



# 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

Sylvain Pasquet, Ludovic Bodet, Amine Dhemaied, Amer Mouhri, Quentin Vitale, Fayçal Rejiba, Nicolas Flipo, Roger Guérin

## ► To cite this version:

Sylvain Pasquet, Ludovic Bodet, Amine Dhemaied, Amer Mouhri, Quentin Vitale, et al.. 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*, Elsevier, 2015, 113, pp.38-50. <10.1016/j.jappgeo.2014.12.005>. <hal-01103105>

**HAL Id: hal-01103105**

**<http://hal.upmc.fr/hal-01103105>**

Submitted on 14 Jan 2015

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



## 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

Sylvain Pasquet<sup>a,b,c,\*</sup>, Ludovic Bodet<sup>a,b,c</sup>, Amine Dhemaied<sup>d</sup>, Amer Mouhri<sup>a,b,c,e</sup>, Quentin Vitale<sup>a,b,c</sup>, Fayçal Rejiba<sup>a,b,c</sup>, Nicolas Flipo<sup>e</sup>, Roger Guérin<sup>a,b,c</sup>

<sup>a</sup>Sorbonne Universités, UPMC Univ Paris 06, UMR 7619 METIS, F-75005 Paris, France

<sup>b</sup>CNRS, UMR 7619 METIS, F-75005 Paris, France

<sup>c</sup>EPHE, UMR 7619 METIS, F-75005 Paris, France

<sup>d</sup>École des Ponts ParisTech, UMR 8205 CERMES, F-77420 Champs-sur-Marne, France

<sup>e</sup>Mines ParisTech, Centre de Géosciences, F-77300 Fontainebleau, France

---

### Abstract

When applied to hydrogeology, seismic methods are generally confined to the characterisation of aquifers 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.

*Keywords:* hydrogeology, seismic methods, surface waves, P-wave, shear-wave, water table,  $V_P/V_S$  ratio, Poisson's ratio

---

\*Corresponding author: UMR 7619 METIS, Sorbonne Universités, UPMC Univ Paris 06, 4 Place Jussieu, 75252 Paris Cedex 05, France. Phone: +33 (0)1 44 27 48 85 - Fax: +33 (0)1 44 27 45 88.

*Email address:* sylvain.pasquet@upmc.fr (Sylvain Pasquet)

## 1 **1. Introduction**

2 Characterisation and monitoring of groundwater resources and associated flow and transport  
3 processes mainly rely on the implementation of wells (piezometers). The interpretation of hydro-  
4 geological observations is however limited by the variety of scales at which these processes occur  
5 and by their variability in time. In such a context, using geophysical (mostly electromagnetic and  
6 electrical) methods often improves the very low spatial resolution of borehole data and limit their  
7 destructive nature (Gu erin, 2005; Hubbard and Linde, 2011). These methods regularly help to char-  
8 acterise the geometry of the basement (Mouhri et al., 2013), identify and assess the physical and  
9 environmental parameters affecting the associated flow and transport processes (McClymont et al.,  
10 2011), and possibly follow the evolution of these parameters over time (Michot et al., 2003; Gaines  
11 et al., 2010). They also tend to be proposed to support the implantation of dense hydrological  
12 monitoring networks (Mouhri et al., 2013).

13 Among the geophysical tools applied to hydrogeology, seismic methods are commonly used at  
14 different scales, but remain mainly confined to the characterisation of the aquifer geometry. With  
15 dense acquisition setups and sophisticated workflows and processing techniques, seismic reflection  
16 produce detailed images of the basement with the resolution depending on the wavelength (Haeni,  
17 1986a; Juhlin et al., 2000; Bradford, 2002; Bradford and Sawyer, 2002; Haines et al., 2009; Kaiser  
18 et al., 2009). These images are routinely used to describe the stratigraphy in the presence of  
19 strong impedance contrasts, but do not allow for distinguishing variations of a specific property  
20 (Pride, 2005; Hubbard and Linde, 2011). From these images, hydrogeologists are able to retrieve  
21 the geometry of aquifer systems, and allocate a lithology to the different layers with the help of  
22 borehole data (Paillet, 1995; Gu erin, 2005).

23 Surface refraction seismic provides records from which it is possible to extract the propagation  
24 velocities of seismic body waves. This method has the advantage of being relatively inexpensive  
25 and quick to implement, and is easily carried out with a 1D to 3D coverage (Galibert et al., 2014).  
26 It is frequently chosen to determine the depth of the water table when the piezometric surface is  
27 considered as an interface inside the medium (*i.e.* free aquifer) (Wallace, 1970; Haeni, 1986b, 1988;  
28 Paillet, 1995; Bachrach and Nur, 1998). But the seismic response in the presence of such interfaces,  
29 and more generally in the context of aquifer characterisation, remains complex (Ghasemzadeh  
30 and Abounouri, 2012). The interpretation of the estimated velocities is often difficult because

31 their variability mainly depend on the “dry” properties of the constituting porous media. In these  
32 conditions, borehole seismic (up-hole, down-hole, cross-hole, *etc.*) are regularly used to constraint  
33 velocity models in depth, though they remain destructive and laterally limited (Haeni, 1988; Sheriff  
34 and Geldart, 1995; Liberty et al., 1999; Steeples, 2005; Dal Moro and Keller, 2013).

35 Geophysicists seek to overcome these limitations, especially through the joint study of compres-  
36 sion (P-) and shear (S-) wave velocities ( $V_P$  and  $V_S$ , respectively), whose evolution is by definition  
37 highly decoupled in the presence of fluids (Biot, 1956a,b). The effect of saturation and pore fluids  
38 on body wave velocities in consolidated media has been subject to many theoretical studies (Berry-  
39 man, 1999; Lee, 2002; Dvorkin, 2008) and experimental developments (Wyllie et al., 1956; King,  
40 1966; Nur and Simmons, 1969; Domenico, 1974; Gregory, 1976; Domenico, 1977; Murphy, 1982;  
41 Dvorkin and Nur, 1998; Foti et al., 2002; Prasad, 2002; Adam et al., 2006; Uyanik, 2011), espe-  
42 cially in the fields of geomechanics and hydrocarbon exploration. From a theoretical point of view,  
43 this approach proves suitable for the characterisation of aquifer systems, especially by estimating  
44  $V_P/V_S$  or Poisson’s ratios (Stümpel et al., 1984; Castagna et al., 1985; Bates et al., 1992; Bachrach  
45 et al., 2000). Recent studies show that the evaluation of these ratios, or derived parameters more  
46 sensitive to changes in saturation of the medium, can be systematically carried out with seismic  
47 refraction tomography using both P and SH (shear-horizontal) waves (Turesson, 2007; Grelle and  
48 Guadagno, 2009; Mota and Monteiro Santos, 2010).

49 The estimation of the  $V_P/V_S$  ratio with refraction tomography requires to carry out two separate  
50 acquisitions for  $V_P$  and  $V_S$ . While P-wave seismic methods are generally considered well-established,  
51 measurements of  $V_S$  remain delicate because of well-known shear-wave generation and picking  
52 issues in SH-wave refraction seismic methods (Sheriff and Geldart, 1995; Jongmans and Demanet,  
53 1993; Xia et al., 2002; Haines, 2007). Indirect estimation of  $V_S$  is commonly achieved in a relative  
54 straightforward manner by using surface-wave prospecting methods, as an alternative to SH-wave  
55 refraction tomography (*e.g.* Gabriels et al., 1987; Jongmans and Demanet, 1993; Park et al., 1999;  
56 Socco and Strobbia, 2004; Socco et al., 2010). Such approach has recently been proposed for  
57 geotechnical (Heitor et al., 2012) and hydrological applications in sandy aquifers (Cameron and  
58 Knapp, 2009; Konstantaki et al., 2013; Fabien-Ouellet and Fortier, 2014). Konstantaki et al. (2013)  
59 highlighted major variations of  $V_P/V_S$  and Poisson’s ratios that was correlated with the water table  
60 level. Retrieving  $V_P$  and  $V_S$  from a single acquisition setup thus appears attractive in terms of time

61 and equipment costs, even if SH-wave methods provide high quality results in reflection seismic  
62 (Hunter et al., 2002; Guy et al., 2003; Haines and Ellefsen, 2010; Ghose et al., 2013). Moreover,  
63 Pasquet et al. (2014) recently evaluated the applicability of the combined use of SH-wave refraction  
64 tomography and surface-wave dispersion inversion for the characterisation of  $V_S$  .

65 In order to address such issues in more complex aquifer systems (*e.g.* unconsolidated, heteroge-  
66 neous or low permeability media), we performed high spatial resolution P-, surface- and SH-wave  
67 seismic surveys in the Orgeval experimental basin (70 km east from Paris, France) under two dis-  
68 tinct hydrological conditions. This basin is a part of a research observatory managed by the OR-  
69 ACLE network (<http://bdoracle.irstea.fr/>) and has been studied for the last 50 years, with  
70 particular focuses on water and pollutant transfer processes occurring at different scales throughout  
71 the basin (Flipo et al., 2009). The basin drains a stratified aquifer system characterised by tabular  
72 layers, well-delineated all over the basin by Mouhri et al. (2013) thanks to extensive geological and  
73 geophysical surveys including Electrical Resistivity Tomography (ERT), Electrical Soundings (ES),  
74 Time Domain ElectroMagnetic (TDEM) soundings and borehole core sampling. The hydrogeolog-  
75 ical behaviour of the Orgeval watershed is influenced by the aquifer system, which is composed  
76 of two main geological units: the Oligocene sand and limestone (Brie formation on Fig. 1b) and  
77 the Middle Eocene limestone (Champigny formation on Fig. 1b) (Mouhri et al., 2013). These two  
78 aquifer units are separated by a clayey aquitard composed of green clay and marl (Fig. 1b). Most  
79 of the basin is covered with table-land loess of about 2–5 m in thickness, essentially composed of  
80 sand and loam lenses of low permeability. These unconsolidated deposits seem to be connected to  
81 the Oligocene sand and limestone, forming a single aquifer unit. This upper aquifer is monitored by  
82 a dense network of piezometers (Fig. 1a) (Mouhri et al., 2013) which have allowed for establishing  
83 maps of the piezometric level for high and low water regimes in 2009 and 2011 (Kurtulus et al.,  
84 2011; Kurtulus and Flipo, 2012). It thus offers an ideal framework for the study of the  $V_P/V_S$  ratio  
85 through the combined analysis of P-wave refraction, SH-wave refraction and surface-wave disper-  
86 sion data. Measurements were carried out under two distinct hydrological conditions in order to  
87 evaluate the ability of this approach to detect variations of the water table level, and assess its  
88 practical limitations.

## 89 2. Location of the experimentation and acquisition strategy

### 90 2.1. Choice of the site

91 The experiment location has been selected in a plateau area, where the upper layers of the  
92 aquifer system are known to be the most tabular. The site is located in the southeast part of the  
93 Orgeval basin, at 70 km east from Paris, near the locality of Les Granges (black square Fig. 1a).  
94 A piezometer (PZ3 on Fig. 1a) with its water window in the Brie aquifer is situated in the middle  
95 of a trail crossing the survey area in the southeast-northwest direction. Thanks to the ORACLE  
96 facilities, the piezometric head level in the upper aquifer is continuously recorded in PZ3 on an  
97 hourly basis (Fig. 2a). Two acquisition campaigns were carried out in the site under two distinct  
98 hydrological conditions. The first campaign took place between March 12<sup>th</sup> and March 14<sup>th</sup> 2013  
99 during a high flow regime (*i.e.* high water level or HW on Fig. 2a), with a piezometric head level  
100 measured at 1.15 m. The second campaign was conducted between August 26<sup>th</sup> and August 28<sup>th</sup>  
101 2013 during a low flow regime (*i.e.* low water level or LW on Fig. 2a), with a recorded piezometric  
102 head level of 2.72 m. During both HW and LW campaigns, the piezometric head level was measured  
103 from ground level at the base of PZ3.

