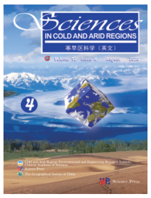

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Theoretical expressions for soil particle detachment rate due to saltation bombardment in wind erosion

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ABSTRACT

Saltation bombardment is a dominate dust emission mechanism in wind erosion. For loose surfaces, splash entrainment has been well understood theoretically. However, the mass loss predictions of cohesive soils are generally empirical in most wind erosion models. In this study, the soil particle detachment of a bare, smooth, dry, and uncrusted soil surface caused by saltation bombardment is modeled by means of classical mechanics. It is shown that detachment rate can be analytically expressed in terms of the kinetic energy or mass flux of saltating grains and several common mechanical parameters of soils, including Poisson's ratio, Young's modulus, cohesion and friction angle. The novel expressions can describe dust emission rate from cohesive surfaces and are helpful to quantify the anti-erodibility of soil. It is proposed that the mechanical properties of soils should be appropriately included in physically-based wind erosion models.

Keywords: wind erosion; saltation bombardment; cohesive soil; anti-erodibility

1 Introduction

Soil erodibility is a practical concept representing the susceptibility of soils to water or wind erosion (Cook 1937; Bryan *et al*., 1989; Webb and Strong, 2011; Funk, 2016). It is often quantificationally expressed as soil erodibility index, *i. e*., the potential mass loss per unit area per unit time from a bare, smooth, uncrusted surface, while modeling wind erosion (Chepil and Woodruff, 1963; Woodruff and Siddoway, 1965; Wilson, 1994; Fryrear *et al*., 1998; Van Pelt *et al*., 2004). Since soils consist of inorganic and organic solids, water, and air (Lal and Shukla, 2004), it is naturally assumed that soil erodibility index is a function of the properties of these four components. Over the past several decades, various empirical expressions, explicitly including particle-size distribution, organic matter content, and moisture content, have been established (Bryan, 1968; Webb and McGowan, 2009; Wagner, 2013). At the present time, these valuable empirical relations of soil erodibility are used, calibrated or extended worldwide (*e.g*., Borrelli *et al*., 2014; Pi *et al*., 2017; Zhang *et al*., 2017). A major defect of non-process-based wind erosion models is that there exist many empirical parameters required to be determined locally. As pointed out by Webb and Strong (2011), representing soil erodibility dynamics should be regarded as a priority in the ongoing development of wind erosion models.

