Catena 160 (2018) 212–221

Contents lists available at ScienceDirect

Catena

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

A study of clod evolution in simulated rain on the basis of digital elevation models

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ARTICLE INFO

Keywords:
Surface roughness
Silt loam soil
Cloddiness
Image analysis
Splash erosion
Swelling

ABSTRACT

Soil roughness is a key parameter to our understanding of soil properties and soil-water interaction, most of which occur at millimeter scales. Soil irregularities, such as aggregates, clods and interrill depressions, influence water infiltration and overland flow. The objective of this study is to observe and quantify clod evolution under cumulated precipitation. We prepared two soil trays with loose silt soil and pre-sieved clods put on top, at low and high concentrations. These trays were then subjected to a set of five successive artificial rainfalls. The digital elevation models (DEM) were recorded for each tray, at millimetric resolution, at the initial stage and after each subsequent rainfall. The clods were automatically segmented on the DEM and the diameter, surface area and volume of these clods were measured by computer.

The isolated clods showed comparable behavior on both trays. The small clods were almost always decreasing in volume until they disappeared. The other clods swelled during the first rain or the first two rains, and then decreased in area and volume. The decrease was faster for volume than for area. This probably reflected a soil detachment phenomenon, which mostly affected the heights of the clods. On the high concentration tray, the close inter-proximity of the clods induced merging and the formation of blocks.

The rate of decrease of clod volume as a function of cumulative precipitation could be modeled using exponential and linear equations. Small and intermediate-sized clods showed an exponential decrease that was smoother as the clod size increased. Large clod volume decrease was almost linear. We were further able to model the trend of the slope parameter of the exponential decrease, as a function of clod size. Our study has shown how the DEM recording and image analysis can be used to quantify the evolution of clods under rainfall, improve our understanding of clod dynamics under rainfall and roughness parameterization. The size dependency of clod volume decrease is important for soil conservation decisions. This will obviously affect crust formation, surface armoring, soil erosion and surface permeability to water and gas.

1. Introduction

Soil microtopography underlies soil-water interaction such as erosion, deposition and infiltration, and in turn, many of these surface processes alter surface morphology. Hence, surface microtopography results from the interaction and feedback between soil and water mechanisms. Some studies have already been undertaken to predict the changes occurring when raindrops hit the soil surface and cause the breakdown of aggregates and clods by slaking, micro-cracking, mechanical disruption and transfer of soil fragments by splash (Bradford et al., 1987; Nearing et al., 1994; Bresson and Moran, 2004; Marzen et al., 2015). Other studies have focused on soil crust formation (Le Bissonnais et al., 1989; Freebairn et al., 1991; Bielders and Baveye, 1995; Le Bissonnais et al., 1995; Bresson et al., 2004; Gallardo-Carrera et al., 2007) or soil loss evaluation (Römkens et al., 2001; Licznar and Nearing, 2003; de Bie, 2005).

After tillage implements, the surface of cultivated soil is built up at small scales from an arrangement of clods and aggregates. According to Römkens and Wang (1986), Huang and Bradford (1992) and Takken (2000), several types of surface roughness can be determined: Micro relief variations of the order of one millimeter are due to soil grains and aggregates. Surface variations of the order of 10 mm are due to cloddiness and are studied as random roughness. An oriented roughness of > 100 mm may also be present and caused by tillage (Allmaras et al., 1966). On a wider scale, surface variations define our very landscape. Here, our paper shall focus solely on cloddiness.

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http://dx.doi.org/10.1016/j.catena.2017.09.017
Received 15 December 2016; Received in revised form 21 September 2017; Accepted 25 September 2017

Major studies have already investigated the role of tillage practice in erosion or run-off control (Moldenhauer and Koswara, 1968; Lyles et al., 1969; Stuttard, 1984; Elwell, 1989; Darboux et al., 2001; Gómez and Nearing, 2005; Hemmat et al., 2007). Some of these studies (Moldenhauer and Koswara, 1968; Lyles et al., 1969; Stuttard, 1984; Elwell, 1989) examined the combined effects of clod size, clod density, soil texture and other soil properties when investigating clod resistance to breakdown by simulated rainfall. Stable clods lessen soil detachment due to raindrop impact, seal development and therefore run-off generation and soil loss. These experiments were performed in a laboratory with artificial soils prepared using air-dried clods.

Measurements of soil cloddiness were mainly expressed in terms of different size ranges obtained by sieving. However, in Elwell (1989), a different approach was chosen. A process-orientated model following clod breakdown under rainfall was introduced. The height of an initial hemispherical clod was reduced due to soil erosion. Inferred variables related to clod geometry (height and diameter at ground level). These dimensions were deduced from elementary vertical measurements taken from above the tray. Then, the rate of detachment of the soil was estimated by regression analysis based on the average cumulated depth of soil detached against cumulative rainfall energy.

Photogrammetry and laser scanners have been used to measure surface elevations at plot or micro plot scale. The derived digital elevation models (DEMs) are suitable to study the variations of soil surface roughness (Darboux et al., 2001; Jester and Klik, 2005; Haubrock et al., 2009; Eitel et al., 2011). In our recent studies (Taconet et al., 2010; Taconet et al., 2013; Chimi-Chiadjeu et al., 2014; Vannier et al., 2014), we demonstrated that it is possible to retrieve automatically the characteristics of clods from millimetric-resolution DEM of the soil surface using different segmentation methods.

