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Using microtomography, image analysis and flow simulations to characterize soil surface seals

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ABSTRACT

Raindrops that impact on soil surface affect the pore structure and form compact soil surface seals. Damaged pore structure reduces water infiltration which can lead to increased soil erosion. We introduce here methods to characterize the properties of surface seals in a detailed manner. These methods include rainfall simulations, x-ray microtomography, image analysis and pore-scale flow simulations. Methods were tested using clay soil samples, and the results indicate that the sealing process changes several properties of the pore structure.

1. Introduction

Soil erosion is a complex process influenced by a large number of factors related to soil properties and environmental conditions. Even after significant effort, many of these factors are still not satisfactorily understood. Consequently, erosion models still have very limited predictive power (Jetten et al., 1999).

Raindrops that impact on soil surface influence its erosion and change the structure of soil surface in various ways (Kinnell, 2005). The mechanical action of impact may detach soil particles from the surface and lift them into the flowing water. If the detached particles are small enough, they may remain suspended and become transported to water courses. Detachment and possible deposition of particles also alter the structural properties of the soil surface. Such dynamic processes can lead to considerable temporal changes in the soil erodibility (i.e., susceptibility of the soil to erosional processes) during rainfall events.

Surface crusts and seals are formed by raindrop impacts which further lead to slaking and dispersion of the soil, and particle deposition (Moore and Singer, 1990; Assouline, 2004). The soil surface seal is usually a thin (thickness of about 1 mm) compact surface layer with no cracks. Surface crusts on the other hand have cracks and are thicker than seals. Processes that lead to seal formation have many effects on soil erodibility. They increase surface runoff as the permeability of the soil becomes smaller, which may enhance erosion. On the other hand, surface modifications can increase soil strength, and the deposited material may protect the soil matrix against raindrop impacts. Surface texture is also altered as the material washed away by surface runoff is typically from the finer size fraction (Sutherland et al., 1996). Moreover, the structural stability has been found to considerably vary during the crusting process (Darboux and Le Bissonnais, 2007). In addition, reduction of surface roughness may affect the amount of soil loss (Römkens et al., 2001).

Non-destructive imaging techniques, mainly x-ray tomography, are increasingly used in soil structure studies (Taina et al., 2008; Sleutel et al., 2008). Advances in tomographic techniques have resulted in an increasing resolution of the images, which further enables more accurate studies of the details of the pore space. Unfortunately, increasing resolution typically means that, due to the limited image size to voxel size ratio, only smaller samples can be imaged. As soils have structures with many different length scales, there is always a tradeoff between the resolution and the size of the sample in practical imaging studies. Further limitations to sample size or image resolution may result from analyses restricted by computational power and memory. For example, fluid flow simulations in the reconstructed pore structure practically always require use of high-performance computing.

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The three-dimensional pore geometries obtained by x-ray tomography can be used to simulate fluid flow and other transport processes in porous media. Lattice Boltzmann method has gained popularity in such applications as it has turned out to be a convenient and effective tool to simulate flows in porous media including soils (Koponen et al., 1998; Zhang et al., 2005; Koivu et al., 2009; Menon et al., 2011; Khan et al., 2012). In particular, it is able to handle complex geometries due to the simple inclusion of no-slip boundary conditions at the fluid–solid interfaces, which makes it suitable for porous media simulations. Furthermore, lattice Boltzmann method is well-suited for parallel computing, hence allowing flow simulations in large three-dimensional pore geometries resulting from x-ray tomography.

Imaging techniques have been utilized to study modification in the structure of soil surface due to simulated rain (Onofiok and Singer, 1984; Fox et al., 2004; Lee et al., 2008; Soliman et al., 2010). While these studies provide much insight into sealing and crusting processes, they have mostly been limited to qualitative considerations and two-dimensional analyses. In addition, only structural properties have been considered and no connection to hydrodynamics has been investigated.

In this paper, we introduce a set of methods that can be used to characterize the structure of surface seals. Our approach utilizes a number of techniques starting from rainfall simulation used to produce changes in the surface structure of soil samples, which are then imaged using x-ray microtomography. We present several analysis techniques to quantitatively characterize the pore structure with special emphasis on layer-wise analyses, which help to understand the spatial variation of the structural properties of soil in the vertical direction. In such analyses we take into account the actual shape of the rough soil surface to avoid artefacts due to surface roughness. In addition, we use pore-scale numerical simulations to investigate fluid flow through the pore structure obtained by x-ray tomography. The data obtained from flow simulations are also analysed layer-wise for permeability, tortuosity and effective porosity. In this work, we demonstrate the use of this combination of methods for clay soil samples.

