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Temporal Variations of Near-surface Seismic Data at the Ploemeur (France) Hydrogeological Observatory

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SUMMARY

Near-surface seismic methods are mainly used to determine the geometrical characteristics of hydrosystems (and to provide elements that are interesting for hydrogeologists such as separating aquifer layers, setting up systems boundaries, highlighting fractures etc.). Recent methodological advances suggest the high potential of seismic methods to investigate the mechanical properties of the Critical Zone (CZ), by exploiting the full wealth of seismic records. Indeed, the behavior of Shear (S) and Pressure (P) waves in the presence of water is partially decoupled, so that the ratio of their propagation velocities VP/VS is strongly linked to water saturation. We propose here a time-lapse application of this approach. Two seismic acquisitions were carried out under distinct hydrogeological conditions along the same line at the Ploemeur hydrogeological observatory (South Brittany, France). Vertical component seismic data were recorded to extract: (i) P-wave first arrival times and (ii) Rayleigh-wave phase velocities. The significant variations with time and space, of both datasets, indicate marked changes in mechanical properties of the CZ that have to be compared to soil moisture variations in the unsaturated zone and groundwater level variations.

Introduction

Characterisation, study and monitoring of hydrosystems mainly rely on piezometric levels and on local information, frequently under-constrained and based on interpretation of borehole data (log, head) and surface observations. Fortunately, hydrogeophysics provide appropriate tools to interpolate boreholes information and image heterogeneities in the Critical Zone (CZ). While electrical and electromagnetic methods predominate in such context, the use of active near-surface seismic methods has been recently suggested (i) to understand the subsurface geometry, but also (ii) to investigate the mechanical properties of the CZ influenced by water content. A simultaneous estimation of Pressure (P-) wave velocity (V_P) from first arrival times, and Shear (S-) wave velocity (V_S) from surface-wave phase velocities, was successfully carried out on the Ploemeur hydrogeological observatory (Pasquet *et al.*, 2015b). It was possible to estimate V_P/V_S ratio spatial variations whose evolution strongly depends on lithology and water content observed locally. We propose here a time-lapse approach of this methodology to monitor the mechanical property variations associated with water content. Two different datasets obtained under distinct hydrogeological conditions along the same profile at the Ploemeur observatory are presented.

Site presentation

The Ploemeur hydrogeological observatory is located in the South coast of Brittany, 3 km far from the Atlantic Ocean, near the city of Lorient. This site is characterised by a crystalline fractured environment with strong lateral heterogeneities. Electrical Resistivity Tomography (ERT) carried out on the site along a west-east line allows to delineate four main areas (Figure 1): (i) the Ploemeur granite (western part); (ii) the Pouldu micashists (eastern part) overlain by clays; and (iii) a subvertical fault zone striking N 20° (Ruelleu *et al.*, 2010; Schuite *et al*., 2015). Despite the low permeability and porosity of these lithologies, pumping wells implanted in the site have been producing water at the exceptional (and sustainable) rate of approximately 10^6 m^3 per year since 1991 (Touchard, 1999). To understand the hydrogeological processes of this heterogeneous hydrosystem, the site is highly characterized and monitored by several wells and geophysical experiments (http://hplus.ore.fr/en/ploemeur).