104 Electrical Resistivity Tomography was performed during both HW and LW campaigns to accu-  
105 rately describe the stratigraphy in the upper aquifer unit and confirm the tabularity required for  
106 our experiment. We used a multi-channel resistivimeter with a 96-electrode Wenner-Schlumberger  
107 array (Fig. 2b). ERT profiles were implanted on the side of the trail and centred on PZ3 (Fig. 1a),  
108 1 m away from the piezometer and 0.25 m below, respectively. Electrodes were spaced with 0.5 m  
109 to obtain 41.5-m long profiles. The inversion was performed using the *RES2DINV* commercial  
110 software (Loke and Barker, 1996). The origin of the depth axis in Fig. 2 and in figures hereafter  
111 was chosen at ground level in the centre of the line (*i.e.* the water table level is 0.25 m higher  
112 than recorded in PZ3). The ORACLE experimental facilities provided soil and air temperatures  
113 during both campaigns thanks to probes installed near the survey area. At HW, air temperature  
114 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  
115 in depth. In comparison, air temperature was around 22°C at LW, with a soil temperature varying  
116 from 18.5°C at 0.5 m in depth to 18°C at 1 m in depth. With such fluctuations between both  
117 campaigns, the variation of ground resistivity due to temperature cannot be neglected. To account  
118 for those effects, Campbell et al. (1949) proposed an approximation stating that an increase of

119 1°C in temperature causes a decrease of 2 % in resistivity. We used this approximation to correct  
120 resistivity values obtained at HW from the temperature differences observed between HW and LW  
121 periods, after extrapolating both temperature profiles in depth with an exponential trend (Oke,  
122 1987). The comparison of the corrected HW ERT profile with the LW ERT profile shows no sig-  
123 nificant variation of the resistivity values and clearly depicts the stratigraphy with three distinct  
124 tabular layers (Fig. 2c) that are consistent with those observed at the basin scale (Fig. 1b). The  
125 most superficial layer has a thickness of 0.2 to 0.25 m and an electrical resistivity ( $\rho$ ) of about  
126 30  $\Omega$ .m. This thin layer, corresponding to the agricultural soil, was not observed at the basin scale.  
127 It presents higher resistivity values at LW that can be explained by lower water content at the  
128 surface. The second layer, associated with the table-land loess, is characterised by lower electri-  
129 cal resistivity values (around 12  $\Omega$ .m), with a thickness of about 3.5 m. The semi-infinite layer  
130 has higher electrical resistivity values (around 35  $\Omega$ .m), and can be related to the Brie limestone  
131 layer. ERT and log results offer a fine description of the site stratigraphy. These results, combined  
132 with piezometric head level records, provide valuable *a priori* information for the interpretation of  
133 seismic data.

## 134 2.2. Seismic acquisition

### 135 2.2.1. Acquisition setup

136 An identical seismic acquisition setup was deployed during both HW and LW campaigns. It  
137 consisted in a simultaneous P- and surface-wave acquisition followed by a SH-wave acquisition  
138 along the same line. The seismic line was centred on PZ3 (Fig. 1a) along the ERT profile, with the  
139 origin of the  $x$ -axis being identical to the one used for ERT (Fig. 2b). While a small receiver spacing  
140 is required to detect thin layers with seismic refraction, a long spread is needed for surface-wave  
141 analysis in order to increase spectral resolution and investigation depth. To meet both requirements,  
142 we used a dense multifold acquisition setup with 72 geophones and a 0.5 m receiver spacing to  
143 obtain a 35.5-m long profile (Fig. 3). We carried out a topographic leveling using a tacheometer to  
144 measure the relative position and elevation of each geophone. The maximum difference of elevation  
145 along the profile is around 0.5 m which represent a slope of less than 1.5 %. A 72-channel seismic  
146 recorder was used with 72 14-Hz vertical component geophones for the P-wave profile, and 72 14-Hz  
147 horizontal component geophones for the S-wave profile. First shot location was one half receiver  
148 spacing away from first trace, and move up between shots was one receiver interval. 73 shots were



149 recorded along each profile for a total number of 5256 active traces.

150 The P-wave source consisted in an aluminium plate hit vertically by a 7-kg sledgehammer. The  
151 plate was hit 6 times at each position to increase signal-to-noise ratio. The SH-waves were generated  
152 with a manual source consisting of a heavy metal frame hit laterally by a 7-kg sledgehammer. The  
153 SH-wave source was hit 8 times at each position. For both P- and SH-wave acquisitions, the  
154 sampling rate was 1 ms and the recording time was 2 s (anticipating low propagation velocities).  
155 A delay of  $-0.02$  s was kept before the beginning of each record to prevent early triggering issues  
156 (*i.e.* time shift between the recording starting time and the actual beginning of the seismic signal).

### 157 2.2.2. Recorded seismograms

158 The collected data presented on Fig. 4 are of good quality with low noise level, and did not  
159 require specific processing other than basic trace normalisation. P-wave seismograms recorded  
160 during both HW (Fig. 4a) and LW (Fig. 4c) campaigns present similar characteristics. P-wave  
161 first arrivals are clearly visible before 0.04 s (P on Fig. 4a and 4c), with three different apparent  
162 velocities visible at first glance: 200 m/s for the first two traces, then 800 m/s for the next 7  
163 to 10 traces, and around 2000 m/s for the farthest traces. They are followed by the air wave,  
164 characterised by higher frequencies and a velocity of 340 m/s (A on Fig. 4a and 4c). At last come  
165 P-SV waves (or Rayleigh waves), corresponding to a high-amplitude and low-frequency wave-train  
166 with an apparent velocity of about 150 m/s (R on Fig. 4a and 4c). SH-wave shots records obtained  
167 during both HW (Fig. 4b) and LW (Fig. 4d) campaigns also show similar features. They contain  
168 lower frequency signal, with coherent events consistent with SH-wave first arrivals (SH on Fig. 4b  
169 and 4d). These first arrivals have three distinct apparent velocities (around 70 m/s for the first two  
170 traces, 175 m/s for the next 30 traces, and 450 m/s for the farthest traces). SH-wave first arrivals  
171 are directly followed by Love waves (L on Fig. 4b and 4d), which present an apparent velocity of  
172 about 175 m/s. Early P-wave arrivals are visible on horizontal geophones records, especially on  
173 Fig. 4b between 15 and 20 m and before 0.1 s. Even under such excellent experimental conditions,  
174 it is always challenging to guarantee the horizontality of geophones. These early events are one of  
175 the main features that make first arrival picking delicate when carrying out SH-wave surveys.

176 **3. Processing and results**

177 *3.1. Body waves*

178 For both HW and LW, P- and SH-wave traveltimes were easily identified and picked in the  
 179 raw data from near to long offsets. First arrivals of 5 shots (1 direct shot, 1 reverse shot and  
 180 3 evenly spaced split-spread shots) were interpreted as simple 2D models with tabular dipping  
 181 layers (Wyrobek, 1956; Dobrin, 1988). Traveltimes corresponding to the interpreted models were  
 182 computed and represented along with observed traveltimes. In the absence of a proper estimation of  
 183 the traveltimes relative errors and in order to propose an estimate of the accuracy of the interpreted  
 184 models, we introduced a perturbation of  $\pm 5\%$  on interpreted models ( $+5\%$  on velocities and  $-5\%$   
 185 on thicknesses for the lower model, and  $-5\%$  on velocities and  $+5\%$  on thicknesses for the upper  
 186 model), and calculated the corresponding theoretical traveltimes. For the sake of readability, only  
 187 direct and reverse shots traveltimes were represented Fig. 5 along with  $\pm 5\%$  perturbations. 1D  
 188 models corresponding to the centre of the profile (*i.e.* the position of PZ3) were extracted and  
 189 represented with the corresponding  $\pm 5\%$  perturbation (Fig. 5).

190 P-wave first arrivals picked for the HW campaign (Fig. 5a) were interpreted as a 3-layer model,  
 191 with interfaces between layers slightly dipping southeast (less than  $1\%$ ). These three layers have  
 192 P-wave velocities from surface to depth of  $250 \pm 12.5$  m/s,  $750 \pm 37.5$  m/s and  $2000 \pm 100$  m/s,  
 193 respectively. The two upper layers have thicknesses at the centre of the profile of  $0.85 \pm 0.043$  m and  
 194  $3 \pm 0.15$  m, respectively (Fig. 5c). P-wave first arrivals observed for the LW campaign (Fig. 5d) were  
 195 interpreted with 4 layers presenting slightly dipping interfaces towards southeast (less than  $0.5\%$ ).  
 196 The corresponding velocities are  $170 \pm 8.5$  m/s,  $300 \pm 15$  m/s,  $825 \pm 41.25$  m/s and  $2000 \pm 100$  m/s  
 197 from top to bottom. The thicknesses of the three upper layers at the centre of the model are  
 198  $0.15 \pm 0.008$  m,  $1.2 \pm 0.06$  m and  $2.65 \pm 0.133$  m, respectively (Fig. 5f). The first layer observed  
 199 during the LW campaign is missing in the interpretation of first arrivals of the HW campaign.  
 200 Indeed, early triggering issues prevented us from picking first arrivals corresponding to this thin  
 201 layer.

202 SH-wave first arrivals picked for both HW (Fig. 5b) and LW (Fig. 5e) campaigns were inter-  
 203 preted as 3-layer models, with interfaces slightly dipping southeast (less than  $0.25\%$ ). For HW,  
 204 these three layers are characterised from top to bottom by SH-wave velocities of  $50 \pm 2.5$  m/s,  
 205  $165 \pm 8.25$  m/s and  $400 \pm 20$  m/s, respectively. The two upper layers are  $0.35 \pm 0.018$  m and

206  $3.65 \pm 0.183$  m thick, respectively (Fig. 5c). As for LW, the  $V_S$  model at the centre of the pro-  
 207 file is composed of a low velocity ( $65 \pm 3.25$  m/s) and thin ( $0.3 \pm 0.015$  m) layer in surface, a  
 208  $3.5 \pm 0.175$  m thick layer with a velocity of  $170 \pm 8.5$  m/s, and a semi-infinite layer with a velocity  
 209 of  $425 \pm 21.25$  m/s (Fig. 5f).

210 Despite known limitations of the refraction interpretation technique (*e.g.* in presence of low  
 211 velocity layers, velocity gradients, *etc.*), the interpreted velocity models are highly satisfying and  
 212 provide a description of the stratigraphy in very good agreement with ERT and log results. When  
 213  $V_S$  show 3 layers corresponding to this stratigraphy,  $V_P$  present a fourth layer that is consistent  
 214 with the observed water table level, especially for HW (Fig. 5c). These velocity models are quite  
 215 stable in depth, as demonstrated by the  $\pm 5$  % error bars displayed on Fig. 5. Furthermore, the  
 216 calculated residuals between observed and calculated traveltimes remain mostly below 5 %, with  
 217 only a few over 10 %, and Root Mean Square (RMS) errors calculated for direct and reverse shots  
 218 are around 2-2.5 % (Fig. 6). These low values point out the good consistency of the estimated  
 219 velocity models and reinforce the confidence in our interpretations.