During wind erosion events, dust particles are emitted from soils through aerodynamic lifting, disaggregation and saltation bombardment (Shao, 2008; Kok *et al*., 2012). The last one is a dominant mechanism in respect that most aeolian sand-size grains and aggregations move in saltation. For small particles, aerodynamic lifting is generally unimportant because the inter-particle cohesion is large compared with gravity and aerodynamic force, except a few special cases such as "free" particles (Shao and Klose, 2016; Zhang *et al*., 2016) or dust devils (Neakrase *et al*., 2016; Wang, 2016; Kurgansky, 2018). Threshold friction velocity, being an indispensable parameter in most wind erosion models, reflects the capacity of the soil surface to resist aerodynamic lifting. Threshold theories for loose and dry surfaces and the influence of soil moisture are continually developed (*e.g*., Shao and Lu, 2000; Mckenna Neuman, 2003; Bagnold, 2005; Wang, 2006; Bolte *et al*., 2011). A recent wind tunnel experiment indicates that turbulence effects aerodynamic lifting (Li *et al*., 2020). The size distribution of emitted particles from dust aggregates or snow crystals owing to disaggregation can be well described by using the power law for brittle material fragmentations (Kok, 2011; Comola *et al*., 2017). As one of four crucial sub-processes in the aeolian sediment transport (Anderson and Haff, 1991), sand-bed impact has been studied in detail (*e.g*., Zheng, 2009). For loose soils, the vertical dust flux generated by saltation bombardment can be successfully predicted by several schemes with respect to air density, friction velocity, threshold friction velocity, and constant coefficients (Kok *et al*., 2012). However, how to quantify binding strength of dust particles is a challenge (Shao, 2008). In fact, the significance of the mechanical properties of bare or crusted soils in the breakdown of soil structures and dust emission has long been noted in studies of wind erosion (Chepil and Woodruff, 1963; Smalley, 1970; Wilson, 1994; Rice *et al*., 1997; Zobeck *et al*., 2003; Wang *et al*., 2006). They are characterized by rupture modulus (Richards, 1953), surface strength (Rice *et al*., 1997; Rice *et al*., 1999), or binding energy (Shao *et al*., 1993). A mathematic model of sand grain impact and soil failure indicates that soil erodibility might depend on inter-particle cohesive forces (Smalley, 1970). Early laboratory experiments of water erosion reveals that soil detachment by rainfall is proportional to the ratio of the kinetic energy of raindrops to the shear strength of soils (Al-Durrah and Bradford, 1981; Al-Durrah and Bradford, 1982; Nearing and Bradford, 1985; Torri *et al*., 1987). According to this result, the detachment function in the Texas Tech wind erosion analysis model is constructed by employing the method of dimensional analysis (Wilson, 1994). Another remarkable progress independently achieved by aeolian researchers is the abrasion law, *i.e*., the mass removal of target materials per impact is proportional to the kinetic energy of the impacting particle (Greeley *et al*., 1982; Anderson, 1986; Hagen, 1991). This empirical law is theoretically improved after extracting a non-dimensional parameter containing the Young's modulus and yield stress of the target materials like rocks from a general model of collision and damage (Wang *et al*., 2011; Wang, 2020).

Recently, a large number of direct shear tests for erodible soils have been performed (Li, 2015; Fang *et al*., 2018; Zhang *et al*., 2018) and the role of shear strength is still being explored (Zou *et al*., 2015; Sunamura, 2018). Tensile and shear strengths can be added to the standard spring-dashpot contact model while numerically modeling the saltation developing over cohesive surfaces by the discrete element method (Comola and Lehning 2017; Comola *et al*., 2019). From the viewpoint of soil mechanics (Fredlund and Rahardjo, 1993; Terzaghi *et al*., 1996), the deformation, motion, and failure of topsoils are involved in the process of saltation bombardment, and these behaviors cannot be intuitively and uniquely described by one parameter. In our study, a simple analytical model for the erosion of a bare, smooth, dry, and uncrusted soil surface due to saltation bombardment is built upon the principle and method of classical mechanics.

2 Model

The soil behavior in response to external forces can be described by soil mechanics. Basic differential equations of mass conservation, momentum balance and constitutive relation are referred to Fredlund and Rahardjo (1993) and Terzaghi *et al*. (1996). An unsaturated soil will reduce to a perfectly elastic body if the terms with respect to pore-air and pore-water pressures in the constitutive relation are neglected. Such an oversimplification offers rough estimations of the quantities of displacement and stress to be predicted (Terzaghi *et al*., 1996). Different from previous work attempting to establish a general theoretical frame (Wang *et al*., 2011), here we focus on the special case of erosion caused by the normal impact between a saltating sand grain and a half-space comprised of the soil, as presented in Figure 1, in order to avoid complex numerical computations and meanwhile to capture the physical essence. It is also assumed that the rigid impactor itself rebounds from rather than beds in the topsoil. Given an arbitrary point N in the soil, our purpose is to assess whether failure occurs or not. The meanings and symbols of the main variables and parameters are listed in Table 1.