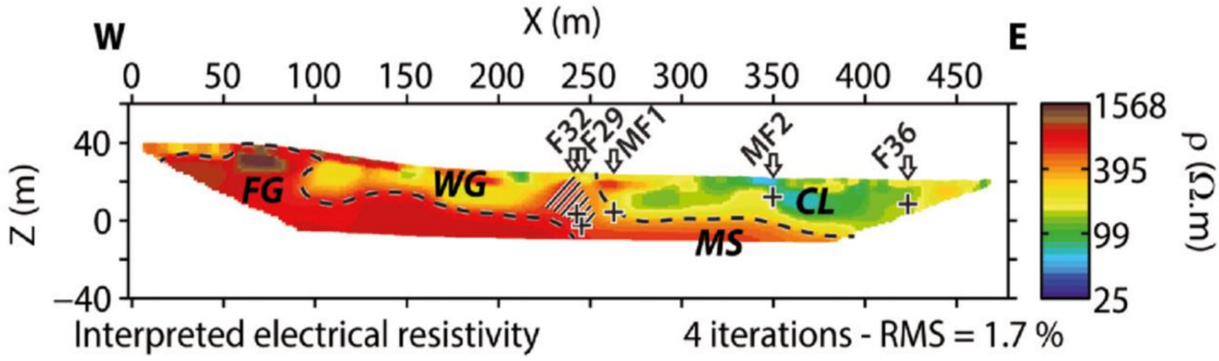

Figure 1 *Electrical resistivity values interpreted from electrical resistivity tomography carried out along a west-east line at the Ploemeur observatory. Four main structures are delineated, from west to east: (i) fresh Ploemeur granite (FG), (ii) weathered Ploemeur granite (WG), (iii) clays (CL) and (iv) Pouldu micashists (MS).The hashed area corresponds to the possible location of the subvertical fault zone. The arrows represent the projected positions of the nearest monitoring wells. Black crosses show piezometric levels measured in May 2012. From Pasquet et al. (2015b).*

Seismic acquisitions

Pasquet *et al.* (2015a, b) have recently applied seismic methods and validated them as relevant tools to image CZ mechanical properties. A unique acquisition setup was proposed to estimate both V_P and

V_S, from, respectively, P-wave first arrival time tomography and Rayleigh-wave dispersion inversion (Socco and Strobbia, 2004). The aim here is to use this methodology to determine temporal variations of mechanical properties at the Ploemeur hydrogeological observatory. For this purpose, two seismic acquisitions were performed perpendicularly to the contact zone, on the same line as the ERT profile (Figure 1), in distinct hydrogeological conditions (October 2011, low water situation and May 2012, nearly high water situation). In both cases, a 72-channel seismic recorder with 14 Hz vertical component geophones, a 4-m spacing and 2 roll-alongs were used. The source consisted of an aluminium plate hit by a 5 kg sledgehammer. This plate was hit 6 times at each position to increase the signal-to-noise ratio. The sampling rate was 0.25 ms and the recording time was 2 s to include the full surface-wave wavefield. A delay of -0.02 s was used to prevent early triggering issues.

As seismic acquisitions were carried out along the same profile but at different periods, water content should be the only varying hydrogeological parameter. However, despite similar acquisition configurations, both setups were slightly different in May and in October due to equipment availability. In May, we acquired a 476-m long profile with a 48-trace shift between each roll. In October, the first roll was shifted of 48 traces while the second was shifted of 24 traces, leading to a 450-m long profile. It is important to underline as well that operators changed during each of the acquisitions. In addition, the top surface conditions (dry or moist) inevitably influence the sources- and geophones-ground coupling. Variations in the positioning of geophones and source also must have varied with time. Moreover, the presence of active wells and military flights during recordings consisted in non-negligible noise sources. Due to such perturbations, it was thus important to define a level of significant variation of the data, i.e. variation which was not due to noise, experimental uncertainties, or manual picking errors for instance. We proposed to define this level thanks to a thorough statistical study including an analysis of picking errors. This study as well as previous works on such issues (e.g. Bergamo *et al*., 2016) showed it was possible to safely interpret both P-wave first arrival times and Rayleigh-wave phase velocities variations.

Seismic data variations

First arrival times were thus picked manually and differences between October and May were calculated and presented in a source-offset diagram (Figure 2-A). The latter shows the distribution of first arrival time absolute differences for each source-receiver couple. Two distinct zones with significant differences are observed: (i) between 200–300 m, where picked first arrival times are higher in May than in October, (ii) between 340–360 m, where picked first arrival time differences are higher in October than in May.

