Characterizing the sediment bed in terms of resistance to motion: toward an improved model of saltation thresholds for aeolian transport

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ABSTRACT: Models of aeolian transport thresholds generate a wide range of predictions, and error in threshold modeling leads to uncertainty in predicting aeolian events. This paper proposes a new characterization of the representative grain size for use in prediction of transport thresholds. This characterization is based on the distribution of resistance to motion in the sediment bed. The traditional grain size distribution uses a mean diameter to represent the sediment bed. However, the distribution of inertial forces resisting motion is not linearly proportional to the distribution of grain diameters, so that an arithmetic mean does not adequately represent the distribution of the resisting forces. A simple relation of shear stress to weight force is used to represent the threshold condition. Based on comparison with threshold observations drawn from the literature, the model provides reliable predictions of threshold stress and shear velocity for dry quartz grains over a wide range of grain sizes. Given that the dataset was drawn from studies employing a variety of experimental conditions and techniques, and that these studies spanned a range of nearly eight decades, the model is considered to provide a robust approximation of threshold conditions.

KEYWORDS: SEDIMENT TRANSPORT; INITIATION OF MOTION; TRANSPORT THRESHOLD; THRESHOLD SHEAR VELOCITY; AEOLIAN TRANSPORT; GRAIN SIZE DISTRIBUTION;

1. Introduction

Collectively, models of the threshold shear velocity required to initiate aeolian transport (e.g., Bagnold 1936, Chepil 1945, 1959, Lyles and Krauss 1971, Iversen and White 1982, Shao and Lu 2000, Cornelis and Gabriels 2004) generate a wide range of predictions (Horikawa et al. 1982, Sarre 1987, Cornelis and Gabriels 2003), as illustrated in Figure 1. The problem is particularly apparent for large grain sizes ($d_{50} > 0.8 \text{ mm}$). Thus, a basis for confident prediction of transport thresholds and even whether a given wind event will generate transport is not currently available. In addition, many of the best performing mass flux models (Sarre 1988) incorporate a threshold shear velocity term (e.g., Kawamura 1951, Owen 1964, Lettau and Lettau 1977, White 1979, Shao et al. 1996), and uncertainty in threshold estimates will therefore propagate to transport predictions (Sherman et al. 2013). Uncertainties in threshold and mass flux modeling undermine efforts to model aeolian systems from micro- to regional scales, in terms of both numbers of transport events and total mass flux (Sherman et al. 2011, Barchyn et al. 2014).

Aeolian systems are complex, and many simplifications are incorporated into attempts to represent their physical characteristics and behavior (Bauer 2009). One common simplification is the use of a single characteristic grain size to represent the range of sizes present in natural environments. This representative grain size is almost universally determined as the mean diameter of the most frequently occurring size class in the distribution. However, this approach does not account for the fact that grain mass – which determines the weight force acting to hold a given particle in place and prevent motion – does not scale linearly with grain diameter. Thus, as the degree of sorting decreases for sediment populations with a given

mean diameter, and larger and larger grains are therefore present, the ability of the sediment bed to resist general motion will become increasingly skewed towards grain sizes larger than the mean (e.g., Nickling 1988, Namikas 2006, Namikas et al. 2009). Further, grain sorting is commonly presumed to influence grain-on-grain resting angles, with larger grains protruding farther from the bed and sheltering smaller grains from exposure to the wind field (e.g., Logie 1981, Wiberg and Smith 1987, McKenna Neuman 2003).

In this paper, we propose a new characterization of the representative grain size for prediction of transport thresholds. This characterization is based on the distribution of resistance to motion in the particles that comprise the sediment bed. Through an analysis of previously published threshold observations, we relate observed threshold shear velocities to this mass-weighted size distribution. Results show that a simple force balance approach to modeling aeolian thresholds for sand size grains provides excellent predictive ability for a wide range of data drawn from more than a dozen previous studies.

