Near-surface S-wave velocity from an uphole survey using explosive sources

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Summary

A near-surface S-wave velocity model was obtained from an uphole survey using seismic events identified as S-waves generated by explosive sources. Arrival times correspond to this wave mode identification. The model was obtained from picking zero offset events, which has uncertainty because of other events that interfere. The complexity of the wave field increases as the energy source is closer to the surface. Probable velocity inversions were observed. A lithological profile with depth, which was generated from drilling cuttings, shows a good correlation with this velocity model. The uphole data were also compared to data from a 2D seismic line acquired at the same place. These surface data show events with characteristics of S-wave refractions, besides Rayleigh waves and probably other events. The reflection data shows a lower frequency content than the uphole data, and some complex variations noticed in the latter perhaps are part of the low-frequency high-energy ground-roll in the former. Refractions on the horizontal component data from the 2D line can also be correlated with the velocities obtained from the uphole.

Introduction

The land near surface is typically heterogeneous, which affects S-wave propagation, distorting seismic events from deeper layers. Techniques to obtain a better S-wave velocity (Vs) model of the near surface can improve the seismic image of deeper targets. In addition, they can provide useful information about the near surface.

The near-surface Vs model can be obtained from surface (indirect) methods or from borehole (direct) data. The surface seismic methods include analysis of Rayleigh (surface) waves and refractions, which can provide wide spatial coverage. However these methods, besides the corresponding mathematical model assumptions, have limitations such as poor horizontal resolution (Socco et al., 2010) and troublesome event picking (e. g.. Al Dulaijan, 2008).

Borehole data surveys allow to relate Vs to depth and to lithological properties, although they are local. There are two kinds of borehole surveys: downhole, with sources at the surface and receivers inside the borehole, and uphole, the other way around (see Cox, 2000). Downhole surveys have had engineering applications (e. g. Kim et al., 2004). Uphole surveys, on the other hand, appear less commonly used, and the difficulty to get appropriate S-wave sources in this case has been mentioned in the literature (Bang and Kim, 2007).

This article explores uphole data and Vs models obtained from a field experiment carried out by Ecopetrol SA, at a Valley in the Andes mountains of Colombia. The potential of this method to obtain a near-surface Vs model, and its potential application to a land surface 3C seismic survey are explored. Velocity models, analysis of the method and the resulting data are presented below.

Field Data

The data analyzed here come from a multicomponent experiment, which included two shallow boreholes approximately 3 Km apart, acquired simultaneously with a 3C seismic surface survey, in the
Magdalena Valley of Colombia. The two boreholes, are identified by 1 and 2 in Figure 1(a). Borehole 1 was located in a flat area on a Quaternary Formation, about 400 m away from a river and on its flood plain, and Borehole 2 was located on moderately rough terrain, on Tertiary rocks.

The seismic energy was provided by two energy source types: dynamite charges (150 g) and 2 to 4 caps, located intermingled inside the borehole, and separated by 2.5 m from each other, as illustrated in (Figure 1(b)). The maximum depth was 60 m depth. The receivers were 3C accelerometers deployed on the surface with a maximum offset of 200 m, and separated by 5 m in Borehole 1 and by 2.5 m in Borehole 2.

This work is focused on Uphole 1. The chosen data correspond to a receiver line with maximum offset of 100 m. Figure 2 shows a lithological profile at this location, obtained by analyzing the drilling cuttings. Most of the profile corresponds to clays interbedded with sands, however there is a layer of conglomerates and other hard materials between 23 and 42 m depth.

Figure 3 shows examples of the data obtained in borehole 1, for source depths of 55, 45, 30, 20 and 10 m. Figure 3a corresponds to the Vertical component and Figure 3b to the Horizontal one. Noticeable events are the strong first breaks (FB) on the vertical component and a later hyperbolic, high energy event on the horizontal component. In Borehole 2 a more complex seismogram could be observed, with many more irregular, non-hyperbolic events, as shown in a previous work (Guevara et al., 2011).

Figure 1: Upholes field layout: (a) Location. The boreholes are identified by numbers. (b) Profile of the borehole, showing the typical sources distribution.

Figure 2: Stratigraphic profile (Borehole 1) from drilling cuttings.

Figure 3: Example records from Uphole 1 for different source depths.(a) Vertical Component (b) Horizontal component. These data are the focus of this work.

The Vs velocity model
The S-wave velocity model was generated assuming that S-waves were generated by explosive sources inside the borehole. As the strong event on the vertical component or First Breaks (FB) corresponds to direct P-waves generated by the source, the strong event on the horizontal component can correspond analogously to direct S-waves. Similar results on real data have been provided in the literature, (e.g. White and Sengbush, 1963; Lash, 1985), and it has also been shown theoretically for waves generated in a borehole (e.g. Heelan, 1953; Lee and Balch, 1982).

Additionally a test for this hypothesis using the Dix NMO equation with the resulting velocity model is shown below. The horizontal polarization of the event also corresponds to S-waves. The S-wave detected on the horizontal component at the surface could also be generated from P-wave conversion to S upon its transmission through an interface. However, it doesn’t agree with the high energy of this event, as shown from the literature (e.g. Muskat and Meres, 1940).