Rayleigh-wave phase velocities were extracted using windowing and dispersion stacking techniques, following the workflow proposed by O'Neill *et al*. (2003). At both periods, a 20-m wide window was used with 6 reverse and 6 direct shots. For each identifiable propagation mode, phase velocity absolute differences were calculated and represented as a Rayleigh-wave phase velocity difference pseudo-section, function of the wavelength and the location of the centre, Xmid, of each stacking window (Figure 2-B). The fundamental mode shows two distinct zones with non-negligible differences: (i) between 200–300 m where phase velocities are higher in October than in May, (ii) in the western part, between 50-100 m, with higher velocities in October between 50 and 75 m, then higher velocities at depth in May between 75 and 100 m.

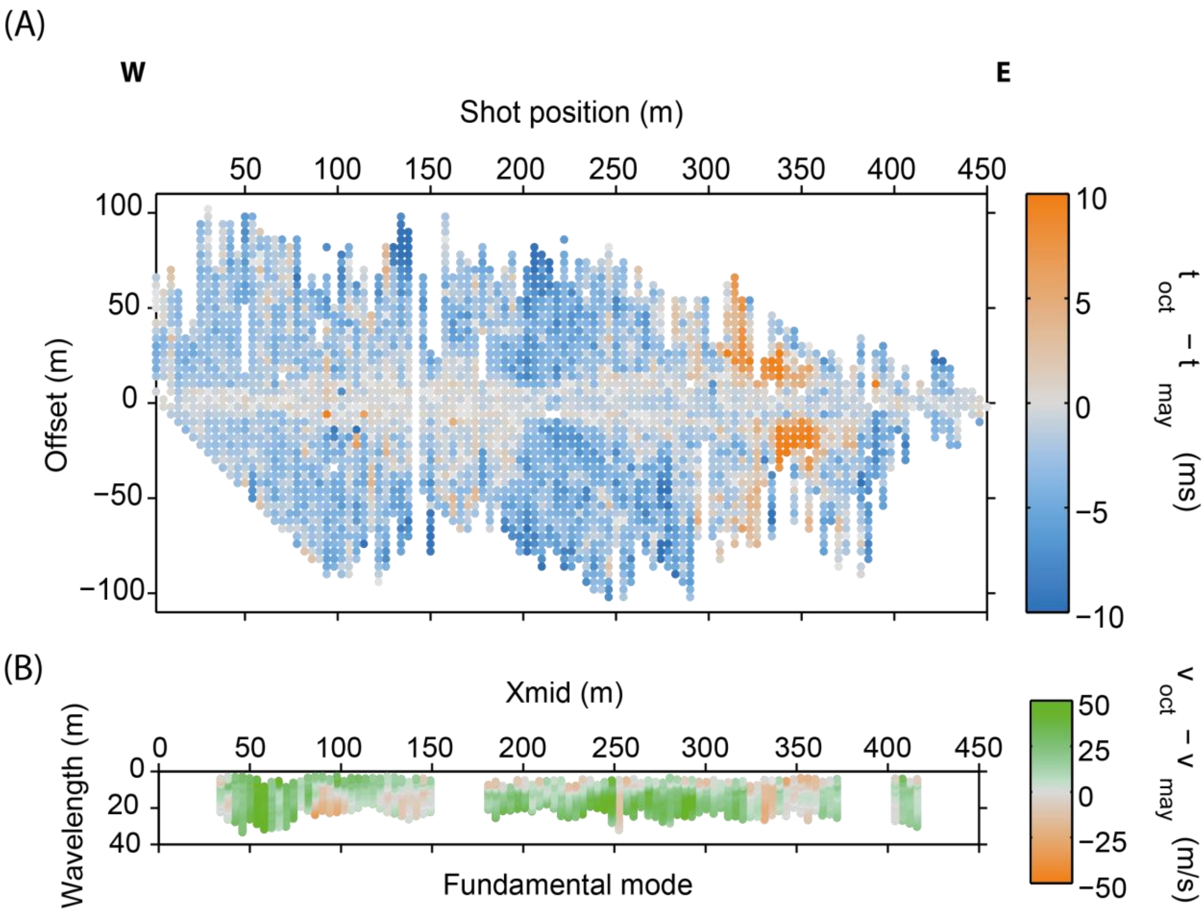

Figure 2 *(A) P-wave picked first arrival time absolute differences, represented as a function of the offset and source positions. (B) Absolute differences of picked Rayleigh-wave phase velocity dispersion curves. Only the fundamental propagation mode is presented as a function of the wavelength and the spread mid-point (Xmid). In both cases, the differences are calculated between October 2011 and May 2012.*

