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Micromechanical modelling of rainsplash erosion in unsaturated soils by Discrete Element Method

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ABSTRACT

The rainsplash erosion is one important mechanism in natural and artificial slopes and the raindrops impact contributes to the amount of solids conveyed at the outlet of a mountain basin. Rainsplash erosion involves individual (or small clusters of) soil particles, it is a dynamic (temporally and spatially variable) process and mainly occurs in unsaturated soils where capillarity forces allow steep slopes to be stable. The Discrete Element Method (DEM) was firstly applied in this paper for the analysis of rainsplash erosion assuming realistic rainfall intensities, and a range of both slope steepness and capillary forces in a parametric analysis. The DEM numerical results highlight the specific role of the slope steepness, capillarity force, and rainfall intensity towards the final volume of the solid eroded from the ground surface at the computational domain. It is also valuable that the numerical results are in good agreement with literature formulations, and increasing power law functions were found to relate well the eroded volume to rainfall intensity.

1. Introduction

The rainsplash erosion consists in the mobilization of soil particles from the ground surface due to the impact of the rain droplets (Kinnell, 1990; Hudson, 1995; Kinnell, 2005). Specifically, rainsplash erosion is a gradual cumulative process, which involves the sequential displacement of individual particles of soil (or clusters), which are detached and displaced downwards from the zones where the droplets fall. Thus, the process occurs at a particle scale, is time-dependent (dynamic) and also spatially-variable because the local arrangement of the uppermost solid particles affects their chance to be mobilized or not. Nevertheless, this process can affect large areas – up to hundreds of square meters – during a heavy rainstorm, and huge amounts of solid material can be conveyed to the outlet of a mountain basin.

A complication to this process often derives from the unsaturated soil condition of the very first centimetres of the ground surface. In fact, unsaturated soils are characterized by an additional cohesion among the solid particles which depends on the matric suction, i.e. the difference of air-pressure (u_a) to pore water pressure (u_w), and it is well-known that soil suction relates to soil volumetric water content (through the so-called retention curve), soil conductivity (expressed by the soil conductivity curve), and to the specific hydraulic boundary conditions which are applied by the atmosphere at the ground surface. In principle, during the impact of each rain droplet the suction is modified at the impact area. Thus, the rainsplash erosion is somehow regulated by the time-space evolution of the soil suction at the ground surface. These cascading processes are still challenging to be modelled at particle scale during a dynamic process such the impact of a rain droplet.

Rainsplash erosion is one of the transport mechanisms in coarse-grained cohesionless materials. A typical example is that of short steep slopes, such as bench terrace risers (van Dijk, 2002, 2003). Rainsplash may lead artificial unprotected excavations to overcome their serviceability limit. Along natural slopes, the threat that rainsplash may mobilize high amounts of solid particles must be seriously taken into account because hyperconcentrated flows may be generated, as observed in real case histories (Cascini et al., 2014; Cuomo et al., 2015).

Thus, the interest to have accurate quantitative estimates of the rainsplash erosion spans from agriculture practices to the hyperconcentrated flows risk management, up to civil protection purposes. For a quantitative analysis, it is clear that physically-based approaches are absolutely required. But while the needs are obvious, it is still problematic to tackle this issue due to either the complexity of the rainsplash-related mechanisms or to the lack of methods applied and validated to provide quantitative estimates of the solids detached.

Starting from the available literature, this paper aims to provide a novel contribution to the topic proposing the application of the Discrete Element Method (DEM) to the numerical simulation of a sequence of droplets falling at the ground surface in a reference test area along a slope. This would be the first time that such kind of approach, usually

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referred as "micromechanical", is tested to the numerical simulation of splash erosion (Della Sala, 2014). The novelty is that the effects of each raindrop on each solid grain impacted are simulated, and this is reasonable as the erosion is a dynamic and spatial-dependent process acting on discrete portions of the ground surface, while the previous literature treated the erosion process as a continuous process both in space and time. In the paper, a parametric analysis is performed and the numerical results are compared to experimental evidences reported in the literature and the possible applications of this approach are discussed as well.

2. Literature review

Rainsplash erosion involves a series of complex processes mainly classifiable into three stages (Kinnell, 2005): i) collision and deformation of a falling raindrop at the ground surface; ii) rupture and collapse of the drop into a thin disk of fluid spraying radially outwards from the point of impact; iii) jetting of daughter ejection droplets in parabolic-like trajectories away from the original point of impact.

To date, the methods available in the literature for the rainsplash erosion analysis are mostly based on the experimental evidence. It is remarkable that the understanding of rainsplash process has been considerably improved in the last decades by laboratory testing (Poesen and Savat, 1981; Nearing and Bradford, 1985; Ghadiri and Payne, 1986, 1988; Poesen and Torri, 1988; Sharma and Gupta, 1989; Salles et al., 2000; Mouzai and Bouhadef, 2003; Ma et al., 2008; Long et al., 2011), and field experiments (Morgan, 1981; Parlak and Parlak, 2010; Ghahramani et al., 2012; Geißler et al., 2012; Angulo-Martinez et al., 2012).

