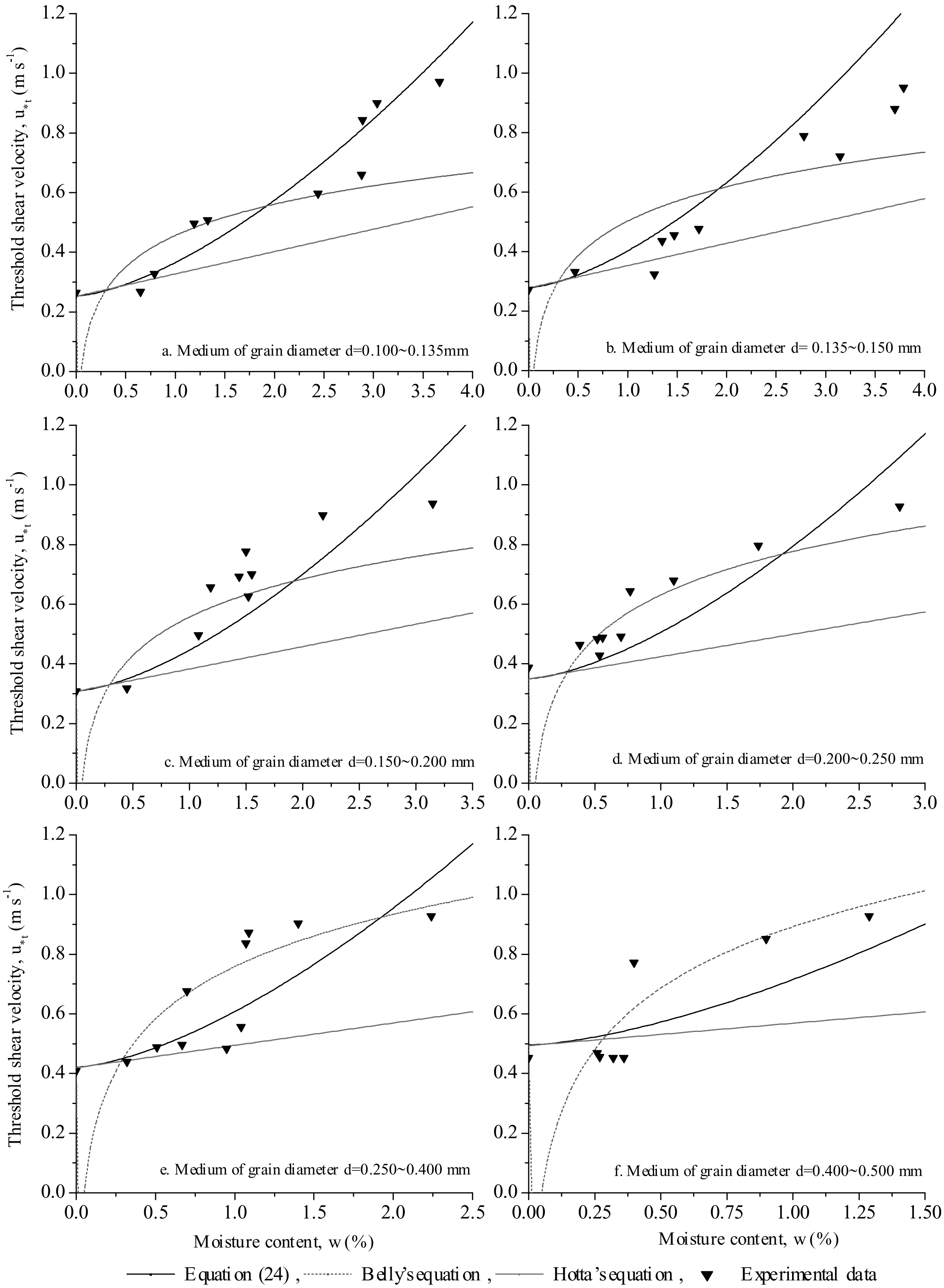

Figure 5. Comparison of the threshold shear velocities predicted by Belly's, Hotta et al.'s and our formula with the threshold shear velocities obtained in experiments for six size samples: (a) 0.100–0.135 mm, (b) 0.135–0.150 mm, (c) 0.150–0.200 mm, (d) 0.200–0.250 mm, (e) 0.250–0.400 mm, and (f) 0.400–0.500 mm.

particle movement was in the initial stages of becoming fully sustained, and in the present study, we defined the threshold as the point at which movement of the first few particles began and this movement could be visually observed.