## 220 3.2. P-SV waves

### 221 3.2.1. Extraction of dispersion

222 Surface-wave dispersion images were obtained from P-wave shot gathers for both HW and  
 223 LW campaigns (Fig. 7). After correction for geometrical spreading, the wavefield was basically  
 224 transformed to the frequency-phase velocity ( $f - c$ ) domain in which maxima should correspond to  
 225 Rayleigh-wave propagation modes (Russel, 1987; Mokhtar et al., 1988). Anticipating slight shallow  
 226 lateral variations, we used the entire spread to analyse surface waves. A 70-trace extraction window  
 227 (34.5-m wide) was actually used in order to be roughly centred on PZ3 ( $x = 24.25$  m). For both flow  
 228 regimes, we obtained dispersion images from direct (Fig. 7a, HW and 7d, LW) and reverse (Fig. 7b,  
 229 HW and 7e, LW) shots on each side of the window. The comparison of both single dispersion images  
 230 presented only slight differences, confirming the validity of the 1D approximation (Jongmans et al.,  
 231 2009). These images were thus stacked in order to increase the signal-to-noise ratio (Fig. 7c, HW and  
 232 7f, LW). The stacking was achieved by summing the frequency-phase velocity spectra of windowed  
 233 data (*e.g.* O'Neill et al., 2003), which clearly enhanced the maxima.

234 The dispersion data present a strong “effective character”, which aspects are for instance dis-  
 235 cussed by Forbriger (2003a,b) and O'Neill and Matsuoka (2005). In shallow seismic data, large

236 velocity contrasts and/or velocity gradients often generate wavefields with dominant higher modes.  
 237 Guided waves may also appear with large amplitudes at high frequencies and phase velocities. In  
 238 that case, the identification of different propagation modes and the picking of dispersion curves  
 239 is challenging and requires a thorough analysis of the observed dispersion images, or alternative  
 240 inversion approaches (*e.g.* Maraschini et al., 2010; Boiero et al., 2013). To facilitate mode identifi-  
 241 cation, we relied on preliminary picking and inversions along with trial and error forward modelling  
 242 based on *a priori* geological knowledge and results from refraction analysis. Such approach actu-  
 243 ally highlighted a “mode-jump” occurring around 35 Hz on each dispersion image, confirming the  
 244 presence of overlapping modes. Some maxima yet remained hard to identify as propagation modes  
 245 in the extracted dispersion images, either because they could be seen as secondary lobes of the  
 246 wavefield transform, or because they were too close to other maxima. To prevent from including  
 247 “misidentified modes” in dispersion data, maxima were not picked in those areas.

248 On each dispersion image, coherent maxima were finally extracted with an estimated standard  
 249 error in phase velocity defined according to the workflow described in O’Neill (2003). Corresponding  
 250 error bars are not presented on Fig. 7 to keep images readable. Four propagation modes were  
 251 observed and identified as fundamental (0), first (1), second (2) and third (3) higher modes (Fig. 7).  
 252 The apparent phase velocity of the fundamental mode increases with decreasing frequency (from  
 253 175 to 350 m/s). As recommended by Bodet (2005) and Bodet et al. (2009), we limited dispersion  
 254 curves down to frequencies ( $f_{lim}$ ) where the spectral amplitude of the seismogram became too low  
 255 (15 Hz on Fig. 7), thus defining the maximum observed wavelength  $\lambda_{max}$  ( $\sim 22.5$  m on Fig. 7).

### 256 3.2.2. Inversion

257 Assuming a 1D tabular medium below each extraction window, we performed a 1D inversion  
 258 of dispersion data obtained during both HW and LW campaigns. We used the Neighbourhood  
 259 Algorithm (NA) developed by Sambridge (1999) and implemented for near-surface applications by  
 260 Wathelet et al. (2004) and Wathelet (2008). Theoretical dispersion curves were computed from  
 261 the elastic parameters using the Thomson-Haskell matrix propagator technique (Thomson, 1950;  
 262 Haskell, 1953). NA performs a stochastic search of a pre-defined parameter space (namely  $V_P$ ,  $V_S$ ,

263 density and thickness of each layer), using the following misfit function ( $MF$ ):

$$MF = \sqrt{\sum_{i=1}^{N_f} \frac{(V_{cal_i} - V_{obs_i})^2}{N_f \sigma_i^2}}, \quad (1)$$

264 with  $V_{cal_i}$  and  $V_{obs_i}$ , the calculated and observed phase velocities at each frequency  $f_i$ ;  $N_f$ , the  
265 number of frequency samples and  $\sigma_i$ , the phase velocity measurement error at each frequency  $f_i$ .

266 Based on site *a priori* geological knowledge and results from refraction analysis, we used a  
267 parametrisation with a stack of three layers (soil, partially saturated loess and fully saturated  
268 loess) with an uniform velocity distribution overlaying the half-space (Brie limestone layer). An  
269 appropriate choice of these parameters is considered as a fundamental issue for the successful  
270 application of inversion (Socco and Strobbia, 2004; Renalier et al., 2010). The thickness of the  
271 soil layer was allowed for ranging from 0.05 to 1 m, while the thicknesses of the partially and  
272 fully saturated loess could vary between 0.5 and 3.5 m. The half-space depth (HSD), of great  
273 importance since it depends on the poorly known depth of investigation of the method, was fixed  
274 to about 40 % of the maximum observed wavelength (8 m) as recommended by O'Neill (2003)  
275 and Bodet et al. (2005, 2009). The valid parameter range for sampling velocity models was 1 to  
276 750 m/s for  $V_S$  (based on dispersion observations and refraction analysis). Anticipating a decrease  
277 of  $V_S$  in the saturated zone, we did not constraint velocities to increase with depth in the two  
278 layers corresponding to the partially and fully saturated loess, as it is usually done in surface-wave  
279 methods (Wathelet, 2008). P-wave velocity being of weak constraint on surface-wave dispersion,  
280 only S-wave velocity profile can be interpreted.  $V_P$  however remain part of the actual parameter  
281 space and were generated in the range 10 to 2500 m/s. Density was set as uniform (1800 kg/m<sup>3</sup>).  
282 A total of 75300 models were generated with NA (Fig. 8a, HW and 8c, LW). Models matching  
283 the observed data within the error bars were selected, as suggested by Endrun et al. (2008). The  
284 accepted models were used to build a final average velocity model associated with the centre of the  
285 extraction window (dashed line Fig. 8b, HW and 8d, LW). Thickness and velocity accuracy was  
286 estimated with the envelope containing the accepted models.

287 For both HW (Fig. 8b) and LW (Fig. 8d) campaigns, the inversion led to very similar 4-layer  
288  $V_S$  models. While velocities in the second and third layers were not constrained to increase with  
289 depth, neither final  $V_S$  model presents decreasing velocities. These two models are characterised  
290 by the same very thin low velocity layer in surface (around  $0.052 \pm 0.025$  m in thickness with a

291 S-wave velocity of  $8 \pm 3$  m/s). The second layer is slightly thicker for LW ( $0.67 \pm 0.14$  m) than for  
 292 HW ( $0.56 \pm 0.11$  m), and has higher  $V_S$  values for LW ( $86 \pm 15$  m/s) than for HW ( $79 \pm 10$  m/s).  
 293 The third layer has identical thickness for both flow regimes ( $3.47 \pm 0.25$  m), but  $V_S$  is slightly  
 294 higher for LW ( $179 \pm 10$  m/s) than for HW ( $169 \pm 5$  m/s). The half-space is also characterised by  
 295 very similar velocities for both flow regimes, with 459 m/s for HW (between 430 and 570 m/s),  
 296 and 464 m/s for LW (between 380 and 740 m/s). Dispersion curves being less well defined at low  
 297 frequencies, a larger variability (*i.e.* larger error bars) of half-space velocities is observed, especially  
 298 for LW.

299 This first layer is actually very thin and “slow” but was identified on the field and corresponds  
 300 to a “mode-jump” in the fundamental mode at about 35 Hz. The high frequency part of this  
 301 mode could not be picked on dispersion images (Fig. 7) due to stronger higher modes above that  
 302 frequency, and was thus not included as *a priori* information in our parameterisation. Using only  
 303 the fundamental mode in the inversion would obviously have given different results, with theoretical  
 304 dispersion curves not necessarily presenting this “mode-jump”. The incorporation of higher modes  
 305 in the inversion process allowed us to constrain the fundamental mode behavior at high frequency,  
 306 even though we could not identify it above 35 Hz. Indeed, all models included within the error  
 307 bars (Fig. 8) present the same “mode-jump” at frequencies higher than 35 Hz, leading to velocity  
 308 models with a thin low velocity layer at the surface.

### 309 3.3. Cross-validation of $V_S$ models

310 Models obtained from surface-wave dispersion inversion (in red, Fig. 9a for HW and 9c for  
 311 LW) are remarkably similar to the models obtained from SH-wave refraction interpretation (in  
 312 green, Fig. 9a for HW and 9c for LW), and are thus very consistent with the stratigraphy observed  
 313 on ERT and log results (Fig. 2).  $V_S$  obtained through surface-wave dispersion inversion are how-  
 314 ever characterised for both flow regimes by a very thin and low velocity layer in surface that is  
 315 not observed with SH-wave refraction interpretation. The error bars of  $V_S$  models retrieved from  
 316 refraction analysis were estimated by introducing a perturbation of  $\pm 5\%$  on the central model  
 317 parameters (in green, Fig. 9a for HW and 9c for LW). As for error bars of  $V_S$  models retrieved  
 318 from surface-wave dispersion inversion (in red, Fig. 9a for HW and 9c for LW), they correspond to  
 319 the envelope of accepted models for each hydrological regime (*i.e.* fitting the error bars in Fig. 8).

320 As a final quality control of inversion results, forward modelling was performed using the 1D

321  $V_S$  average models obtained from both surface-wave dispersion inversion and SH-wave refraction  
322 interpretation. While models obtained from both methods are remarkably similar, the theoret-  
323 ical dispersion curves computed from surface-wave dispersion inversion results (in red, Fig. 9b for  
324 HW and 9d for LW) provide the best fit with the coherent maxima observed on measured dis-  
325 persion images. The theoretical modes are consistent with the picked dispersion curves, and are  
326 well-separated from each other while they looked like a unique and strong mode at first glance.  
327 Interestingly, theoretical dispersion curves calculated from refraction models (in green, Fig. 9a for  
328 HW and 9c for LW) are clearly following this effective dispersion which remains representative  
329 of the stratigraphy since models from both methods are in good agreement. There is however no  
330 evidence of water table level detection, though several authors noticed a significant  $V_S$  velocity  
331 decrease in the saturated zone (O'Neill and Matsuoka, 2005; Heitor et al., 2012).

#### 332 4. Discussion and conclusions

333 When studying aquifer systems, hydrogeologists mainly rely on piezometric and log data to  
334 estimate the spatial variations of water table level and lithology. However, these data provide only  
335 local information and require the implantation of boreholes which remain expensive and destructive.  
336 Geophysical methods are increasingly proposed to interpolate this piezometric and lithological  
337 information between boreholes and build high resolution hydrological models. If electrical and  
338 electromagnetic methods have shown their efficiency for the fine characterisation of the lithology,  
339 they remained nonetheless unable to detect the water table level in clayey geological formations such  
340 as loess. In order to assess the ability of seismic methods to retrieve water table level variations,  
341 we carried out seismic measurements in a site characterised by a tabular aquifer system, well-  
342 delineated thanks to ERT, log and piezometer data. Measurements were completed under two  
343 distinct hydrological conditions (HW and LW). A simultaneous P- and surface-wave survey was  
344 achieved with a single acquisition setup, followed by a SH-wave acquisition along the same line.  
345 A simple refraction interpretation of P- and SH-wave first arrivals provided quasi-1D  $V_P$  and  $V_S$   
346 models in conformity with the stratigraphy depicted by ERT and logs during both campaigns.  $V_S$   
347 models obtained through surface-wave dispersion inversion are matching those obtained with SH-  
348 wave refraction interpretation, except for a thin low velocity layer in surface, which has only been  
349 identified in surface-wave dispersion inversion results. The recomputation of theoretical dispersion



350 curves provided results that are very consistent with the measured dispersion images and proved to  
351 be a reliable tool for validating the 1D  $V_S$  models obtained from SH-wave refraction interpretation  
352 and surface-wave dispersion inversion.

