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Auto-estimation of Up-down Wavefields in a Horizontal Borehole using Single Component Data

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SUMMARY

The standard requirement for up-down wavefield separation in seismic data is to use multi-component data. An important application for such separation is to remove the interference from multiple reflections from either the free surface or the internal subsurface structures. As an alternative, we propose an automatic scheme of estimating the up-down wavefields in a horizontal borehole using only single component measurements. The scheme builds upon recent developments of the Marchenko method. The up-down fields are constructed essentially from the surface reflection response (surface seismic data), together with the direct waves' travel time from the borehole data. No prior information of the subsurface is needed, and an automatic working flow is suggested. The numerical test using a synthetic field model shows good results compared to that from a conventional multi-component approach.

Introduction

The usual requirement for up-down wavefield separation, for an acoustic wavefield, is to have both pressure (p) and vertical particle velocity (vz) measurements, and then use different methods based on "PZ summation" for calculating the up-down wavefields (Amundsen and Reitan, 1995; Schalkwijk et al., 2003). The separated wavefields can be used for imaging without any downgoing multiples (Sonneland and Berg, 1987; Amundsen, 2001). Now, for single-component horizontal borehole data, the recent development in the Marchenko method (Rose, 2002; Wapenaar et al., 2013) offers an idea for constructing the wavefield into up-downgoing components at the borehole depth using surface reflection responses and a so called "focusing wavefield". The focusing wavefield is a wavefield, which when emitted from one side of a general 3D medium, focuses at a chosen position inside the medium. The iterative scheme described in the Marchenko method is a recipe for finding it. Liu et al. (2016) propose using the direct waves from borehole data to initialize the iterative scheme and show an application of robust target imaging near a borehole using the estimated up-down wavefields. Here, instead of selecting out the direct waves, we propose an alternative workflow for automatically incorporating the travel time from borehole data to initialize the Marchenko method, thus enabling one to estimate the up-down wavefields at the borehole depth using only single component data. We illustrate the workflow with synthetic field data and compare the results with those from a conventional multi-component approach.

Method

The method requires a complete surface seismic reflection dataset and the recordings from the surface to a horizontal borehole. Further, it is assumed that source designature and SRME (surface-related multiple elimination) have been applied to the surface reflection data $\mathscr{R}^{\cup}(\mathbf{x}_0^{''}|\mathbf{x}_0,t)$ (with the first coordinate vector standing for the receiver position and the second for the position of the source). The up-down wavefields, here denoted as the Green's functions, $G^{-}(\mathbf{x}_i^{'}|\mathbf{x}_0^{''},t)$ and $G^{+}(\mathbf{x}_i^{'}|\mathbf{x}_0^{''},t)$, in the horizontal borehole level ∂D_i are related to the focusing wavefields, $f_1^{+}(\mathbf{x}_0|\mathbf{x}_i^{'},t)$ and $f_1^{-}(\mathbf{x}_0|\mathbf{x}_i^{'},t)$, via the following relations (Wapenaar et al., 2014). Assuming that the causality of $f_1^{-}(\mathbf{x}_i^{'}|\mathbf{x}_0^{''},t \geq t_d) = 0$ holds (where $t_d(\mathbf{x}_i^{'}|\mathbf{x}_0^{''})$ is the direct arrival time from $\mathbf{x}_0^{''}$ to $\mathbf{x}_i^{'}$), then for $t \geq t_d(\mathbf{x}_i^{'}|\mathbf{x}_0^{''})$, we have

$$G^{-}(\mathbf{x}_i^{'}|\mathbf{x}_0^{''},t) = \int_{\partial D_0}\int_{-\infty}^{t} \mathscr{R}^{\cup}(\mathbf{x}_0^{''}|\mathbf{x}_0,t-t^{'}) f_1^{+}(\mathbf{x}_0|\mathbf{x}_i^{'},t^{'}) dt^{'} d\mathbf{x}_0; \tag{1}$$