2. Materials and methods

2.1. Soil samples

Soil samples for the present study were taken from an experimental field located in Jokioinen, south-west Finland (60°48′N and 23°28′N). The soil is classified as Vertic Cambisol according to the FAO (2006) classification system, and it has clayey texture (see Table 1). The samples were collected in May 2010 from the field that had been ploughed in the previous autumn. Undisturbed soil core monoliths (height 45 cm) were taken, starting from the soil surface, with a tractor-driven soil auger to plastic pipes (diameter 30 cm) using a drilling method similar to that described by Persson and Bergström (1991). Before rainfall simulations, the drilled cores were stored in the dark under field-moisture conditions at +5 °C.

2.2. Rainfall simulations

The rainfall simulations were performed with a drop-former-type laboratory simulator (Uusitalo and Aura, 2005). The equipment consists of a steel frame to which 96 drop-forming capillaries are attached. The inner diameter of the capillary tubes is 0.51 mm, and a wire mesh with 3 mm openings is located below the capillaries in order to break the drops formed in the capillaries. The wire mesh is 1.8 m above the soil surface. Deionized water was pumped to a column above the drop former, and the water level in the column was kept fixed. Capillaries were fed from the column, and the water level determined the intensity of the rain.

To bring different samples to similar initial conditions, soil cores were saturated with deionized water from below for three days and water was left to drain out for one night before the rainfall simulations. Soil cores were then exposed to rain in three phases. In the first phase, a simulated rainfall with an intensity of 5 mm/h was applied for 5 h. After this, cores were let to drain and stabilize overnight, and a second rainfall simulation of the same intensity and duration was applied in the next day. Immediately after this rainfall simulation cores were further exposed to a 2-h simulated rain with an intensity of 25 mm/h. The kinetic energies for the used rainfall intensities 5 mm/h and 25 mm/h were approximately $80\,\mathrm{J\,m^{-2}\,h^{-1}}$ and $390\,\mathrm{J\,m^{-2}\,h^{-1}}$, respectively. For imaging purposes, smaller samples were cut from the top layer of the soil to polyethylene tubes of a diameter of 2.8 cm.

2.3. X-ray microtomography

X-ray microtomography (μCT) is a non-destructive technique which produces high-resolution three-dimensional images of the internal structure of materials (Landis and Keane, 2010). The studied sample is placed in an x-ray beam and the intensity of the transmitted radiation is measured to obtain an x-ray projection of the sample. The sample is rotated in the x-ray beam and projections are taken from a large number of directions. These shadowgrams are computationally reconstructed to a three-dimensional array of the values of x-ray attenuation coefficients. As the attenuation coefficient is closely related to the density of the material, μCT provides a three-dimensional image of the density variations inside the sample, which can be further processed to acquire information of the internal structure.

In this work, we used a SkyScan 1172μCT scanner which is a table top device based on x-rays produced by a conventional x-ray tube. The voxel resolution can be varied from a sub-micron scale up to tens of micrometres. Since the sample must always be located inside the x-ray beam, there is an inherent compromise between sample size and resolution, i.e., better resolution indicates that smaller samples can be scanned. All images used in this work had a voxel size of 17 μm, which is adequate for our purposes and enables a sufficiently large sample size. Samples were imaged by using source voltage and current of 100 kV and 90 μA, respectively.

2.4. Image analysis

After obtaining the reconstructed density data from μCT, images were processed for further analysis. First the images were filtered to reduce noise and then segmented to pore and solid phases, which enabled quantitative investigations of the pore structure characteristics. In segmentation, grey-scale histograms were used to select manually the threshold grey-scale values. Segmentation is a crucial step, as it may considerably affect the subsequent analyses. More sophisticated techniques have

Table 1
Particle-size distribution of the soil.

0–0.002	0.002–0.005	0.005–0.02	0.02–0.05	0.05–0.2	0.2–0.5	0.5–2	(mm)
50.4	19.7	12.3	8.6	3.3	3.4	2.3	(%)