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A combined use of Archie and van Genuchten models for predicting hydraulic conductivity of unsaturated pyroclastic soils

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ABSTRACT

Hydrogeophysics has been developing in recent years to improve characterization and monitoring of saturated/unsaturated aquifers, through the combination of geophysical and hydrogeological methods. To exploit the potential benefits of this integration, definition of petrophysical relationships that allow the translation of geophysical data into hydrogeological parameters (and vice versa) is essential. In this paper, Archie's and van Genuchten's models, which relate electrical resistivity and hydraulic conductivity to the degree of saturation, are combined to obtain a closed-form link between hydraulic conductivity and electrical resistivity. Such an expression is used to characterize pyroclastic deposits covering Sarno Mountains (southern Italy), which are often affected by landslide phenomena. As expected, an inverse relationship is found between hydraulic conductivity and electrical resistivity due to predominance of the electrolytic component over the interfacial component of the electrical conductivity. The variability of the hydraulic conductivity marks out the texture of the investigated pyroclastic horizons. Finally, a hydraulic conductivity–matric suction relationship is retrieved by using an empirical correlation between electrical resistivity and matric suction.

1. Introduction

Many studies have shown that integrating geophysical and hydrogeological methods allows not only to obtain more accurate hydrostratigraphical models, but also to monitor hydraulic and geochemical processes (groundwater flow, solute transport, specific ion concentration) with high space and time resolution over a wide range of spatial scales (Breede et al., 2011; Campanella, 2008; Cosentini et al., 2012; Di Maio et al., 2013; Falgas et al., 2011; Nwankwoala and Udom, 2008; Ramalho et al., 2012). In particular, strong correlations between electrical conductivity and hydraulic conductivity are expected since they are both functions of the connected pore volumes and specific surface areas as well as of the saturation degree. In this framework, soil electrical conductivity measurements have been used to map soil water content (Di Maio and Piegari, 2011; Michot et al., 2003; Zhou et al., 2001). On the other hand, on the basis of the network model of Bernabe and Revil (1995), a generalized log–log linear electrical–hydraulic conductivity correlation function, whose slope is dependent on the geologic and geochemical soil properties, has been found (Purvance and Andricevic, 2000). Moreover, different electrical–hydraulic conductivity relationships have been derived, mostly for saturated media, by combining *i*) Kozeny–Carman type equations with the quadrature conductivity or *ii*) hydraulic conductivity expressions derived by percolation theory (applied to porous media) with the formation factor (Lesmes and Friedman, 2005; Slater, 2007). More recently, a relationship between electrical and hydraulic conductivity has been proposed by assuming that equations from percolation theory (Katz and Thompson, 1986; Thompson et al., 1987) also hold for unsaturated media (Doussan and Ruy, 2009).

In this paper, we propose a combined use of the semi-empirical Archie's and van Genuchten's laws to relate electrical resistivity (ρ) with hydraulic conductivity (K). In particular, the retrieved relationship is applied to resistivity data acquired on the rock steep slopes of the Sarno Mountains (Campania region, southern Italy), which are covered by sequences of ash-fall pyroclastic horizons. In this geological setting, heavy and/or prolonged rainfalls periodically induce fast and dangerous moving flows of ash-fall deposits since historical times. After the calamitous event that occurred in May 1998, many geological, geotechnical and geophysical investigations have been performed in the attempt to assess the sliding susceptibility in the Sarno area (Basile et al., 2003; Cascini et al., 2005; De Vita et al., 2012; Guadagno et al., 2003; Piegari and Di Maio, 2013a,b). Although many key aspects regarding landslide hazard analysis have been studied (e.g. stratigraphical setting, soil mineralogical and geotechnical properties, morphological factors, triggering mechanisms), a consensus on which hydrological models and hydrological thresholds should be used for reliable predictions of landslide occurrence is not yet reached. Nevertheless, it is doubtless that the knowledge of the hydraulic conductivity values is essential for characterizing water movement in unsaturated pyroclastic soils. Thus, linking

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K to physical quantities that allow for in-situ monitoring, such as electrical resistivity, can provide helpful tools for estimating the hydraulic conductivity field and developing early warning systems for slopes prone to failure triggered by rainfall.

In the following sections, the proposed methodology is illustrated and the retrieved K functions are discussed and compared with those found in the literature (Cascini and Sorbino, 2004; Cascini et al., 2005).

2. Combining van Genuchten and Archie models

The (second) Archie's law (Archie, 1942) is an empirical relationship that describes how the resistivity of a partially saturated rock varies with its porosity and water saturation

$$\rho = \alpha \cdot \rho_w \cdot \varphi^{-\mu} \cdot S^{-b}, \tag{1}$$

where ρ_w is the pore-filled water resistivity, φ is the porosity, b is the saturation index, μ is the cementation factor and α is the pore geometry coefficient; generally $\alpha < 1$ for rocks characterized by intergranular porosity and $\alpha > 1$ for rocks characterized by fracture porosity (Kwader, 1985). Although Archie's law was derived for a relatively small number of rocks and for a relatively small range of fluid conductivities and porosities, it has been successfully used for the last 70 years due to its wide applicability related to its variable parameters, i.e. cementation and saturation exponents (Glover et al., 2000). However, Archie's law does not take into account surface conduction, which is more and more significant as the amount of clay minerals increases. Anyway, even when this law is modified to consider surface conduction (Clavier et al., 1984; Mele et al., 2014; Waxman and Smits, 1968), it is only valid for a single conducting phase that partially saturates a non-conducting matrix. Recently, a generalization of Archie's law to n-conducting phases has been proposed by Glover (2010), who also provides a summary of the most common mixing models for electrical conductivity in porous media.

