Near-surface *S*-wave velocity models from two uphole surveys

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Abstract

Two uphole surveys were carried out at the location of an on-shore 3C survey in Colombia. An *S*-wave velocity model was obtained from these data, based on events apparently generated by the source. High variations in the velocity model with depth were observed and related to lithological characteristics. These variations can hardly be observed using surface seismic data. This velocity model can be useful in the computation of statics correction in the processing of converted-wave (PS) or *S*-wave seismic data, as well as in engineering and other near surface applications.

Introduction

The near-surface layer can have a detrimental effect on the S-wave data from deep rocks in 3C seismic surveys. On the other hand, near surface S-waves can provide useful information about the near surface for engineering (e. g. related to the earthquake response) and environmental purposes. Analysis of S-wave velocity in the near surface can help in both cases.

The S-wave velocity can be derived indirectly from surface seismic data, and alternatively from shallow holes. Surface data has lower resolution but more spatial coverage, as long as holes information is more accurate and can be directly related to lithological properties, but is more local.

Rayleigh waves have been a source of information about S-wave velocity in the surface seismic method. A popular method that uses this wave mode is known as the MASW (Multichannel Analysis of Surface Waves) (Xia et al., 1999). S-refractions have also been used for this purpose, however not as frequently as the former (e.g. Al Dulaijan, 2008), since it is not an standard procedure in the industry, as an analogous method is for P-waves.

Downhole surveys, usually with offset close to zero, using pure *S*-wave energy sources, have also been useful, especially in engineering applications (e. g. Kim et al., 2004). Less work has been carried out on upholes, which are the subject of this article, partially because of the difficulty to generate appropriate *S*-waves there (Bang and Kim, 2007).

A preferred method to correct for the near surface delay caused by S-waves in converted wave processing has been the stacking of common receiver gathers, assuming that all the other delay time corrections are right (e.g. Cary and Eaton, 1993). However a near-surface velocity model of the S-wave could provide a more accurate solution, more consistent with the physics of the problem, as happens with the refraction method applied in P-wave exploration.

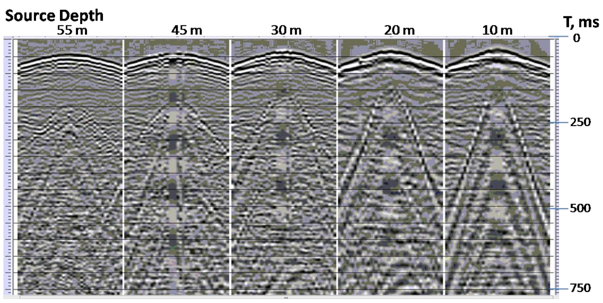
To investigate these issues, an experiment that included two uphole surveys was carried out in a valley of the Northern Andes Mountains in Colombia. The experiment intended to obtain correlation between the uphole events and the lithology of the near surface, and to get information useful for statics correction in the processing of converted (PS) waves. The two shallow boreholes were acquired at sites showing different geomorphological features. Techniques like geological modeling, and tomography could help interpret the information from the two surveys. A first approach to the analysis of these data is presented in the following.

Field data

The data used in this work was generated at two shallow boreholes, identified in the following by numbers 1 and 2, in which uphole data were acquired in conjunction with a 3C surface survey. The energy was generated by small explosions inside each borehole, separated by 2.5 m in depth from each other shot. The total depth of each borehole was about 60 m. On the surface 3C receivers (accelerometers) were deployed along three lines centered at each borehole in directions separated by 60º, and with a maximum offset of 200 m. The receivers are separated by 5 and 10 m in the borehole 1 and by 2.5 and 5 m in the borehole 2.

The two boreholes were approximately 3 Km apart. The terrain was different in each case: borehole 1 was located in a flat area, about 100m away from a river, on its flood plain. Borehole 2 was located in a moderately rough terrain, at an elevation of 50 m above borehole 1.

Figure 1 shows examples of the data obtained in borehole 1, for source depths of 55, 45, 30, 20 and 10 m. Fig. 1a corresponds to the Vertical component and Fig. 1b to the Horizontal one. The First Breaks (FB) on the Vertical component data and an event with noticeable energy on the Horizontal data, whose arrival time is less by as much as the source is shallower, can be o bserved. Figure 2 shows data obtained in the borehole 2, with sources at 55, 42.5, 30, 22.5 and 15 m. More events and with lesser symmetry than those from borehole 1 can be observed in this case. However strong first breaks on the vertical and a delayed strong event on the horizontal can also be identified here.



