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Influence of moisture on the entrainment of sand by wind

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Abstract

The theory of wet granular material is applied to the study of the influence of moisture on the entrainment of sand by wind in the first process of aeolian sand transport. The interparticle force due to water bridge is calculated using the toroidal approximation at first; and then the moment balance of a grain in the surface layer of sand bed is considered; finally, the change of threshold friction velocity with water content is obtained.

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Keywords: Threshold friction velocity; Moisture; Granular material

1. Introduction

Aeolian erosion occurs only when a threshold value of the wind velocity is reached and this threshold depends on the features of a sandy bed surface. Among the several factors that govern threshold conditions, moisture content is one of the most significant because it contributes greatly to the binding forces that keep the particles together [1–3].

Although many studies were conducted to determine the influence of moisture on the entrainment of soil or sand particles by wind, its effect is still not well understood [4–7]. To date, numerous models [1,2,8–16] to predict the change of threshold friction velocity with moisture content have been developed. Most models are empirical (Chepil56 [8], Belly64 [9], HKKH84 [10], SF95 [12], SRL96 [13]) or semi-empirical (FMB99 [2]). The detailed descriptions of these models can be found in the review paper of Cornelis and Gabriels [3] and references therein. Here we pay more attention to the three typical theoretical models, namely MN89 [1], GD90 [11] and CGH04 [14–16]. The establishing procedures of them are analogous. Two critical points while modeling the entrainment of wet sands by wind are how to simplify the natural grain contact while water exist and how to calculate the interparticle force due to moisture. The grain contact was reasonably approximated by disymmetric cones in model MN89. This treatment leads to a non-dimensional geometric coefficient in the expression of interparticle force. As pointed out by Cornelis and Gabriels [3], MN89 is not practical because the geometric coefficient cannot be readily determined. In model CGH04, one principal radius of curvature of the air–water surface was supposed to be related to the third power of another and then the effects of grain shape were successfully eliminated. However, this assumption was not examined carefully. Although it seems that the contact of spherical grains as in model GD90 is simplest, direct contact seldom occurs under their hypothesis of grain shape because there are no absolutely smooth particles in practice. Once the mode of grain contact is founded, the next step every model cannot avoid is to determine the interparticle force due to moisture. Moisture is retained in sandy bed by two processes, water film and water bridge [1,4]. Water film may appear on the grain surface. Water bridge may form around the contact points of the grains. The contribution of water film to interparticle force is much lower than that of water bridge [17]. The water only appear on the grain surface in model GD90. The interparticle force due to water bridge, namely capillary force, is the sum of two components. One part is due to surface tension of the water at three-phrase contact line. The other is due to the pressure different across the water–air interface. Taking into account these two components and using respective simplifications of grain contact, the capillary force was all written as an analytical function of the pressure difference between the inside of water bridge and its outside in both MN89 and CGH04. A slight difference between two models is the coefficient before

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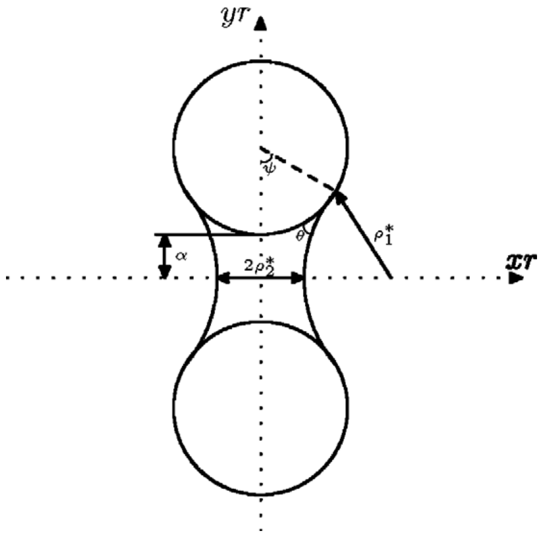

Fig. 1. Water bridge bonding two spherical monosized grains.

the negative power of pressure difference. But, the relation between the pressure difference and the moisture content was empirically obtained in both models. In other words, the interparticle force was not computed accurately. It should be noticed that the interparticle force in CGH04 we mentioned does not include Coulomb force and van der Waals force which were considered in their original derivations [16].

