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A theoretical model on the relation between wind speed and grain size in dust transportation and its paleoclimatic implications

Zhen-Ting Wang [a,b,*], Zhong-Ping Lai [a,b,c]

[a] *State Key Laboratory of Cryosphere Sciences, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, PR China*
[b] *Key Laboratory of Salt Lake Resources and Chemistry, Qinghai Institute of Salt Lake, Chinese Academy of Sciences, Xining 810008, PR China*
[c] *State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710075, PR China*

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ABSTRACT

In studies of paleoclimate and paleoenvironment based on loess-palaeosol deposits, the rigorous relations between climate elements and the properties of loessic sediment are scarce because the dynamic processes controlled by the related physical laws are often ignored or arbitrarily simplified. In the current study, the horizontal distance of a suspended dust particle is re-estimated using classical mechanics and the relation between wind speed and the grain size of primary loess is then established. The actual application of this new theoretical relation is given by an example of Duowa profile, western Chinese Loess Plateau. The numerical results imply that the Qaidam Basin could be a likely dust source of the Chinese Loess Plateau.

1. Introduction

Loess can be simply defined as a terrestrial clastic sediment, composed predominantly of silt size particles, which is formed essentially by the accumulation of wind-blown dust (Pye, 1995). This well-known and generally accepted definition clearly provides the following formative and geometrical properties of loess: 1) the origin is aeolian, and 2) the grain size ranges from 2 μm to 63 μm according to the modified Udden–Wentworth classification (Shao, 2008). As an important parameter in the physics of wind-blown sand (Bagnold, 1941; Shao, 2008), grain size is naturally and widely used as a reliable proxy of the wind condition when the loess was forming. For example, the peaks in the change of the coarse fraction of >40 μm with time in the Chinese loess was referred to record the times when the winter monsoon strengthened under the assumption that the coarse fraction of the dust is greatest when the wind is strongest (Porter and An, 1995). Other grain size parameters, such as the median grain size and the ratio of grains <2 μm to >10 μm, can equally serve as the indication of winter monsoon (Ding et al., 1994; Liu and Ding, 1998). In these previous works about the paleoclimate from the viewpoint of the loess record, two aspects should be made clear. First, how to describe wind? This does not seem to be a problem. Wind, the flow of gas, can be well described by direction, speed, pressure, and turbulent intensity *etc.* However, it is very strange that the term of "wind intensity/strength" is frequently used. This variable is nothing but wind speed, since it can be expressed as the wind speed measured with anemometer with precision of 0.1 m/s (Maia-Carneiro et al., 2012). Second, how to establish the quantitative relation between grain size and wind speed? As far as we know, von Kármán, an outstanding aerodynamic theoretician of the twentieth century, firstly made an estimate of the distance traveled by a suspended dust particle (Malina, 1941). After more than 40 years, researchers performed the analogous derivations (Tsoar and Pye, 1987). The grain size of 20 μm was traditionally and sometimes absolutely regarded as the threshold of long-term suspension (Shao, 2008; Pye, 1987). In fact, the empirical expression of the dust height due to turbulence in the original derivations, *i.e.* Eq. (8) in (Malina, 1941) or Eq. (6) in (Tsoar and Pye, 1987), has a very large error (Taylor, 1915). Moreover, different from the constant molecular viscosity coefficient, the eddy viscosity coefficient depends on the flow field (Oertel, 2003). Therefore, it is necessary to re-estimate the horizontal distance that a suspended particle traveled and then investigate the relation between wind speed and the grain size in dust transportation.

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* Corresponding author at: State Key Laboratory of Cryosphere Sciences, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, PR China. Tel.: +86 13139239338.
E-mail addresses: wangzht@lzu.edu.cn (Z.-T. Wang), zplai@isl.ac.cn (Z.-P. Lai).

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2. Theoretical model

Dust particles can be emitted from the ground through three main mechanisms, *i.e.* aerodynamic lift, saltation bombardment, and auto-abrasion (Shao, 2008; Kok et al., 2012). The maximum height of dust in the dust devils frequently occurring in desert conditions was observed to be 1500–4500 m (Sinclair, 1969; Hess and Spillane, 1990). Here we only consider the subsequent transport and deposition of suspended dust particles.

An ideal dust trajectory from source to loess deposit is illustrated in Fig. 1 where the influence of topography is taken into account. Two displacement components of the dust particle can be roughly expressed as

$$X = Ut \tag{1}$$

and

$$h + Y = h + X\tan\theta = U_f t \tag{2}$$

where U, t, θ are wind speed, time, and slope angle, respectively. The settling velocity is given by Stokes' law

$$U_f = \frac{\rho_s g d^2}{18\mu} \tag{3}$$

where ρ_s, g, d, μ are sand density, gravity accleration, grain diameter, air dynamic viscosity.

