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Hydrodynamic parameters estimation from self-potential data in a controlled full scale site

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A B S T R A C T

A multi-physical approach developed for the hydrodynamic characterization of porous media using hydrogeophysical information is presented. Several pumping tests were performed in the Hydrogeosite Laboratory, a controlled full-scale site designed and constructed at the CNR-IMAA (Consiglio Nazionale delle Ricerche – Istituto di Metodologia per l'Analisi Ambientale), in Marsico Nuovo (Basilicata Region, Southern Italy), in order to obtain an intermediate stage between laboratory experiments and field survey. The facility consists of a pool, used to study water infiltration processes, to simulate the space and time dynamics of subsurface contamination phenomena, to improve and to find new relationship between geophysical and hydrogeological parameters, to test and to calibrate new geophysical techniques and instruments. Therefore, the Hydrogeosite Laboratory has the advantage of carrying out controlled experiments, like in a flow cell or sandbox, but at field comparable scale. The data collected during the experiments have been used to estimate the saturated hydraulic conductivity k_s [ms^{-1}] using a coupled inversion model working in transient conditions, made up of the modified Richards equation describing the water flow in a variably saturated porous medium and the Poisson equation providing the self-potential ϕ [V], which naturally occurs at points of the soil surface owing to the presence of an electric field produced by the motion of underground electrolytic fluids through porous systems. The result obtained by this multi-physical numerical approach, which removes all the approximations adopted in previous works, makes a useful instrument for real heterogeneous aquifer characterization and for predictive analysis of its behavior.

1. Introduction

A key problem in aquifers characterization is the requirement of a large number of direct and high resolution measurements of system parameters and state variables. Measurements of state variables typically include the drawdown induced in observation boreholes by pumping tests. This method is intrusive and consequently the hydrogeological system is perturbed by drillings. On the contrary, geophysical approaches aim at using non-intrusive techniques to obtain a large amount of information on the subsurface and with moderate costs. In the last few decades hydrologists have increasingly resorted to hydro-geophysical information to estimate groundwater flow parameters (Cassiani and Medina, 1997; Cassiani et al., 1998; Jardani and Revil, 2009; Straface et al., 2010; Troisi et al., 2000). A key innovation in this field is based on the passive measurements of the self-potential generated by (1) ground water flow through a so-called electrokinetic coupling (Allègre et al., 2014; Aubert and Atangana, 1996; Birch, 1993, 1998; Darnet et al., 2003; Fournier, 1989; Ishido and Mizutani, 1981; Jouniaux et al., 1999; Pozzi and Jouniaux, 1994; Revil and Leroy, 2001) and (2) electro-chemical processes associated with gradients of the chemical potentials of charge carriers (ionic species and electrons) in the pore water (e.g., Maineult et al., 2006; Naudet et al., 2004; Revil et al., 2005; Straface and De Biase, 2013). A general theory of all these effects was developed by Pride (1994), Revil and Linde (2006), Revil et al. (2009). In the self-potential approach, the measured response is a function of an unknown source of electrical currents and resistivity structure. Therefore, there is an inherent ambiguity when interpreting the self-potential data when the earth resistivity is unknown. This difficulty can be solved upon merging different kinds of measurements obtained from other non-intrusive techniques, i.e. DC and EM-based electrical resistivity tomography and (Jardani and

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Revil, 2009) or borehole data (Straface et al., 2010). Interpretation schemes that could model the self-potential field recorded during pumping tests were developed (Jardani et al., 2009; Malama et al., 2009a,b; Revil et al., 2003; Rizzo et al., 2004; Soueid Ahmed et al., 2014; Straface et al., 2007a; Titov et al., 2002, 2005). Data from several pumping tests can be combined and used in a tomographic fashion to characterize heterogeneity in the aquifer (for recent field examples see, Bohling et al., 2007; Cardiff et al., 2009; Li et al., 2007; Straface et al., 2007b). Straface et al. (2007a) used experimental hydraulic heads and self-potential signals associated with a pumping test in an inverse model based on the Successive Linear Estimation (SLE) (Yeh et al., 1996), to estimate the transmissivity distribution of a small-scale aquifer. Bianchi Jannetti et al. (2010) extended the moment equations-based inverse method of Hernandez et al. (2003, 2006) to quasi-steady state flow conditions and presented its first application by using hydraulic heads and self-potential signals collected during a pumping test at the Montalto Uffugo research site. In these works the authors used self-potential signals in a two-dimensional inverse modeling. Nevertheless, the self-potential method is able to locate the spatial distribution of electrical sources in the earth generated by the coupling electrokinetic mechanism. In other words, it provides a 3D information estimate of the free surface location unlike borehole readings which provides a depth-averaged hydraulic head. In fact, even though a pumping test generates a velocity field in the aquifer, water inside an observation well is approximately at rest (or the Dupuit assumption can be considered to be locally valid). This means that pseudo-hydrostatic pressure conditions are established in the water column contained by the well. Therefore, the hydraulic head does not depend on the transducer vertical position, but attains a constant value, representing a depth averaged quantity in that location. On the other hand, the self-potential source inversion problem is highly non-unique. There are several possible distributions of the sources that can fit the data equally. This dilemma is common to nearly all geophysical inverse problems, but it is even more crucial for passive potential field techniques (Jardani et al., 2008). Jardani et al. (2013) have recently proposed a remedy to this problem, adopting a fully coupled inversion approach. Moreover, as with all geophysical techniques, data errors degrade our ability to interpret the measured signal. Common sources of self-potential measurement noise can be associated with the degradation or drift of the measuring non-polarizable electrodes, poor contact between the electrode and soil, cultural noise (Clerc et al., 1998; Corwin, 1973; Perrier et al., 1997; Petiau, 2000) and Haines jumps electrical disturbance, occurring during drainage experiments (Haas and Revil, 2009). As a consequence, joint inversion of self-potential and borehole-based head data requires estimating the relative weight of the different data types adopted (Bianchi Jannetti et al., 2010). In this context, a relevant question is how these two types of measurements can be combined within a three-dimensional inverse modeling approach. Some authors have recently worked on this issue, focusing on synthetic case studies operating in steady state conditions (Soueid Ahmed et al., 2014), or on analytical solutions requiring simplifying assumptions to solve the involved equations (Malama, 2014). The innovation presented with this study, instead, is the characterization of a variably saturated, unconfined aquifer through the inversion of hydrogeophysical experimental data in transient flow conditions. The theory and the model we developed are both of general nature and therefore applicable in problems involving heterogeneous and anisotropic media, even though the setup adopted for the experimental apparatus is homogeneous and isotropic. The choice of this configuration, is only a starting point for the validation of such a complex modeling approach, as it also deals with real experimental data. The hydrogeophysical experiment was carried out at the Hydrogeosite Laboratory at the Istituto di Metodologie per l'Analisi Ambientale (IMAA) of the Consiglio Nazionale delle Ricerche (CNR) site in Marsico Nuovo (Potenza, Italy). We illustrate the first results of the characterization effected using the hydraulic and geophysical measurements recorded during the pumping tests in the Hydrogeosite Laboratory. The results open new perspectives, owing to the great increase in information, regarding the possibility of improving the characterization of the real heterogeneous porous media.