[39] Second, the definition of sediment moisture content differed. Several authors have measured the sediment moisture before beginning the wind tunnel test [e.g., *Azizov*, 1977; *Logie*, 1982; *Chen et al.*, 1996], whereas others measured the moisture content after the wind tunnel tests [e.g., *Chepil*, 1956; *Bisal and Hsieh*, 1966; *Saleh and Fryrear*, 1995; *Dong et al.*, 2002a], as was the case in the present study. *Cornelis et al.* [2004a] measured the moisture content both before and after their wind tunnel tests. Because wind dries the surface sediment quickly, it thus causes a considerable difference in the moisture content before and after the wind tunnel test. Differences in the sampling depth for moisture analysis also lead to differences in the moisture content. The reported sampling depth ranges from 1 to 6 mm. Surface moisture content is overestimated when the sampling depth increases because moisture content decreases rapidly toward the surface.

[40] Third, sediments with different physical and chemical characteristics were used in the various studies. The bonding effects of the same sediment moisture content differ considerably when the grain size composition, organic matter content, salt content, and other chemical properties such as the mineral composition of the soil differ. *Gregory and Darwish* [1990] noted that if clay particles were present, the water adsorbed on those particles was not available to form a water film around the larger particles, and a higher moisture content was needed before a cohesive force developed. *Bisal and Hsieh* [1966] found that finer-textured soils required a higher water content to effectively prevent soil movement by the wind. It has also been found that the maximum moisture content at which dune sand particles began to be moved by the wind was only 3%, but that this value reached more than 20% for a peat soil with abundant organic matter (S. Y. Gao and Z. B. Dong, unpublished wind tunnel results, 1998).

[41] Finally, different experimental methods were used, especially the method of adding moisture to the sediments. Reviewing the published literature revealed that moisture can be added to the sediments by means of water vapor, spraying water on the top surface, spraying and mixing water into the sediments, soaking water from the bottom of the sediments (as in the present study), and directly wetting the sediments by immersion in water. The surface properties of sediments, including the degree of compaction, are disturbed by the process of adding moisture, and the extent of the disturbance differs among these methods. The initiation of particle movement is very sensitive to the properties of the surface sediment, thus different methods of adding water will have different effects on threshold wind velocity. In view of the above facts, it is to be expected that different authors reached different conclusions.

6. Conclusions

[42] We used the static moment method to develop an equation that describes the effect of sediment moisture content on the threshold wind velocity at which movement of the sediment particles begins. The threshold shear velocity is directly related to surface moisture content, and the new equation basically follows Bagnold's threshold equation for loose dry sands, but with a proportionality coefficient added to account for sediment moisture content. We determined the parameters contained in the equation based on the observed threshold shear velocities of sediments of different sizes and with different moisture contents in a wind tunnel. The equation has a sounder basis in physics than empirical functions, but the parameters to be determined empirically account for important but unknown mechanisms that define the relationship between the interparticle cohesive forces and moisture content. We considered the effect of sediment moisture content on threshold wind velocity in terms of interparticle cohesive forces, and defined these forces in terms of the square of the particle diameter, square of the surface tension, and inverse of the magnitude of the matric potential. We converted matric potential to a moisture content using the water retention model of *Gardner* [1970]. All the relationships used to convert moisture content into interparticle cohesive force must be calibrated. Thus, both experimental and theoretical investigations are still needed to fully understand the effect of sediment moisture content on threshold wind velocity.

[43] Experimental study is important when it is not possible to adequately understand the physical mechanisms responsible for the effect of moisture content on particle entrainment. However, the existing results reported in the literature differ considerably. These differences are caused by such factors as different definitions of threshold shear velocity and moisture content, different experimental samples, and different methods. Thus, the existing results are difficult to compare. To facilitate such comparisons, researchers need to reach common ground in defining their experimental methods in future studies.

[44] The effect of moisture content on threshold shear velocity is also closely associated with other soil properties such as the mechanical composition, organic matter content, and other physical and chemical properties. Additional experiments on samples free of bonding agents other than moisture will be needed to isolate the effects of moisture.

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