2. Traditional approach to modeling transport thresholds

For the case of dry grains large enough that interparticle cohesion can reasonably be ignored (Gregory and Darwish 1990, Merrison 2012), models of aeolian transport thresholds generally define threshold shear velocity (u_{*t} (m/s)) following Bagnold's (1936) approach:

$$u_{*t} = A \sqrt{\frac{\rho_s - \rho_a}{\rho_a} g d_{50}} \quad (1)$$

where ρ_s and ρ_a are the density of sediment and air (kg/cm^3), respectively, g is acceleration due to gravity (m/s^2) and A is a dimensionless coefficient proportional to the square root of the Shields parameter, the dimensionless ratio of fluid forces to inertial forces at the onset of motion. Equation 1 is based on the balance of particle moments for the inertial and aerodynamic forces, which can be described in terms of threshold shear stress (τ_t) per unit area (N/m^2) imparted on the grain by the wind field. Threshold shear stress is related to threshold shear velocity as:

$$u_{*t} = \sqrt{\frac{\tau_t}{\rho_a}} \quad (2)$$

This framework appropriately describes the physics of entrainment, but from a practical standpoint the utility of this approach to accurately predict transport thresholds is limited due in part to disagreement regarding the correct value of A and, in some cases, the correct method to determine its value (e.g., via Reynolds number, empirical observations, or parameterization). There is agreement that the value of A should be near constant for sand sized grains (e.g., Bagnold 1941, Greely and Iversen 1985, Cornelis and Gabriels 2004), but there has been no consensus in the literature regarding its value. This leads to uncertainty in prediction of transport thresholds and is a significant source of error in subsequent mass flux modeling (Sherman et al. 2013).

There are several possible reasons for disagreement about the appropriate values for threshold model parameters among previous studies, including differing experimental procedures, wind tunnel design, threshold criteria and shear velocity estimation techniques

(Lyles and Krauss 1971, McKenna Neuman and Nickling 1994, Iversen et al. 1987). Another potential source of error lies in the common approach of representing the sediment bed in terms of a characteristic mean grain diameter. This approach does not account for natural variability in grain size range; i.e. threshold conditions should differ for sediment beds that have the same mean diameter but different size distributions. Characterization of grain size in terms of the distribution of the resistance to motion of grains should more closely represent the threshold conditions of the bed, and could potentially improve model predictions.

3. Threshold shear velocity as a function of resistance to motion and grain size-range

The basic physical explanation of the onset of motion for dry sands in air is simple; aerodynamic forces must overcome resisting forces. The conceptual approach herein ignores force direction, grain resting angles and grain rotation, which results in a simple force magnitude balance describing the threshold condition. For the case of sand grains in air, grain weight is several orders of magnitude greater than that of an equal volume of air, so the buoyancy force is negligible. Further, according to theoretical considerations (Merrison 2012), for grains larger than about 0.08 mm in diameter the weight force resisting motion becomes orders of magnitude larger than interparticle cohesive force (Figure 2) and can be ignored. Thus, in situations where cohesion due to moisture is not a concern the primary force resisting motion for naturally occurring sand size sediments is weight. It follows, therefore, that the threshold of general motion should be controlled by the distribution of particle masses present in the sediment bed.

3.1 Defining grain size distributions in terms of resistance to motion

The potential effects of sorting on transport threshold observations have been noted by several researchers (e.g., Grass 1971; Logie 1981; Nickling 1988, McKenna Neuman 2003, Davidson-Arnott et al. 2008). Research has also shown that mass flux model performance degrades as experimental sediment samples trend from well sorted toward more widely distributed populations (Horikawa et al. 1986). McKenna Neuman (2003) suggests that this departure is due to use of the mean diameter to represent the population, which in the case of naturally graded sands may not be representative of the resistance to motion of the sediment bed. Indeed, McKenna Neuman (2003) noted that the use of a larger representative size would improve threshold model performance when evaluating models from Greely and Iversen (1985) and Shao and Lu (2000). This suggests that an explicit inclusion of some measure of the distribution of resistance to motion within the sediment bed should improve model performance. For example, contrast the relative masses of grains with diameters of 0.5 mm, 0.1 mm, and 0.3 mm (the mean of the first two diameters). The largest grain would be nearly 5 times more massive than the mean, and 125 times more massive than the smallest. Clearly, the resistance to general motion would vary between sediment beds having the same 0.3 mm mean grain size but differing proportions of large and small grains (i.e., different sorting). Thus, use of the mean diameter alone to characterize the sediment bed could produce significant error in threshold predictions.

