Geoderma 281 (2016) 39–48

Contents lists available at ScienceDirect

Geoderma

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

The effects of rock fragment shapes and positions on modeled hydraulic conductivities of stony soils

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ARTICLE INFO

Article history:
Received 21 December 2015
Received in revised form 6 June 2016
Accepted 27 June 2016
Available online 7 July 2016

Keywords:
Soil matrix
Rock fragments
Effective saturated hydraulic conductivity
HYDRUS-2D modeling

ABSTRACT

Mountainous soils usually contain a large number of rock fragments, particles with a diameter larger than 2 mm, which can influence soil hydraulic properties that are required to quantitatively describe soil water movement in stony soils. The objective of this study was to numerically estimate both the saturated hydraulic conductivity of a stony soil and its dependence on a relative content of rock fragments (stoniness), and the shape, position and distribution of rock fragments in a soil matrix. The assessment method was based on a numerical version of Darcy's classic experiment that involved steady-state flow through a porous material under a unit hydraulic gradient. Our experiments, involving hypothetical stony soils in this particular case, were simulated using mainly the two-dimensional (2D) numerical model, HYDRUS-2D. A limited number of simulations were carried out using a three-dimensional HYDRUS model. Three different shapes of hypothetical rock fragments were used in the study: a sphere, an ellipsoid with two different positions, and a pyramid, all represented by their 2D cross-sections (i.e., a circle, an ellipse, and a triangle, respectively). The mean relative effective saturated hydraulic conductivity (K_{rs}) for the same stoniness was almost the same for all simulated scenarios and fine soil textures. A stoniness between 0.07 and 0.5 $cm^3\ cm^{-3}$ can cause a decrease of K_{rs} in the range of 0.17–0.70. Numerical experiments were divided into 3 scenarios. The largest and the smallest values of K_{rs} were different for different shapes of RFs (scenario A), different orientations of the slab-sided elliptical RFs (scenario B), and regular or irregular distributions of spherical RFs (scenario C). The largest difference between K_{rs} values (0.26) was found in scenario B when the slab-sided elliptical RFs were oriented either horizontally or vertically for stoniness of 0.24 or 0.31 $cm^3 cm^{-3}$. Simulated K_{rs} values were underestimated in all scenarios as compared to the Ravina and Magier (1984) function. The smallest differences (−1.1%–2.5%) between numerically simulated and calculated (the Corring and Churchill (1961) method for a cylindrical shape of RFs) K_{rs} values were found for scenario A with its 2D representation of spherical rock fragments. Calculated (the Corring and Churchill (1961) method for a spherical shape of RFs) K_{rs} values corresponded well with those simulated using a 3D representation of spherical rock fragments. Numerical models provide a unique opportunity to evaluate the effects of different factors on the saturated hydraulic conductivity of stony soils that may be nearly impossible to measure in practice.

1. Introduction

Soils containing a significant fraction of rock fragments (RF) are generally denoted as stony soils and can be present in many forested and mountainous areas. The shape, size, degree of weathering, and geological origin of rock fragments can all strongly influence the soil's hydrophysical properties, especially the soil's water retention and hydraulic conductivity (Brouwer and Anderson, 2000; Cousin et al., 2003). According to Poesen and Lavee (1994), about 30% of soils in Western Europe and about 60% of soils in the Mediterranean region are stony soils. According to Šály (1978), up to 80% of Slovak forest soils contain stones and their stone content generally increases with depth. Furthermore, about 47% of Slovak agricultural soils are referred to as stony soils (Hraško and Bedrna, 1988). The spatial distribution of rock fragment in hillslopes is mostly controlled by slope gradient and topographic position (Chen et al., 2012). It is expected that rock fragments, and their size, shape, position, and spatial distribution in the soil, can strongly influence the stony soils' properties and can affect

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Abbreviations: RF, rock fragments; REV, representative elementary volume; RM, the Ravina and Magier (1984) function; CCS, the Corring and Churchill (1961) function for a spherical shape of rock fragments; CCC, the Corring and Churchill (1961) function for a cylindrical shape of rock fragments.

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http://dx.doi.org/10.1016/j.geoderma.2016.06.034

soil water movement, infiltration (Al-Qinna et al., 2014; Chen et al., 2012), and the occurrence of runoff (Hlaváčiková et al., 2015).

Stony soils are composed of a soil matrix, small particles with a diameter of less than 2 mm, and larger rock fragments, e.g., gravel, cobbles, stones, and boulders. The most important characteristics of a stony soil are its stone content (stoniness), water retention curves, and the hydraulic conductivity functions of both the soil matrix and rock fragments, as well as bulk characteristics representing the stony soil as a whole. Stoniness (R_v) is the ratio of the volume of rock fragments to the total volume of the soil.

The presence of stones can affect the hydraulic conductivity of a soil in several ways. On the one hand, stones reduce the effective cross-sectional area through which water flows, and combined with the fact that an increase in stoniness results in greater curvatures of flow paths, this can result in lower hydraulic conductivities (Bouwer and Rice, 1984; Childs and Flint, 1990; Ma et al., 2010; Novák et al., 2011; Ravina and Magier, 1984). In contrast, shrink-swell phenomena may create temporal lacunar pores (i.e., voids along the soil/stone interface) that can cause preferential flow and thus an increase in the saturated hydraulic conductivity (Sauer and Logsdon, 2002; Shi et al., 2008; Verbist et al., 2009; Zhou et al., 2009).