In the present paper, we shall consider the evolution of soil clods under simulated rainfall. The main objective is to demonstrate the capability of automatic analysis of soil surface DEM in modeling clod evolution under rainfall. Two indices of surface roughness characterizing the area and volume of the clods are defined. We relate them to previous studies of roughness evolution under cumulated precipitation, performed with different indices. Then, we use them to study the influence of clod initial concentration and finally, to introduce a trend modeling of clod evolution under simulated rainfall.

2. Materials and methods

2.1. Soil preparation

Two trays of a 50 × 50 cm^2 surface area and a depth of 10 cm were used. Their permeable bottom allowed for water percolation. The trays were prepared with soil collected from the top 15 cm of the A horizon of an Alfisol (Soil Survey Division Staff, 1993). This silt loam soil had a composition of 11% of clay, 60% of silt and 29% of sand, and an organic matter content of 2%. Initial soil moisture was 2.4% of the total soil mass. Using a hand scoop, the trays were filled with loose soil, creating a structure similar to a seedbed (except for the rows). Air-dried clods of various sizes were set upon the soil surfaces. On each tray, a different clod concentration was used: the low clod concentration (LCC) tray had a clod concentration of 530 m^{-2} (Fig. 1) and the high clod concentration (HCC) tray of 805 m^{-2} (Fig. 2).

Soil surface evolution was performed with a laboratory rainfall simulator, similar in design to the one described in Foster et al. (1979). It was equipped with 4 oscillating nozzles (Spraying Systems Co., Wheaton, Illinois, USA. Veejet type 6550) fed at 0.7 bar with deionised water. The simulator was located 6.1 m above the soil surface, allowing raindrops to reach the soil surface with a velocity close to their terminal velocity. Raindrops had a median size diameter of 1.5 mm. Rainfall intensity was set by adjusting the number of sweeps per minute. A set of five successive rainfalls of two intensities and different durations was carried out in order to produce changes in surface elevations and clod arrangement (Table 1). Initial intensity was 33 $\text{mm}\cdot\text{h}^{-1}$ (56 sweeps/min). During the first rainfall, every clod reached saturation. At the very beginning of the second rainfall, percolation was visually observed from the bottom outlet of both trays. Then, in order to speed up clod erosion, rain intensity was increased to 42 $\text{mm}\cdot\text{h}^{-1}$ (72 sweeps/min). The three ensuing rains were stopped once the soil surfaces seemed to have evolved visually. We could see a smoothing and leveling of clods until disappearance of some of them. The HCC tray was also subjected to the formation of blocks of clods as will be presented later in more detail.

For each stage, the soil surface elevation was recorded with an instantaneous-profile laser scanner (Darboux and Huang, 2003) at a grid spacing of 0.5 mm in x and y, and of 0.1 mm in z. Briefly, the scanner consisted in lasers generating a line on the soil surface and a camera set at an angle. The shape of the laser line recorded by the camera allowed the measurement of the surface geometry along a profile in the x-z plane. The laser-camera assembly was moved automatically along a rail (x-axis), allowing for the measurement of the whole surface geometry. Since the horizontal spatial resolution (i.e. the ability of the scanner to measure laps) was better than 0.5 mm, the spacing of 0.5 mm in xy was maintained. With a rough surface, there were about 20% of missing data points due to shadow effect, i.e. the laser is hidden from the

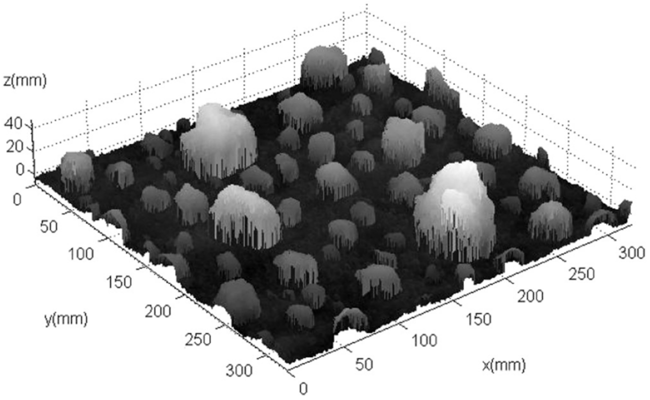

Fig. 1. DEM of the low clod concentration (LCC) tray.

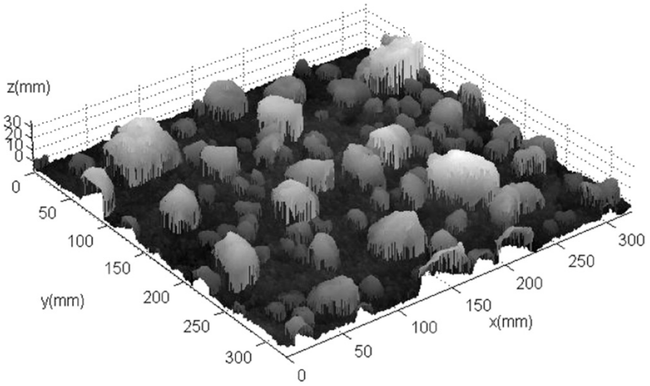

Fig. 2. DEM of the high clod concentration (HCC) tray.

Table 1
Characteristics of rainfall simulations.

	Intensity ($\text{mm}\cdot\text{h}^{-1}$)	Duration (min)	Cumulated rainfall P (mm)
Rainfall n° 1	33	60	33
Rainfall n° 2	33	60	66
Rainfall n° 3	42	38	93
Rainfall n° 4	42	51	129
Rainfall n° 5	42	90	192