In particular, the raindrop detachment and transport has been measured using a variety of techniques, including trays and boards (Van Dijk et al., 2002, 2003) and splash cups (Ghahramani et al. 2012; Geißler et al., 2012). To date, the classical method for quantifying the splash erosion relies on the use of splash cups, or small traps that collect the soil particles detached and transported by splash (Ellison, 1947; Morgan, 1978; Poesen and Torri, 1988; Salles and Poesen, 1999; Van Dijk et al., 2003; Legout et al., 2005).

Most of the experimental studies show that the mobilization rate of soil particles (D_r, kg/m^2/s) on bare soil – defined as the weight of solids mobilized by rainfall at a unitary area of the ground surface per unit time (Ma et al., 2008) – can be expressed by one of the following equations of:

$$D_r \propto I^a s^c \tag{1}$$

$$D_r \propto KE^b s^c e^{-dh} \tag{2}$$

where I is the rainfall intensity (mm/h), s is the slope expressed in m/m or as a sine of the slope angle, KE is the kinetic energy of the rain (J/m^2) and h is the depth of the water table (m), while a, b and c are empirical parameters to be fitted from experimental evidences from the field or laboratory.

Based on a great amount of experimental evidences, mathematical erosion models were set up and applied to real cases. For instance, Jayawardena and Bhuiyan (1999) provided an empirical correlation between rainfall intensity and the erosion rate. Alternatively, starting from the experimental evidence of splash tests, in the physically-based model LISEM (Jetten, 2002) the rate of splash erosion was related to: i) the so-called soil aggregate stability (median number of drops to decrease the aggregate by 50%); ii) the rainfall kinetic energy; iii) the depth of the surface water layer; and iv) the amount of rainfall and the surface over which the splash takes place. In addition, the amount of solid particles detached by raindrop impact and leaf drip were related to rainfall intensity, vegetation cover and soil texture in the so-called physically-based model SHESED (Wicks and Bathurst, 1996).

As suggested by the above equations, the erosion of soil particles due to raindrops impact is related to the rainfall characteristics. Generally speaking, a rainfall can be defined by the intensity and the drop size distribution. In turns, each drop size corresponds to a different terminal velocity (van Dijk et al., 2002) at the ground surface.

The literature provides power law relationships between the median drop diameter D (mm) and the rainfall intensity I (mm/h), which can be expressed in the general form of Eq. (3):

$$D = a\ I^{\beta} \tag{3}$$

where the coefficients α (in h) and β are available from several studies (Laws and Parsons, 1943; Atlas, 1953; Brandt, 1988; Kelkar, 1959; Zanchi and Torri, 1980; van Dijk et al., 2002). For instance, Zanchi and Torri (1980) obtained α equal to 0.98 (considering an air temperature equal to 20 °C) and β equal to 0.292 for a rainfall intensity variable between 1 and 140 mm/h in a Florence site (Central Italy).

As formerly reported by Atlas and Ulbrich (1977), a raindrop of a given diameter D impacts the ground surface at a terminal velocity (v), usually expressed by exponential or power law equations requiring estimate of Reynolds number, which depends, in turn, on air and fluid densities, dynamic viscosity and surface tension. Van Dijk et al. (2002) proposed a simplified third-order-polynomial equation (Eq. (4)) under standard conditions of air pressure (1 bar) and air temperature (20 °C) and for raindrop sizes variable between 0.1 and 7 mm, as follows:

$$v = 0.0561D^3 - 0.912D^2 + 5.03D - 0.2541 \tag{4}$$

According to Mouzai and Bouhadef (2003), the rainsplash erosion is related to raindrop force and raindrop pressure applied on the ground surface, that are strictly dependent on density, diameter, fall height, velocity of the raindrop and impact area. In particular, the authors proposed that the raindrop impact force (F) is expressed as follows:

$$F = \frac{mv^2}{D} \tag{5}$$

where m, D and v are the mass, the diameter and the terminal velocity of the raindrop, respectively.

With reference to the displacement of the detached particles, recent investigations with multiple and high-speed cameras, were performed by Long et al. (2011) in order to investigate the 3D particle trajectory and velocity during both the impact, detachment, transport and deposition processes. In addition to these ballistic measurements, the authors used photogrammetric techniques to analyse the change in the surface morphology caused by a single droplet impact. Through these measurements, both the particles travel distances and the total amount of eroded solids were investigated, providing valuable insights into the raindrop erosion processes. Particularly, the experimental results demonstrated the influence of the interactions of particle size and droplet characteristics on detachment and transport over different slope angles.

3. Discrete Element Method (DEM) applied to rainsplash erosion analysis

3.1. Theoretical basis

This paper proposes an application of a particle-scale numerical model for the analysis of the rainsplah erosion process. This is a novel attempt, which cannot be found in the current literature.

The Discrete Element Method (DEM) was firstly introduced by Cundall and Strack (1979). It is based on the use of an explicit numerical scheme in which the interaction of the soil particles is monitored contact by contact and the motion of the particles modelled particle by particle.