The solution to the Boussinesq problem, which describes the elastic deformation of a homogeneous half-space under a concentrated force P normal to its surface, has been obtained (Lurie and Belyaev, 2005; Popov, 2010). In the rectangular coordinate system in Figure 1, the stress field can be expressed by,

$$\sigma_x = -\frac{P}{2\pi R}\ \{\frac{3x^2 z}{R^4} - \frac{1-2\nu}{R+z}\ [1 - \frac{y^2(2R+z)}{R^2(R+z)}\ ]\} \tag{1a}$$

$$\sigma_y = -\frac{P}{2\pi R}\{\frac{3y^2z}{R^4} - \frac{1-2\nu}{R+z}[1 - \frac{x^2(2R+z)}{R^2(R+z)}]\} \quad (1b)$$

$$\sigma_z = -\frac{3Pz^3}{2\pi R^5} \quad (1c)$$

$$\tau_{yz} = -\frac{3Pyz^2}{2\pi R^5} \quad (1d)$$

$$\tau_{zx} = -\frac{3Pxz^2}{2\pi R^5} \quad (1e)$$

$$\tau_{xy} = -\frac{Pxy}{2\pi R^3}[\frac{3z}{R^2} - \frac{(1-2\nu)(2R+z)}{(R+z)^2}] \quad (1f)$$

where $R = \sqrt{z^2 + y^2 + x^2}$, ν is the Poisson's ratio, σ and τ denote normal and shear stress, respectively.

It is assumed that the eroded volume has a semi-elliptical shape with the equatorial and polar radii of a and b. Based on the expressions of stress components *(1)*, three principal stresses at (a, 0, 0) are calculated,

$$\sigma_1 = \frac{P(1-2\nu)}{2\pi a^2}, \sigma_2 = 0, \sigma_3 = -\frac{P(1-2\nu)}{2\pi a^2} \quad (2)$$

Different from the targets of rocky materials we modeled previously (Wang *et al.*, 2011; Ning *et al.*, 2019), the failure of soils is assessed by the Mohr-Coulomb failure criterion (Shield, 1955),

$$\sigma_1 - \sigma_3 = 2c\cos\phi - (\sigma_1 + \sigma_3)\sin\phi \quad (3)$$

where c is cohesion, ϕ is friction angle.

From Equations *(2)* and *(3)*, we have,

$$\frac{P(1-2\nu)}{2\pi a^2} = c\cos\phi \quad (4)$$

Similarly, the principal stresses at (0, 0, b) and the equation about b are,

$$\sigma_1 = \sigma_2 = \frac{P(1-2\nu)}{4\pi b^2}, \sigma_3 = -\frac{3P}{2\pi b^2} \quad (5)$$

and

$$\frac{P}{2\pi b^2}\left(c_1 - c_2\sin\phi\right) = 2c\cos\phi \quad (6)$$

where $c_1 = \frac{7}{2-\nu}, c_2 = \frac{5}{2+\nu}$.

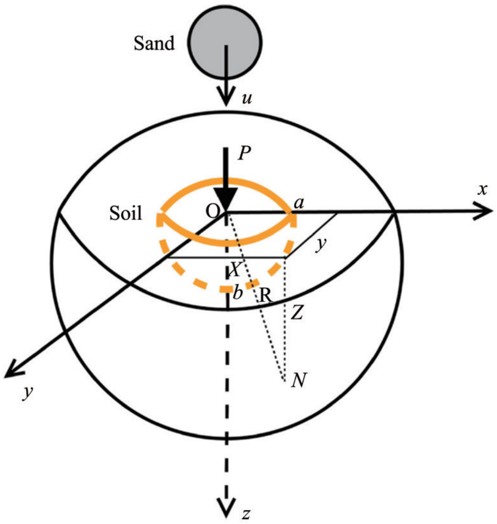

Figure 1 The normal impact between a saltating sand grain and a half-space comprised of the soil. u and P are the vertical speed of the saltating grain and the collision force acting upon the soil. Given an arbitrary point N under the coordinate of (x, y, z), the stress and displacement can be computed. The eroded volume is denoted by a semi-elliptical shape with the equatorial and polar radii of a and b, respectively

Table 1 Meanings and symbols of the main variables and parameters. The international system of units is applied

