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Contribution of Seismic Methods to Hydrogeophysics

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SUMMARY

The characterisation and monitoring of aquifer systems mainly rely on piezometric and log data. Delineating spatial variations of lithology between piezometers is a delicate task, which inevitably generates errors possibly propagating into hydrogeological models. Seismic methods have been proposed to: (i) improve the low spatial resolution of borehole data, (ii) provide a characterisation of the subsurface geometry, and (iii) estimate the physical parameters of the medium influenced by the presence of water and the associated flow and transport processes. The joint study of pressure (P-) and shear (S-) wave seismic velocities (VP and VS, respectively), whose evolution is strongly decoupled in the presence of fluid, has been proposed through the estimation of the VP/VS ratio and Poisson's ratio. A specific methodology has been developed for the combined exploitation of P- and surface waves present on single seismic records. The use of this methodology in several geological and hydrogeological contexts allowed for estimating VP/VS ratio lateral and temporal variations in good agreement with a priori geological information and existing geophysical and piezometric data. Laser-based ultrasonic techniques were also proposed to put these processing techniques in practice on perfectly controlled physical models and study elastic wave propagation in partially saturated porous media.

Introduction

The characterisation and monitoring of aquifer systems and associated flow and transport processes mainly rely on piezometric and log data, e.g. on local information. Delineating spatial variations of the lithology between piezometers is a delicate task, which inevitably generates errors possibly propagating into hydrogeological models. In this case, geophysical imaging methods provide appropriate tools to interpolate boreholes data and estimate heterogeneities in the geological model. Time Domain Electromagnetic Methods (TDEM), Electrical soundings (ES) and Electrical Resistivity Tomography (ERT) are regularly performed to assess the regional geological structure and the local connectivity between the stream network and the different aquifer units. However, if electrical and electromagnetic methods show their efficiency for the multi-scale characterisation of the lithology, they remain unable to detect the water table level in clayey formations.

In the framework of the French national project CRITEX[1], seismic methods have been proposed, along with ERT, in order to: (i) improve the low spatial resolution of borehole data, (ii) provide a characterisation of the subsurface geometry, and (iii) estimate the physical parameters (mechanical, electrical, etc.) of the medium influenced by the presence of water and the associated flow and transport processes. The joint study of pressure (P-) and shear (S-) wave seismic velocities (VP and VS, respectively), whose evolution is strongly decoupled in the presence of fluid, has been proposed through the estimation of the V_P/V_S ratio and Poisson's ratio ν.

While P-wave seismic methods can be considered well-established, measurements of V_S remain delicate because of well-known shear-wave generation and picking issues. As an alternative to shear-wave refraction seismic, surface-wave methods are now classically suggested (e.g. Socco et al. 2010). If these methods provide 1D V_S models in a relative straightforward manner, specific processing techniques are required to retrieve pseudo-2D V_S sections, using for instance offset-moving windows and dispersion stacking to narrow down the lateral extent of dispersion measurements (e.g. Bergamo et al., 2012). Simultaneously retrieving V_P and V_S with such an optimised approach appears promising and attractive in terms of time and equipment costs, more particularly in the context of near-surface applications. An acquisition methodology combining pressure- and surface-wave seismic methods has thus been developed to estimate the V_P/V_S ratio from a single acquisition setup. We present here the results obtained using this acquisition strategy in various hydrogeological context, at both field and laboratory scales.

Continuous aquifer

This methodology was implemented on a simple site located in the Orgeval basin (70 km east from Paris, France). This basin is a part of a research observatory managed by the ORACLE network and has been studied for the last 50 years. It drains a stratified aquifer system characterised by tabular sedimentary units, well-delineated all over the basin by Mouhri et al. (2013) thanks to extensive geological and geophysical surveys including ERT, ES, TDEM soundings and borehole core sampling. Two acquisition campaigns were conducted under two distinct hydrological conditions, successively during high water (HW) and low water (LW) regimes.

The seismic survey consisted in a simultaneous P- and surface-wave acquisition. A 72 channel seismic recorder was used with 14 Hz vertical component geophones. A 0.5 m receiver spacing was used to obtain a 35.5-m long profile. We performed two shots on both sides of the profile, one half receiver spacing away from the first and last traces, using an aluminium plate hit vertically by a 5-kg sledgehammer. The combined analysis of P-wave first arrival times and surface-wave dispersion data allowed the estimation of 1D Poisson's ratios (Figure 1) directly from V_P/V_S ratios in the surface layers of the aquifer system studied in the Orgeval Critical Zone Observatory, and confirmed the relationship between ν and the water table level (Pasquet et al., 2015). Indeed, we observe a contrast

[1] The CRITEX project aims to describe the hydrological, hydrogeological and geochemical behavior of the critical zone of watersheds thanks to innovative research equipment.

of Poisson's ratio that does not match any identified geological interface. In addition, the ν values observed on either side of the interface are indicative of a transition between saturated and non-saturated areas. It was thus possible to detect the level of the water table in different hydrological conditions on a laterally continuous multi-layer aquifer system.