In this study, water is assumed to be the only conducting phase, which completely or partially saturates the pore space, as the matrix conductivity and the clay content of the investigated soils are negligible at shallow depths (De Vita et al., 2012). By rewriting Archie's law as $\rho = aS^{-b}$, with $a = \alpha\rho_w\varphi^{-\mu}$, the degree of saturation S is expressed in terms of electrical resistivity values, i.e.

$$S(\rho) = \left(\frac{\rho}{a}\right)^{-\frac{1}{b}}, \tag{2}$$

and the values of the positive constants a and b are derived from experimental data curve fitting. The obtained S values are then used to calculate the K values characterizing the investigated soils.

As it is well known, K is a soil hydraulic property that mainly depends on water saturation, S, and soil structure. Generally, the lower the content of fine grained soils (silts and clays), the more abrupt are the changes in K by varying the water content.

Unlike the commonly used approaches to estimate K (see Section 3.3), in the following K values are retrieved by an indirect method based on the knowledge of ρ–S curves and the Mualem–van Genuchten hydraulic conductivity function (Mualem, 1976; van Genuchten, 1980), viz.

$$K(S) = K_{sat} \cdot S^{0.5} \cdot \left[1 - \left(1 - S^{\frac{1}{m}}\right)^m\right]^2, \tag{3}$$

where K_{sat} is the saturated hydraulic conductivity, m is a parameter related to the pore size distribution and S is the effective saturation degree given by $S = (\theta - \theta_r)/(\theta_s - \theta_r)$, where θ is the volumetric water content and θ_r and θ_s are the residual and saturated water contents, respectively.

By expressing S in terms of the resistivity values in Eq. (3), we obtain the following closed-form equation relating K and ρ in unsaturated soils

$$K(\rho) = K_{sat} \cdot [S(\rho)]^{0.5} \cdot \left\{1 - \left[1 - (S(\rho))^{\frac{1}{m}}\right]^m\right\}^2. \tag{4}$$

The hydraulic conductivity function (4) depends on four empirical parameters, K_{sat}, m, a and b, and it can be used whenever S values can be described as function of electrical resistivity data.

3. Application to a study area

3.1. Geological setting of the Sarno Mountains (Campania region, southern Italy)

The study area is located on Sarno Mountains that are Mesozoic carbonate reliefs bordering the south-eastern sector of the Campanian Plain (southern Italy). The structure consists of a sequence of dolomitic limestone alternating with Lower Cretaceous microcrystalline and detritic limestone and Upper Cretaceous gray limestones. The cover mainly consists of continental debris and pyroclastic deposits overlapping both the Campanian plain and the carbonate ridges. The ash-fall pyroclastic covers are from 2 to 5 m thick (De Vita et al., 2006; Di Maio and Piegari, 2012) and are originated from the eruptive activities of the Ischia island (from 150 ky to 1302 AD), the Phlegrean Fields (from 39 ky to 1538 AD) and the Mount Somma–Vesuvius (from 25 ky to 1944 AD). Soils derived from ash-fall pyroclastic deposits, because of their typical vesicular structure, are characterized by low values of dry unit weight and very high values of void ratio and porosity (Bell, 2000; Esposito and Guadagno, 1998). In particular, pumiceous fragments can be characterized by unit weight lower than the unit weight of water and are able to float (Fisher, 1961; Schmidt, 1981). Sinking tests carried out on these materials suggest the presence of two different types of pores since pumiceous pyroclasts sink in water after a prolonged time (Esposito and Guadagno, 1998; Whitam and Sparks, 1986). This result is explained by the interconnections between the intra-particle voids. Thus, the contributions of both inter-particle and intra-particle pores are critical for characterizing the peculiar water retention capacity of pumiceous pyroclasts.

The pyroclastic soil specimens, whose physical properties are here analyzed (Section 3.2), were collected in two landslide-prone areas, where catastrophic debris-flows occurred on the 5th and 6th of May 1998 (Fig. 1). According to De Vita et al. (2012), the typical stratigraphic column of pyroclastic soil for the sample area, classified using lithological and pedological criteria (Terribile et al., 2000) and the Unified Soil Classification System (Holtz and Kovacs, 1981), is: A — humus (peat); B — very loose pyroclastic horizons subjected to highly pedogenetic processes with dense root apparatuses (silty sand); C — very loose pumiceous lapilli horizon with a low degree of weathering (well-graded gravel, fine to coarse gravel–poorly graded gravel); Bb — buried soil or palaeosoil (silty sand); Cb — very loose pumiceous lapilli with a low degree of weathering (well-graded gravel, fine to coarse gravel–poorly graded gravel), corresponding to a deposit from the preceding eruption; Bb_{basal} — basal buried palaeosoil (silty sand), corresponding to intensely pedogenized pyroclastic deposits; and R — fractured carbonate bedrock with open joints filled by soil derived from the above palaeosoil horizon.

3.2. Electrical resistivity vs. water saturation

Resistivity laboratory analyses were performed on fifteen undisturbed pyroclastic samples, belonging to B, Bb and Bb_{basal} horizons, to obtain experimental characteristic curves ρ–S (Di Maio and Piegari, 2011). The samples were saturated by capillary rise with raining water at room temperature and standard pressure conditions. Measurements of the electrical resistivity and the corresponding water content started from the saturated condition and continued by drying up the samples up to