According to this working hypothesis, the events for zero offset were picked (Figure 4a) and velocity models with depth were obtained for P and S-waves (Figure 4b). Picking the S-wave event was less obvious than P-wave FB, and even harder for some depths, such as shallower than 20 m. and about 30 m depth, because apparently some other events interfere. The resulting model of Figure 4b shows a number of layers, the Vs layering can be related to the lithological profile shown in Figure 2. Also there is a strong velocity increase for P-waves at about 5 m depth, whereas S-wave velocity increases slowly with increasing depth. These characteristics match the expected near surface behavior due to the different response between P and S-wave due to the water table (Stümpel et al., 1984 Molotova and Vassiliev 1960).

The S-wave velocity model shows more complex features than the P-wave one, and possibly two velocity inversions, at about 25 and 45 m depth (Fig. 4a). Figure 4b, together with a smooth model, illustrate one of these possible velocity inversions, between 42 and 52 m depth. This velocity inversion model can be correlated with the stratigraphic profile (Fig. 2). The later model (dashed line) would be interesting for a near surface research purpose, however a simpler model (continuous line) could be enough to improve the deep seismic data.

A test for the velocity field obtained according to this hypothesis is to reproduce the time variation with offset of the real data by using this velocity model, and with the Dix NMO equation for a borehole:

$$T_p = \sqrt{\left(\frac{z_s}{V_{ave}}\right)^2 + \left(\frac{x_r - x_s}{V_{rms}}\right)^2}$$

where $z_s \equiv$ source depth,
$x_s, x_r \equiv$ source and receiver surface location
$V_{ave}, V_{rms} \equiv$ average and RMS velocities.
Figure 5 shows the resulting offset-arrival times plotted on the seismic data gathers for source depths of 45 m (Figure 5a) and 10 m (Figure 5b). A good match can be observed in Figure 6a. For the 10 m source depth the curve agrees with the high energy short offset events and for larger offsets possibly higher velocity refractions prevail.

Relationship between the uphole and the surface seismic data

As mentioned earlier, a 2D 3C seismic line was acquired at the same location (see Figure 1), then an analysis of the relationship between the two datasets is relevant. An explosive source of energy was used for the seismic line, with a charge size of 2700 g and at a depth of 10 m. Receivers were separated by 10 m.

Figure 6 shows a shot record of this seismic line, whose source was located 20 m from the uphole 1. Data from three hundred receivers in each direction are shown, so the farthest offset is 3000 m. Fig. 6a corresponds to the horizontal component and Fig. 6b to the vertical one. Notice the strong low velocity events on the horizontal component, at which three velocities have been measured: 369 m/s, 894 m/s and 1367 m/s. It can be noticed that similar velocities were found at uphole 1 (Fig. 2b). Figure 7 is a close up of the same surface seismic shot gather, including only offsets lower than 100 m and arrival times less than 0.8 s. It can be compared to Fig. 8, corresponding to the shot from uphole 1 at 10 m depth. Some resemblance of the events can be noticed, especially the strongest in both components. However the surface seismic data show lower frequency, stronger events, and reverberations, and the uphole record shows a number of higher frequency events.
Discussion

It was possible to obtain a near-surface S-wave velocity model using the uphole data using the zero-offset picks on the horizontal component of the event identified as S-wave generated directly from the explosive source. S-waves generated by explosive sources are supported by theoretical studies. Besides that, the events have strong amplitude and horizontal linear polarization, and the NMO curve agrees with the velocity model. A more detailed study of the complete wavefield generated (including the energy source variations) can provide additional evidence for this hypothesis.

The velocity model obtained can be related to the lithological profile (Fig. 2) and to events identified as refractions that were observed on a 3000 m shot gather with the energy source 20 m apart from the uphole (Fig. 6). A velocity inversion, from the Vs uphole model can be explained with the lithological model. This inversion cannot be detected by the refraction method, because of its own theoretical assumptions.

However the S-wave event picking has noticeable uncertainty and is prone to errors compared to the FB picking used for P-waves from upholes, mostly because a mix of wave modes, especially at the shallower depth. Some of this events can be related to anisotropy in the near surface, which can be tested with analysis in other directions. Due to these uncertainty additional testing of the model obtained would be also advisable.

The shallower weathering layer (i.e. the shallower 5 m depth in this case), causes a big time delay for the S-wave, (about 50 ms), but can hardly be characterized in detail with the uphole method used.

These results can be related to an analogous experiment carried out in Alberta, Canada, presented by Parry, 1996. In that work events picked in the horizontal component were identified as P to S-wave conversions. Higher resolution and difference in the energy of the events of the two components can be noticed in our case. These differences can be explained by differences in the energy source (low energy explosives), in the receivers (accelerometers vs geophones) and probably in the terrain characteristics (tropical vs temperate).

Conclusions

Events on the uphole horizontal component were identified as S-waves generated at the source. They enabled us to obtain a near-surface Vs model from the upholes.

An S-wave events picking method analogous to the zeros offset first-breaks picking method used for P-wave velocity surveys was used. However, the picking of events for S-wave analysis is harder than the FB picking used for P-waves.

The uphole data appear to provide additional data that can be related to the 2D seismic line and to the available lithological profile. The surface methods, besides their own assumptions, have resolution limitations.
The S-wave events picking was even harder for the shallower events. However, the most shallow layer, in this case less than 15 m deep from the surface, produces a greater effect on the time delay because of its lower velocity and typically higher heterogeneity.

Information on the near surface S-wave velocity field from upholes can be related to surface reflection seismic data to generate a more extended model.

Techniques like geological modeling and tomography could help to obtain information from this type of survey. Additional information on the wave field could also be obtained.

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References