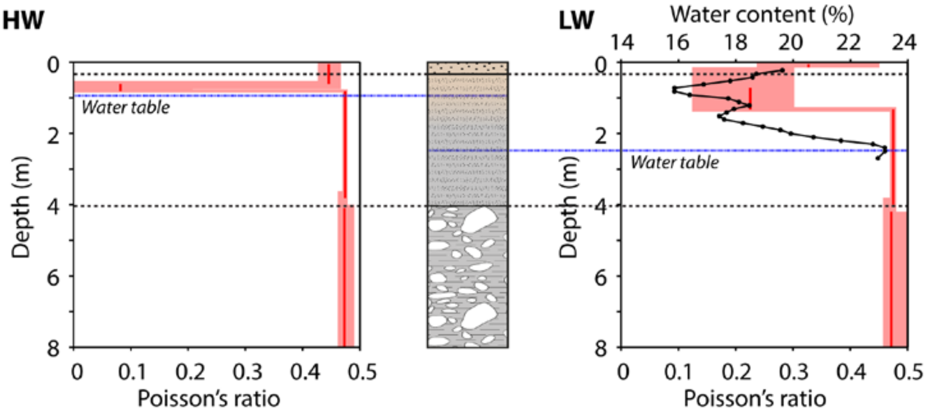

Figure 1 *1D models of Poisson's ratio ν (red lines) obtained on the Orgeval site during periods of high water (HW) and low water (LW), with corresponding uncertainties (red envelope). VP was retrieved by interpretation of P-wave first arrival times and VS by inversion of surface-wave dispersion. Water table levels observed at both periods are represented with blue dotted lines. Lithological boundaries interpreted from borehole and ERT data are represented with black dotted lines. Water content measurements performed on auger sounding samples collected during the LW campaign are superimposed on the Poisson ratio (black dots and line).*

Fractured aquifer

The methodology was also validated in a fractured aquifer environment with strong discontinuities and lateral variations in lithology at the surface and at depth in the Plœmeur hydrological observatory (south of Brittany, France). The crystalline bedrock aquifer present in the area is composed of tectonic units developed during the Hercynian orogeny, and marked by numerous syn-kinematic intrusions of upper-Carboniferous leucogranites (Ruelleu et al., 2010). A productive pumping site is located at the intersection of a contact between granite and micaschists, and a subvertical fault zone, clearly highlighted by ERT results (Figure 2a).

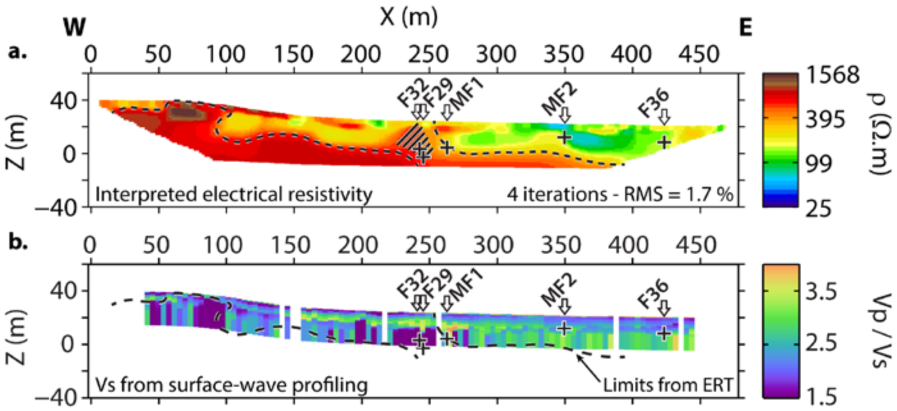

Figure 2 *(a) Electrical resistivity tomography (ERT) obtained on the site of Plœmeur. (b) Pseudo-section of V_P/V_S ratio obtained along the same profile using V_P from P-wave refraction tomography and V_S from surface-wave profiling. Lithological boundaries interpreted from the ERT are represented with black dots. The hashed area corresponds to the possible contact zone between granite and micaschists. The positions of the piezometric wells are shown with white arrows, corresponding groundwater levels being symbolized by black crosses.*

A seismic survey consisting in a simultaneous P- and surface-wave acquisition was performed along the ERT profile. We used a 72 channel seismic recorder with 14 Hz vertical component geophones, a 4 m receiver spacing and 2 roll-alongs to finally obtain a 476-m long profile. First shot location was one half receiver spacing away from first trace, and move up between shots was one receiver interval in order to achieve the high coverage required to perform refraction tomography and to stack dispersion data. The combined P-wave refraction tomography and surface-wave profiling made it possible to retrieve a 2D pseudo-section of V_P/V_S ratio (Figure 2b), which clearly highlighted lateral variations in lithology previously observed on ERT measurements. Again, several local contrasts observed on the V_P/V_S images could be linked to the variations of piezometric level and water saturation thanks to boreholes located near the acquisition profile (Pasquet et al., accepted).

