Data-Driven Picking of the First Breaks Between two Boreholes

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Abstract

This work presents an automatic, data-driven, procedure to obtain the first peaks of borehole GPR data. An important stage for a crosswell GPR tomography that can be performed manually or automatically. The crucial step in this is filtering out the signal from the noise in order to clean the first break. This must be done carefully as to preserve both the amplitudes and the phase of the received signal. An analysis of the 1-D EM velocity in the inter-borehole continuum reveals a complimentary role between the surface and the borehole velocity estimates.

Introduction

Crosswell seismic tomography is a widely used technique in geoscience in petroleum reservoir characterization, geotechnical applications and mining. In a similar way borehole radar tomography has been used in numerous fields of activity: mining and civil engineering, hydrogeology, archaeology, non-destructive testing, and environmental sciences (e.g., Kim et al., 2004; Hollender et al., 1999) when adjacent boreholes are available.

The borehole radar can provide information on the distribution of the subsurface material properties, using velocity or the attenuation factor through tomographic inversion. Due to the specificity of electromagnetic signals in geological media the tomographic inversion is far from being a straightforward problem (Peterson, 2001; Maurer and Green, 1997; Vasco et al., 1997) not mentioning the fact it is an ill-posed inverse problem.

There are several advantages of crosswell geometry over surface GPR. Because the propagation of the electromagnetic signal is highly attenuated in the near surface and the higher frequencies are degraded there is a strong depth and resolution limitation in the final image. The borehole radar tomography on the other hand can produce a high-resolution description of the rock formations in the space between boreholes through the whole length of the well.

This paper gives some preliminary results of a crosswell GPR data set in order to discuss some of the data characteristics and give some insight on the subsurface.

We have performed the crosswell measurements just after the release of 600 l of water through a hole situated in the mid distance between the two boreholes. The measurements aimed at the detection of the small velocity variations caused by vertical water movement. Those are very difficult to obtain with surface measurements.

The Data Set

Fieldwork was done in Santa Catarina island, Florianópolis County. The local geology is constituted of unconsolidated sandy deposits of mixed origin: marine, fluvial and eolic. The soil is a gray-brownish fine sand with less than 5 % of silts and clay with a hydraulic flux of 2.8 m/yr and an effective porosity of 0.2 (Corseuil et al., 2000).

The transmitter was placed in one borehole and the receiver in another one 20 m away, as shown in Figure 1. Data acquisition was done in successive runs, in each of which the transmitter was kept at a fixed position, moving the receiver between 0.6 m below the surface and the bottom of the hole 9.8 m down, in 0.2 m steps. After the receiver has traveled the full length of the hole, the transmitter was moved down 0.2 m and the process was repeated making another run. This surveying procedure was repeated until the transmitter has traveled the whole length of the borehole at 9.8 m depth. We refer to this field procedure as cross-run, or X-R.

At the beginning both antennae were flush with the surface, with their center at 0.6 m below the surface. The receiver ran up and down the borehole for each run. We have inverted all even runs so to make the receiver move only down the hole. We consider the X-R enough to adequately scan the region of interest.

The X-R was followed by a level-run, or L-R, where both transmitter and receiver antennas are lowered simultaneously from 0.6 m below the surface to 9.8 m down the borehole in 0.2 m steps, as shown in Figure 1. The L-R was done for cross-checking the X-R as the latter contains the former. With the L-R is possible to estimate a 1-D velocity distribution in the space between boreholes.

The survey had a total of 47 L-R's and X-R's the former with 47 traces each, amounting to 2209 traces. We have used a MALA equipment with 100 MHz antennas and a 700 MHz time window.

We have also done a CMP profile on the surface, along the distance that separates the two boreholes. The CMP was done with a Pulse Ekko 100 with 200 MHz antennas and a pulser of 1000 V, using a stepsize of 0.1 m.

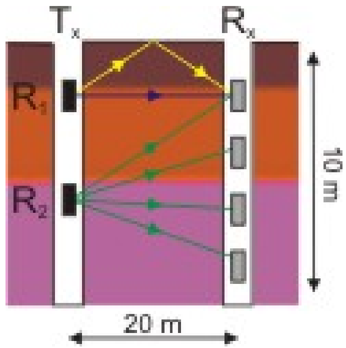

Figure 1. R_1 is a level-run showing two possibilities of straight-line trajectories: a horizontal one, in blue, and a reflected one, in yellow, on the surface. The latter may reach the receiver R_X earlier than the former if the shallow velocities in the inter-borehole velocity continuum, in darker color, are higher. R_2 is a cross-run showing some of the possible straight-line trajectories to the receiver R_X.

Results

The processing included dewow, SEC and constant gains and the picking the first breaks. The attenuation constant was estimated by the exponential factor obtained fitting the average envelope of all traces with an exponential curve.

