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Surface-wave Dispersion Stacking on a Granite-micaschists Contact at Ploemeur Hydrological Observatory, France

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SUMMARY

In the context of a geophysical survey at the Ploemeur hydrological observatory (France), we performed surface-wave profiling for the characterisation of shallow subsurface Shear-wave velocities. Since we anticipated lateral variations but needed great investigation depth, we deployed multifold acquisition geometries and used roll-along dispersion stacking to enable efficient measurements of multi-modal dispersion data. Several offset moving windows have been tested. Represented as pseudo-sections, the phase velocities extracted using a 12-trace window clearly showed three areas coherent with field observation and interestingly consistent with electrical conductivities and P-wave first arrival times. This cross-quality control has been of great help in the choice of the moving window size and revealed itself to be a rewarding step prior to the inversion process.

Introduction

Water supply in crystalline context is mainly relying on surface reservoirs, because of the low porosity (limited storage capacity) and permeability (limited yields) of crystalline rocks. As a result of contamination risks, groundwater resources are more and more under pressure. Multiple fracture system and weathering may increase rock permeability at the kilometric scale, localising water flow. Wells are productive only when connected to the main fracture system, therefore, the high heterogeneity implies well position to be chosen carefully. Estimating the mechanical properties of the aquifer system may considerably help the delineation of the weathered and fractured areas prior to drilling implementation. The present study addresses such issues in a crystalline context at the Ploemeur site, located on the south coast of Brittany (France), 3 km far from the ocean, near the city of Lorient. In this area, pumping wells have been producing water at a rate of about 10^6 m^3 per year since 1991 (Touchard, 1999), with limited head decrease and no seawater intrusion. This high productivity may be explained by the specific geological context, at the contact between granites and micaschists. Wells are located next to a sub-vertical fracture system which is intersecting a horizontal system, allowing drainage of a large area (Ruelleu et al., 2010).

Several geophysical surveys have been recently performed to characterise the near-subsurface of the Ploemeur site. Seismic methods are more particularly proposed here to focus on the contact between granite and micaschists and to estimate the shallow mechanical properties of the aquifer system. Anticipating the existence of a strong weathering gradient, we performed simultaneous Pressure-wave (P-) refraction tomography and surface-wave profiling along a seismic line intersecting the contact zone. As for instance recently suggested by Olona et al. (2010), the combined interpretation of Pressure- and Shear-wave velocities (Vp and Vs) can help the characterisation of both weathered layer and bedrock in a crystalline context. From a practical point of view, measurements of Vs remain delicate because of well-known Shear-wave (SH-) generation and picking issues in SH-refraction seismic methods. Indirect estimation of Vs can be achieved in a relative straightforward manner by using surface-wave prospecting methods, as an alternative to SH-wave refraction tomography. Using typical seismic shot gathers, the recorded wavefield is basically transformed to the frequency-wavenumber domain, in which surface-wave propagation modes can be picked as dispersion curves. These curves can then be inverted as a 1D Vs structure with depth. When the method is implemented along linear sections, each 1D velocity structure is represented at its corresponding spread mid-point in order to obtain a pseudo-2D Vs section (e.g. Socco et al., 2010).

Surface-wave methods are limited by the well-known trade-off between lateral resolution and investigation depth (Gabriels et al., 1987). On one hand, the inverse problem formulation requires the investigated medium to be assumed 1D below the spread. Additionally, the spread itself has to be short enough to achieve lateral resolution if profiling is performed. On the other hand, long spreads are required to record long wavelengths in order to increase the investigation depth and to mitigate near-field effects (Bodet et al., 2005). Several countermeasures exist to overcome such drawbacks, especially when the seismic set-up provides redundant data. Offset moving windows and dispersion stacking techniques can be for instance used to narrow down the lateral extent of dispersion measurements (e.g.: Neducza, 2007; Socco et al., 2009; Boiero and Socco, 2010). Such approach has been applied here to analyse the surface waves recorded along the P-wave refraction line. But it appeared important to evaluate the shallow lateral variations along the line in order to ensure a pertinent choice of the size of the moving window. For this purpose, we proposed P-wave first arrivals and electrical conductivities as a mean of comparison prior to any inversion process.

P-wave first arrival times

The seismic survey, conducted in October 2011, consisted in the simultaneous P- and surface-wave acquisition along a 448 m seismic line (AB in Figure 2) deployed approximately in the W-E direction, perpendicular to the contact zone trend. A 72 channels Geometrics seismic recorder has been used with 14 Hz vertical component geophones. Receiver spacing was 4 m, first shot location was 2 m away from first trace, and move up between shots was one receiver interval. The source-receiver offset range varied from 2 to 286 m with a fold up to 97 and a common mid-point spacing of 2 m. Two successive rolls provided a total of 112 active channels. The site being located near a military base, seismic data were affected with a significant noise level.

