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DOI
10.3997/2214-4609.201701199

Publication date
2017

Document Version
Accepted author manuscript

Published in
79th EAGE Conference & Exhibition 2017

Citation (APA)
Liu, Y., Arntsen, B., van der Neut, J., & Wapenaar, K. (2017). Up-Down Wavefields Reconstruction in Boreholes Using Single-Component Data. In *79th EAGE Conference & Exhibition 2017: Paris, France* Article We A5 12 EAGE. https://doi.org/10.3997/2214-4609.201701199

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Up-Down Wavefields Reconstruction in Boreholes Using Single-Component Data

Y. Liu* (Norwegian University of Science & Technology), B. Arntsen (Norwegian University of Science & Technology), J. van der Neut (Delft University of Technology), K. Wapenaar (Delft University of Technology)

Summary

A standard procedure in processing vertical seismic profile (VSP) data is the separation of up-and downgoing wavefields. We show that the up-down wavefields in boreholes can be reconstructed using only single-component borehole data, given that a full set of surface reflection data is also available. No medium parameters are required. The method is wave-equation based for a general inhomogeneous lossless medium with moderately curved interfaces. It relies on a focusing wavefield from the Marchenko method, which gives the recipe for finding this wavefield that satisfies certain focusing conditions in a reference medium. The up-down wavefields are then reconstructed at borehole positions using this focusing wavefields and the surface reflection response. We show that the method is applicable to boreholes with any general orientation. The requirement is that the source positions in the surface data are regularized to be the same as those in the borehole data, and that source deconvolution and surface multiple removal are applied for the surface data. Numerical results from a field in the North Sea are shown, and three different borehole geometries (horizontal, deviated and vertical) are tested. The result shows that the reconstructed up-down wavefields agree well with those by conventional separation methods.

Introduction

An important processing step for borehole data is the separation of the up-down wavefields. Conventional vertical seismic profile (VSP) up-down separation methods rely on the different apparent velocities (or dip) of the up-down wavefields. A common approach is to use a velocity filter to separate them in the frequency-wavenumber (f-k) domain (Embree et al., 1963; Treitel et al., 1967; Dankbaar, 1985). More sophisticated wave-equation based methods are used now for multi-component data. They are based on eigenvalue decomposition of the equation of motion with certain boundary conditions in horizontally-layered media (Ursin, 1983). The up-down components are computed as an angle-dependent combination of two or more measured data components (Barr and Sanders, 1989; Wapenaar et al., 1990; Amundsen and Reitan, 1995; Schalkwijk et al., 2003). We show another wave-equation based method that reconstructs the up-down wavefields in boreholes using only single-component borehole and surface pressure data. The decomposition is achieved by using the focusing wavefield from the Marchenko method (Rose, 2002; Broggini et al., 2012; Wapenaar et al., 2013). The up-down wavefields at borehole positions from surface sources are then computed using the surface reflection data, the direct traveltimes measured in the borehole, and the focusing wavefield. We show that the method works for any general borehole orientation, and the results are compared to those by conventional methods. Numerical results using synthetic field model data are shown. Two borehole geometries, the deviated and the vertical, are tested. The reconstructed up-down wavefields are compared with those by conventional methods in each case. Discussion and conclusion are made based on the numerical results.

Method

An illustration of the required quantities for computing the up-down wavefields, together with the acquisition geometry is shown in Fig. 1. Fig. 2 shows the overall workflow of the method. First, the focusing wavefield for each borehole receiver position is computed from the known surface reflection response and the direct wavefield in the borehole data by using an iterative Marchenko scheme,

$$f^{+}_{1,k}(\mathbf{x}''_0|\mathbf{x}'_i,t) = f^{+}_{1,0}(\mathbf{x}''_0|\mathbf{x}'_i,t) + \theta(t+t_d(\mathbf{x}''_0|\mathbf{x}'_i)) \int_{\partial D_0}\int_{-\infty}^{\infty} \mathscr{R}^{\cup}(\mathbf{x}''_0|\mathbf{x}'_0,t) f^{-}_{1,k-1}(\mathbf{x}'_0|\mathbf{x}'_i,t+t')dt'd\mathbf{x}'_0, \quad (1)$$

$$f^{-}_{1,k}(\mathbf{x}''_0|\mathbf{x}'_i,t) = \theta(t_d(\mathbf{x}''_0|\mathbf{x}'_i)-t) \int_{\partial D_0}\int_{-\infty}^{\infty} \mathscr{R}^{\cup}(\mathbf{x}''_0|\mathbf{x}'_0,t-t') f^{+}_{1,k}(\mathbf{x}'_0|\mathbf{x}'_i,t')dt'd\mathbf{x}'_0, \quad (2)$$