Generally, grain size-range distributions are represented in terms of the proportion or frequency present in each of a set of size classes defined by narrow ranges of diameter (e.g.,

Krumbein 1934). Consider, for example, four grain size distributions all characterized by a mean diameter of 0.25 mm (2ϕ) with sorting values of 0.2, 0.4, 0.6, and 0.8, respectively (Figure 3a). To approximate the distribution of weight force resisting motion in these grain size distributions, the midpoint diameter of each size class can be used to calculate the mass of a single grain representative of that size class (assuming spherical shape and using a density of 2650 kg/m³ for quartz grains). When the mass of the representative grain of each size class is multiplied by the relative frequency of that class, the diameter-frequency distribution is in effect transformed to a mass-weighted frequency distribution (Figure 3a). This new distribution should provide an improved representation of the distribution of resistance to motion within the sediment sample. The grain diameter corresponding to the mean of the mass-weighted distribution (d_{r50}) is the parameter used herein to represent the dominant resistance to motion of the sediment bed, and is defined as:

$$d_{r50} = 2 * \sqrt[3]{\frac{3}{4\pi} * \frac{\sum(f*V)}{100}} \quad (3)$$

Where f is the frequency (%) of each size class and V is the volume of the midpoint grain for each size bin (m³). The summation inside of the radical determines the mean mass-frequency grain and the remainder of Equation 3 converts that grain to a corresponding diameter.

Because grain mass increases exponentially with diameter, d_{r50} is increasingly shifted to larger diameters as sorting value increases (Figure 3a). For the example sediment beds in figure 3, the differences between d_{50} and d_{r50} correspond to increases in diameter of 0.014, 0.064, 0.17, and 0.38 mm, respectively, from the original mean of 0.25 mm. Clearly, if grain size

distributions are weighted by grain mass, increases in the range of sizes present in the sediment bed can have a dramatic effect on the expected resistance to motion. This effect is illustrated in Figure 3b, which shows the increase from d_{50} to d_{r50} for a wide range of d_{50} and sorting values.

3.2 Threshold model development

In the simplest approximation, the bed shear stress necessary to initiate motion is proportional to the weight force resisting motion. This proportionality assumes that similar weight force acts over the same unit area as shear stress acts and that interparticle cohesion and buoyancy force for sand grains in air are negligible. Given a representative grain size of d_{r50} , it follows that:

$$\tau_t \propto m_{dr}g \quad (4)$$

where m_{dr} is the mass (kg) of d_{r50} .

To evaluate this approximation using the mass-weighted representative grain, data from previous studies were collected from the literature (Table 1). A total 27 threshold observations from 13 studies containing suitable data were identified (Bagnold 1936, Kawamura 1951, Chepil 1959, Belly 1964, Kadib 1965, Lyles and Krauss 1971, Logie 1981, Logie 1982, Horikawa et al. 1983, McKenna Neuman and Nickling 1989, McKenna Neuman 2003, 2004, Cornelis and Gabriels 2004). Data were parsed from available studies using the following criteria: a reported (or readily inferred) experimental observation of transport threshold, sufficient description of grain size distribution, experimental conditions were clearly defined, and results were deemed

reliable (e.g., only the Yoneza sand from Horikawa et al. 1983 is used because those authors lacked confidence in results from other experimental sediments). Grain size distributions and descriptive statistics were calculated by digitizing grain frequency plots where available, or were estimated statistically where only the size-range of sediments used in the experiment was reported (the ranges were quite small so this approach was deemed acceptable). It is worth noting that collectively these studies include a wide range of experimental conditions and techniques and span eight decades, thus many of the potential sources of error and disagreement between studies should be encapsulated in the dataset.