353 While  $V_S$  remains constant in partially and fully saturated loess,  $V_P$  exhibits a strong increase  
354 at a depth consistent with the observed water table level, especially for HW. This correlation is  
355 yet not so obvious for LW. Furthermore,  $V_P$  values observed in the saturated loess remain lower  
356 (around 800 m/s) than the expected values in fully saturated sediments (usually around 1500-  
357 1600 m/s). It is however quite hard to find in the literature a range of typical  $V_P$  values that  
358 should be expected in various partially and fully saturated sediments. Most of the existing studies  
359 present  $V_P$  values in saturated sands, where the relationship between  $V_P$  and water saturation  
360 remains quite simple and is thoroughly described by many authors (*e.g.* Bachrach et al., 2000; Foti  
361 et al., 2002; Prasad, 2002; Zimmer et al., 2007a,b). With more complex mixtures (*e.g.* containing a  
362 significant proportion of clays), the behavior of  $V_P$  with the saturation becomes more complicated  
363 (Fratta et al., 2005).  $V_P$  values around 800 m/s have already been observed in saturated loess  
364 by Danneels et al. (2008) when studying unstable slopes in Kyrgyzstan. In such low permeability  
365 materials, full saturation can be hard to reach (due to an irreducible fraction of air in the pores),  
366 thus limiting the maximum  $V_P$  velocity (Lu and Sabatier, 2009; Lorenzo et al., 2013). The study  
367 of  $V_P$  alone thus remains insufficient to lead back to hydrological information. In order to cope  
368 with this limitation,  $V_P/V_S$  (Fig. 10a for HW, 10c for LW) and Poisson's ratios (Fig. 10b for HW,  
369 10d for LW) were computed with  $V_S$  models retrieved from SH-wave refraction interpretation (in  
370 green) and surface-wave dispersion inversion (in red). In any case,  $V_P/V_S$  and Poisson's ratios were  
371 computed with  $V_P$  retrieved from P-wave refraction interpretation.

372 For HW,  $V_P/V_S$  ratio (Fig. 10a) is around 4 in the soil layer, and Poisson's ratio (Fig. 10b)  
373 ranges between 0.45 and 0.48. These values are typical of saturated soils (Uyanik, 2011), and may be  
374 explained by the presence of a melting snow cover on the site during the acquisition. Directly down  
375 the soil, the loess layer is characterised down to 0.75-0.85-m deep by  $V_P/V_S$  ratio values of 1.5 and  
376 Poisson's ratio values of 0.1. These values are unusually low, even for non-saturated sediments, and  
377 might be explained by the presence of a frozen layer (Wang et al., 2006). At this depth, consistent  
378 with the water table level (0.9 m),  $V_P/V_S$  and Poisson's ratios values increase to 4.5 and 0.47-0.48,  
379 respectively. This kind of contrast in a single lithological unit is typical of a transition between



380 partially saturated (low  $V_P/V_S$  and Poisson's ratios) and fully saturated sediments (high  $V_P/V_S$   
381 and Poisson's ratios).  $V_P/V_S$  and Poisson's ratios remain constant in the deepest part of loess  
382 and in the Brie limestone layer, reinforcing the assumption of a continuously saturated aquifer. A  
383 similar contrast is visible for LW on  $V_P/V_S$  (Fig. 10c) and Poisson's (Fig. 10d) ratios. The depth  
384 of this contrast (between 1.25 and 1.40 m) is not in very good agreement with the water table level  
385 (2.47 m), but yet do not correspond to any stratigraphic limit. The low  $V_P/V_S$  and Poisson's ratios  
386 values (around 1.7 and 0.24, respectively) in the upper part of the loess support the assumption of  
387 a partially saturated area, while the high values of these ratios (around 4.5 and 0.48, respectively)  
388 computed in the deepest part of the loess and in the Brie limestone layer are consistent with a fully  
389 saturated porous medium.

390 These results are supported by water content measurements performed on auger sounding  
391 samples collected during the LW campaign (soil samples could not be collected during the HW  
392 campaign due to unfavorable weather conditions). As can be observed on Fig. 10e, the water  
393 content decreases between the soil and the upper part of the loess, and reaches a minimum around  
394 0.8-0.9 m. Between 1.2 and 1.5 m, a small peak of moisture is observed, probably corresponding  
395 to a rainfall event that occurred 24 hours before the sounding (pluviometry data are available at  
396 <http://bdoracle.irstea.fr/>). This peak is followed by a progressive increase of water content  
397 that reaches a maximum at a depth corresponding to the water table level. Auger refusal was  
398 encountered at 2.70 m, thus limiting the number of measurements in the saturated zone. The  
399 differences observed for LW between the water table level and the depth of the contrast of  $V_P/V_S$   
400 and Poisson's ratios can be explained by several mechanisms. In near-surface sediments, capillary  
401 forces create a saturated zone above the water table (Lu and Likos, 2004; Lorenzo et al., 2013)  
402 that can reach up to 60 cm in such silty sediments (Lu and Likos, 2004). Refraction probably  
403 occurs above the water table on this capillarity fringe. The rainfall event observed on Fig. 10  
404 might have a similar effect, since the depth of the peak of moisture corresponds to the depth at  
405 which the  $V_P/V_S$  contrast occurs. The decrease of water content between the rainfall peak and  
406 the water table probably creates a low velocity zone that alters the first arrivals interpretation  
407 (irrespective of the acquisition configuration). The relevance of this tabular interpretation might  
408 be called into question if the studied medium is characterised by continuously varying properties  
409 with velocities increasing progressively from the partially saturated area to the fully saturated

410 area (Cho and Santamarina, 2001). Despite an advanced and thorough analysis of surface-wave  
411 dispersion, no decrease of  $V_S$  is detected in the fully saturated zone. This is probably due to very  
412 weak variations of water content between the partially and fully saturated areas (Fig. 10e), which do  
413 not produce a significant decrease of  $V_S$  in such material (Dhemaied et al., 2014). Such issues have  
414 to be addressed thanks to laboratory experiments by combining analogue modelling and ultrasonic  
415 techniques (Bergamo et al., 2014; Bodet et al., 2014) on water saturated porous media (Pasquet,  
416 2014). Despite these theoretical issues, our approach provided encouraging results that call for  
417 more experimental validation. Furthermore, the use of single acquisition setup to retrieve both  
418  $V_P$  and  $V_S$  from refraction interpretation and surface-wave analysis appears promising in terms  
419 of acquisition time and costs. Associated with existing piezometric data, seismic measurements  
420 could be carried out at a wider scale throughout the entire basin to build high resolution maps of  
421 the piezometric level. Its application in more complex (*e.g.* 2D) cases should also provide valuable  
422 information for the study of stream-aquifer interactions.

## 423 5. Acknowledgments

424 This work was supported by the french national programme EC2CO – Biohefect (project  
425 “Études expérimentales multi-échelles de l’apport des vitesses sismiques à la description du contin-  
426 uum sol-aquifère”). It was also supported by the ONEMA NAPROM project and the workpackage  
427 “Stream-Aquifer Interfaces” of the PIREN Seine research program. It is a contribution to the GIS  
428 ORACLE (Observatoire de Recherche sur les bassins versants ruraux Aménagés, pour les Crues,  
429 Les Étiages et la qualité de l’eau) that maintains the experimental facilities of the Orgeval basin.  
430 We kindly thank P. Ansart (IRSTEA) for technical assistance and logistic support during field  
431 work.

432 **6. References**

- 433 Adam, L., Batzle, M., Brevik, I., 2006. Gassmann's fluid substitution and shear modulus variability in carbonates  
 434 at laboratory seismic and ultrasonic frequencies. *Geophysics* **71**(6), F173–F183.
- 435 Bachrach, R., Dvorkin, J., Nur, A., 2000. Seismic velocities and Poisson's ratio of shallow unconsolidated sands.  
 436 *Geophysics* **65**(2), 559–564.
- 437 Bachrach, R., Nur, A., 1998. High-resolution shallow-seismic experiments in sand, Part I: Water table, fluid flow,  
 438 and saturation. *Geophysics* **63**(4), 1225–1233.
- 439 Bates, C.R., Phillips, D., Hild, J., 1992. Studies in P-wave and S-wave seismics, in: *Symposium on the Application*  
 440 *of Geophysics to Engineering and Environmental Problems*, EEGS, Oakbrook, Illinois, USA.
- 441 Bergamo, P., Bodet, L., Socco, L.V., Mourgues, R., Tournat, V., 2014. Physical modelling of a surface-wave survey  
 442 over a laterally varying granular medium with property contrasts and velocity gradients. *Geophysical Journal*  
 443 *International* **197**(1), 233–247.
- 444 Berryman, J.G., 1999. Origin of Gassmann's equations. *Geophysics* **64**(5), 1627–1629.
- 445 Biot, M.A., 1956a. Theory of propagation of elastic waves in a fluid-saturated porous solid. I. Low-frequency range.  
 446 *The Journal of the Acoustical Society of America* **28**(2), 168–178.
- 447 Biot, M.A., 1956b. Theory of propagation of elastic waves in a fluid-saturated porous solid. II. Higher frequency  
 448 range. *The Journal of the Acoustical Society of America* **28**(2), 179–191.
- 449 Bodet, L., 2005. *Limites théoriques et expérimentales de l'interprétation de la dispersion des ondes de Rayleigh :*  
 450 *apport de la modélisation numérique et physique*. Ph.D. thesis. École Centrale de Nantes et Université de Nantes.  
 451 Nantes, France.
- 452 Bodet, L., Abraham, O., Clorenec, D., 2009. Near-offset effects on Rayleigh-wave dispersion measurements: Physical  
 453 modeling. *Journal of Applied Geophysics* **68**(1), 95–103.
- 454 Bodet, L., Dhemaied, A., Martin, R., Mourgues, R., Rejiba, F., Tournat, V., 2014. Small-scale physical modeling of  
 455 seismic-wave propagation using unconsolidated granular media. *Geophysics* **79**(6), T323–T339.
- 456 Bodet, L., van Wijk, K., Bitri, A., Abraham, O., Côte, P., Grandjean, G., Leparoux, D., 2005. Surface-wave inversion  
 457 limitations from laser-Doppler physical modeling. *Journal of Environmental and Engineering Geophysics* **10**(2),  
 458 151–162.
- 459 Boiero, D., Wiarda, E., Vermeer, P., 2013. Surface- and guided-wave inversion for near-surface modeling in land and  
 460 shallow marine seismic data. *The Leading Edge* **32**(6), 638–646.
- 461 Bradford, J.H., 2002. Depth characterization of shallow aquifers with seismic reflection, Part I—The failure of NMO  
 462 velocity analysis and quantitative error prediction. *Geophysics* **67**(1), 89–97.
- 463 Bradford, J.H., Sawyer, D.S., 2002. Depth characterization of shallow aquifers with seismic reflection, Part  
 464 II—Prestack depth migration and field examples. *Geophysics* **67**(1), 98–109.
- 465 Cameron, A., Knapp, C., 2009. A new approach to predict hydrogeological parameters using shear waves from  
 466 multichannel analysis of surface waves method, in: *Symposium on the Application of Geophysics to Engineering*  
 467 *and Environmental Problems*, EEGS, Fort Worth, Texas, USA.
- 468 Campbell, R.B., Bower, C.A., Richards, L.A., 1949. Change of electrical conductivity with temperature and the

