Computers & Geosciences 97 (2016) 49–57

Contents lists available at ScienceDirect

Computers & Geosciences

journal homepage: www.elsevier.com/locate/cageo

Case study

Structural soil crust development from raindrop impacts using two-dimensional discrete element method

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ARTICLE INFO

Article history:
Received 12 May 2015
Received in revised form
3 September 2016
Accepted 7 September 2016
Available online 9 September 2016

Keywords:
MicroCT
Discrete element method
Two-dimensional model
Structural soil crust development
Coefficient of restitution
Porosity difference

ABSTRACT

The mechanical nature of crust formation as a result of raindrop impacts was simulated within a discrete element modeling environment. Simulations were conducted in two-dimensions (2D) using both linear and non-linear elastic contact models. The 2D approach was found to minimize the computational effort required and maximize the number of particles in the soil profile. For the non-linear model, the effect of the coefficient of restitution (COR) for soil-rain and soil-soil was investigated. Finally, the comparison between the linear and nonlinear elastic contact model was presented. The simulation indicated that the COR for rain-soil had negligible effect on the crust development but the computational time was exponentially increased with increasing coefficient value. In contrast, the COR for soil-soil had a dominant influence on the crust development. To validate the numerical results, a micro computerized tomography (microCT) technique was applied to characterize the changes in pore structure to a USCS SP soil after exposure under a rainfall simulator. Additionally, the effect of cyclic wetting and drying (without rainfall) on the changes in porosity was investigated. The experimental results showed that the rainfall simulator sufficiently densified the soil but the effect of cyclic wetting and drying was negligible. The numerical simulations showed similar changes in porosity along the depth of the soil profile as compared with the experimental results thus validating the DEM technique to simulate crust development.

1. Introduction

A soil crust is defined as a thin layer (3–5 mm) of low porosity formed at the soil (near) surface. The crust can be developed by either biological or physical processes. A biological soil crust is formed due to biological organisms (i.e., cyanobacteria, algae, microfungi, lichens, and bryophytes) that can bind soil particles together (Belnap et al., 2001; Greene et al., 1990). A physical crust is normally classified as either structural or depositional process. The depositional crust is formed due to the dispersion of clay particles by the flowing of surface water runoff (Fan et al., 2008; Neave and Rayburg, 2007; Ran et al., 2012). The structural crust is developed as a result of the impact of raindrops that mechanically rearrange the soil particles in this upper region (McIntyre, 1958). This structural crust is believed to form on soils that contain low organic matter and high amounts of silt (Belnap et al., 2001).

Regardless of the type of crust development process, a significant change in the soils physical state can occur such as a greater bulk density, lower hydraulic conductivity, lower infiltration rate, and stiff penetration resistance (Asgedom and Hasegawa, 2005; Assouline and Mualem, 1997; Baumhardt et al., 1990; Carmi and Berliner, 2008; Diekkrüger and Bork, 1994; Hoogmoed and Stroosnijder, 1984; McIntyre, 1958; Morin et al., 1989; Neave and Rayburg, 2007; Nishimura et al., 1993; Robinson and Woodun, 2008). These features tend to increase the surface water runoff and subsequent soil erosion above the crust layer (Singer and Le Bissonnais, 1998; Singer and Shainberg, 2004). At the crust layer itself, erosion is reduced due to the increased cohesion of the soil and higher resistance to shearing stresses. The processes that contribute to crust formation are complex and it is often difficult to predict the resulting effect on the soil. Additionally, a decrease in the infiltration rate influences the recharge of the groundwater. As a result, the water management in both agricultural and urban settings can be extensively affected.

Many studies on the aspects resulting in crust development have been experimentally performed (Asgedom and Hasegawa, 2005; Assouline and Mualem, 1997; Hoogmoed and Stroosnijder, 1984; McIntyre, 1958; Neave and Rayburg, 2007; Nishimura et al., 1993; Ran et al., 2012; Robinson and Woodun, 2008.). These works have primary focused on evaluating raindrop (i.e., rainfall intensity, raindrop size, and terminal velocity so on) and soil characteristics (i.e., percentage of fine particles, initial moisture content, size of aggregate, and so on) that lead to crust formation. Furthermore, it cannot be described by an analytical method

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http://dx.doi.org/10.1016/j.cageo.2016.09.004
0098-3004/

because the development of soil crust may be attributed to a series of complex interactions (i.e., compaction, detachment, erosion and deposition) between water and soils. Although crusting processes are broadly understood as a result of the above soil characteristics and mechanisms, the relative contribution to structural crust formation attributed to each remains unknown. Thus, few numerical investigations have been conducted on crust development using a stochastic approach (Ma et al., 2008) and only a single study using three-dimensional (3D) discrete element model (DEM) has been recently published (Sjoblom, 2014). The method by Ma et al. (2008) showed good agreement with experimental results but was limited for field applications as it was based on the median grain size of the soil. The heterogeneity of soil size, which was not included in Ma et al. (2008), indeed plays an important role in crust formation. To take into account the heterogeneity of soil size, DEM can be a good approach. The DEM uses discrete elements to form a material (i.e., soil using appropriate particle properties, size, shape, and gradation) (Ting et al., 1989) and simulates the dynamic behavior of the granular material after the collision (An and Tannant, 2007). Thus the DEM approach enables a convenient method to simulate the complicated mechanical nature of raindrops impacting a soil layer. For this work, YADE (Šmilauer et al., 2010), an open source discrete element program was selected.