Physical modelling with granular materials

To better understand the results of these field experiments, physical modelling and non-contacting ultrasonic techniques have been proposed to study, in the laboratory, the propagation of elastic waves through the transition between the unsaturated zone and the saturated zone in a series of models built with granular materials (glass beads). For that purpose, we conducted a series of experiments on physical models perfectly controlled in terms of geometry and physical parameters following the methodology described by Bodet et al., 2014.

For this study, we built a glass aquarium with dimensions 800 x 400 x 300 mm, filled with glass beads (GBs) with a diameter of 1000 µm over a thickness of 255 mm. The acquisition setup involved a laser-Doppler vibrometer allowing for recording the vertical particle displacement velocities at the surface of the granular medium excited by a mechanical source. Maintaining the source at the same position, the surface of the medium was scanned by the laser with a constant step so as to retrieve 500-mm long profiles. For a single source position, the wavefield was thus recorded as a "seismogram" representing the vertical component of the particle motion velocity at the surface of the granular medium. For each acquisition, time domain reflectometry (TDR) data were also recorded with a probe implanted on the side of the model.

The processing tools, previously validated on the field, helped to highlight changes in first arrival times (Figure 3a) and phase velocities (Figure 3b) for different water levels in the models. TDR data recorded for each model (Figure 3c) should in the short term provide an estimation of the vertical profiles of saturation, thus making possible to invert first arrival times and dispersion curves for V_P and V_S models. The resulting models should then be compared to existing analytical models to find the hydrological parameters of granular medium (porosity, saturation).

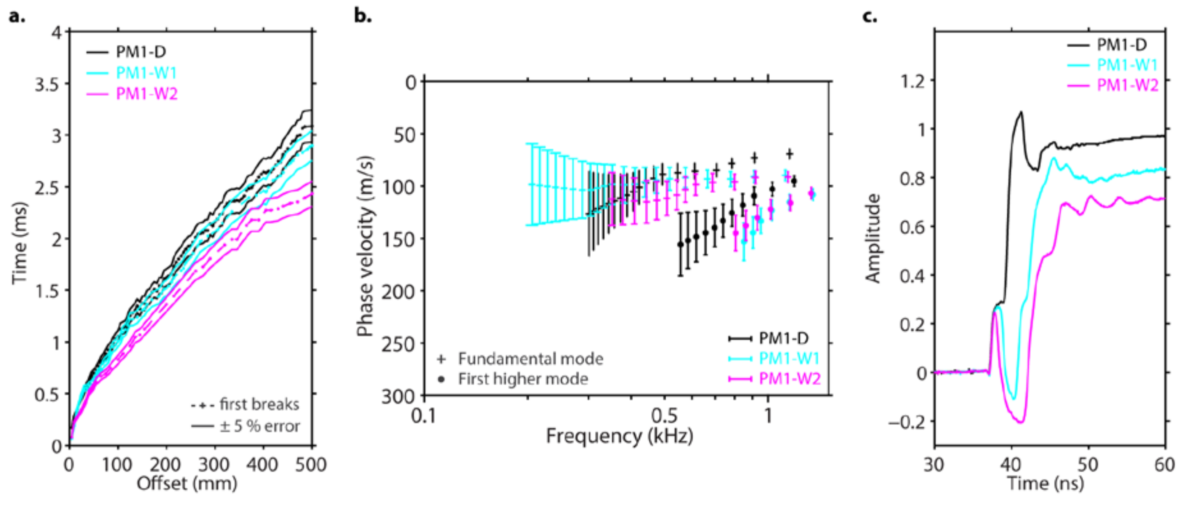

Figure 3 *(a) P-wave first arrivals picked for the dry model PM1-D (black), and the wet models PM1-W1 (cyan) and PM1-W2 (magenta). (b) Dispersion curves of the identified P-SV propagation modes for each model. (c) TDR data recorded for the different water levels.*

Conclusions

Seismic methods have been proposed for the geophysical characterisation of aquifer systems. A specific methodology has been developed for the combined and optimised exploitation of P- and surface waves present on single seismic records. The use of this methodology in several geological and hydrogeological contexts allowed for estimating V_P/V_S ratio lateral and temporal variations in good agreement with a priori geological information and existing geophysical and piezometric data. Laser-based ultrasonic techniques were also proposed to put these processing techniques in practice on perfectly controlled physical models and study elastic wave propagation in partially saturated porous media. Timelapse data are currently being processed to monitor the seasonal variations in V_P/V_S ratio, in order to definitely confirm seismic methods as key hydrogeophysical tools.

Acknowledgements

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