$$G^{+}(\mathbf{x}_i^{'}|\mathbf{x}_0^{''},t) = -\int_{\partial D_0}\int_{-\infty}^{t} \mathscr{R}^{\cup}(\mathbf{x}_0^{''}|\mathbf{x}_0,t-t^{'}) f_1^{-}(\mathbf{x}_0|\mathbf{x}_i^{'},-t^{'}) dt^{'} d\mathbf{x}_0 + f_{1,0}^{+}(\mathbf{x}_0^{''}|\mathbf{x}_i^{'},-t). \tag{2}$$

So, the up-down fields can be computed given $t_d(\mathbf{x}_i^{'}|\mathbf{x}_0^{''})$, $\mathscr{R}^{\cup}(\mathbf{x}_0^{''}|\mathbf{x}_0,t)$ and $f_1^{\pm}(\mathbf{x}_0|\mathbf{x}_i^{'},t)$ ($f_{1,0}^{+}(\mathbf{x}_0^{''}|\mathbf{x}_i^{'},-t)$ is the initial estimate of f_1^{+}). Since the iterative Marchenko method is a recipe for finding $f_1^{\pm}$ and the ingredients are no more than $\mathscr{R}^{\cup}$ and $t_d(\mathbf{x}_i^{'}|\mathbf{x}_0^{''})$, which are in the surface reflection data and the borehole data, we can estimate the up-down wavefield at the horizontal borehole level ∂D_i with only single-component data.

Next, we suggest an idea for extracting $t_d(\mathbf{x}_i^{'}|\mathbf{x}_0^{''})$ from borehole data automatically. As the direct arrivals in the data usually have the biggest amplitude, one can easily extract the travel time curve with the biggest amplitude. However, since the assumption is not always true, the extracted curve may very well have some discontinuities, so we first subsample the curve, then run an algorithm to look for discontinuities larger than a certain prior chosen value. If such a jump is found, then the algorithm estimates the slope of the curve in the vicinity of the jump (either before or after the jump, depending on its distance and side to the zero offset) and then correct the jump with the slope calculated. After this travel time curve correction, one can interpolate the curve back to its original receiver sampling interval and choose a desired wavelet to convolve with the curve for simulating the direct wavefield as the initial estimate of f_1^{+} in the iterative Marchenko scheme. Fig. 1 summarizes the general procedure.

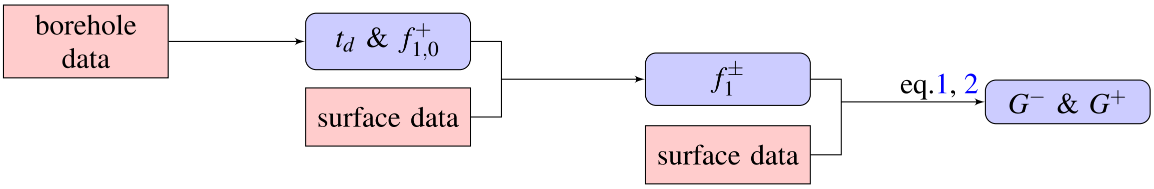

Figure 1 *The general workflow for estimating the up-down wavefields in the horizontal borehole.*

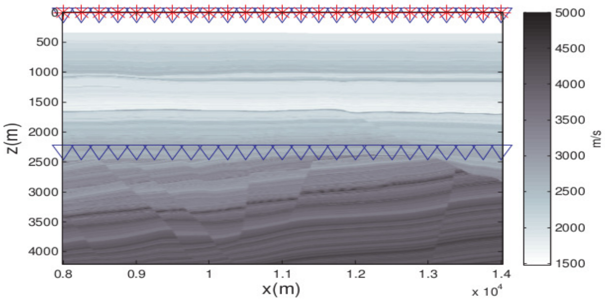

Figure 2 *P-wave velocity model and datasets geometries. The stars denote sources and the triangles denote receivers.*