Meaning	Symbol	Units	Meaning	Symbol	Units
Coordinate component	x, y, z	m	Poisson's ratio	ν	
Concentrated force	P	N	Young's modulus	E	Pa
Normal stress	$\sigma_x, \sigma_y, \sigma_z$	Pa	Cohesion	c	Pa
Shear stress	$\tau_{xy}, \tau_{yz}, \tau_{zx}$	Pa	Friction angle	ϕ	
Principal stress	$\sigma_1, \sigma_2, \sigma_3$	Pa	Equatorial radius	a	m
Sand grain mass	m	kg	Polar radius	b	m
Sand grain speed	u	m/s	Impact duration	$\delta t, T$	s
Eroded volume	V	m^3	Impact times	n	
Mass flux density	q	kg/(m^2·s)	Sand diameter	d	m
Surface height	h	m	Density	ρ_s, ρ_b	kg/m^3
Displacement	w	m	Restitution coefficient	e	
Abrasion rate	Ar	g/s	Constant coefficients	A	
			Abraded area	S	m^2

There are three unknown quantities a, b, P in Equations *(4)* and *(6)*. A third relation must be found. The magnitude of time-averaged impact force P is determined by the momentum theorem,

$$P = \frac{mu(1+e)}{\delta t} \tag{7}$$

where m, u, e, and δt are the mass and speed of the saltating grain, the coefficient of restitution, and impact duration, respectively. The Hertzian contact theory reveals that the coefficient of restitution e depends upon the severity of the impact. For low-speed impacts we studied, a constant e is assumed because it slowly decreases with increasing the impact speed (Johnson, 1985).

The impact duration is estimated as,

$$\delta t \approx \frac{w}{u} \tag{8}$$

where the z component w of displacement at $z=b$ has the form of (Popov, 2010),

$$w = \frac{P(1+\nu)(3-2\nu)}{2\pi E b} \tag{9}$$

where E is the Young's modulus.

Combining Equations *(7)*–*(9)*, the third relation is,

$$\frac{P^2}{2\pi E b} \approx \frac{mu^2(1+e)}{(1+\nu)(3-2\nu)} \tag{10}$$

Consequently, the eroded volume per impact can be derived from Equations *(4)*, *(6)*, and *(10)*. Since the physical processes related to wind erosion are often particle-size dependent (Shao, 2008), it is rescaled in terms of the diameter of the saltating grain,

$$\frac{V}{d^3} \sim \frac{a^2 b}{d^3} \propto \frac{c_1 - c_2 \sin\phi}{\cos^2\phi} \cdot \frac{\rho_s u^2 E}{c^2} \tag{11}$$

where V is the detached volume per impact, d and ρ_s are the diameter and density of the saltating sand grain, and the mass expression of $m = \rho_s \pi d^3/6$ has been inserted, and the constants e and ν are implicatively contained in the proportionality coefficient.

Define the incoming mass flux density q as the mass perpendicularly striking an unit surface area per unit time, the mass transported by wind through the cross sectional area of one grain in the duration of T is

$$\delta m = \frac{1}{4} q \pi d^2 T = \frac{1}{6} n \rho_s \pi d^3 \tag{12}$$

where the grain number n is equivalent to impact times.

The length of "sand column" is,

$$l \propto \frac{\frac{1}{6} n \pi d^3}{\frac{1}{4} \pi d^2} = \frac{2}{3} n d \tag{13}$$

in which a constant volume concentration of sand grains is assumed and will be implicitly contained in the proportionality coefficient of the final expression.

From Equations *(12)* and *(13)*, the impact times n and speed u are,

$$n = \frac{3qT}{2\rho_s d} \tag{14}$$

and

$$u = \frac{l}{T} \propto \frac{q}{\rho_s} \tag{15}$$

The change rate of surface height $\dot{h}$ due to soil loss is,

$$\dot{h} = -\frac{4nV}{\pi d^2 T} \tag{16}$$

Substituting *(11)*, *(14)* and *(15)* into *(16)*, we have,

$$\dot{h} = -A \frac{c_1 - c_2 \sin\phi}{\cos^2\phi} \cdot \frac{q^3 E}{\rho_s^2 c^2} \tag{17}$$

where A is a positive constant needed to be determined experimentally.