YADE is a widely used DEM environment and has several advantages for use in this work including, multi-threaded computation engine, specific soil grain size distribution generation, 2D capabilities, and prebuilt consolidation methods. In YADE, both linear elastic and nonlinear elastic contact models are natively available. The linear elastic contact model (Cundall and Strack, 1979), assumes that the force is linearly related to the displacement. Inaccurate predictions of soil behavior can arise in this case, as it is somewhat simplifying the nature of soil-soil interactions. For the nonlinear contact model (Hertz, 1882; Mindlin, 1949), the normal force is represented by a spring-dashpot and the tangential or rolling friction force is represented by a second spring-dashpot. In addition, there is a Coulomb friction coefficient for the shear interactions between the two spring-dashpots. This model provides the better insight into the interaction between the soil particles even though it can be computationally expensive to implement.

In order to model the non-linear behavior of soil as a result of raindrop impacts accordingly, the viscous parameter as an input for the simulation is necessary. However, the viscous damping ratio of soil is difficult to measure and estimate. Therefore, the coefficient of restitution (COR), which is the ratio of a particle's speed before and after impact with another particle, is alternatively used to represent the viscous element (Antypov and Elliott, 2011). It is natively converted in YADE using Eq. (1).

$$\boldsymbol{\beta_n} = \frac{-(\log \boldsymbol{e_n})}{\sqrt{\boldsymbol{\pi}^2 + (\log \boldsymbol{e_n})^2}} \qquad \boldsymbol{\beta_s} = \frac{-(\log \boldsymbol{e_s})}{\sqrt{\boldsymbol{\pi}^2 + (\log \boldsymbol{e_s})^2}} \tag{1}$$

where β_n is the normal viscous damping ratio; e_n is the normal coefficient of restitution; β_s is the shear viscous damping ratio; and e_s is the shear coefficient of restitution.

To simulate the mechanical nature of raindrops impacting a soil layer, there are two types of collisions occurring in series: 1) the kinetic energy transference from raindrop to soil and 2) soil to the surrounding soil. Thus, two types of COR for rain-soil and soil-soil as input parameters are necessary in order to simulate the nonlinear behavior of crust formation.

Previous work to evaluate the COR of geologic materials has been in the application of rockfall hazard analysis (Asteriou et al., 2012; Chau et al., 2002; Durda et al., 2011; Giani et al., 2004; Imre et al., 2008). It was found that the COR for the rock was independent of the drop height as well as the impact speed (Durda et al., 2011; Imre et al., 2008). As a result, the value was found to be approximately 0.8 in both investigations. However, the COR for the rock was dependent of the slope angle (Chau et al., 2002) and the range was found to be from 0.2 to 0.8.. Few studies for the COR of sands have been accomplished at present. Similar to Chau et al. (2002), Matsushima et al. (2009) evaluated the COR for sands at various slope angles and found the range of the value from 0.2 to 0.9. Instead of using the slope angle, Wang et al. (2008) investigated the COR for sands at various collision angles and found the range of the values from 0.2 to 0.8. However, both papers neglected the COR for the soils at a 0° angle (horizontal surface) and the COR for water-soil has been unknown. Therefore, the calibration of the COR for both rain-soil and soil-soil is required.

A series of studies at Drexel University exploring soil crust development both experimentally (Alizadehtazi et al., 2013) and numerically has been initiated over the past several years. The first numerical study evaluated the effect of two parameters (the rain event rate and the duration) using a linear elastic model in a 3D DEM (Sjoblom, 2014). It was found that the near surface soil crust is rapidly developed during the rain event and maintained a steady state with continued rain impacts. In addition, the slower raindrop rates can produce a more consistent and stable crust. As a further study, the soil crust development due to raindrop impact was evaluated using a nonlinear elastic model in a 2D DEM (Yeom and Sjoblom, 2015). It was surmised that the COR for rain-soil was negligible parameter input to simulate the soil crust development but the computational time was exponentially increased with increasing COR. The current work expands on these initial findings.

Considering this background, the objective of this work was to determine the mechanism of structural crust development in a soil. To isolate the effects of raindrop impacts only, a numerical model was used to evaluate the rate and extent of densification throughout the first centimeter of a simulated soil. Investigation into the validity of the numerical model required the evaluation of the effect of the COR for soil-soil in the nonlinear elastic model and how this perturbs the simulated development of a soil crust. Additionally, the authors investigated the effectiveness of a nonlinear elastic model as compared to the linear elastic model to simulate the soil crust. All numeric results were then compared to an experimental study of rainfall on a subject soil. To evaluate the extent of crust formation on the experimental soil, micro computerized tomography techniques were utilized. The micro computerized tomography technique (microCT) is a non-destructive imaging technique to evaluate the internal structure and composition of a specimen based on X-ray absorption differences. The process of soil sealing as a result of raindrop impacts was evaluated and observed using microCT previously (Fohrer et al., 1999; Hyväluoma et al., 2012; Macedo et al., 1998). Pires et al. (2007) also used this technique to assess the structural changes along the depth for a Brazilian soil and observed a soil crust with the thickness of 2–4 mm in their sample.

2. Materials and modeling of the soil crust

2.1. Modeling of the soil crust

The material simulated in this study was derived from an ongoing experimental study at Drexel University (Alizadehtazi et al., 2013). This material was used as an analog to create distribution of spheres for the DEM simulation. The grain size analysis of this material was shown in Fig. 1(a) and was conducted in accordance with ASTM D422 (2007). To reduce the computational cost in the simulation, a subset of the range of particle sizes was chosen (Fig. 1 (a)) and used for the generation of particles package in DEM as shown in Fig. 1(b). This filtering essentially truncated the larger