Sand is a glaring example of granular material which is of great interest in physicists. The purpose of this research is to calculate the interparticle force due to water bridge using the theory of wet granular material and then give a new theoretical model for the effect of moisture on the entrainment of sand by wind.

2. Interparticle force

The exact value of capillary force can only be obtained by solving numerically the Laplace–Young equation for the surface shape of water bridge. Many researches, e.g. [18–20], have shown that the error of toroidal approximation is very small. In the toroidal approximation, the force can be calculated either on the three-phase contact area [21] or on the gorge of the water bridge [22]. A more accurate approximation was given by Lian et al. [20] and it is therefore used here.

Fig. 1, in which θ and ψ are the contact angle and half-filling angle, gives the coordinates to describe the geometrical shape of a water bridge bonding two spherical monosized grains of radius r and separated by a distance $2\alpha r$. In the case of toroidal approximation, two dimensionless principle radii with respect to grain radius can be derived as

$$\rho_1^* = \frac{\rho_1}{r} = \frac{\alpha + 1 - \cos\psi}{\cos(\psi + \theta)} \tag{1}$$

$$\rho_2^* = \frac{\rho_2}{r} = \sin\psi + \rho_1^*[\sin(\psi + \theta) - 1] \tag{2}$$

The water volume corresponding to one grain in Fig. 1 is

$$\begin{aligned} \nu = \frac{V}{\pi r^3} = & \left[\rho_1^{*2} + (\rho_1^* + \rho_2^*)^2\right]\rho_1^*\cos(\theta + \psi) \\ & - \frac{1}{3}\rho_1^{*3}\cos^3(\theta + \psi) - \frac{1}{2}\rho_1^{*2}(\rho_1^* + \rho_2^*) \\ & \times [\sin(2\theta + 2\psi) + \pi - 2\theta - 2\psi] \\ & - \frac{1}{3}(2 + \cos\psi)(1 - \cos\psi)^2 \end{aligned} \tag{3}$$

The maximum value of dimensionless local mean meridian curvature is

$$(H_F^*)_{\max} = \frac{2\sin\psi - \rho_1^* - \rho_2^*}{2\rho_1^*\sin\psi} \tag{4}$$

In the absence of gravitational effects of water bridge, the dimensionless interparticle force is

$$f_c = \frac{F_c}{\pi r \gamma} = 2k_y\rho_2^*\{1 + k_y\rho_2^*[k_H(H_F^*)_{\max} + k_H - 1]\} \tag{5}$$

where γ is the surface tension, k_y is the ratio of the real radius to the approximate radius at the neck, k_H is the dimensionless mean curvature defined as $(H^*+1)/[(H_F^*)_{\max}+1]$ in which H^* is the real mean curvature.

On the base of rigorous numerical results, it was found that k_y and k_H are relatively insensitive to the bridge volume and can be empirically expressed in terms of separation

$$k_y = 1.0 - 0.00032\,\exp\left(6.8\frac{\alpha}{\alpha_c}\right) \tag{6}$$

$$k_H = 0.91 - 0.10\frac{\alpha}{\alpha_c} - 0.61\left(\frac{\alpha}{\alpha_c}\right)^2 \tag{7}$$

where α_c is the dimensionless critical rupture separation distance. This parameter can be determined by strictly considering the minimization of free surface energy. Based on their numerical solutions, Lian et al. [20] gave the following simple expression

$$\alpha_c \simeq 0.5(1 + 0.5\theta)\sqrt[3]{\pi\nu} \tag{8}$$

The expression of interparticle force, Eq. (5), is applicable for separation distances up to α_c and for any bridge volume and contact angle.

3. Moisture content

The moisture content is defined as the ratio of the mass of water to the mass of sand grains

$$w = \frac{m_w}{m_s} = \frac{n\rho_w V}{4\rho_s\pi r^3/3} = \frac{3n\nu\rho_w}{4\rho_s} \tag{9}$$