Figure 2 shows the results from X-R 23 for which transmitter is fixed at 4.5 m while the receiver runs down the hole from 0.6 m below the surface to 9.8 m. The silent zone at the beginning of X-R 23 is just noise due to the proximity of the receiver to the borehole mouth. The first useful trace, i.e., where S/N ratio is workable, is at 1.2 m deep. There is a cross-over point, COP, at receiver positions at about 3.6 m (Figure 2), where two direct wave arrivals coalesce. Shallower than the COP the wavefronts reflected at the surface arrive earlier than the direct arrivals. This happens because the higher EM velocities above the saturated zone. The COP position for the two arrivals is a function of the velocity contrast between the saturated and the vadoze zone above it and also due to the curvature of both the direct and surface-reflected rays as affected by Snell's Law. Note that the COP point occurs bellow water level.

The first step in estimating the first breaks is enhancing the S/N ratio by filtering traces. The first step in estimating the first breaks is enhancing the S/N ratio by filtering traces. The filter uses the Discrete Wavelet Transform (DWT) in the form of filter banksthat divide a signal frequency band into subbands. The filter banks are comprised of low-pass filters, the output being the the approximation coefficients that decompose the signals into a number of components. The signal is then reconstructed by the Inverse Discrete Wavelet Transform (IDWT) from the coefficients above a given threshold to yield a "de-noised" version of the signal. The filtering procedure thus consists of three steps: (1) computation of the time-frequency components, (2) extraction of the desired components, (3) computation of the filtered signal from the modified components.

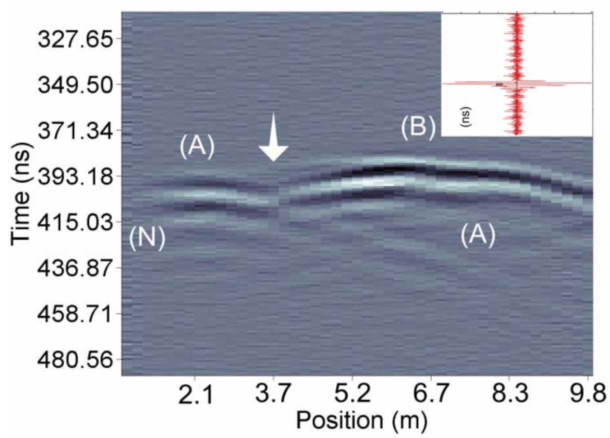

Figure 2. Run 23 showing the direct wave arrivals (B), and arrivals from the wavefront reflected at the surface (A). The arrow shows the position of the COP, where the latter arrives earlier than the direct arrivals. At the beginning of the run where noise dominates there are no recorded arrivals (N). The inset at the right upper corner shows trace 9 of this run (receiver at 2.4 m).

The filter is applied twice, with both signal amplitude and phase preserved as shown in Figure 3. With the filtered signal we have a few choices for picking the first break times (Yelf, 2004), depicted in Figure 4. We can choose the time at the zero crossing (ZC), at medium height (MH), or at the first maximum (FM) as the first break of the signal. Due to the stability of the pickings we have chosen the MH point as the best estimate for the first break.

The automatic picking of the MH times is done by comparing a 7 ns windowed RMS

$$A_{RMS} = \sqrt{\left(\sum_{k=k1}^{k=k2} T_k^2\right)/(k2-k1+1)}. \qquad (1)$$

with the accumulated standard deviation estimated by

$$\sigma_{RMS} = \sqrt{\left(\sum_{k=1}^{k_f}(T_k - A_{RMS})^2\right)/(k_f)}. \qquad (2)$$

When

$$A_{RMS} \geq n\,\sigma_{RMS} \qquad (3)$$

with n=2, the algorithm searches the three choices of first breaks shown in Figure 4.

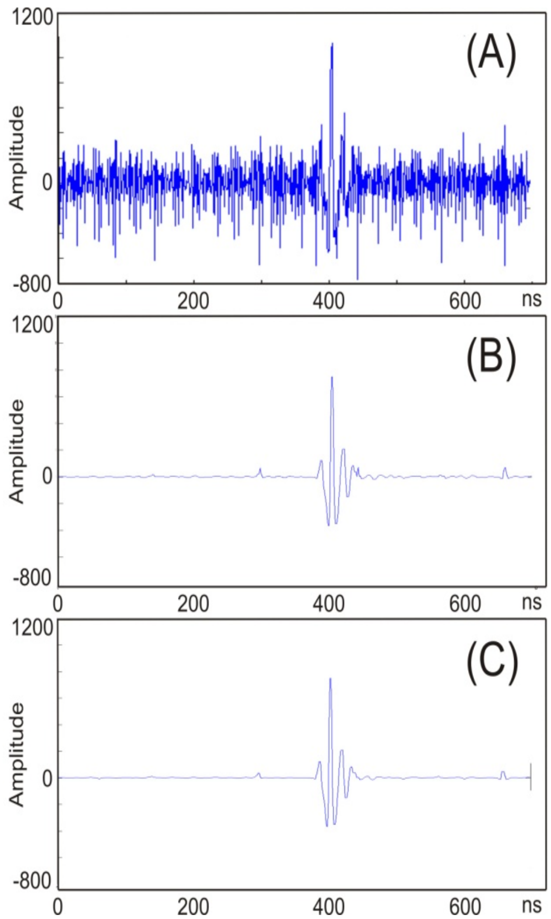

Figure 3. (A) Trace 15 of X-R 19. (B) is the result of applying the filter once and (C) is after applying the filter twice. Note that both signal amplitude and phase are preserved.