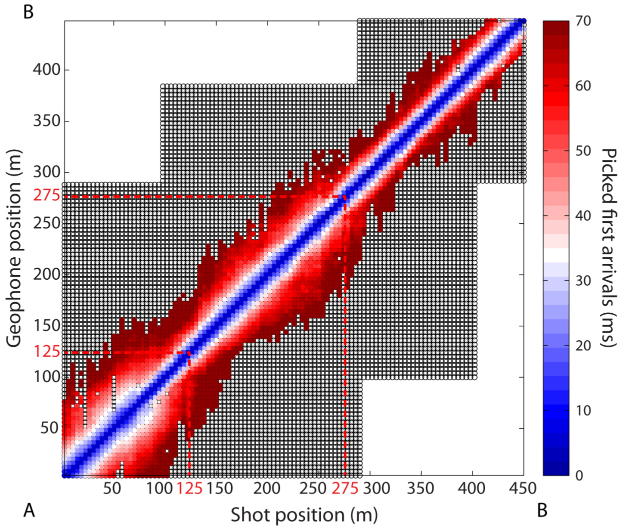

Figure 1 *Shot position vs. geophone position diagram. Black dots correspond to the existing traces and coloured dots represent picked first arrivals. Three main areas are clearly visible and delineated by the red marks.*

P-wave first arrival times were picked manually. In order to control their quality and coherence along the line, they were represented in a shot position vs. geophone position diagram (Figure 1). In this diagram, the colorscale corresponds to the picked first break times (black dots correspond to the existing traces that have not been picked due to poor signal-to-noise ratio). Three main areas are clearly visible: the first area (from 0 to 125 m) is characterised by the shortest first arrival times (i.e. shallow high velocity zone); the area between 125 and 275 m depicts slightly increasing times; the third area (from 275 m up to the end of the line) shows great arrival times (compared to the first area), probably associated with shallow low velocities. The eastern area is clearly affected by the poorest signal-to-noise ratio. First breaks could not be picked on more than the first 15 traces (when almost 25 first breaks were picked in the first two areas), probably due to attenuating subsurface properties.

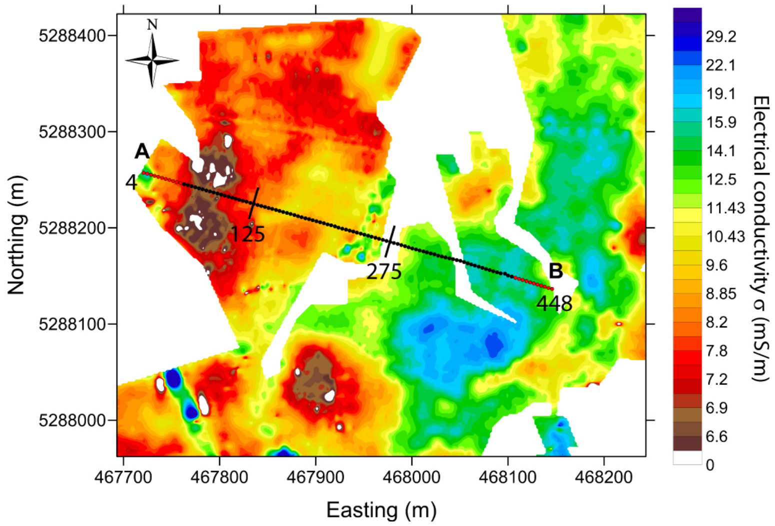

Figure 2 *Electrical conductivity mapping results with location of the seismic profile (AB). Extent of surface-wave analysis is represented in black between 46 and 406 m. Markers at 125 m and 275 m delineate the three areas observed in Figure 1.*

The distribution depicted on Figure 1 appears interestingly related to the lateral variability observed on a map of electrical conductivity collected prior to the seismic survey (with a Geonics EM-31 device). This map, presented on Figure 2, shows smooth lateral variations of electrical conductivity values (from less than 5 to over 30 mS/m) of the subsurface. Western low conductivity values are clearly associated with the presence of very shallow granite. On the contrary, higher conductivity values in the East can be attributed to clays overlaying weathered micaschists. Such distribution seems in agreement with the assumption of the contact zone striking North 20° in the area. Along the seismic profile (AB on Figure 2), very low conductivity values occur between 0 and 125 m on the granite side, and are coherent with short first arrival times. High conductivity values observed between 275 m and the end of the line are coherent as well with the shallow low velocity zone suggested by long first arrival times. In the centre part (from 125 to 275 m), intermediate conductivity values are coherent with slightly decreasing shallow velocities observed in Figure 1, suggesting a thickening of the weathered layer.

