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In situ determination of the soil surface crust hydraulic resistance

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SUMMARY

This paper proposes a new method to determine the soil surface crust resistance in situ. The method is based on the assumption that the crust is well established prior to the infiltration. In this case, and for steady infiltration regime the hydraulic resistance of the crust, can be inferred from the infiltration rate and the relationship between soil conductivity and water pressure head. The proposed method combines two types of in situ experiments: (i) rain simulation experiments; and (ii) single ring infiltration tests on the same soil after removal of the crust in order to assess the soil hydraulic properties. The effectiveness of the proposed methodology was tested by reproducing numerically the experiments. The comparison of the numerical results with observations was satisfactory. Further validation and tests on other soil types are required in order to confirm our results.

1. Introduction

Soil surface sealing and crusting is widespread in various parts of the world as a wide variety of soils may develop soil crusting when exposed to rainfall. It is now well established that surface crust impacts hydrology, soil erosion, water quality or agriculture as it significantly reduces infiltration, triggers runoff and hence soil erosion and solute transport and may prevent seedling emergence thus favouring desertification.

Investigations on the effects of surface crusting on infiltration rates were conducted since the middle of the 20th century. McIntyre (1958) found a crust–soil conductivity ratios varying from 1/2000 to 1/200 for a 0.1 mm thick crust and Tackett and Pearson (1965) found ratios from 1/240 to 1/2 for a 5 mm thick crust. During the last decades several laboratory (e.g. Morin et al., 1981; Sharma et al., 1981; Chiang et al., 1993; Bielders and Baveye, 1995; Assouline and Mualem, 1997; Augeard et al., 2007, among others) and few field experiments; (e.g. Valentin and Ruiz Figueroa, 1987; Casenave and Valentin, 1989; Vandervaere et al., 1997) have been undertaken in order to investigate the factors involved in rainfall-induced seal formation (see Assouline (2004) for a review) and improve our knowledge about soil crusting effects.

Several approaches were suggested to model the effect of surface sealing on infiltration. The simpler models were developed for a well established saturated crust prior to infiltration, with constant values of thickness and saturated conductivity. Sometimes, the crust effect was accounted through the hydraulic resistance, which is the ratio between the crust thickness and the corresponding conductivity (Hillel and Gardner, 1969). These models generally applied the Green and Ampt approach to compute infiltration in the crusted soil (e.g., Hillel and Gardner, 1969, 1970; Ahuja, 1983).

Later, more sophisticated models were proposed in the literature. Some authors considered a system of two individual layers (Chu, 1985; Romkens et al., 1990; Ahuja and Swartzendruber, 1992; Philip, 1998; Simunek et al., 1998; Smith et al., 1999; Corradini et al., 2000), each considered as uniform. Note that even though these models consider the crust as a layer with properties different from those of the underlying soil, they do not deal with the formation process of the seal.

Several attempts to model the seal formation during the rainfall were made. Among these, Moore (1981) considered that the saturated conductivity of the upper layer decreases exponentially with time, while all other properties remain identical to those of the underlying soil. Later, Mualem and Assouline (1989) considered the seal as a nonuniform layer with a bulk density varying with depth from a maximum value at the soil surface to that of the undisturbed bulk soil. Originally conceptual, this model was supported later by experimental observations (Roth, 1997; Bresson et al., 1998).

Even though the two layer models either uniform or not are more realistic, their practical implementation and parameterization can

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be problematic due to the large number of input parameters usually involved (Rawls et al., 1990; Nearing et al., 1996). Moreover, these models have been generally tested in controlled conditions and calibrated using data of laboratory-simulated rainfall experiments. Such data, e.g. head measurements (Diekkruger and Bork, 1994) or X-ray bulk density measurements (Augeard et al., 2007), are difficult to obtain in situ. The calibration may be subjective and time consuming if conducted manually. Calibration by inverse modeling raises the problems of non-uniqueness of the solutions (Simunek et al., 1998; Hopmans and Simunek, 1999) and lack of convergence (Wildenschild and Jensen, 1999).

For all these reasons, simpler approaches like that of Hillel and Gardner (1969) may be more adapted to determine the crust resistance and quantify its effects on infiltration for practical in situ and well established crusts.

In this context, the purpose of this paper is to propose a new in situ method to determine the hydraulic resistance of a well-formed crust using in situ measurements consisting in rainfall simulation experiments combined with ring infiltration tests and pedotransfer functions (PTF).