2. Theoretical background

The grain of a porous medium in contact with a fluid, develops an electrical charge on the interface between the grain and the fluid. As a result, of the proton exchange and the sorption of cations and anions onto its surface, a triple layer configuration is formed: (1) a fixed charge of density (q_0) occurring at the mineral surface, (2) the Stern layer produced by the sorption of ions onto the mineral surface (q_S) and finally (3) a diffuse layer of anions and cations of the bulk pore water attracted or repelled according to the sign of the charge (q_b) (Davis et al., 1978; Revil et al., 2003). When the water flows within a porous medium, the excess of ions in the diffuse electrical layer are transported downstream, producing an excess of net charge and then an electric field parallel to the flow direction. This effect is called electrokinetic coupling (Briggs, 1928) and was observed for the first time by Reuss (1809).

The water flow is due to two components, a main one owing to the hydraulic gradient and a secondary one, generally of lower order than the former, to the natural electric potential. The general constitutive equation of the groundwater flow in a variably saturated aquifer is (Straface and De Biase, 2013)

$$\boldsymbol{u} = -L(S_w)\nabla\phi - k_r(S_w)k_s\nabla h \tag{1}$$

where $\boldsymbol{u}$ is the Darcy velocity [ms^{-1}], L the coupling electrokinetic term [$\mathrm{m}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$], S_w represents the saturation degree, ϕ is the electric potential [V], k_r is the relative hydraulic conductivity [dimensionless], $k_s = k_0\rho g/\mu$ is the saturated hydraulic conductivity [ms^{-1}], in which k_0 is the intrinsic permeability [m^2], ρ is the density of the fluid, g is the gravitational acceleration [ms^{-2}], μ is the dynamic viscosity of the fluid [Pa m] and finally, h is the hydraulic head [m]. The term L is set equal to $\frac{\varepsilon_f\zeta}{\mu F}$ with ε_f the dielectric constant of the porous medium [Fm^{-1}], ζ the zeta potential [V], i.e. the electrical potential located at the shear plane where the relative velocity between the deformable solid and the pore water is zero, and F the formation factor which can be defined, when the surface conductivity is negligible, by the ratio of the saturated rock resistivity to the resistivity of the saturating water. When the component, owing to the electric potential, is negligible compared to that due to the hydraulic potential, the average velocity $\boldsymbol{u}$ is only represented by the mechanical component of the Darcy velocity

$$\boldsymbol{u} = -k_r(S_w)k_s\nabla h \tag{2}$$

For $S_w = 1$, Eq. (2) coincides with the classical Darcy's law. The relative hydraulic conductivity k_r and the saturation degree S_w are assumed to be represented by the Gardner model (Gardner, 1958; Russo, 1988)

$$k_r = e^{-\alpha_G\psi} \tag{3}$$

$$S_e = \left[(1 + 0.5\alpha_G|\psi|)e^{-0.5\alpha_G|\psi|}\right]^{\frac{2}{l+2}} \tag{4}$$

in which α_G is a pore-size distribution parameter [m^{-1}] and $\psi = p/(\rho g)$ is the capillary pressure head [m], l is a parameter that accounts for the dependence of the tortuosity and the correlation factors on the water content, estimated to be about 0.5 as an average for many soils (Mualem, 1976), $S_e = (S_w - S_r)/(1 - S_r)$ is the effective dimensionless reduced water content and S_r is the residual (irreducible) saturation degree.