with

$$f^{+}_{1,0}(\mathbf{x}''_0|\mathbf{x}'_i,t) \approx G_d(\mathbf{x}'_i|\mathbf{x}''_0,-t), \quad (3)$$

where $\theta(t)$ is the Heaviside function that passes the results for $t > 0$ and $G_d(\mathbf{x}'_i|\mathbf{x}''_0,-t)$ is denoted as the time-reversed direct wavefield from the borehole data. After this step, the focusing function is used in Eq. 4 and 5 to compute the up-down wavefields $G^{\pm}(\mathbf{x}'_i|\mathbf{x}''_0,t)$, which states for $t \geq t_d(\mathbf{x}''_0|\mathbf{x}'_i)$,

$$G^{-}(\mathbf{x}'_i|\mathbf{x}''_0,t) = \int_{\partial D_0}\int_{-\infty}^{t} \mathscr{R}^{\cup}(\mathbf{x}''_0|\mathbf{x}_0,t-t') f^{+}_{1}(\mathbf{x}_0|\mathbf{x}'_i,t')dt'd\mathbf{x}_0 \quad (4)$$

and

$$G^{+}(\mathbf{x}'_i|\mathbf{x}''_0,t) = f^{+}_{1,0}(\mathbf{x}''_0|\mathbf{x}'_i,-t) - \int_{\partial D_0}\int_{-\infty}^{t} \mathscr{R}^{\cup}(\mathbf{x}''_0|\mathbf{x}_0,t-t') f^{-}_{1}(\mathbf{x}_0|\mathbf{x}'_i,-t')dt'd\mathbf{x}_0. \quad (5)$$

For this step, again, the surface reflection data and the direct wavefield traveltime are needed. A full set of the surface reflection response with source signal deconvolution and surface multiple removal is necessary for the method.

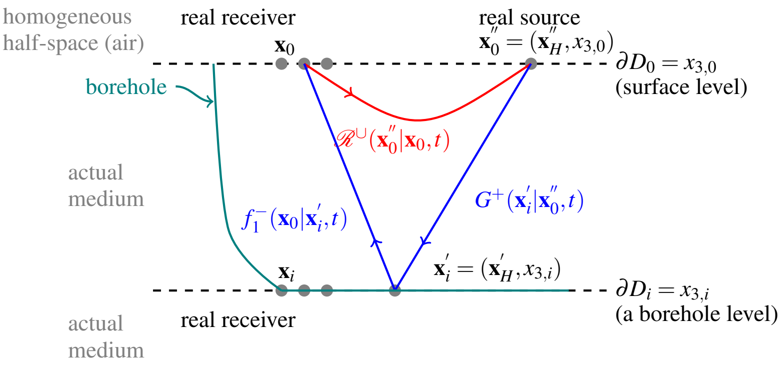


Figure 1 *Notation convention and illustration of the required quantities. Here ∂D_0 denotes a transparent surface level, and ∂D_i denotes a borehole level. The red color represents the known surface reflection response $\mathscr{R}^{\cup}(\mathbf{x}''_0|\mathbf{x}_0,t)$, and the blue represent the unknown. $f_1^-(\mathbf{x}_0|\mathbf{x}'_i,t)$ is the upgoing component of the focusing function from the focus position $\mathbf{x}'_i$ to a surface position $\mathbf{x}_0$ and $G^+(\mathbf{x}'_i|\mathbf{x}''_0,t)$ is downgoing wavefield to be constructed by using Eq.5.*

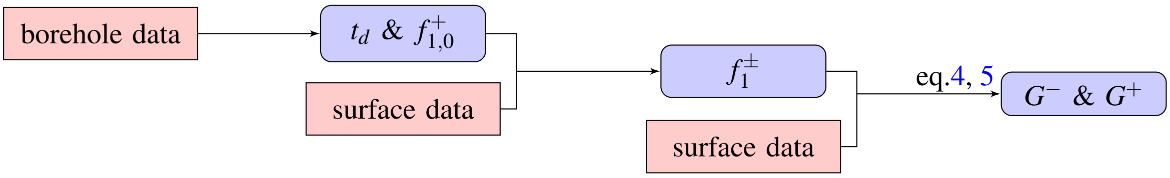
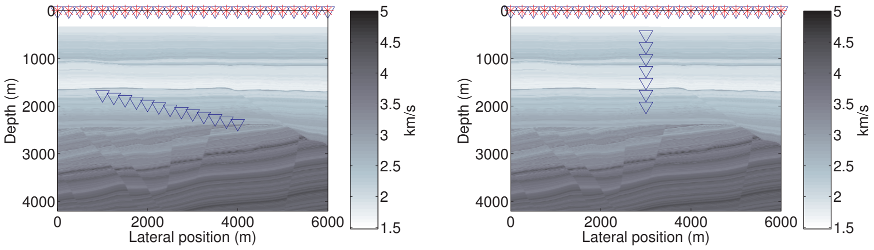