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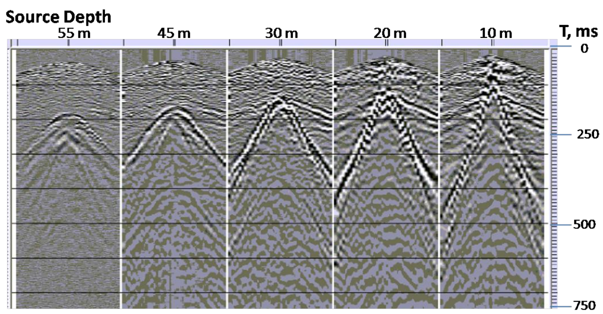

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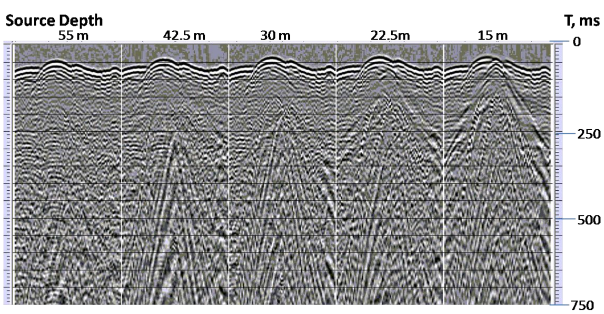
Figure 1: Gathers from uphole survey 1 for five source depths: a) Vertical component. b) Horizontal component.



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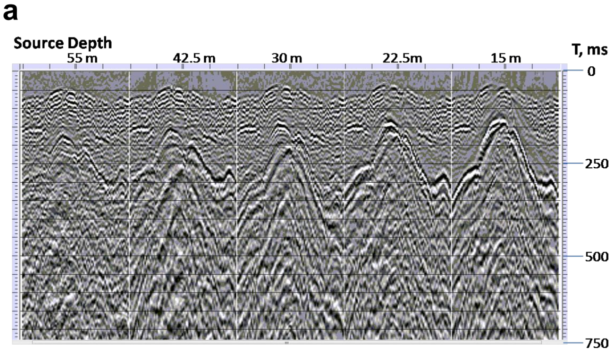

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Figure 2: Gathers from uphole 2 for five source depths: a) Vertical component. b) Horizontal component.

Interpretation of the results

It was assumed,as a working hypothesis, that the strongest event on the vertical component corresponds to a direct P-wave, and the strongest one on the horizontal correspond to a direct *S*-wave. Consequently, picking of the FB on the vertical component enabled the computation of a velocity model for the near-surface P-wave. Similarly from picking the strong event on the horizontal component a model of the near surface *S*-wave velocity can be obtained. Figure 3 shows the resulting velocities obtained from data from borehole 1, and Figure 4 the corresponding result for borehole 2.

However it can be observed that it is difficult to pick this strong event on the horizontal component data from the shallower boreholes (approx. depth less than 15 m), since a mix of wave modes is present on these records. Fig. 10b, which shows data from the source at a depth of 10 m illustrates this problem.

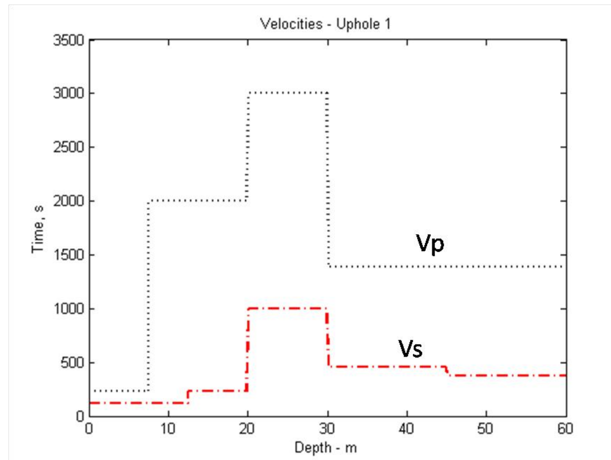

Figure 3: Velocity model for borehole 1 obtained from the zero-offset strong event data picking.