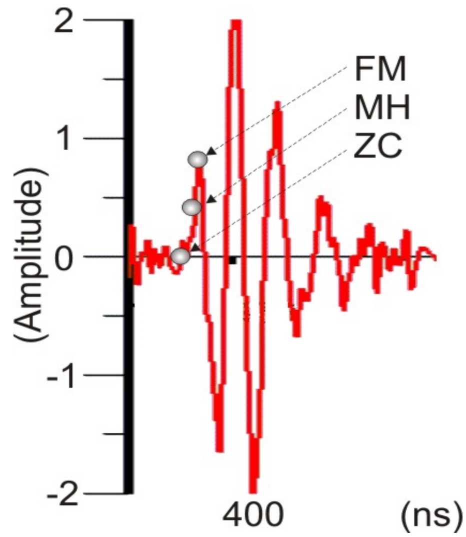

Figure 4. Three choices for the signal first break: the time at the zero crossing (ZC), at medium height (MH), or at the first maximum (FM).

We can compare the velocities estimated with the L-R and the CMP. There is an important difference between those two velocity models as seen in Figure 5. The CMP velocities are significantly higher than the L-R estimates. Figure 5 shows that the CMP velocity estimates change from 0.1 to 0.09 m/ns just above 2 m. This is the inferred top of the capillary fringe above the water level. Completely saturated sand was found at 2 m in the boreholes. The L-R also display an important increase in velocity between 3 and 7 m indicating a lower saturation zone. That corresponds to fine grained white sand (90 % quartz) and mica as revealed in the borehole description.

Conclusions

The results from this work show that it possible to obtain useful information analyzing the 1-D structure in the crosswell space. There is a minimum depth for the operation of the antennas, in our case 1.2 m. One important finding is that the observed first breaks do not always corresponds to the direct wave arrivals but may be due to the wavefronts reflected at the surface, which traveled through a higher velocity horizon above the water table. The cross-over point between the two arrivals is a function of the contrast in the velocities between the saturated zone and the one above it but also due to the curvature of the surface-reflected rays as affected by Snell's Law. The cross-over point occurs bellow water level in the saturated zone. The CMP velocities are significantly higher than the L-R estimates. In particular the CMP was able to detect the inferred top of the capillary fringe above the saturated sand. There is a lower saturation zone between 3 and 7 m seen in the L-H data set.

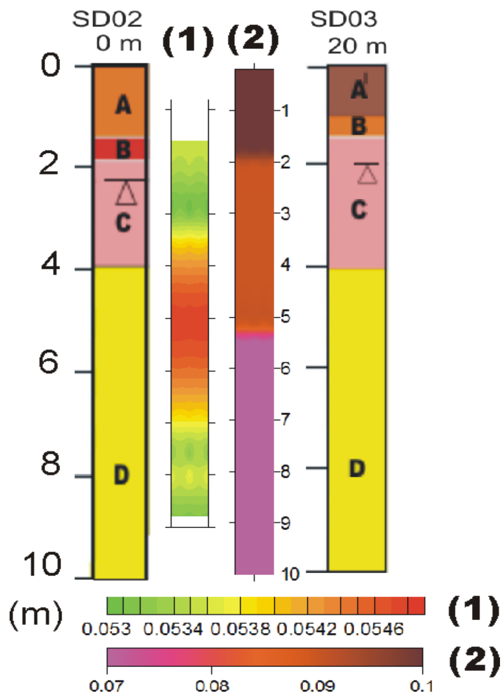

Figure 5. Summary of the results obtained in the two boreholes and in one CMP linking them. Borehole 1-D velocities were obtained by just dividing the direct distance between transmitter and receiver by travel time of the L-R. (1) level-run 1-D velocities. (2) is CMP velocities. Velocity color bars are displayed in the bottom of figure. The description of boreholes SD2 and SD3 is: A – grayish clay, A' – fine grained dark sand with 80 % of organic matter, B – fine grained brown sand (80 % quartz) and organic matter, B' – clayish fine grained dark brown sand (75 % quartz) and organic matter, C - fine grained pink sand (90 % quartz) and mica, D - fine grained white sand (90 % quartz) and mica. Note that velocity color code is independent of the stratigraphy color code.

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