- 469 relation of osmotic pressure to electrical conductivity and ion concentration for soil extracts. *Soil Science Society*  
470 *of America Journal* **13**, 66–69.
- 471 Castagna, J.P., Amato, M., Eastwood, R., 1985. Relationships between compressional-wave and shear-wave velocities  
472 in clastic silicate rocks. *Geophysics* **50**(4), 571–581.
- 473 Cho, G.C., Santamarina, J.C., 2001. Unsaturated particulate materials - particle-level studies. *Journal of Geotechnical*  
474 *and Geoenvironmental Engineering* **127**(1), 84–96.
- 475 Dal Moro, G., Keller, L., 2013. Unambiguous determination of the  $V_s$  profile via joint analysis of multi-component  
476 active and passive seismic data, in: *Near Surface Geoscience 2013 – 19th European Meeting of Environmental and*  
477 *Engineering Geophysics*, EAGE, Bochum, Germany.
- 478 Danneels, G., Bourdeau, C., Torgoev, I., Havenith, H.B., 2008. Geophysical investigation and dynamic modelling of  
479 unstable slopes: case-study of Kainama (Kyrgyzstan). *Geophysical Journal International* **175**(1), 17–34.
- 480 Dhemaied, A., Cui, Y.J., Tang, A.M., Nebieridze, S., Terpereau, J.M., Leroux, P., 2014. Effet de l'état hydrique sur  
481 la raideur mécanique, in: *GEORAIL 2014, 2ème Symposium International en Géotechnique Ferroviaire*, Marne-  
482 *la-Vallée*, France.
- 483 Dobrin, M.B., 1988. *Introduction to geophysical prospecting*. 4 ed., McGraw-Hill Book Co.
- 484 Domenico, S.N., 1974. Effect of water saturation on seismic reflectivity of sand reservoirs encased in shale. *Geophysics*  
485 **39**(6), 759–769.
- 486 Domenico, S.N., 1977. Elastic properties of unconsolidated porous sand reservoirs. *Geophysics* **42**(7), 1339–1368.
- 487 Dvorkin, J., 2008. Yet another  $V_s$  equation. *Geophysics* **73**(2), E35–E39.
- 488 Dvorkin, J., Nur, A., 1998. Acoustic signatures of patchy saturation. *International Journal of Solids and Structures*  
489 **35**(34–35), 4803–4810.
- 490 Endrun, B., Meier, T., Lebedev, S., Bohnhoff, M., Stavrakakis, G., Harjes, H.P., 2008. S velocity structure and radial  
491 anisotropy in the Aegean region from surface wave dispersion. *Geophysical Journal International* **174**(2), 593–616.
- 492 Fabien-Ouellet, G., Fortier, R., 2014. Using all seismic arrivals in shallow seismic investigations. *Journal of Applied*  
493 *Geophysics* **103**, 31–42.
- 494 Flipo, N., Rejiba, F., Kurtulus, B., Tournebize, J., Tallec, G., Vilain, G., Garnier, J., Ansart, P., Lotteau, M., 2009.  
495 *Caractérisation des fonctionnements hydrologique et hydrogéologiques du bassin de l'Orgeval*. Technical Report.  
496 *PIREN Seine*.
- 497 Forbriger, T., 2003a. Inversion of shallow-seismic wavefields: I. Wavefield transformation. *Geophysical Journal*  
498 *International* **153**(3), 719–734.
- 499 Forbriger, T., 2003b. Inversion of shallow-seismic wavefields: II. Inferring subsurface properties from wavefield trans-  
500 forms. *Geophysical Journal International* **153**(3), 735–752.
- 501 Foti, S., Lancellotta, R., Lai, C.G., 2002. Porosity of fluid-saturated porous media from measured seismic wave  
502 velocities. *Géotechnique* **52**(5), 359–373.
- 503 Fratta, D., Alshibli, K.A., Tanner, W., Roussel, L., 2005. Combined TDR and P-wave velocity measurements for the  
504 determination of in situ soil density—experimental study. *Geotechnical Testing Journal* **28**(6), 12293.
- 505 Gabriels, P., Snieder, R., Nolet, G., 1987. In situ measurements of shear-wave velocity in sediments with higher-mode  
506 Rayleigh waves. *Geophysical Prospecting* **35**(2), 187–196.

- 507 Gaines, D., Baker, G.S., Hubbard, S.S., Watson, D., Brooks, S., Jardine, P., 2010. Detecting perched water bodies  
508 using surface-seismic time-lapse travelttime tomography, in: *Advances in Near-surface Seismology and Ground-*  
509 *penetrating Radar*. Society of Exploration Geophysicists, American Geophysical Union, Environmental and Engi-  
510 *neering Geophysical Society*, pp. 415–428.
- 511 Galibert, P.Y., Valois, R., Mendes, M., Guérin, R., 2014. Seismic study of the low-permeability volume in southern  
512 France karst systems. *Geophysics* **79**(1), EN1–EN13.
- 513 Ghasemzadeh, H., Abounouri, A.A., 2012. Effect of subsurface hydrological properties on velocity and attenuation  
514 of compressional and shear wave in fluid-saturated viscoelastic porous media. *Journal of Hydrology* **460–461**,  
515 110–116.
- 516 Ghose, R., Carvalho, J., Loureiro, A., 2013. Signature of fault zone deformation in near-surface soil visible in shear  
517 wave seismic reflections. *Geophysical Research Letters* **40**(6), 1074–1078.
- 518 Gregory, A.R., 1976. Fluid saturation effects on dynamic elastic properties of sedimentary rocks. *Geophysics* **41**(5),  
519 895–921.
- 520 Grelle, G., Guadagno, F.M., 2009. Seismic refraction methodology for groundwater level determination: “Water  
521 seismic index”. *Journal of Applied Geophysics* **68**(3), 301–320.
- 522 Guérin, R., 2005. Borehole and surface-based hydrogeophysics. *Hydrogeology Journal* **13**(1), 251–254.
- 523 Guy, E.D., Nolen-Hoeksema, R.C., Daniels, J.J., Lefchik, T., 2003. High-resolution SH-wave seismic reflection inves-  
524 tigation near a coal mine-related roadway collapse feature. *Journal of Applied Geophysics* **54**(1–2), 51–70.
- 525 Haeni, F.P., 1986a. Application of continuous seismic reflection methods to hydrologic studies. *Ground Water* **24**(1),  
526 23–31.
- 527 Haeni, F.P., 1986b. Application of seismic refraction methods in groundwater modeling studies in New England.  
528 *Geophysics* **51**(2), 236–249.
- 529 Haeni, F.P., 1988. Application of seismic-refraction techniques to hydrologic studies. Technical Report TWRI -  
530 02-D2. United States Geological Survey.
- 531 Haines, S.S., 2007. A hammer-impact, aluminium, shear-wave seismic source. Technical Report OF 07-1406. United  
532 States Geological Survey.
- 533 Haines, S.S., Ellefsen, K.J., 2010. Shear-wave seismic reflection studies of unconsolidated sediments in the near  
534 surface. *Geophysics* **75**(2), B59–B66.
- 535 Haines, S.S., Pidlisecky, A., Knight, R., 2009. Hydrogeologic structure underlying a recharge pond delineated with  
536 shear-wave seismic reflection and cone penetrometer data. *Near Surface Geophysics* **7**(5-6), 329–339.
- 537 Haskell, N.A., 1953. The dispersion of surface waves on multilayered media. *Bulletin of the Seismological Society of*  
538 *America* **43**(1), 17–34.
- 539 Heitor, A., Indraratna, B., Rujikiatkamjorn, C., Golaszewski, R., 2012. Characterising compacted fills at Penrith  
540 Lakes development site using shear wave velocity and matric suction, in: *11th Australia - New Zealand Conference*  
541 *on Geomechanics: Ground Engineering in a Changing World*, Melbourne, Australia.
- 542 Hubbard, S.S., Linde, N., 2011. Hydrogeophysics, in: *Treatise on Water Science*. Elsevier, pp. 401–434.
- 543 Hunter, J.A., Benjumea, B., Harris, J.B., Miller, R.D., Pullan, S.E., Burns, R.A., Good, R.L., 2002. Surface and  
544 downhole shear wave seismic methods for thick soil site investigations. *Soil Dynamics and Earthquake Engineering*

- 545 **22**(9–12), 931–941.
- 546 Jongmans, D., Bièvre, G., Renalier, F., Schwartz, S., Beaurez, N., Orengo, Y., 2009. Geophysical investigation of a  
547 large landslide in glaciolacustrine clays in the Trièves area (French Alps). *Engineering Geology* **109**(1–2), 45–56.
- 548 Jongmans, D., Demanet, D., 1993. The importance of surface waves in vibration study and the use of Rayleigh waves  
549 for estimating the dynamic characteristics of soils. *Engineering Geology* **34**(1–2), 105–113.
- 550 Juhlin, C., Palm, H., Müllern, C.F., Wällberg, B., 2000. High-resolution reflection seismics applied to detection of  
551 groundwater resources in glacial deposits, Sweden. *Geophysical Research Letters* **27**(11), 1575–1578.
- 552 Kaiser, A.E., Green, A.G., Campbell, F.M., Horstmeyer, H., Manukyan, E., Langridge, R.M., McClymont, A.F.,  
553 Mancktelow, N., Finnemore, M., Nobes, D.C., 2009. Ultrahigh-resolution seismic reflection imaging of the Alpine  
554 Fault, New Zealand. *Journal of Geophysical Research: Solid Earth* **114**(B11), B11306.
- 555 King, M.S., 1966. Wave velocities in rocks as a function of change in overburden pressure and pore fluid saturants.  
556 *Geophysics* **31**(1), 50–73.
- 557 Konstantaki, L.A., Carpentier, S.F.A., Garofalo, F., Bergamo, P., Socco, L.V., 2013. Determining hydrological and  
558 soil mechanical parameters from multichannel surface-wave analysis across the Alpine Fault at Inchbonnie, New  
559 Zealand. *Near Surface Geophysics* **11**(4), 435–448.
- 560 Kurtulus, B., Flipo, N., 2012. Hydraulic head interpolation using anfis—model selection and sensitivity analysis.  
561 *Computers & Geosciences* **38**(1), 43–51.
- 562 Kurtulus, B., Flipo, N., Goblet, P., Vilain, G., Tournebize, J., Tallec, G., 2011. Hydraulic head interpolation in an  
563 aquifer unit using ANFIS and Ordinary Kriging. *Studies in Computational Intelligence* **343**, 265–276.
- 564 Lee, M.W., 2002. Modified Biot-Gassmann theory for calculating elastic velocities for unconsolidated and consolidated  
565 sediments. *Marine Geophysical Researches* **23**(5-6), 403–412.
- 566 Liberty, L.M., Clement, W.P., Knoll, M.D., 1999. Surface and borehole seismic characterization of the boise hy-  
567 drogeophysical research site, in: *Symposium on the Application of Geophysics to Engineering and Environmental*  
568 *Problems*, EEGS, Oakland, California, USA.
- 569 Loke, M.H., Barker, R.D., 1996. Rapid least-squares inversion of apparent resistivity pseudosections by a quasi-  
570 Newton method. *Geophysical Prospecting* **44**(1), 131–152.
- 571 Lorenzo, J.M., Smolkin, D.E., White, C., Chollett, S.R., Sun, T., 2013. Benchmark hydrogeophysical data from a  
572 physical seismic model. *Computers & Geosciences* **50**, 44–51.
- 573 Lu, N., Likos, W.J., 2004. *Unsaturated soil mechanics*. John Wiley & Sons.
- 574 Lu, Z., Sabatier, J.M., 2009. Effects of soil water potential and moisture content on sound speed. *Soil Science Society*  
575 *of America Journal* **73**(5), 1614–1625.
- 576 Maraschini, M., Ernst, F., Foti, S., Socco, L.V., 2010. A new misfit function for multimodal inversion of surface  
577 waves. *Geophysics* **75**(4), G31–G43.
- 578 McClymont, A.F., Roy, J.W., Hayashi, M., Bentley, L.R., Maurer, H., Langston, G., 2011. Investigating groundwater  
579 flow paths within proglacial moraine using multiple geophysical methods. *Journal of Hydrology* **399**(1–2), 57–69.
- 580 Michot, D., Benderitter, Y., Dorigny, A., Nicoulaud, B., King, D., Tabbagh, A., 2003. Spatial and temporal moni-  
581 toring of soil water content with an irrigated corn crop cover using surface electrical resistivity tomography. *Water*  
582 *Resources Research* **39**(5), 1138.

