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Detecting different water table levels in a shallow aquifer with combined P-, surface and SH-wave surveys: Insights from V_P/V_S or Poisson's ratios

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ABSTRACT

When applied to hydrogeology, seismic methods are generally confined to the characterisation of aquifer geometry. The joint study of pressure- (P) and shear- (S) wave velocities (V_P and V_S) can provide supplementary information and improve the understanding of aquifer systems. This approach is proposed here with the estimation of V_P/V_S ratios in a stratified aquifer system characterised by tabular layers, well-delineated thanks to Electrical Resistivity Tomography, log and piezometer data. We carried out seismic surveys under two hydrological conditions (high and low flow regimes) to retrieve V_S from both surface-wave dispersion inversion and SH-wave refraction interpretation, while V_P were obtained from P-wave refraction interpretation. P-wave first arrivals provided 1D V_P structures in very good agreement with the stratification and the water table level. Both V_S models are similar and remain consistent with the stratification. The theoretical dispersion curves computed from both V_S models present a good fit with the maxima of dispersion images, even in areas where dispersion curves could not be picked. Furthermore, V_P/V_S and Poisson's ratios computed with V_S models obtained from both methods show a strong contrast for both flow regimes at depths consistent with the water table level, with distinct values corresponding to partially and fully saturated sediments.

1. Introduction

Characterisation and monitoring of groundwater resources and associated flow and transport processes mainly rely on the implementation of wells (piezometers). The interpretation of hydrogeological observations is however limited by the variety of scales at which these processes occur and by their variability in time. In such a context, using geophysical (mostly electromagnetic and electrical) methods often improves the very low spatial resolution of borehole data and limits their destructive nature (Guérin, 2005; Hubbard and Linde, 2011). These methods regularly help to characterise the geometry of the basement (Mouhri et al., 2013), identify and assess the physical and environmental parameters affecting the associated flow and transport processes (McClymont et al., 2011), and possibly follow the evolution of these parameters over time (Michot et al., 2003; Gaines et al., 2010). They also tend to be proposed to support the implantation of dense hydrological monitoring networks (Mouhri et al., 2013).

Among the geophysical tools applied to hydrogeology, seismic methods are commonly used at different scales, but remain mainly confined to the characterisation of the aquifer geometry. With dense acquisition setups and sophisticated workflows and processing techniques, seismic reflection produces detailed images of the basement with the resolution depending on the wavelength (Haeni, 1986a; Juhlin et al., 2000; Bradford, 2002; Bradford and Sawyer, 2002; Haines et al., 2009; Kaiser et al., 2009). These images are routinely used to describe the stratigraphy in the presence of strong impedance contrasts, but do not allow for distinguishing variations of a specific property (Pride, 2005; Hubbard and Linde, 2011). From these images, hydrogeologists are able to retrieve the geometry of aquifer systems, and allocate a lithology to the different layers with the help of borehole data (Paillet, 1995; Guérin, 2005).

Surface refraction seismic provides records from which it is possible to extract the propagation velocities of seismic body waves. This method has the advantage of being relatively inexpensive and quick to implement, and is easily carried out with a 1D to 3D coverage (Galibert et al., 2014). It is frequently chosen to determine the depth of the water table

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when the piezometric surface is considered as an interface inside the medium (*i.e.*, free aquifer) (Wallace, 1970; Haeni, 1986b; Haeni, 1988; Paillet, 1995; Bachrach and Nur, 1998). But the seismic response in the presence of such interfaces, and more generally in the context of aquifer characterisation, remains complex (Ghasemzadeh and Abounouri, 2012). The interpretation of the estimated velocities is often difficult because their variability mainly depends on the "dry" properties of the constituting porous media. In these conditions, borehole seismic (up-hole, down-hole, cross-hole, *etc.*) is regularly used to constraint velocity models in depth, though they remain destructive and laterally limited (Haeni, 1988; Sheriff and Geldart, 1995; Liberty et al., 1999; Steeples, 2005; Dal Moro and Keller, 2013).

Geophysicists seek to overcome these limitations, especially through the joint study of compression (P-) and shear (S-) wave velocities (V_P and V_S, respectively), whose evolution is by definition highly decoupled in the presence of fluids (Biot, 1956a,b). The effect of saturation and pore fluids on body wave velocities in consolidated media has been subject to many theoretical studies (Berryman, 1999; Lee, 2002; Dvorkin, 2008) and experimental developments (Wyllie et al., 1956; King, 1966; Nur and Simmons, 1969; Domenico, 1974; Gregory, 1976; Domenico, 1977; Murphy, 1982; Dvorkin and Nur, 1998; Foti et al., 2002; Prasad, 2002; Adam et al., 2006; Uyanık, 2011), especially in the fields of geomechanics and hydrocarbon exploration. From a theoretical point of view, this approach proves suitable for the characterisation of aquifer systems, especially by estimating V_P/V_S or Poisson's ratios (Stümpel et al., 1984; Castagna et al., 1985; Bates et al., 1992; Bachrach et al., 2000). Recent studies show that the evaluation of these ratios, or derived parameters more sensitive to changes in saturation of the medium, can be systematically carried out with seismic refraction tomography using both P and SH (shear-horizontal) waves (Turesson, 2007; Grelle and Guadagno, 2009; Mota and Monteiro Santos, 2010).