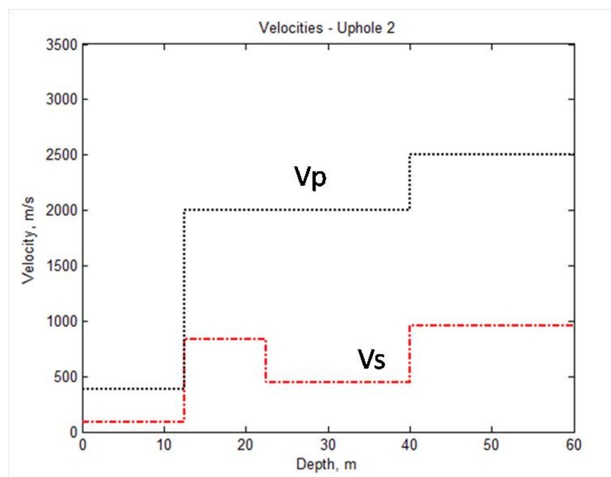

Figure 4: Velocity model for borehole 2 obtained from the zero-offset strong event data picking.

In order to test the assumption about the nature of the events on the horizontal component, that is to say direct *S*-wave, or equivalently, *S*-waves generated by the source, a time-offset curve calculation was carried out using the Dix approximation. The result for the source at 45 m depth in borehole 1 is shown in Figure 5. The light dots correspond to the time calculated, which correspond closely to the arrival of the strong event, supporting the hypothesis.

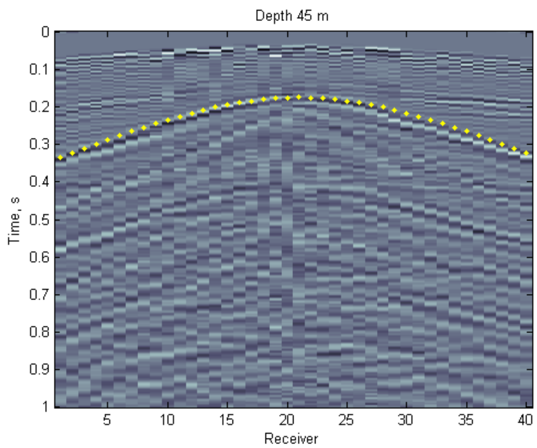

Figure 5: Comparing the field data from the horizontal component with a time-offset curve assuming a model of *S*-wave generated at the source.

It can be noticed the high Vp/Vs ratio in both cases, compared to the usually assumed for rocks, which is about 1.7 or 2 (Figure 6). In Uphole 1 this ratio is as high as 16 above 20 m depth, and about 3 in the deeper locations. In Uphole 2 it is about 4 in the shallower part, becoming 2.5 at the deeper zone. It can also noticed a high velocity between 20 and 30 m in Uphole 1 and a velocity inversion below this zone. These features correspond to the lithology observed there, coarse rocks below 20 m and clayish material about 40 m and deeper. Borehole 2 appears to be situated in a more complex location, with high velocity rocks close to the surface and strong horizontal variations.

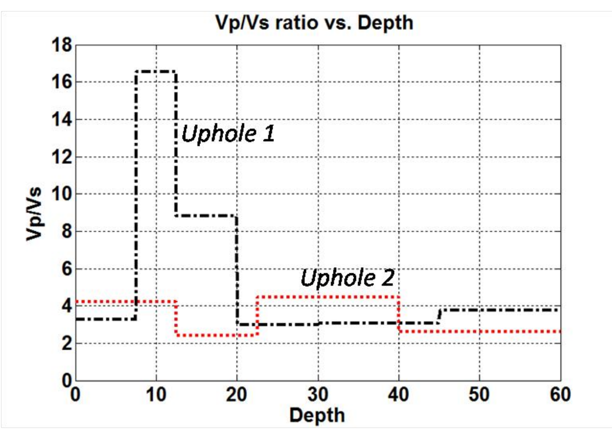

Figure 6: Variation of Vp/Vs ratio with depth for uphole 1 and uphole 2.