- 583 Mokhtar, T.A., Herrmann, R.B., Russell, D.R., 1988. Seismic velocity and Q model for the shallow structure of the  
584 Arabian Shield from short-period Rayleigh waves. *Geophysics* **53**(11), 1379–1387.
- 585 Mota, R., Monteiro Santos, F.A., 2010. 2D sections of porosity and water saturation from integrated resistivity and  
586 seismic surveys. *Near Surface Geophysics* **8**(6), 575–584.
- 587 Mouhri, A., Flipo, N., Rejiba, F., de Fouquet, C., Bodet, L., Kurtulus, B., Tallec, G., Durand, V., Jost, A., Ansart,  
588 P., Goblet, P., 2013. Designing a multi-scale sampling system of stream–aquifer interfaces in a sedimentary basin.  
589 *Journal of Hydrology* **504**, 194–206.
- 590 Murphy, W.F., 1982. Effects of partial water saturation on attenuation in Massilon sandstone and Vycor porous  
591 glass. *The Journal of the Acoustical Society of America* **71**(6), 1458–1468.
- 592 Nur, A., Simmons, G., 1969. The effect of saturation on velocity in low porosity rocks. *Earth and Planetary Science*  
593 *Letters* **7**(2), 183–193.
- 594 Oke, T.R., 1987. *Boundary layer climates*. Taylor & Francis.
- 595 O'Neill, A., 2003. Full-waveform reflectivity for modelling, inversion and appraisal of seismic surface wave dispersion  
596 in shallow site investigations. Ph.D. thesis. University of Western Australia. Perth, Australia.
- 597 O'Neill, A., Dentith, M., List, R., 2003. Full-waveform P-SV reflectivity inversion of surface waves for shallow  
598 engineering applications. *Exploration Geophysics* **34**(3), 158–173.
- 599 O'Neill, A., Matsuoka, T., 2005. Dominant higher surface-wave modes and possible inversion pitfalls. *Journal of*  
600 *Environmental and Engineering Geophysics* **10**(2), 185–201.
- 601 Paillet, F.L., 1995. Integrating surface geophysics, well logs and hydraulic test data in the characterization of  
602 heterogeneous aquifers. *Journal of Environmental and Engineering Geophysics* **1**(1), 1–13.
- 603 Park, C.B., Miller, R.D., Xia, J., 1999. Multichannel analysis of surface waves. *Geophysics* **64**(3), 800–808.
- 604 Pasquet, S., 2014. Apport des méthodes sismiques à l'hydrogéophysique : importance du rapport  $V_p/V_s$  et contri-  
605 bution des ondes de surface. Ph.D. thesis. Université Pierre et Marie Curie. Paris, France.
- 606 Pasquet, S., Sauvin, G., Andriamboavonjy, M.R., Bodet, L., Lecomte, I., Guérin, R., 2014. Surface-wave dispersion  
607 inversion versus SH-wave refraction tomography in saturated and poorly dispersive quick clays, in: *Near Surface*  
608 *Geoscience 2014 – 20th European Meeting of Environmental and Engineering Geophysics, EAGE, Athens, Greece*.
- 609 Prasad, M., 2002. Acoustic measurements in unconsolidated sands at low effective pressure and overpressure detection.  
610 *Geophysics* **67**(2), 405–412.
- 611 Pride, S.R., 2005. Relationships between seismic and hydrological properties, in: *Hydrogeophysics*. Springer, pp.  
612 253–290.
- 613 Renalier, F., Jongmans, D., Savvaidis, A., Wathelet, M., Endrun, B., Cornou, C., 2010. Influence of parameterization  
614 on inversion of surface wave dispersion curves and definition of an inversion strategy for sites with a strong contrast.  
615 *Geophysics* **75**(6), B197–B209.
- 616 Russel, D.R., 1987. Multi-channel processing of dispersed surface waves. Ph.D. thesis. Saint Louis University. Saint  
617 Louis, Missouri, USA.
- 618 Sambridge, M., 1999. Geophysical inversion with a neighbourhood algorithm—I. Searching a parameter space.  
619 *Geophysical Journal International* **138**(2), 479–494.
- 620 Sheriff, R.E., Geldart, L.P., 1995. *Exploration seismology*. 2 ed., Cambridge University Press.



- 621 Socco, L.V., Foti, S., Boiero, D., 2010. Surface-wave analysis for building near-surface velocity models - Established  
622 approaches and new perspectives. *Geophysics* **75**(5), A83–A102.
- 623 Socco, L.V., Strobbia, C., 2004. Surface-wave method for near-surface characterization: a tutorial. *Near Surface*  
624 *Geophysics* **2**(4), 165–185.
- 625 Steeples, D.W., 2005. Shallow seismic methods, in: *Hydrogeophysics*. Springer, pp. 215–251.
- 626 Stümpel, H., Kähler, S., Meissner, R., Milkereit, B., 1984. The use of seismic shear waves and compressional waves  
627 for lithological problems of shallow sediments. *Geophysical Prospecting* **32**(4), 662–675.
- 628 Thomson, W.T., 1950. Transmission of elastic waves through a stratified solid medium. *Journal of Applied Physics*  
629 **21**(2), 89–93.
- 630 Turesson, A., 2007. A comparison of methods for the analysis of compressional, shear, and surface wave seismic data,  
631 and determination of the shear modulus. *Journal of Applied Geophysics* **61**(2), 83–91.
- 632 Uyanik, O., 2011. The porosity of saturated shallow sediments from seismic compressional and shear wave velocities.  
633 *Journal of Applied Geophysics* **73**(1), 16–24.
- 634 Wallace, D.E., 1970. Some limitations of seismic refraction methods in geohydrological surveys of deep alluvial basins.  
635 *Ground Water* **8**(6), 8–13.
- 636 Wang, D.Y., Zhu, Y.L., Ma, W., Niu, Y.H., 2006. Application of ultrasonic technology for physical–mechanical  
637 properties of frozen soils. *Cold Regions Science and Technology* **44**(1), 12–19.
- 638 Wathelet, M., 2008. An improved neighborhood algorithm: Parameter conditions and dynamic scaling. *Geophysical*  
639 *Research Letters* **35**(9), L09301.
- 640 Wathelet, M., Jongmans, D., Ohrnberger, M., 2004. Surface-wave inversion using a direct search algorithm and its  
641 application to ambient vibration measurements. *Near Surface Geophysics* **2**(4), 211–221.
- 642 Wyllie, M.R.J., Gregory, A.R., Gardner, L.W., 1956. Elastic wave velocities in heterogeneous and porous media.  
643 *Geophysics* **21**(1), 41–70.
- 644 Wyrobek, S.M., 1956. Application of delay and intercept times in the interpretation of multilayer refraction time  
645 distance curves. *Geophysical Prospecting* **4**(2), 112–130.
- 646 Xia, J., Miller, R.D., Park, C.B., Wightman, E., Nigbor, R., 2002. A pitfall in shallow shear-wave refraction surveying.  
647 *Journal of Applied Geophysics* **51**(1), 1–9.
- 648 Zimmer, M., Prasad, M., Mavko, G., Nur, A., 2007a. Seismic velocities of unconsolidated sands: Part 1 — Pressure  
649 trends from 0.1 to 20 MPa. *Geophysics* **72**(1), E1–E13.
- 650 Zimmer, M., Prasad, M., Mavko, G., Nur, A., 2007b. Seismic velocities of unconsolidated sands: Part 2 — Influence  
651 of sorting- and compaction-induced porosity variation. *Geophysics* **72**(1), E15–E25.



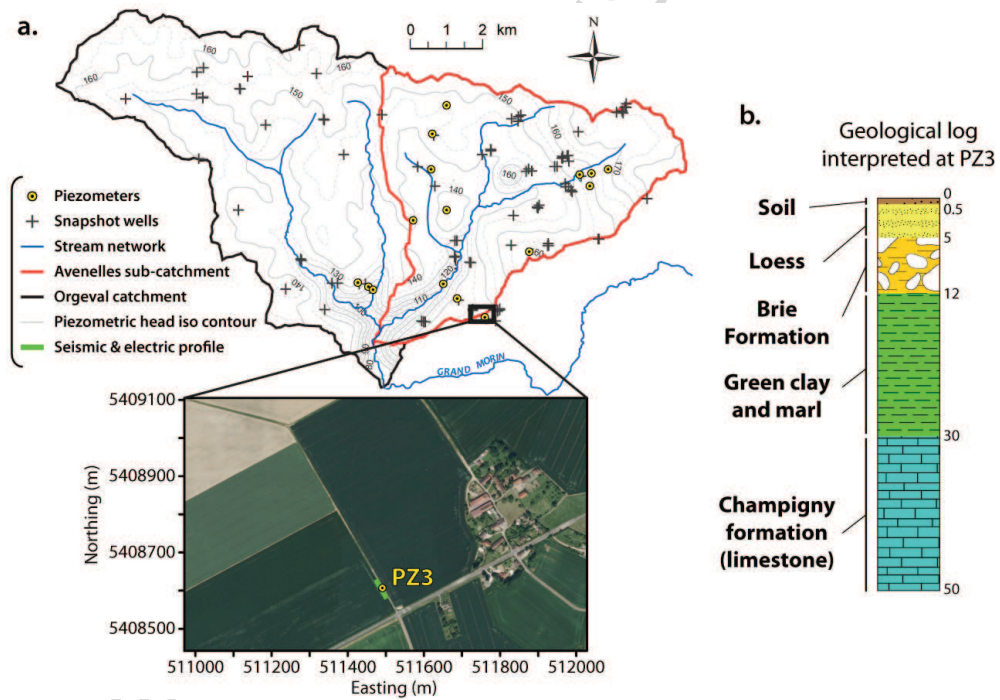


Figure 1: (a) Situation of the Orgeval experimental basin, and location of the experiment. (b) Geological log interpreted at PZ3.