Surface-wave dispersion extraction

An offset moving window has been used to stack surface-wave dispersion with multiple shot gathers of common spread length and mid-points but with different offsets along the seismic line. Whatever the window length, 6 direct and 6 reverse shots were selected to perform dispersion stacking. Using more shots would narrow down the effective study area and would tend to unbalance the frequency content in the data. For each shot, the wavefield was transformed to the frequency-wavenumber domain and normalised. The 12 dispersion images were then stacked as a final dispersion image. The moving window was shifted along the line with a step of one receiver spacing, in order to obtain evenly spaced dispersion curves at each spread mid-point (Xmid). Eventually, visual browsing of dispersion images along the line enabled the identification of coherent maxima associated with the fundamental (mode 0) and a first higher mode (mode 1), which were picked and extracted as dispersion data.

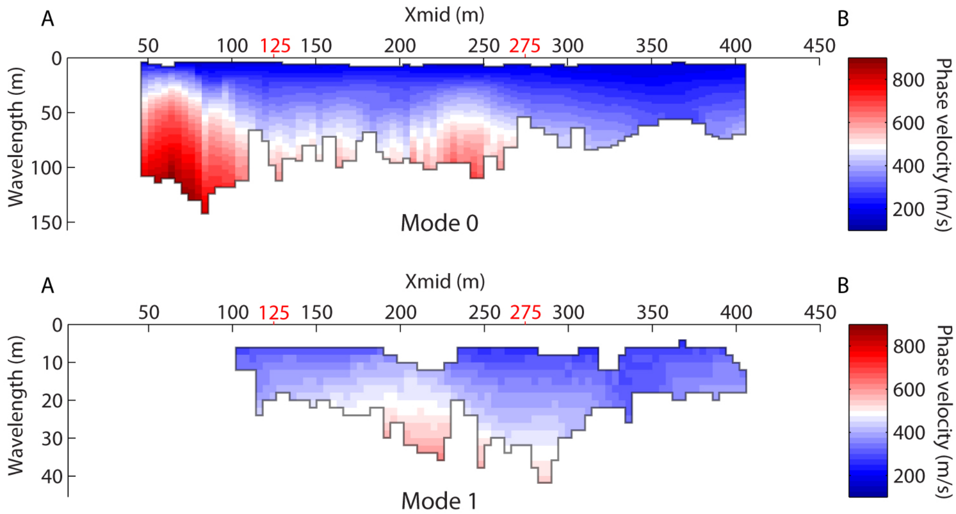

Figure 3 *Pseudo-section of Rayleigh-wave phase velocity dispersion curves picked along the AB line after dispersion stacking with a 12 trace moving window and 6 shots on each side of the window.*

Each dispersion curve is presented at its corresponding spread mid-point position along the line so as to obtain a Rayleigh-wave phase velocity pseudo-section, as for instance recently suggested by Strobbia et al. (2011). This representation is very convenient to control the quality of picked dispersion, and more particularly to check the validity of mode identification. Several window lengths have been tested (from 6 to 24 traces). The best compromise between wavenumber resolution, depth investigation and lateral extent of dispersion measurements appeared delicate to find. Results provided by a 12-trace window, presented on Figure 3, have been finally chosen, thanks to fruitful comparison with P-wave first arrival times and electrical conductivity values. Indeed, the fundamental mode depicted on this pseudo-section (mode 0 on Figure 3) shows significant lateral variations of Rayleigh-wave behaviour that are consistent with conductivities and first arrival times (the fundamental mode behaviour being by definition guided by the shallow subsurface properties).

Western high velocities exist above the shallow granite, from the beginning of the line to 125 m. In the East, from 275 m to the end of the line, low velocities correlate well with the presence of shallow clays overlaying weathered micaschists. Between 125 and 275 m, intermediate velocities correspond to the thickening of the weathered layer. The first higher mode (mode 1 on Figure 3), whose behaviour is by definition more difficult to interpret, shows less lateral variations. Similar to the results provided by other data, there are no significant features delineating the extent of the contact zone. But it is important to note that the pseudo-section only provides qualitative information about the lateral variations of the shallow subsurface properties. The dispersion data have to be inverted for Vs structures before any interpretation of the medium at depth.

Conclusions

In the context of a geophysical survey at the Ploemeur hydrological observatory, we performed surface-wave profiling for the characterisation of shallow subsurface Vs. Since we anticipated lateral variations but needed great investigation depth, we deployed multifold acquisition geometries and used roll-along dispersion stacking to enable efficient measurements of multi-modal dispersion data. Several offset moving windows have been tested. Represented as pseudo-sections, the phase velocities extracted using a 12-trace window clearly showed three areas coherent with field observation and interestingly consistent with electrical conductivities and P-wave first arrival times. These three areas can be associated with: shallow granite in the western part; weathered granite in the centre part; weathered micaschists overlaid by clays in the eastern part. This cross-quality control has been of great help in the choice of the moving window size and revealed itself to be a rewarding step prior to the inversion process.

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