Example

The P-wave velocity model for simulating the synthetic data is shown in Fig. 2. The source and receiver numbers in both the surface and borehole datasets are 241, with a spacing interval of 25 meters. Examples of the common-source gathers from the borehole dataset are shown in Fig.3. The top row in Fig. 4 shows original travel time curves with the maximum amplitude, and some obvious discontinuities can be seen. The bottom row in the figure shows the curve corrected by the procedure described above. The focusing wavefields f_1^+ are shown in Fig.5. These are computed through the iterative Marchenko method using the travel time curve, its simulated direct wavefield, and the surface reflection response from the surface data. Then finally, the up-down wavefields are computed by using eq. 1 and 2, and its comparison with that from multi-component data (bottom row) is shown in Fig.6 and 7. FK dip filtering is applied for the multi-component results to remove the artefacts seen as the straight lines. First, we see that in both figures, both approaches recover the major events and resemble each other in general. This confirms that this method of estimating up-down wavefield works quite well. However, they are still a few significant differences, especially for those with larger offsets (the ones in the first and third column). Although the multi-component results (bottom row) suffer a bit from the FK filtering, they contain more events with higher propagation angles. The single-component results miss those events because they are essentially constructed from the surface reflection response which, with the acquisition geometry used in the model, has a smaller propagation angle to the target as compared to the borehole data. This limited acquisition aperture at the surface is most likely the reason why the match in the middle column is better than the ones on the side.

Discussion and conclusions

We present a new automatic workflow for constructing the up-down wavefields in a horizontal borehole using the surface reflection response. The method requires only single component measurements at the surface and in the borehole. The automatic procedure of using the travel time from borehole data to initialize the Marchenko method is straightforward and can work also in the presence of head waves. It is also possible to extend the method for boreholes that are slightly deviated. The numerical results suggest this single-component data approach could be a good supplement to the conventional multi-component approach without any extra practical field cost.

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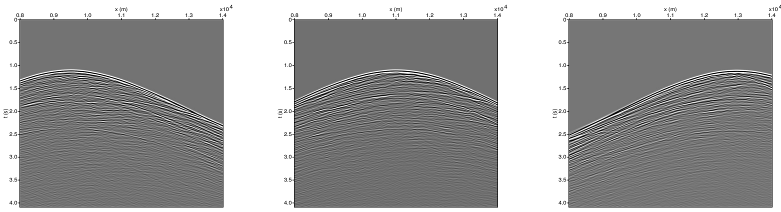
We like to acknowledge the ROSE consortium at NTNU, Dutch Technology Foundation (grant VENI.13078), Jan Thorbecke at TUD, and Alexander Kritski at Statoil for the field velocity model.



(a) (b) (c)

Figure 3 *Common-source gathers in the borehole data of a source at a) 9.5km, b) 11km, and c) 13km.*

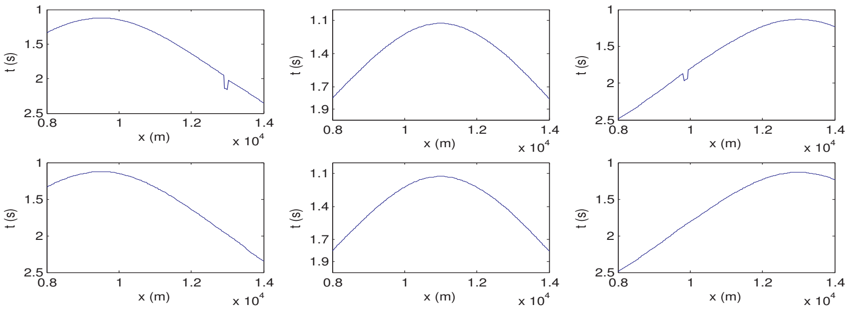
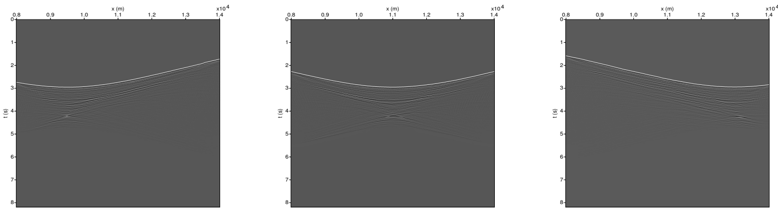