3 Results and discussion

The concise derivation as given above leads to two new analytical detachment Formulas *(11)* and *(17)* suitable for the prediction of soil loss caused by individual and continuous impacts of saltating grains respectively. The method we used is similar to the dust production model which attempts to combine an empirical bombardment formula and a saltation model (Alfaro and Gomes, 2001). However, this so-called physically-based model focuses on the mathematic expression of particle size distribution rather than the mechanical processes we insist on investigating (Wang *et al.*, 2011; Ning *et al.*, 2019; Wang, 2020). Different from surface strength, binding energy and shear strength previously used or arbitrarily defined by some aeolian researchers (Shao *et al.*, 1993; Wilson, 1994; Rice *et al.*, 1997; Rice *et al.*, 1999), four common mechanical parameters in soil engineering are introduced together. Their meanings are clear and obvious. Poisson's ratio ν and Young's modulus E quantify the elastic property of soil. Cohesion c and friction angle ϕ, originating from the failure criterion, characterize the inter-particle normal stress and internal friction. All of them should be measured for different types of erodible soils. Unfortunately, they have not appeared in the "standard" methods for wind erosion research (Webb *et al.*, 2015). Some values of c and ϕ can be estimated from direct shear tests (Li, 2015; Zhang *et al.*, 2018). As far as we know, cohesion among them is frequently taken into account to determine the threshold friction velocity. Soil moisture has a strong impact on cohesion. Very recently, the effects of soil moisture on erodibilities of several bare soils are experimentally investigated (De Oro *et al.*, 2019). As a macro-phenomenon, soil erodibility dynamics must obey Netwton's laws of motion. Our theoretical work is a small attempt towards the physically-based wind erosion model in light of the first principles. The effects of gravel cover, vegetation vibration, and unsteady airflows on erosion rate should be deduced in the manner of mechanics in the future. At the moment Equations *(11)* and *(17)* are not comparable with those empirical wind erosion models which seems more comprehensive (Jarrah *et al.*, 2020). Therefore, the presented model has to be validated indirectly.

The wind tunnel experimental results (Bridges *et al.*, 2004) were successfully applied to estimate the abrasion coefficient in our previous studies of the abrasion rates of ventifacts (Ning *et al.*, 2019). Fortunately, the abrasions of soil clods by saltating grains are measured in a recent wind tunnel experiment (Dai *et al.*, 2020). Many dry and wet cylinder- and hexagonal prism-shaped clod specimens of four soil types are abraded and the abrasion masses during 300 s under five different saltation mass flux are obtained. We only re-examine their experimental data for dry specimens because water content always changes with time. The abrasion rate can be written as,

$$Ar = -\rho_b \cdot S \cdot \dot{h} \tag{18}$$

where ρ_b and S are the bulk density and abraded area of the target. For the targets constituted of an identical soil, from Equation *(17)*, we get,

$$Ar \propto q^3 \tag{19}$$

The absolute values of the Pearson correlation coefficients are all larger than 0.60 while fitting the experiment data using Equation *(19)*. For the brown calcic soil, our theoretical model works very well, as presented in Figure 2 where the different values of the fitted coefficient are caused by the specimen shapes.