A linear regression model fitted to these data demonstrates that equation 4 is indeed a robust approximation of transport threshold conditions (Figure 4). Values of p_s and p_a of 2650 and 1.2 kg/m³, respectively, are used in all calculations. There is a very strong linear relationship between τ_t and the weight force of d_{r50} ($R^2 = 0.97$, RMSE = 0.047 N/m²). The strength of the relationship indicates that d_{r50} is an appropriate descriptor of bed inertia for transport modeling, and confirms that for sand-size, quartz grains in air a simple consideration of the balance of shear stress to resistance to motion due to weight force can approximate the threshold condition quite well. It should be noted that consideration of submerged weight would need to be included for other fluids or significantly less dense particles.

Bed shear stress is difficult to measure directly (e.g., Namikas 2002), so it is often more convenient to express transport thresholds in terms of shear velocity (u_{*t}). If we consider the weight force resisting motion in Equation 4 to be acting over the same unit area as τ , substituting Equation 2 into Equation 4 yields:

$$u_{*t} \propto \sqrt{\frac{m_r g}{\rho_a}} \quad (5).$$

Fitting equation 5 to the experimental observations of threshold shear velocity (Figure 5) results in the expression:

$$u_{*t} \approx 191 * \sqrt{\frac{m g}{\rho_a}} + 0.2 \quad (6)$$

This model is also quite robust ($R^2 = 0.92$). Given that the experimental studies from which this relationship was derived involved differing definitions of, and approaches to identifying, the moment when transport was initiated, the level of error is considered acceptable (RMSE = 0.05 m/s).

The experimental conditions represented in the dataset cover most of the range of grain sizes for which saltation commonly occurs. The lower boundary of applicability for the relationship ($u_{*t} = 0.2$) is approximately equivalent to the lower limit of observed saltation thresholds (Merrison 2012) and corresponds to the theoretical inversion point below which transport thresholds begin to increase due to intergranular cohesion (Shields 1936, Merrison 2012, Figure 2). Notably, the relationship also remains accurate for the largest grain sizes in the dataset, which were not well represented by standard models (see Figure 1).

4. Discussion and Conclusions

The goal of this analysis was to develop a model based on grain weight force that incorporates the influence of grain size-range on resistance to motion in the sediment bed and reliably predicts aeolian threshold shear velocity for dry sand size grains. This was accomplished by modeling the grain size-range in terms of mass-weighted frequencies (d_{r50}) and using a simple force balance approximation of the threshold condition.

This approach performed well when tested using observations of threshold shear velocity obtained from the literature. The studies from which the data were drawn included a wide range of experimental conditions and techniques so that many of the potential sources of differing results are included in the dataset. The observations included both mechanically and naturally graded sediments, a range of experimental conditions, and differing criteria for identification of the threshold of motion. Despite these differences, the model provides accurate predictions of threshold observations over a wide range of sand sizes and concurs with theoretical and observed lower limits of saltation thresholds.

This paper provides an initial application of the mass-weighted representation of grain size distributions specific to the particular case of aeolian thresholds of motion for dry quartz grains. As a next step it will clearly be of interest to determine whether this characterization of the sediment bed can provide improved results in other areas of aeolian transport where available models diverge widely, such as mass flux models, as well as in other environments where saltation occurs, including fluvial and coastal systems.

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343 heterogeneous sediments. Water Resources Research 23, 1471-1480.

