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A study of initial motion of soil aggregates in comparison with sand particles of various sizes

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ABSTRACT

Critical shear stress and threshold stream power are two important soil characteristics controlling detachment of soil particles by runoff and have been used in process-based erosion models such as WEPP, GUEST and EUROSEM. In this research, laboratory experiments were conducted in a 20 × 350 cm flume to study the effects of particle size and density on initial motion. Two contrasting soil samples, a well-aggregated forest soil and non-cohesive fluvial sand, were used to provide particles with different densities. Each sample was divided into six size classes. Flow bed in the flume was roughed according to testing area for each size class using a plate which sand particles from each size class were glued on it. The initial motion of the particles was determined by two methods. In the first method, slope was increased gradually for a given constant discharge until particles start to move from every point of the testing area. In the second method, flume slope was set to a given steepness and discharge was gradually increased until particles start to move. Three different discharges and three slopes were tested in the first and second methods, respectively. Each test replicated two times. Analysis of the data showed that the particle size and density and also their interaction significantly affect ($P < 0.001$) critical shear stress and threshold stream power. The critical shear stress and threshold stream power increased with increasing particle size and density, but the impact of particle density is higher on the coarser particles than the finer ones. Threshold values measured for the sand particles were about 2.3 times of those measured for soil particles in the three coarser classes, this difference decreased to about 65% (1.65 times) in the three finer classes, and even the difference between the two types of particles was not significant for the finest class (0.125–0.053).

1. Introduction

Soil erosion is a serious environmental problem threatening the future development of agriculture and society. The adverse influences of widespread soil erosion on soil health, agricultural production, water quality, and ecosystem well-being, have long been recognized as severe thread to human sustainability (Lal, 1998). It is not only a major factor responsible for the long-term degradation of land quality, but also a major non-point source for water pollution (Lei et al., 2008). Increased attention to these concerns has led not only to the adoption of improve measures for erosion control, but also to a better understanding of soil erosion mechanics and the development of more reliable erosion prediction tools (Lei et al., 2008).

Soil erosion consists of three processes of detachment or initiation of motion of soil particles, transport of detached particles, and deposition when sufficient energy is no longer available to transport the particles (Morgan, 2005). Knowledge of critical shear stress or threshold stream power is required for the prediction of soil erosion by physically-based soil erosion models (Moody et al., 2005). The force per unit wetted area that acts on a surface is defined as shear stress, τ, and is expressed as:

$$\tau = \rho g h S_f \tag{1}$$

where ρ is the water mass density (kg m^{-3}), g is the gravity constant (m s^{-2}), h is the water depth (m) and S_f is the friction slope (degree) (Chow et al., 1988). Critical shear stress, τ_{cr}, occurs when the shear force exceeds the critical limit for soil detachment.

Detachment has also been related to stream power, Ω, in experimental studies (Merz and Bryan, 1993) as well as in modeling works (Rose et al., 1983a,b; Hairsine and Rose, 1992a,b). Stream power is the product of shear stress and mean flow velocity, U (m s^{-1}):

$$\Omega = \rho g h S_f U \tag{2}$$

where Ω is the stream power (W m^{-2}) (Chow et al., 1988). If S_f is

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assumed to be equal to S, Eq. (2) can be written as follows:

$$\Omega = \rho\, gqS \quad (3)$$

where q is the volumetric flux per unit width ($m^2\ s^{-1}$) and S is the bed slope. Also in the case of stream power, Ω_0 is a threshold value below which no erosion occurs.

Critical shear stress can be related to the weight and angle of repose of particles, which depend on the particles size and form (Julien, 2010). Forces of adhesion strongly determine critical shear stress (Oliveira, 1997). This threshold stress is usually determined by extrapolation of a regression relationship between shear stress and transport rate or, in flume studies, by gradually increasing slope or water discharge rate until 'initial motion' of grains is first detected (James et al., 1990).

In the physically based soil erosion models it has been justified that the critical shear stress/threshold stream power is a bulk characteristic of the soil. However, some works indicate that in a mixture of different size particles, relatively larger particles/aggregates show less resistance to movement than the relatively smaller ones and are transported at a higher rate (Wiberg and Smith, 1985; Asadi et al., 2007, 2011; Shi et al., 2012; Wang et al., 2014). The reason for this behavior could be the presence of different transport mechanisms acting on different size classes, and/or greater resistance to movement (i.e. a higher critical shear stress) of relatively smaller particles. On the other hand, there is considerable discrepancy in the published results regarding the measurements of critical shear stress (i.e. Wilcock, 1988; Petit, 1990; Moody et al., 2005; Bohling, 2009; Araujo et al., 2008; Salehi and Strom, 2012). These discrepancies are not random, but fall into four groups that may be associated with (i) difficulty in defining the beginning of motion of soil particles, (ii) using two broad classes of methods for determining initial motion, (iii) running the measurements under hydraulically different conditions, and (iv) using the cohesive or non-cohesive materials. There are also various theoretical equations (Wiberg and Smith, 1985; James et al., 1990; Leonard and Richard, 2004; Matthieu and Belleudy, 2007; Julien, 2010) for predicting critical shear stress each developed for a certain situation or particular particles.