The estimation of the V_P/V_S ratio with refraction tomography requires to carry out two separate acquisitions for V_P and V_S. While P-wave seismic methods are generally considered well-established, measurements of V_S remain delicate because of well-known shear-wave generation and picking issues in SH-wave refraction seismic methods (Sheriff and Geldart, 1995; Jongmans and Demanet, 1993; Xia et al., 2002; Haines, 2007). Indirect estimation of V_S is commonly achieved in a relative straightforward manner by using surface-wave prospecting methods, as an alternative to SH-wave refraction tomography (*e.g.*, Gabriels et al., 1987; Jongmans and Demanet, 1993; Park et al., 1999; Socco and Strobbia, 2004; Socco et al., 2010). Such approach has recently been proposed for geotechnical (Heitor et al., 2012) and hydrological applications in sandy aquifers (Cameron and Knapp, 2009; Konstantaki et al., 2013; Fabien-Ouellet and Fortier, 2014). Konstantaki et al. (2013) highlighted major variations of V_P/V_S and Poisson's ratios that was correlated with the water table level. Retrieving V_P and V_S from a single acquisition setup thus appears attractive in terms of time and equipment costs, even if SH-wave methods provide high quality results in reflection seismic (Hunter et al., 2002; Guy et al., 2003; Haines and Ellefsen, 2010; Ghose et al., 2013). Moreover, Pasquet et al. (2014) recently evaluated the applicability of the combined use of SH-wave refraction tomography and surface-wave dispersion inversion for the characterisation of V_S.

In order to address such issues in more complex aquifer systems (*e.g.*, unconsolidated, heterogeneous or low permeability media), we performed high spatial resolution P-, surface- and SH-wave seismic surveys in the Orgeval experimental basin (70 km east from Paris, France) under two distinct hydrological conditions. This basin is a part of a research observatory managed by the ORACLE network (http://bdoracle.irstea.fr/) and has been studied for the last 50 years, with particular focuses on water and pollutant transfer processes occurring at different scales throughout the basin (Flipo et al., 2009). The basin drains a stratified aquifer system characterised by tabular layers, well-delineated all over the basin by Mouhri et al. (2013) thanks to extensive geological and geophysical surveys including Electrical Resistivity Tomography (ERT), Electrical Soundings (ES), Time Domain ElectroMagnetic (TDEM) soundings and borehole core sampling. The hydrogeological behaviour of the Orgeval watershed is influenced by the aquifer system, which is composed of two main geological units: the Oligocene sand and limestone (Brie formation in Fig. 1b) and the Middle Eocene limestone (Champigny formation in Fig. 1b) (Mouhri et al., 2013). These two aquifer units are separated by a clayey aquitard composed of green clay and marl (Fig. 1b). Most of the basin is covered with table-land loess of about 2–5 m in thickness, essentially composed of sand and loam lenses of low permeability. These unconsolidated deposits seem to be connected to the Oligocene sand and limestone, forming a single aquifer unit. This upper aquifer is monitored by a dense network of piezometers (Fig. 1a) (Mouhri et al., 2013) which have allowed for establishing maps of the piezometric level for high and low water regimes in 2009 and 2011 (Kurtulus et al., 2011; Kurtulus and Flipo, 2012). It thus offers an ideal framework for the study of the V_P/V_S ratio through the combined analysis of P-wave refraction, SH-wave refraction and surface-wave dispersion data. Measurements were carried out under two distinct hydrological conditions in order to evaluate the ability of this approach to detect variations of the water table level, and assess its practical limitations.

2. Location of the experimentation and acquisition strategy

2.1. Choice of the site

The experiment location has been selected in a plateau area, where the upper layers of the aquifer system are known to be the most tabular. The site is located in the southeast part of the Orgeval basin, at 70 km east from Paris, near the locality of Les Granges (black square Fig. 1a). A piezometer (PZ3 in Fig. 1a) with its water window in the Brie aquifer is situated in the middle of a trail crossing the survey area in the southeast-northwest direction. Thanks to the ORACLE facilities, the piezometric head level in the upper aquifer is continuously recorded in PZ3 on an hourly basis (Fig. 2a). Two acquisition campaigns were carried out in the site under two distinct hydrological conditions. The first campaign took place between March 12th and March 14th 2013 during a high flow regime (*i.e.*, high water level or HW in Fig. 2a), with a piezometric head level measured at 1.15 m. The second campaign was conducted between August 26th and August 28th 2013 during a low flow regime (*i.e.*, low water level or LW in Fig. 2a), with a recorded piezometric head level of 2.72 m. During both HW and LW campaigns, the piezometric head level was measured from ground level at the base of PZ3.

Electrical Resistivity Tomography was performed during both HW and LW campaigns to accurately describe the stratigraphy in the upper aquifer unit and confirm the tabularity required for our experiment. We used a multi-channel resistivimeter with a 96-electrode Wenner–Schlumberger array (Fig. 2b). ERT profiles were implanted on the side of the trail and centred on PZ3 (Fig. 1a), 1 m away from the piezometer and 0.25 m below, respectively. Electrodes were spaced with 0.5 m to obtain 41.5-m long profiles. The inversion was performed using the *RES2DINV* commercial software (Loke and Barker, 1996). The origin of the depth axis in Fig. 2 and in figures hereafter was chosen at ground level in the centre of the line (*i.e.*, the water table level is 0.25 m higher than recorded in PZ3). The ORACLE experimental facilities provided soil and air temperatures during both campaigns thanks to probes installed near the survey area. At HW, air temperature was below 0 °C and soil temperature was increasing from 6.3 °C at 0.5 m in depth to 6.5 °C at 1 m in depth. In comparison, air temperature was around 22 °C at LW, with a soil temperature varying from 18.5 °C at 0.5 m in depth to 18 °C at 1 m in depth. With such fluctuations between both campaigns, the variation of ground resistivity due to temperature cannot be neglected. To account for those effects, Campbell et al. (1949) proposed an approximation stating that an increase of 1 °C in temperature causes a decrease of 2% in resistivity. We used this approximation to correct resistivity values obtained at HW from the temperature differences observed between HW and LW periods, after extrapolating both temperature profiles in depth with an exponential