2. Overview

The method is based on the earlier work by Hillel and Gardner (1969). The crust is considered well established and saturated at surface prior to infiltration. The flux across the crust, q, is given by:

$$q_c = -K_c \frac{h_{surf} - L_c - h_0}{L_c} \tag{1}$$

where K_c and L_c are the saturated hydraulic conductivity and thickness of the crust, respectively, h_{surf} is the water pressure head at the soil–crust interface and h_0 is the water pressure head at the crust surface. Runoff begins when h_0 becomes zero, and considering instantaneous runoff, h_0 can be neglected in Eq. (1). We assume that L_c (of the order of a fraction of cm) is much smaller than h_{surf} (of the order of several cm) and can be neglected in the numerator of Eq. (1) which becomes:

$$q_c = -K_c \frac{h_{surf}}{L_c} = -\frac{h_{surf}}{R_c} \tag{2}$$

where $R_c = L_c/K_c$ is defined as the crust resistance. For a transient regime, h_{surf} is an increasing function of time. It becomes constant when the steady state is reached. The water flux entering the subsoil, q_{surf} is given by:

$$q_{surf} = -K(h_{surf})\left(\frac{dh}{dz} - 1\right) \tag{3}$$

where $K(h_{surf})$ is the soil conductivity corresponding to a water pressure head $h = h_{surf}$ and $(dh/dz - 1)$ is the hydraulic gradient in the subsoil at the soil–crust interface. Due to the continuity of the flux at the soil–crust interface, $q_c = q_{surf}$. When the steady state is reached, dh/dz in the subsoil at the soil–crust interface becomes a negligible quantity, and Eq. (3) reduces to:

$$q_{surf} = q_{steady} = K(h_{surf}) \tag{4}$$

Combining Eqs. (2) and (4) for the crust (Hillel and Gardner, 1969) we have:

$$R_c = -h_{surf}/K(h_{surf}) \tag{5}$$

Note that when the crust thickness L_c cannot be neglected in the numerator of Eq. (1), the crust resistance will be given by: $R_c = (L_c - h_{surf})/K(h_{surf})$ with h_{surf} and $K(h_{surf})$ still given by Eq. (4) since they are fixed by q_{surf} whatever L_c is. The influence of L_c will be examined later.The proposed method uses rainfall simulation experiments and, considering that the crust is well established and becomes very quickly saturated due to its small thickness, assumes that at the end of the rain the steady state regime is reached with Eq. (5) applicable. In this case the crust resistance can be inferred from Eq. (5) provided that the soil properties are known. These are estimated from ring infiltration tests conducted after removing the first cm of the topsoil, combined with PTF according to the method described by Lassabatère et al. (2006). The significance of the determined properties of the soil and the crust hydraulic resistance are tested by reproducing numerically both the ring infiltration tests and rain simulation experiments and comparing numerical results with observations.

3. Materials and methods

3.1. The site study

The experimental site is located in the small catchment of El-Gouazine (18 km^2) in Central Tunisia, (35°54′N, 9°42′E). Even though most of the soils in the catchment are sandy, they are subject to erosion and crusting.

The climate is of semi-arid type. The mean annual rainfall recorded near the site for the period 1928–2000 is 374 mm, with a great inter-annual variability (the standard deviation is 174 mm). Most of the rainfall (70–90%) occurs between November and January. The showers are generally of short duration, less than an hour, and characterized by a very high instantaneous intensity, greater than 70–80 mm/h with duration over 5 min.

The experimental parcel area is 2850 m^2 area with mean elevation of 440 m above sea level and mean slope of about 6%. The parcel has been left fallow for several years, so that the natural vegetation, sparse and stunted, covers less than 20% of the surface.

Three plots (replicates) were chosen for rain simulations. Two plots are located upstream and the third one mid-way. They are denoted by P1, P2 and P3, respectively.

3.2. Field measurements.

3.2.1. Rain simulations

The rain simulator is an oscillating nozzle hanging 4 m above the soil surface. The rain simulation plot with area of 1 m^2 is equipped downstream with a collector of runoff protected from the rain. Runoff is collected in a reservoir and recorded continuously with an automatic float gage type level recorder. The collection reservoir is 0.1 m^2 area, so that a variation of 1 mm in the reservoir corresponds to 0.1 mm runoff on the plot. The nozzle and the plot are protected from the wind by a metallic tower covered with a tent cloth. On each plot, the following rainfall pattern with three showers was applied:

- 35 mm/h intensity for 45 min;
- no rain for the subsequent 15 min;
- 60 mm/h intensity for 15 min;
- no rain for the subsequent 15 min;
- 90 mm/h for the last 10 min.

This scheme covers most of the intensities encountered in the Mediterranean region in general, and those of the site study in particular. Considering that the crust has been present for several years, its characteristics are expected not to be affected by the rain intensities of the experiment.

3.2.2. Ring infiltration tests

For each plot, two ring infiltration tests (replicates) were performed. The two tests were conducted in the immediate vicinity of each of the rain simulation plots to limit the impacts