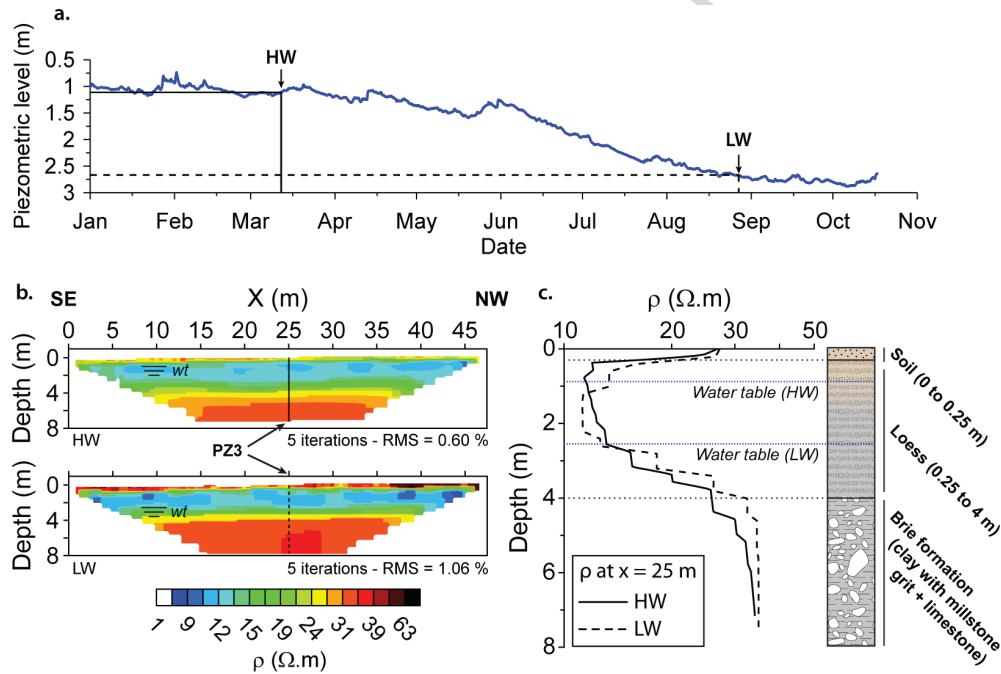


Figure 2: (a) Piezometric head level measured in PZ3 between January 1<sup>st</sup>, 2013 and October 17<sup>th</sup>, 2013. Geophysical surveys were carried out between March 12<sup>th</sup> and March 14<sup>th</sup> 2013 during a high flow regime (*i.e.* high water level, or HW), and between August 26<sup>th</sup> and August 28<sup>th</sup> 2013 during a low flow regime (*i.e.* low water level, or LW). (b) Electrical resistivity values ( $\rho$ ) interpreted from Electrical Resistivity Tomography (ERT) carried out during both HW and LW campaigns. (c) Interpreted geological log and electrical resistivity at PZ3. The origin of the depth axis in (b), (c) and figures hereafter is the ground level at the centre of the ERT profile, while the piezometric head level observed in PZ3 (a) is measured from ground level at the piezometer location, which is 0.25 m higher. The water table level in (b), (c) and figures hereafter is thus 0.25 m higher than in (a).

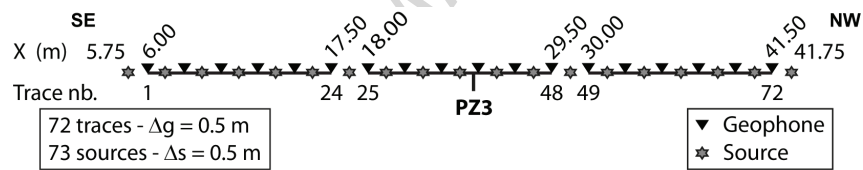


Figure 3: Sketch of the seismic acquisition setup used under both hydrological conditions for combined P-, surface and SH-wave surveys. P- and surface-wave data were obtained using 72 14-Hz vertical geophones, while SH-wave were recorded with 72 14-Hz horizontal geophones. Interval between two geophones ( $\Delta g$ ) and move-up between shots ( $\Delta s$ ) were both 0.5 m. The seismic profile is centred on PZ3. The origin of the  $x$ -axis is identical to the one used for ERT (Fig. 2b).

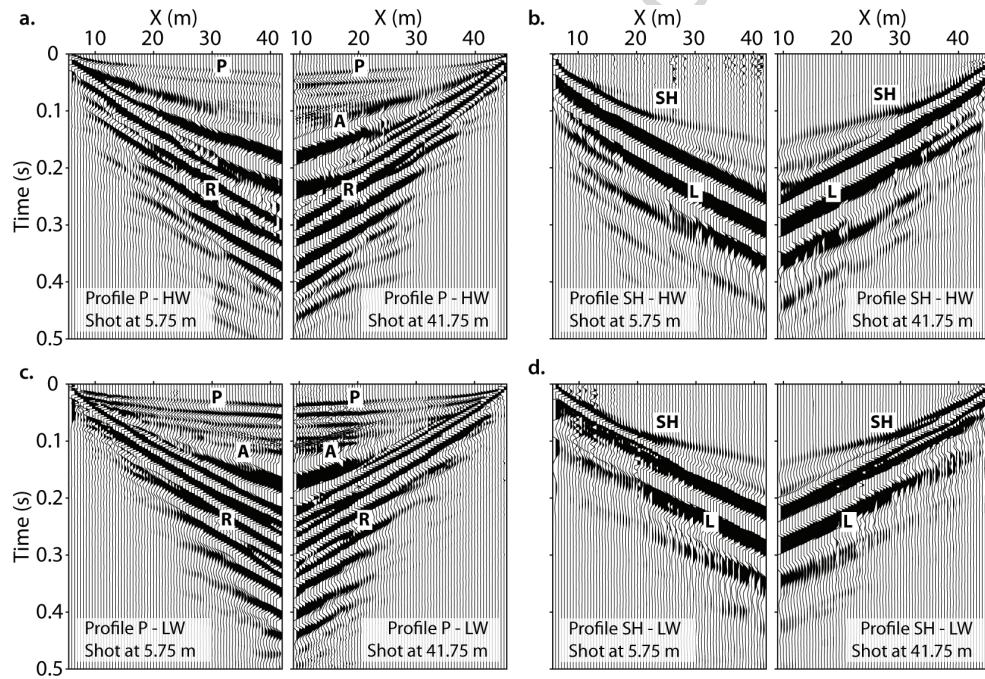


Figure 4: Seismograms of direct ( $x = 5.75$  m) and reverse ( $x = 41.75$  m) shots recorded for HW with vertical (a) and horizontal (b) geophones. Seismograms of direct ( $x = 5.75$  m) and reverse ( $x = 41.75$  m) shots recorded for LW with vertical (c) and horizontal (d) geophones. P-wave (P), air-wave (A) and Rayleigh-wave (R) are observed on seismograms recorded with vertical geophones. SH-wave (SH) and Love-wave (L) are visible on seismograms recorded with horizontal geophones.

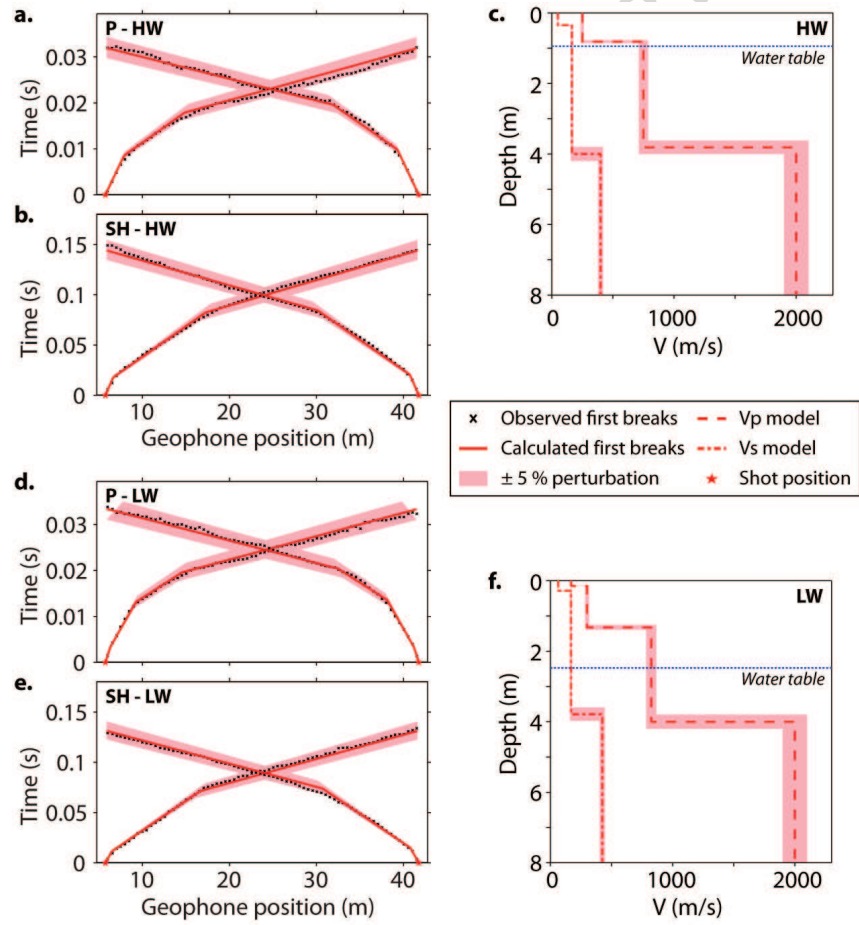


Figure 5: Observed and calculated first arrivals for P-wave (a. for HW, d. for LW), SH-wave (b. for HW, e. for LW) and corresponding  $V_P$  and  $V_S$  interpreted models (c. for HW, f. for LW). Theoretical traveltimes are computed from perturbed models (+5 % on velocities and -5 % on thicknesses for the lower model, and -5 % on velocities and +5 % on thicknesses for the upper model).

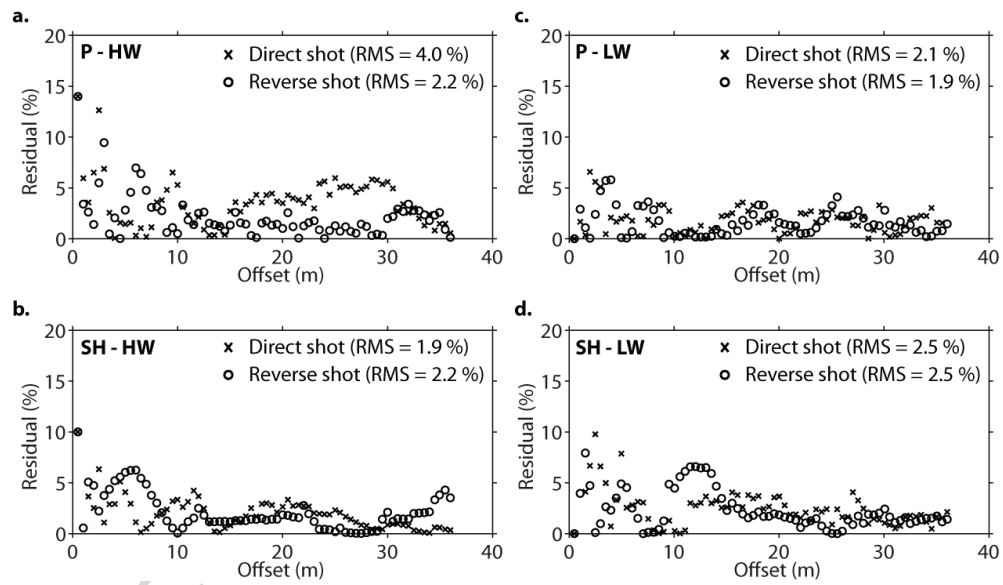


Figure 6: Residuals between observed and calculated first arrivals for P-wave (a. for HW, c. for LW) and SH-wave (b. for HW, d. for LW) represented with the offset position. Direct and reverse shots are represented with crosses and circles, respectively.