Study	d_{50} (mm)	Sorting	d_{r50} (mm)	Observed u^*_t (m/s)	τ (N/m ²)	Predicted u^*_t from Equation 1
McKenna Neuman and Nickling 1989	0.19	0.28	0.21	0.25	0.08	0.20
	0.27	0.32	0.32	0.27	0.09	0.24
	0.51	0.19	0.53	0.38	0.18	0.33
McKenna Neuman 2003, 2004	0.27	0.43	0.34	0.32	0.13	0.24
Belly 1964	0.44	0.40	0.54	0.42	0.22	0.31
Logie 1982	0.24	0.65	0.51	0.34	0.14	0.23
Horikawa et al. 1983 (Yoneza sand)	0.28	0.44	0.34	0.25	0.08	0.25
Kadib 1965 (sand B)	0.31	0.36	0.35	0.44	0.24	0.26
Kadib 1965 (sand D)	1.00	0.29	1.12	1.00	1.23	0.46
Kadib 1965 (sand E)	0.82	0.51	1.00	0.90	0.99	0.42
Kawamura 1951	0.21	0.65	0.27	0.23	0.07	0.21
Lyles and Krauss 1971	0.24	0.06	0.24	0.32	0.13	0.23
	0.51	0.04	0.50	0.48	0.28	0.33
	0.72	0.04	0.72	0.52	0.33	0.39
Bagnold 1936	0.24	0.06	0.24	0.22	0.06	0.23
Logie 1981	0.15	0.04	0.15	0.28	0.10	0.18
	0.21	0.04	0.21	0.32	0.13	0.21
	0.30	0.04	0.30	0.35	0.15	0.25
	0.43	0.04	0.43	0.41	0.21	0.30
	0.20	0.06	0.20	0.27	0.09	0.21
	0.27	0.02	0.27	0.32	0.12	0.24
Chepil 1959	0.36	0.04	0.36	0.36	0.16	0.28
	0.51	0.04	0.50	0.44	0.24	0.33
	0.72	0.04	0.72	0.53	0.34	0.39
Cornelis and Gabriels 2004	0.16	0.09	0.16	0.25	0.08	0.18
	0.36	0.11	0.36	0.32	0.13	0.28
	0.28	0.28	0.31	0.30	0.11	0.24

Table 1. Experimental observations of transport thresholds obtained from the literature, calculated values of d_{r50} for each, and predicted thresholds (Bagnold 1936).

FIGURE CAPTIONS

Figure 1. A selection of models representing the range of predictions generated by available threshold models and observations of specific thresholds from the literature (from Table 1). Note large disagreement for $d_{50} > 0.8$ mm.

Figure 2 Forces that resist motion in aeolian transport systems calculated for quartz grains (2650 kg/m^3). Above a grain diameter of about 0.08 mm, weight force becomes several orders of magnitude larger than cohesive forces. Values for d_{r50} grain for experimental observations (Table 1) are also plotted.

Figure 3. a) Transformations from traditional grain size distributions with mean of $d_{50} = 2 \phi$ and a range of sorting values (0.2, 0.4, 0.6 and 0.8) to mass-weighted frequency distributions of resistance to motion, with means of $dr_{50} = 1.92, 1.67, 1.25$, and 0.67ϕ , respectively. b) cumulative distribution functions of the increase from d_{50} to dr_{50} for a range of mean grain sizes and sorting values. As sorting increases for a given mean diameter, or the mean size in terms of diameter increase for a given sorting, this discrepancy becomes more pronounced.

Figure 4. a) Threshold shear stress versus weight force resisting motion of dr_{50} from experimental observations in Table 1, and residual error associated with linear regression model.

Figure 5. Observed threshold data from Table 1 and the linear regression model from Equation 6. The model encapsulates transport thresholds over the range of many naturally occurring sands for which saltation occur. The coefficient 0.2 m/s is equivalent to the lower limit of theoretical and observed saltation threshold. Note improved goodness of fit for the largest grain sizes in contrast to Figure 1.

Figure 1, 1 column

Figure 2, 1 column

Figure 3, 1.5 or 2 column

Figure 4, 1 column

Figure 5, 1 column