Rock fragments are relatively large compared to fine soil particles of the soil matrix. Therefore, it is necessary to evaluate the bulk soil characteristics for a “representative elementary volume” (REV) (Bear, 1972), the size of which depends mostly on the size and spatial distribution of the rock fragments. The larger the rock fragments are in the stony soil, the larger the REV needed. Buchter et al. (1994) recommended that the dry mass of a stony soil sample should be at least 100 times the mass of the largest particle. However, there is no rule for how large the REV of a stony soil should be for measuring its hydraulic characteristics. The dimension of the REV can vary from decimeters to meters, with its volume extending to about 1 m^3 when the rock fragments have a diameter of 10 cm or larger. The presence of rock fragments further presents problems for measuring the bulk soil hydraulic properties, water contents, water potential, or flow regime in general, due to such practical issues as the difficulty of inserting probes in stony soils (e.g., TDR probes and tensiometers) or installing lysimeters (Cousin et al., 2003; Ma et al., 2010).

Since it is technically difficult to perform hydraulic conductivity measurements on large samples with different stoniness, Novák et al. (2011) proposed the use of numerical models to simulate the classic Darcian flow experiment and to calculate the corresponding saturated hydraulic conductivity. This was done by embedding spherically shaped stones of different sizes (5, 10, and 20 cm in diameter) into a soil matrix of known hydraulic conductivity and then calculating the effective saturated hydraulic conductivity of the bulk sample with stones (K_s^b). Novák et al. (2011) showed that the effective hydraulic conductivity of a soil with a given stoniness is smaller when it contains a single “large” stone than when it contains multiple smaller stones. However, they only considered circular stones in the stoniness range of 0.07–0.31 $cm^3\ cm^{-3}$. From their study, it is not clear if the fine soil texture markedly affects simulated saturated hydraulic conductivities. However, their study indicated that one can similarly assess other factors that can potentially influence the hydraulic resistance to water flow such as different shapes, orientations, positions, and spatial distributions of rock fragments.

Therefore, the objective of this study is to describe and quantify the influence of stoniness and different shapes and positions of rock fragments on the bulk (effective) saturated hydraulic conductivity of stony soils using numerical modeling. This goal is achieved by answering the following questions:

1. How will A) the shape of rock fragments, B) the orientation of rock fragments, and C) the regular and irregular distributions of rock fragments affect the effective saturated hydraulic conductivity of stony soils?
2. How much will the effective saturated hydraulic conductivities of stony soils simulated using the numerical model differ from those calculated using existing empirical equations?
3. Is it possible to assess the effects of soil texture of the soil matrix on the effective saturated hydraulic conductivities of stony soils using a numerical model?
4. From simulated results, is it possible to propose a relationship between stoniness and the effective saturated hydraulic conductivity for different shapes, orientations, or distributions of rock fragments in a stony soil?

2. Theory

Only a few empirical equations for evaluating an effective saturated hydraulic conductivity of stony soils exist (e.g., Brakensiek et al., 1986; Ma et al., 2010; Ravina and Magier, 1984), and most are derived from laboratory experiments. The equation of Ravina and Magier (1984) is often used either in the absolute form to get the effective saturated hydraulic conductivity:

$$K_s{}^b = (1-R_v)K_s{}^f \tag{1}$$

or in the relative form to get the relative effective saturated hydraulic conductivity, K_{rs}:

$$K_{rs} = \frac{K_s{}^b}{K_s{}^f} = 1-R_v \tag{2}$$

where K_s^b and K_s^f are the effective saturated hydraulic conductivities of the bulk soil (denoted by index “b”) and soil matrix (denoted by index “f”), respectively, and R_v is the relative volume of rock fragments in a stony soil (stoniness). According to Eq. (2), K_{rs} linearly decreases with an increasing relative volume of rock fragments. The use of this approach is recommended for sandy soils because their deformation due to water flow is not significant. The preliminary assumption is that properties of the soil matrix such as porosity are invariant with respect to the content of rock fragments.

The effective saturated hydraulic conductivity of a stony soil can also be calculated using the Corring and Churchill (1961) equations. Their equations were obtained from analytical solutions of heat transfer equations in dispersive environments. The equation for a stony soil with spherical rock fragments with a negligible or zero retention capacity that are dispersed in a soil matrix can be expressed as follows:

$$K_s{}^b = K_s{}^f\left(\frac{2(1-R_v)}{2+R_v}\right) \tag{3}$$

For cylindrical shaped rock fragments, it can be written as:

$$K_s{}^b = K_s{}^f\left(\frac{1-R_v}{1+R_v}\right) \tag{4}$$

Peck and Watson (1979) also derived an equation for spherical rock fragments identical to Eq. (3).

3. Methods

3.1. Numerical Darcy experiments

In this study, numerical Darcy experiments were performed in a similar fashion to Novák et al. (2011). A virtual stony soil was created by distributing rock fragments of different shapes and positions in the soil matrix, the hydraulic properties (i.e., the saturated hydraulic conductivity and the retention curve) of which were assumed to be known. Using HYDRUS (2D/3D) (Šimůnek et al., 2008), vertical water flow was then simulated in a vertical cross–section ($1 \times 1\ m^2$) with