Combining Eqs. (1)–(3), we have

$$X = \frac{U}{U_f - U\tan\theta} h \tag{4}$$

and

$$U = \frac{\rho_s g X}{18\mu(h + X\tan\theta)} d^2 \tag{5}$$

Eq. (4) indicates that $X \to \infty$ when $U_f \to U\tan\theta$. In other words, the particles smaller than d_* will suspend freely. This threshold grain size is

$$d_* = \sqrt{\frac{18\mu U\tan\theta}{\rho_s g}} \tag{6}$$

Eq. (5) enables us to reconstruct wind speed from the grain diameter of aeolian sediment if transport distance X, initial height h, and slope angle θ are given. The grain size distribution of loess is commonly non-uniform. Some previous mathematical methods (Sun et al., 2002; Weltje and Prins, 2007) are unhelpful to determine d because the dynamic process is seldom considered simultaneously. As a preliminary study, the mean diameter of particles larger than d_* is treated as d,

$$d = \frac{\int_{d_*}^{+\infty} x f(x) dx}{\int_{d_*}^{+\infty} f(x) dx} \tag{7}$$

where f is the probability density function of grain size. Consequently, (5) is an implicit equation about U.

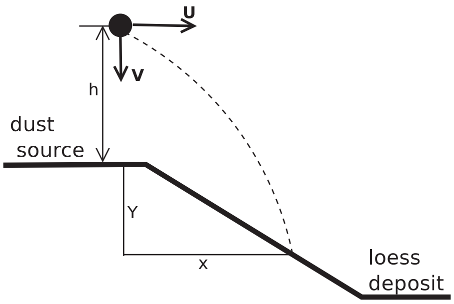

Fig. 1. An ideal dust trajectory from source to loess deposit.

3. An actual application

It will be interesting to show the application of Eqs. (5)–(7) by means of investigating an open problem. The world's thickest and most extensive loess deposits are found in the Chinese Loess Plateau (Liu, 1985; Tsoar and Pye, 1987). The Qaidam Basin (Fig. 2) in the northeastern Tibetan Plateau was proposed to be an important source region of Chinese loess because Yardangs, one of the most severely wind-eroded landscapes on Earth, occurs in its western part and the prevailing wind is northwesterly (Bowler et al., 1987). In contrast, it was argued that the dust contribution of this inland basin is little because the wind-eroded material could be mostly stored in the eastern part of the basin (Sun, 2002). Recently, the role of the Qaidam Basin as a major provenance of loess has been supported by more sedimentological, chronological, and geochemical evidence (Kapp et al., 2011; Pullen et al., 2011; Yu and Lai, 2012; Heermance et al., 2013; Lai et al., 2014). However, the dynamic process of dust transport and deposition, essential to the complete solution of this problem, is not well understood.

One typical grain size distribution of loess in the western Chinese Loess Plateau is lognormal (Zhang et al., 1994; Zhao et al., 2008),

$$f(x) = \frac{1}{xb\sqrt{2\pi}} \exp\left[-\frac{(\log x - a)^2}{2b^2}\right] \tag{8}$$

where a and b are the mean and standard deviation of the natural logarithm of grain size x, respectively.

Substituting (8) into (7), d can be expressed as

$$d = \frac{\exp\left(a + \frac{1}{2}b^2\right)\Phi\left(\frac{a + b^2 - \log d_*}{b}\right)}{1 - \Phi\left(\frac{\log d_* - a}{b}\right)} \tag{9}$$

where $\Phi(x) = \frac{1}{2}\left[1 + erf\left(\frac{x}{\sqrt{2}}\right)\right]$.

For a loess sample, a and b are constant. We select the high-quality data set of the median grain size $\bar{d}$ and the percentage of $x > d_0 = 40\ \mu\text{m}$ at Duowa profile, western Chinese Loess Plateau (Maher and Hu, 2006) (Fig. 2). The chronology of this profile was established by optically stimulated luminescence (OSL) dating method using 4–11 μm poly-mineral grains (Roberts et al., 2001; Maher and Hu, 2006). The uncertainty of the previous published data is mainly caused by the chronological method. The grain size we are concerned with is accurate enough.

The median grain size and the percentage of $x > d_0$ are,

$$\bar{d} = \exp(a) \tag{10}$$

and

$$F_{x>d_0} = 1 - \Phi\left(\frac{\log d_0 - a}{b}\right) \tag{11}$$

Combining Eqs. (10 and (11), two parameters in Eq. (9) can be obtained,

$$a = \log\bar{d} \tag{12}$$

and

$$b = \frac{\log d_0 - \log\bar{d}}{\sqrt{2}erf^{-1}(1 - 2F_{x>d_0})} \tag{13}$$

We numerically solved Eqs. (5), (6), and (9) by using the method of bisection, setting gravity accleration $g = 9.8\ \text{m/s}^2$, sand density $\rho_s = 2.65 \times 10^3\ \text{kg/m}^3$, air dynamic viscosity $\mu = 1.78 \times 10^{-5}\ \text{Pa} \cdot \text{s}$,