

THE EFFECT OF SHEAR STRENGTH AND MOISTURE CONTENT ON THE FLUID VELOCITY THRESHOLD OF WIND EROSION

Luis Zambrano-Cruzatty, Virginia Polytechnic Institute and State University, luissez@vt.edu
 Nina Stark, Virginia Polytechnic Institute and State University, ninas@vt.edu
 Alba Yerro, Virginia Polytechnic Institute and State University, ayerro@vt.edu

INTRODUCTION

Wind erosion is an important component of coastal dune morphodynamics, and has been subject to research since decades (e.g., Bagnold 1941; Han et al. 2009). However, many expressions to predict fluid threshold velocity for wind erosion are not generally valid. For instance, Han et al. (2009) showed that some expressions struggle to predict the threshold velocity for tropical and/or humid coastal areas. We hypothesize that a shear strength limit equilibrium approach can incorporate the effects of moisture content, particle sorting and shape, slope angle, and cohesion into a general equation that would be applicable to a range of environmental and soil conditions. The objective of this study is to test this hypothesis using data sets published by McKenna-Neuman and Nickling (1989).

METHODOLOGY

An infinite slope stability analysis (Taylor 1948) is used to relate the sediment's threshold shear stress and shear strength. The wind force, which is driving the particles with size d upwards, is expressed as a tangential stress (τ_o) acting on the surface (Figure 1) which can be expressed as:

$$\tau_o = u_*^2 \rho_{air} \quad (1)$$

where u_* = threshold velocity and ρ_{air} = air density.

At equilibrium, the movement of the particles is prevented by a shear force (or friction force) acting in the opposite direction on the sliding plane. Hence, the threshold velocity can be obtained equating the shear stress required for equilibrium and the shear strength of the sediments (Equation 2).

$$\tau_r = \tau_f \quad (2)$$

The shear strength of sediment is modeled using an extended Mohr-Coulomb failure envelope initially proposed by Bishop (1959):

$$\tau_f = c' + [(\sigma - u_a)_f + \chi_f(u_a - u_w)_f] \tan(\phi') \quad (3)$$

where c' = effective cohesion, $(\sigma - u_a)_f$ = net normal stress at the slide plane, χ_f = effective stress parameter ranging from 0 to 1, $(u_a - u_w)_f$ = matric suction, and ϕ' = effective angle of internal friction.

The shear stress acting on the slide surface is found solving for equilibrium (Equation 2) in the infinite particle layer. Hence, using equation (1) and (3) the following expression for the threshold velocity is derived:

$$u_* = A_* \sqrt{MF + dg \frac{\rho}{\rho_{air}} \frac{\sin(\phi' + \beta)}{\cos(\phi')}} \quad (4)$$

with

$$MF = \frac{c' + \chi_f(u_a - u_w)_f \tan(\phi')}{\rho_{air}} \quad (5)$$

where ρ = bulk density of the sediments, and A_* is a fitting parameter such that equation (4) becomes Bagnold's (1941) equation for dry conditions. Several studies suggest that A_* is a function of the Reynolds particle

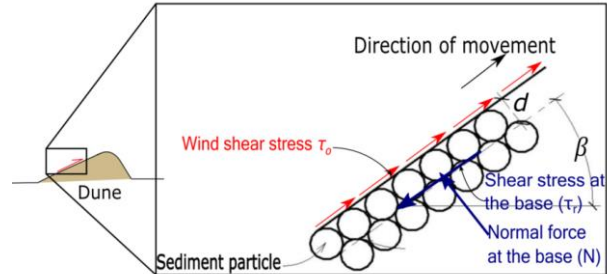


Figure 1 - Model used to analyze equilibrium at the slide surface

number and moisture content (Fécan et al. 1999; Han et al. 2009; Ravi et al. 2006). However, for this study A_* is considered constant and equal to 0.13 to simplify the analysis.

In the case of clean and uniform sands, it applies that $c' = 0$. The friction angle is estimated using Duncan et al. (2014):

$$\phi' = 34 + 10D_r - [3 + 2D_r] \log_{10} \left(\frac{\sigma'_N}{p_a} \right) \quad (6)$$

where D_r = sand relative density estimated at 26%, σ'_N = normal stress at the sliding plane, and p_a = atmospheric pressure.

The matric suction is estimated using a Soil Water Characteristic Curve (SWCC) as a function of saturation or gravimetric water content which is linked by the void ratio e and specific gravity of solids G_s :

$$S_e = \frac{S - S_r}{1 - S_r} = \frac{w - w_r}{e/G_s - w_r} \quad (7)$$

where S_e = the effective saturation, S = saturation, S_r = residual saturation, w = gravimetric water content, and w_r = residual water content.

Evidence from experimental results (Lu & Likos 2004) suggests that the effective stress parameter can be expressed by:

$$\chi_f = S_e^\kappa \quad (8)$$

where κ = fitting parameter greater than 0.

The experimental data compiled for this analysis (McKenna-Neuman & Nickling 1989) were collected in flat wind tunnels, and therefore, $\beta = 0$. The data set consists of three different uniform moist sands with mean diameters of 0.19, 0.27, and 0.51 mm. SWCC are provided for each sand type. Brooks & Corey's (1964) method (BC model) is used to fit the SWCC, because of its simplicity and accuracy on the residual regime. The BC model is expressed by:

$$S_e = \left(\frac{\psi_b}{\psi} \right)^\lambda \quad \psi \geq \psi_b \quad (9)$$

where $\psi = (u_a - u_w)_f$, ψ_b = air entry matric suction pressure, and λ = fitting parameter.