Conclusions

In the context of geophysical surveys at the Ploemeur hydrological observatory, seismic methods were used to image temporal variation of the CZ mechanical properties. Two seismic acquisitions were carried out in distinct hydrogeological conditions: in October 2011 and May 2012. The calculated differences of first arrival times and phase velocities between the two datasets delineate three principal zones, from west to east: (i) the Ploemeur granite (50-100 m, defined from phase velocities), (ii) the fractured contact zone (200-300 m, defined from first arrival times) and (iii) a permeable structure close to the surface, identified as a drain (340-360 m, defined from both first arrival times and phase velocities). The two kinds of datasets, their complementarity and the “amplitudes” of observed variations, confirm the interests of seismic methods in such contexts, as recently showed by Bergamo *et al.* (2016). Following this idea, the next step of the study will be to correlate these seismic observations with hydrogeological data measured locally and to work on links between mechanical properties and water content temporal variations.

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References

Bergamo, P., Dashwood, B., Uhlemann, S., Swift, R., Chambers, J.E., Gunn, D.A. and Donohue, S. [2016] Time-lapse monitoring of climate effects on earthworks using surface waves. *Geophysics*, **81**(2), 1-15. doi:10.1190/GEO2015-0275.1.

O’Neill, A., Dentith, M. and List, R. [2003] Full-waveform P-SV reflectivity inversion of surface waves for shallow engineering applications. *Exploration Geophysics*, **34**(3), 158-73.

Pasquet, S., Bodet, L., Dhemaied, A., Mouhri, A., Vitale, Q., Rejiba, F., Flipo, N. and Guérin, R. [2015] Detecting different water table levels in a shallow aquifer with combined P-, surface and SH-wave surveys: insights from VP/VS or Poisson’s ratios. *Journal of Applied Geophysics*, **113**, 23-50. doi:10.1016/j.jappgeo.2014.12.005.

Pasquet, S, Bodet, L., Longuevergne, L., Dhemaied, A., Camerlynck, C., Rejiba, F., and Guérin, R. [2015] 2D characterization of near-surface VP/VS: surface-wave dispersion inversion versus refraction tomography. *Near Surface Geophysics*, **13**(4), 315-31. doi:10.3997/1873-0604.2015028.

Ruelleu, S., Moreau, F., Bour, O., Gapais, D., and Martelet, G. [2010] Impact of gently dipping discontinuities on basement aquifer recharge: an example from Ploemeur (Brittany, France). *Journal of Applied Geophysics,* **70**(2), 161-68. doi:10.1016/j.jappgeo.2009.12.007.

Schuite, J., Longuevergne, L., Bour, B., Boudin, F., Durand, S., and Lavenant, N. [2015] Inferring field-scale properties of a fractured aquifer from ground surface deformation during a well test. *Geophysical Research Letters*, **42**(24), 2015GL066387. doi:10.1002/2015GL066387.

Socco, L.V. and Strobbia, C. [2004] Surface-wave method for near-surface characterization: a tutorial. *Near Surface Geophysics*, **2**(22). doi:10.3997/1873-0604.2004015.

Touchard, F. [1999] *Caratérisation hydrogéologique d’un aquifère en socle fracturé - Site de Ploemeur (Morbihan)*. PhD thesis, Géosciences Rennes I, Rennes, France. Retrieved from: https://geosciences.univ-rennes1.fr/IMG/pdf/Touchard.pdf.