Discussion

From the NMO curve analysis (Fig. 5) it is possible to support that *S*-waves generated by the source enabled the computation of a velocity model of the *S*-wave velocity in the near-surface. This statement could be confirmed by the amplitude of the events, which are high for short offsets. It is frequently assumed that an explosive source like dynamite doesn't generate *S*-waves, which has been supported theoretically. However, there are examples in the literature which show that it is theoretically possible in cases like boreholes (e.g. Lee and Bach, 1982) and *S*-waves from explosive sources have also been identified on real data (e.g. Lash, 1985). Supporting information has been provided for the data from borehole 1 here. However the results from the data for borehole 2 show also strong events on the horizontal component (Fig. 2b), which deserve more careful analysis due to its more complex characteristics related to the more complex geological setting. One can speculate that it happens more frequently than expected in field surveys.

The velocity model shows strong variation depending on the depth and the location. As can be observed in Figures 3 and 4 it is noticeable even for depth differences of about 10 m. These variations can be detected in the uphole data, but probably not easily on data from surface methods like refractions and Rayleigh waves. The importance of these variations for issues like the computation of statics corrections in seismic processing will be the subject of future research. An accurate model of the near surface can help also to advanced processing methods, such as the generation of adaptive filters and imaging from rough surfaces.

Similarly rapid variations can be observed in the near surface Vp/Vs ratio, which in this case takes values from 16 to 2.5 (Figure 6). These values agree with data of the near surface presented by other authors, such as Molotova and Vassiliev, 1960, and Stümpel *et al.*, 1984, who also found high Vp/Vs ratios and big difference between Vp and Vs models. Delay times of *S*-waves in the near surface can be critically low, as shown for these 100 ms and more observed in the shallower 15 m (See Figs. 1b and 2b) A Vp/Vs ratio corresponding to a consolidated rock (1.7 to 2.0) can hardly be observed before 60 m depth (See Fig. 6)..

The charge size and depth have an important effect in the generation of *S*-waves and other characteristics of the seismic experiment. The effect of the depth in borehole 1 can be observed in Figura 1b. For the corresponding effect of the charge, Figure 7 shows one shot of borehole 1 (Fig. 7a) together with a shot gather of the 2-D 3-C seismic line . There was a 20 m distance between the location of these shots , and the source depth was about 20 m for both. The charge size of the 2-D line was about twenty times bigger. Notice the significant difference in the ground roll generated, much larger in the 2D shot (Fig. 7b). This effect can prevent the detection of subtle geological variations in the near surface using high energy sources.

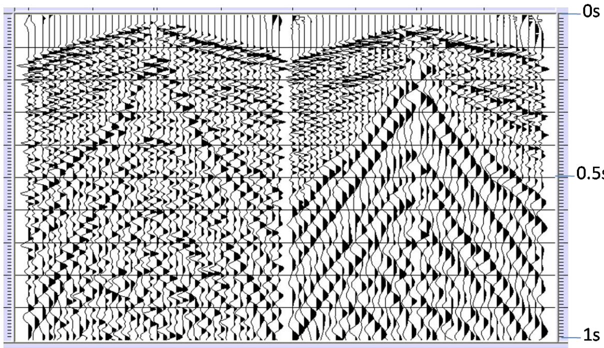

Figure 7: Comparison of uphole and surface seismic data: a) shot gather from borehole 1, source at 20 m depth, b) 2D seismic line shot gather, from a source located 20 m away from borehole 1 and at a depth of 20 m. .

Conclusions

Velocity models of S-wave velocity for the near surface were created from events generated by small explosive sources in two shallow boreholes, picking their arrivals. Checking for consistency with the geologic profile and the arrival times supports this approach.

The velocity model at each location are quite dissimilar. which can be related to their lithological differences. The S-wave velocity models also show noticeable variation with depth. How these variations affect applications such as static corrections can be matter of future research.

These models appear less reliable for depths shallower than 15 m, because other seismic events interfere, adding uncertainty to the first arrivals picking.

More research with uphole data can contribute to improve the correction of the near surface effect in the case of seismic processing of converted waves. It could also contribute to improvement in other processing methods or other technologies related to the near surface..

Acknowledgments

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