Both ψ_b and λ are found using a least square non-linear regression. Figure 2 shows the results obtained for the SWCC parametrization.

Finally, equations 4, 7, 8, and 9 are used to predict the

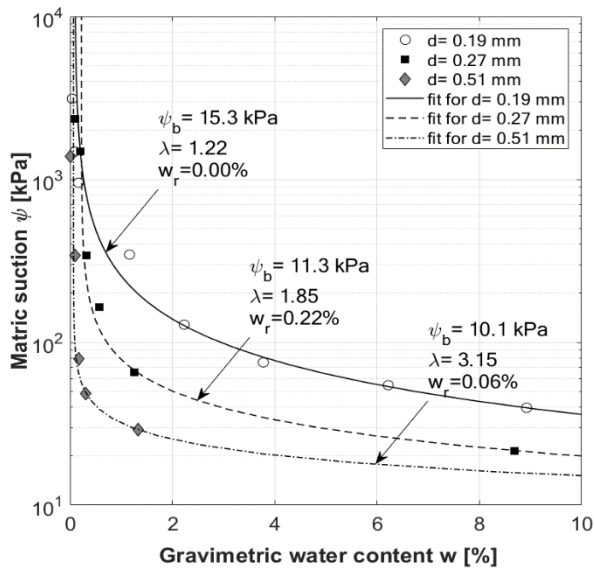


Figure 2 - BC model curves with best-fit parameters for the three SWCC corresponding to the samples tested. After McKenna-Neuman & Nickling (1989)

threshold velocity for values of κ ranging from 2 to 4, since it is not possible to determine it from the data retrieved. The grain size distribution plays an important role on the shape of the SWCC. It can be observed in Figure 2 that as the particle diameter increases, matric suction decreases.

RESULTS

Figure 3 shows that small changes of the κ parameter affect the threshold velocity prediction substantially. Nevertheless, the values of κ that match best the experimental data are congruent with values reported in the literature (Lu and Likos, 2004). It is possible that κ is not constant in this matric suction regime, or results from differences in soil skeleton texture between wind and SWCC test specimens. The non-linearity of κ on the residual regime can also explain the difference in shapes on different prediction equations, which has been observed by several authors such as Han et al. (2009). Figure 4 shows a graph of predicted vs. observed threshold velocities. The predicted results match the observations with values of R^2 ranging from 0.91 to 0.98. The κ values reported in Figure 4 represent the best fitting parameters for the respective grain sizes tested.

DISCUSSION & CONCLUSIONS

The results suggest that the shear strength and moisture content are governing factors of the threshold wind velocity and may be utilized to predict the threshold velocity of wind erosion. The SWCC and the effective stress parameter seem to be of importance to obtain accurate results. Therefore, subsequent investigations should aim to clarify the behavior of these parameters for a wide range of moisture content values. Future research will include collecting controlled laboratory and field data. In summary, this study encourages further investigation, calibration, and validation of the proposed approach utilizing geotechnical soil properties to predict threshold velocity for wind erosion.

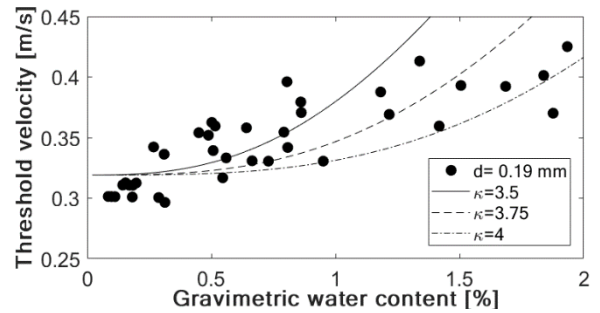


Figure 3 - Calculated and predicted threshold velocities vs. gravimetric water content

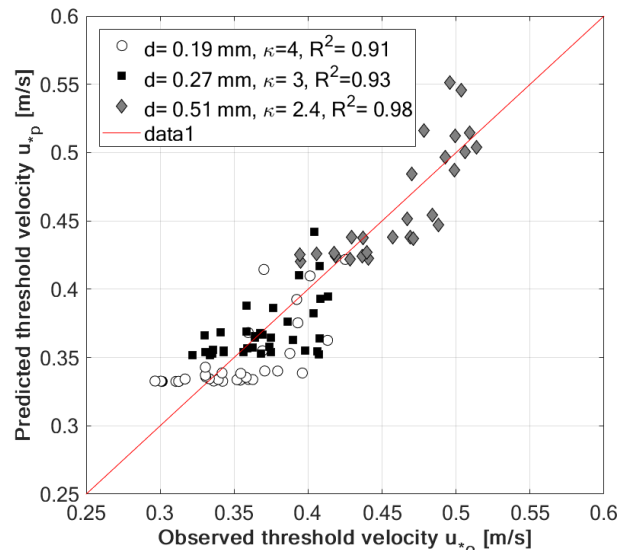


Figure 4 - Predicted vs. observed threshold velocities

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