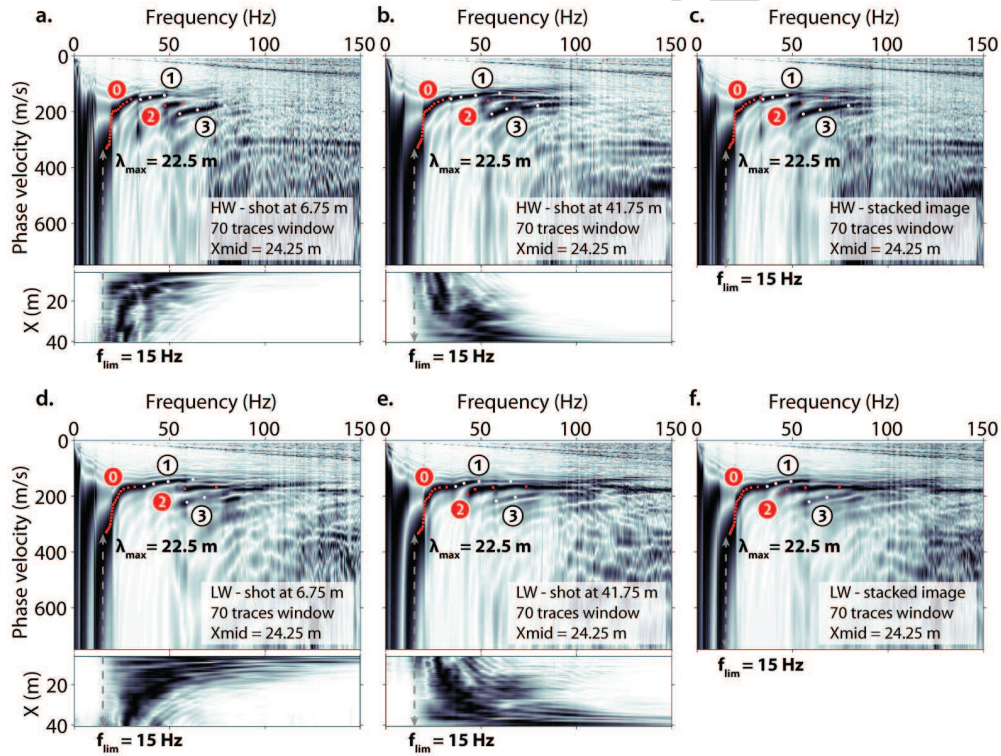


Figure 7: Effect of dispersion stacking for both HW and LW campaigns. Dispersion was extracted with a 40-trace (34.5-m wide) window from direct (a. for HW, d. for LW) and reverse (b. for HW, e. for LW) shots, and corresponding shot spectral amplitude. The result provided by dispersion stacking of images obtained from direct and reverse shots is provided for HW (c) and LW (e) for comparison. Picked dispersion curves are represented for the fundamental (0, in red), first (1, in white), second (2, in red) and third (3, in red) higher modes, without error bars to keep the dispersion images readable. We limited dispersion curves down to frequencies where the spectral amplitude of the seismogram became too low ( $f_{lim}$ ), thus defining the maximum observed wavelength ( $\lambda_{max}$ ).



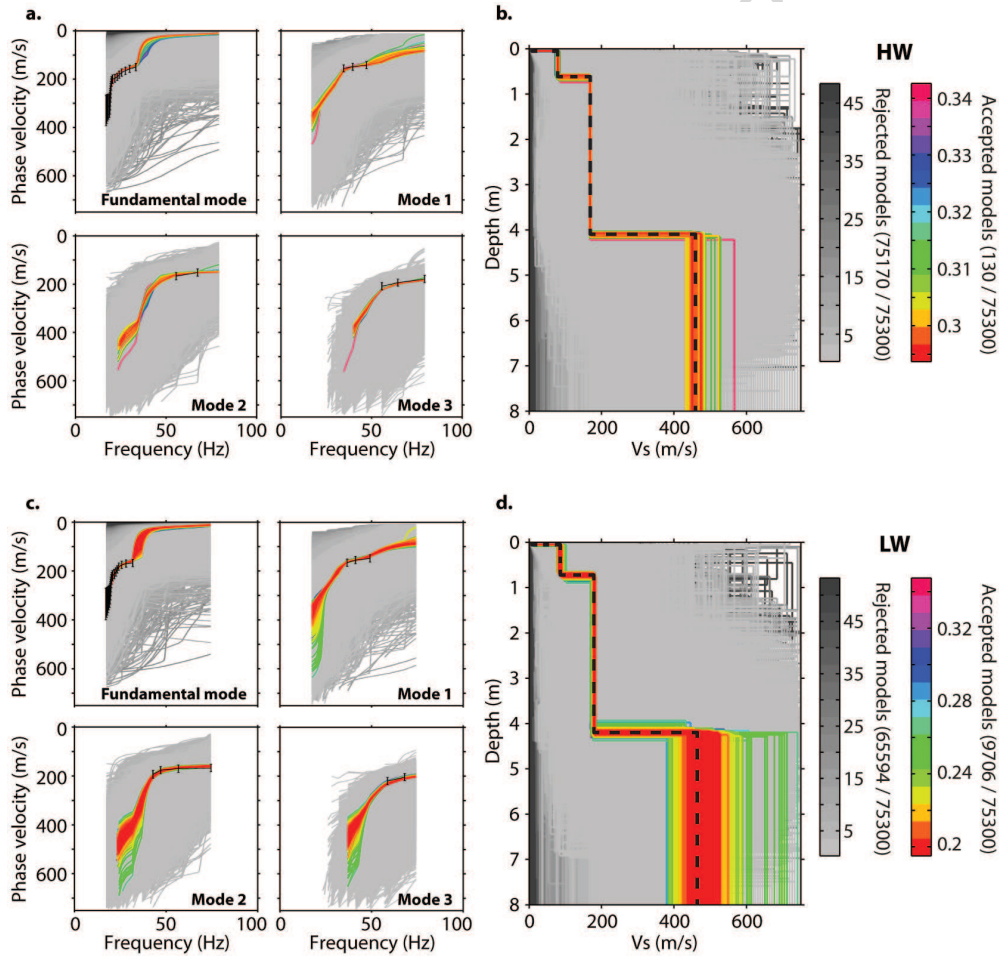


Figure 8: 1D inversion of dispersion data (black error bars) extracted from the stacked dispersion image for HW (a) and LW (c), using the Neighborhood Algorithm (NA) as implemented by Wathelet et al. (2004). Resulting models are represented for HW (b) and LW (d). Rejected models (*i.e.* at least one point of the theoretical dispersion curves calculated from the model does not fit within the error bars) are represented according to their misfit with a grayscale, while accepted models (*i.e.* every single point of the theoretical dispersion curves calculated from the model fits within the error bars) are represented with a colorscale. Average parameters of all accepted models were used to build an average velocity structure associated with the centre of the extraction window (black dashed lines).



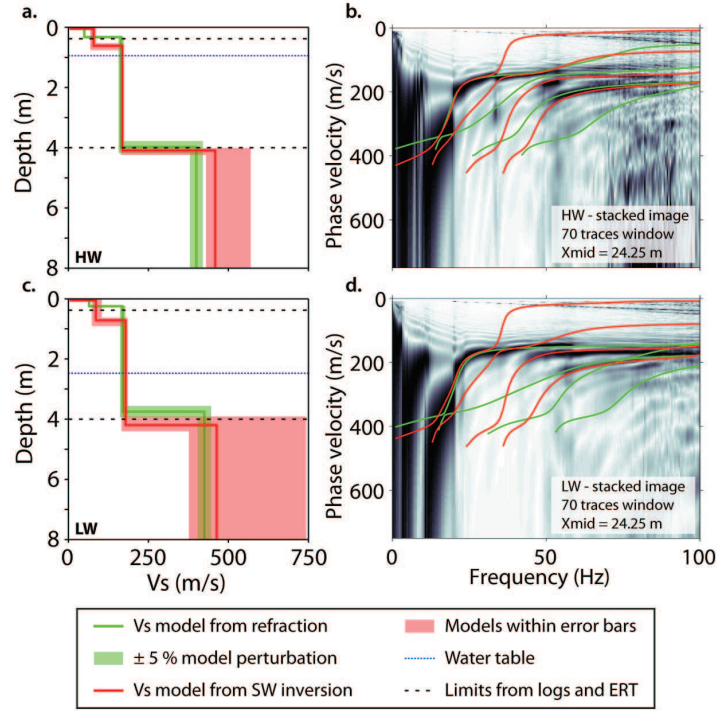


Figure 9: Comparison of 1D  $V_S$  models obtained from SH-wave refraction interpretation (in green) and surface-wave dispersion inversion (in red) for HW (a) and LW (c), with corresponding error bars. The error bars of  $V_S$  models retrieved from refraction analysis were estimated by introducing a perturbation of  $\pm 5\%$  on the central model parameters. As for error bars of  $V_S$  models retrieved from surface-wave dispersion inversion, they correspond to the envelope of accepted models for each hydrological regime (*i.e.* fitting the error bars in Fig. 8). Dispersion curves calculated from both surface-wave dispersion inversion (in red) and refraction interpretation (in green) models are superimposed on the stacked dispersion image obtained for HW (b) and LW (d).

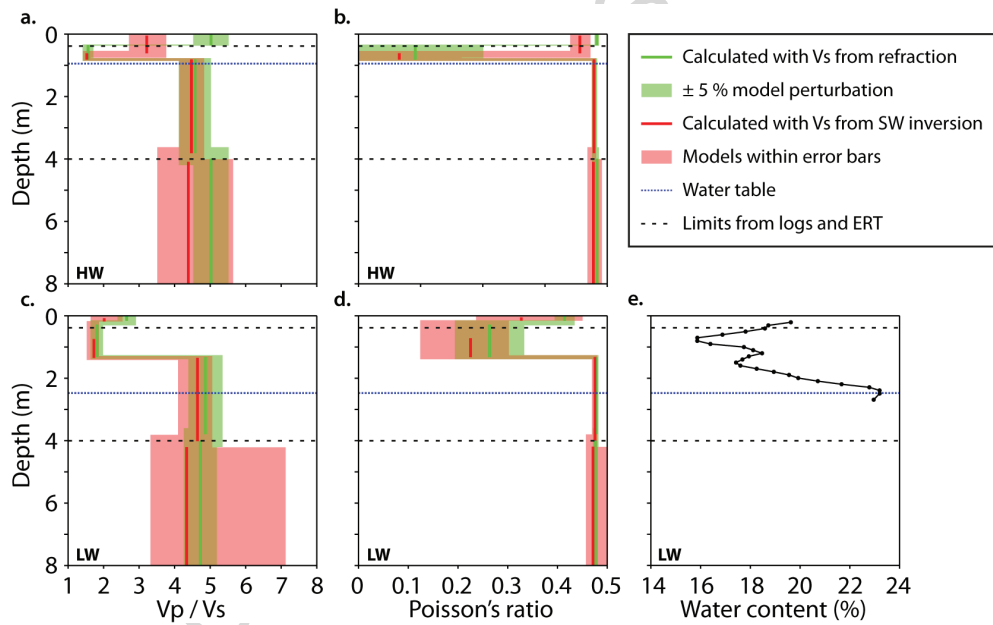


Figure 10:  $V_P/V_S$  (a. for HW, c. for LW) and Poisson's ratios (b. for HW, d. for LW) computed with  $V_S$  models retrieved from SH-wave refraction interpretation (in green) and surface-wave dispersion inversion (in red). In any case,  $V_P/V_S$  and Poisson's ratios are computed with  $V_P$  retrieved from P-wave refraction interpretation. (e) Water content measurements performed on auger sounding samples collected during the LW campaign (soil samples could not be collected during the HW campaign due to unfavorable weather conditions).

- Seismic methods were proposed to assess piezometric level variations
- We worked on a well-constrained experimental site
- A single acquisition setup were used to retrieve  $V_P$  and  $V_S$
- We retrieved  $V_S$  from surface-wave analysis and  $V_P$  from P-wave refraction
- $V_P/V_S$  ratios show strong contrasts at depths consistent with piezometric levels

ACCEPTED MANUSCRIPT