In the process of surface erosion of well aggregated soils especially under flow dominant condition (e.g. rill erosion), the particles are mainly transported as aggregates. It has also been observed that sediment size distribution is bimodal under steady flow (Asadi et al., 2007, 2011; Shi et al., 2012) and rainfall of various kinetic energies (Wang et al., 2014). On the other hand, the study of the initial motion of soil aggregates is very rare, and most of the studies have focus on sand particle and/or cohesive soils. Therefore, this study was aimed to evaluate the initial motion of soil aggregates of various sizes in comparison with sand particles of same size. The initial motion was measured by two methods. The angle of repose was also measured for both soil aggregates and sand particles. Finally, the applicability of the exiting theories for the critical shear stress of sand particles was tested for soil aggregates.

2. Material and method

2.1. Soil sample selection and preparation

Two contrasting soil materials were used in the study to provide particles with different densities. The first soil was a well aggregated forest soil (Mollisols), and the second one was non-cohesive fluvial sand. The forest soil has a clayey texture containing 5.25% and 2.75% organic matter and equivalent calcium carbonate, respectively. Secondary particle (aggregate) size distribution (denoted PSD) of the two samples as measured by wet sieving was almost similar. The soil aggregates were quiet stable in water. Each air-dried sample was divided to six size classes of 0.053–0.125, 0.125–0.5, 0.5–1, 1–1.6, 1.6–2, and 2–2.36 mm by dry sieving. The particle density of the fluvial sand particles was measured using hydrometer method, and the particle density of the forest soil particles (aggregates) was measured using a method suggested by Chepil (1950) (Fig. 1).

2.2. Measuring the angle of repose

In this study the angles of repose (AoR) of soil size classes were determined by a sliding method (Geldart et al., 2006) (Fig. 2a). Soil samples were filled into a hollow container to the brim and were gently leveled with a brush. The sliding AoR was defined as the angle of rotation from horizontal plane to an angle when the particles began to slide. Angle of repose was determined for the six size classes of both soil and sand samples with two repeats. To determine the impact of container dimensions on angle of repose, the measurements were carried out in containers with seven different sizes. The dimensions of the containers were 8 × 4 × 2, 8 × 4 × 4, 8 × 4 × 6, 12 × 4 × 2, 16 × 4 × 2, 8 × 6 × 2 and 8 × 8 × 2 cm. Also the AoRs were measured in a 10 × 5 × 5 cm container which was similar to the test section of the flume used for determining critical shear stress (see Section 2.3).

To evaluate the effect of container size, particle size, particle type (density) and their interaction on the AoR, the measured data were subjected to two-way analysis of variance (ANOVA) using the statistical analysis software, SPSS. Tukey's honestly significant difference (HSD) was used to determine differences in the particle size and soil type among container dimensions at $\alpha = 0.05$ level.

2.3. Experimental flume and the preparation of stream bed

The critical shear stress for soil and sand samples was measured in a solid base tilting flume of 350 cm long (Fig. 2b) with run on facility made from clear plastic. The flume was 20 cm wide and 20 cm deep with a head box and diffuser at one end and open at the other end. A polystyrene, bottom insert (20 cm wide, 5 cm thick and 190 cm long) was place on the floor of the flume with a test section (5 cm wide, 10 cm long, and 5 cm deep) cut in its center. This test section was located 130 cm downstream from the upper end of the polystyrene, and 50 cm upstream from the flume exit. The distance from the flume sidewalls of test area was 7.5 cm. The bed roughness of the flume was adjusted to be the same as the sample by plastic talc (20 cm wide by 5 cm thick and 190 cm long) fixed on the polystyrene surface. The top side of the plastic talc was glued with uniform sand particles of each size classes. Accordingly, six plastic talcs were prepared for the six size classes of 0.053–0.125, 0.125–0.5, 0.5–1.0, 1.0–1.6, 1.6–2, and 2.0–2.36 mm (Fig. 2c). This specific setup was to ensure that (i) the flow is fully developed and in steady state condition on the test area (Rouse, 1946; Ranga raju et al., 2000), (ii) the sidewall effect upon the measured shear stress at the center of the flume is negligible (Moody et al., 2005), and (iii) test section is sufficiently small for a more accurate evaluation of the initial motion of the particles (Lei et al., 2008). The samples were packed in the test section in three layers of 2, 2 and 1 cm. Each layer gently compacted using a piece of cubic wood. The last layer was very

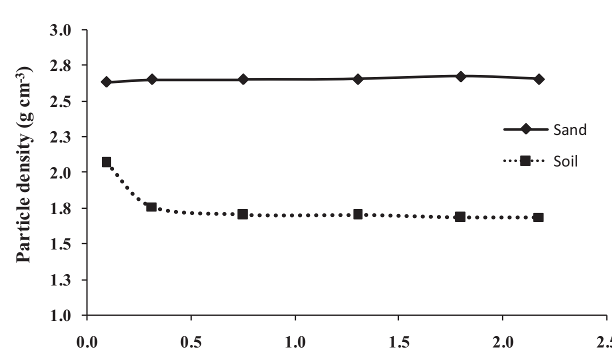

Fig. 1. Particle density of sand and soil size classes.