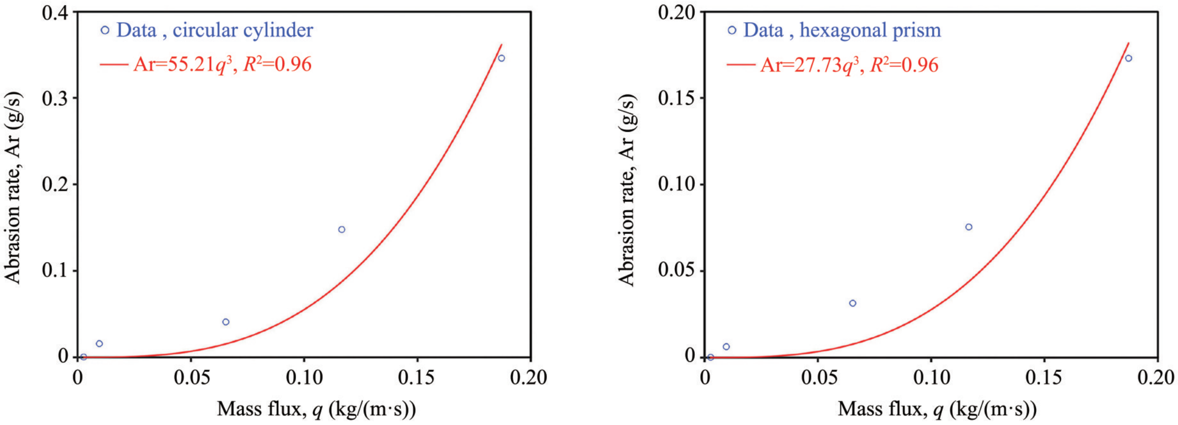

Figure 2 The abrasion rate of brown calcic soil is in direct proportion to the cube of mass flux. The wind tunnel experiment was performed by Dai *et al.* (2020)

It was once speculated that soil anti-erodibility factors might be closely associated with shear strength (Rice *et al.*, 1997; Rice *et al.*, 1999; Zou *et al.*, 2015; Fang *et al.*, 2018), but the theoretical interpretation is less convictive. The right-hand side of Equation *(11)* reflects the ratio of the kinetic energy of the impacting grain to the elastic potential energy of the soil per unit volume at the yield point. The latter, with the units of Pa, is,

$$\lambda = \frac{\cos^2 \phi}{c_1 - c_2 \sin \phi} \cdot \frac{c^2}{E} \tag{20}$$

Given the incoming saltating grains, λ provides an evaluation of the anti-erodibilities of different soils. For the four typical erodible soils classified by the unified soil classification system (USCS), λ values are listed in Table 2, while the other three mechanical parameters, *i.e.*, cohesion c, Young's modulus E and friction angle ϕ, are sourced from geotechnical information available at http://www.geotechdata.info/parameter/parameter.html. The Poisson's ratio of soils normally ranges from 0.1 to 0.5. A constant value of ν=0.3 is assumed in the computation. The descending order of anti-erodibility (CL, ML, SM, and OL) is similar to that of cohesion. This implies that cohesion is more important than the other parameters.

In the future, delicate experiments should be designed and performed to directly examine the soil particle detachment model we developed here. The mechanical parameters of soils, saltation velocity, and detachment rate can be simultaneously measured in triaxial and wind tunnel experiments. The field measurements of the dust emission rates of diffenent soil surfaces are also very helpful. Moreover, it is possible to improve the detachment rate formula based upon the more rigorous contact mechanics theories.

Table 2 Comparison of anti-erodibilities between several erodible soils. The unified soil classification system (USCS) is adopted. The mechanical parameters are sourced from the geotechnical information available at http://www.geotechdata.info/parameter/parameter.html. A constant Poisson's ratio of $\nu = 0.3$ is assumed

USCS	Description	Cohesion c (KPa)	Young's modulus E (MPa)	Friction angle ϕ (°)	Anti-erodibility λ (Pa)
SM	Silty sands	22	16	33	12.70
ML	Silt loam	75	8	28	290.72
CL	Silty clay	97	6.5	25	589.59
OL	Organic silts	5	2.5	27	4.12

4 Conclusions

The analytical expressions for the detachment volume per impact and the detachment rate in saltation bombardment are theoretically derived from the principles of classical mechanics. Four common mechanical parameters of soils, *i.e.*, Poisson's ratio, Young's modulus, cohesion and friction angle, are appropriately introduced into wind erosion. The novel expressions can roughly describe the measured dust emission rates over three different cohesive soil surfaces. The concept of anti-erodibility is quantificationally evaluated. It is expected that the presented work will improve the descriptions of the mechanical properties of soils in physically-based wind erosion models.

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