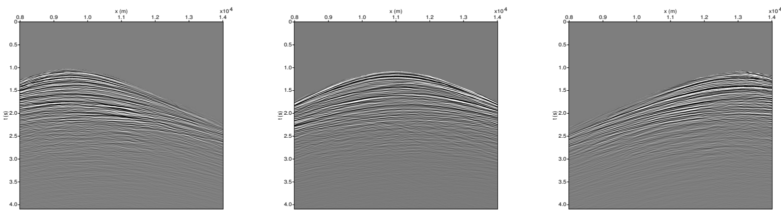
Figure 4 *Automatically extracted travel time curves of the direct wavefield. The top row shows the original curves with the biggest amplitude and the bottom row shows the ones after correction.*

Figure 5 *The subsequently computed downgoing focusing wavefield f_1^+, obtained by the iterative Marchenko method, using the travel time curve from the bottom row in Fig. 4. The focusing position in the horizontal borehole is at a) 9.5km, b) 11km and c) 13km.*

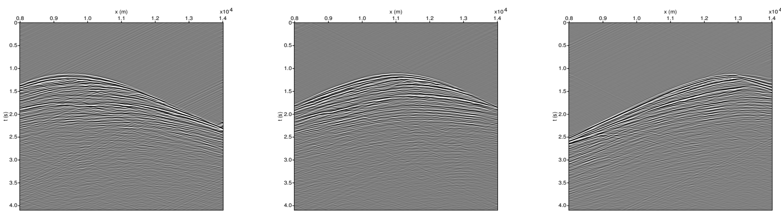


(a) (b) (c)

Figure 6 *The comparison of G^- for various source positions at the surface. The top row shows the results from single-component borehole and surface data. The bottom row shows those from multi-component borehole data. The source position for a) and d) is at 9.5km, b) and e) at 11km, c) and f) at 13km.*



(a) (b) (c)



(d) (e) (f)

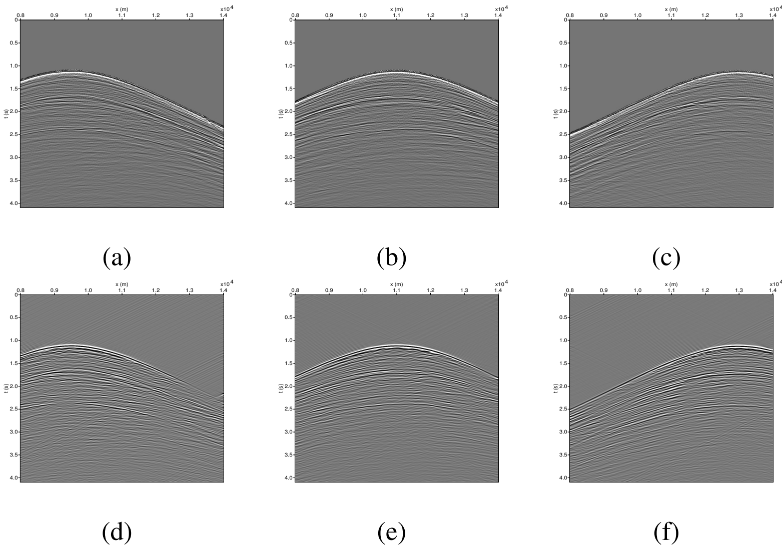


Figure 7 The corresponding comparison for G^{+}.

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