Figure 2 *The general workflow for estimating the up-down wavefields in the horizontal borehole. The red boxes denote the input data, and the round-cornered purple boxes denote the computed results.*

Examples

Fig. 3 shows the P-wave velocity model and the acquisition geometries, one for the deviated well and one for the vertical well. In both cases, there are 241 sources and receivers in the surface reflection data, with a source / receiver spacing of 25 m, so the source and receiver positions are the same in the surface data. A finite difference method (Thorbecke and Draganov, 2011) is used for modelling the data. The source signal in the surface data is a band-limited delta function with a maximum frequency of 55 Hz. The free surface related multiples are not included in the modelling. This gives an ideal surface dataset for testing the method. The source signal in the borehole data is a Ricker wavelet with a peak frequency of 15 Hz.

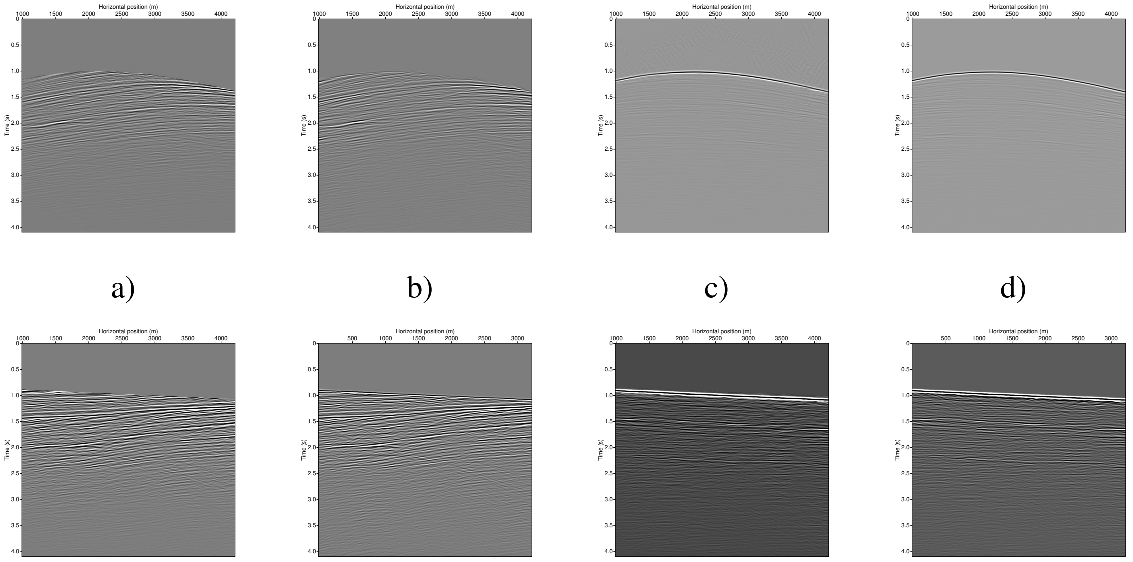
For the deviated well case, common-source gathers of the up-down wavefields by this method are in Fig. 4 a) and c), in comparison with those by multi-component data in Fig. 4 b) and d). The zero-offset comparison of the results is shown in the second row in Fig. 4. We see that the results by both methods agree well. For the vertical well case, the comparison is made in Fig. 5 for a source at $x_1 = 3000$ m. The result by f-k dip filtering is included here because it is a common approach for vertical wells and also only requires single-component data. Again, we see similar results from all three methods.The difference is that the other two methods either need multi-component data or is only suitable for a certain well geometry.



a)

b)

Figure 3 *The P-wave velocity model and the data geometries for a a) deviated borehole and b) vertical borehole. The stars denote sources in both of the surface and borehole data, and the triangles denote receivers.*



a) b) c) d)

e) f) g) h)

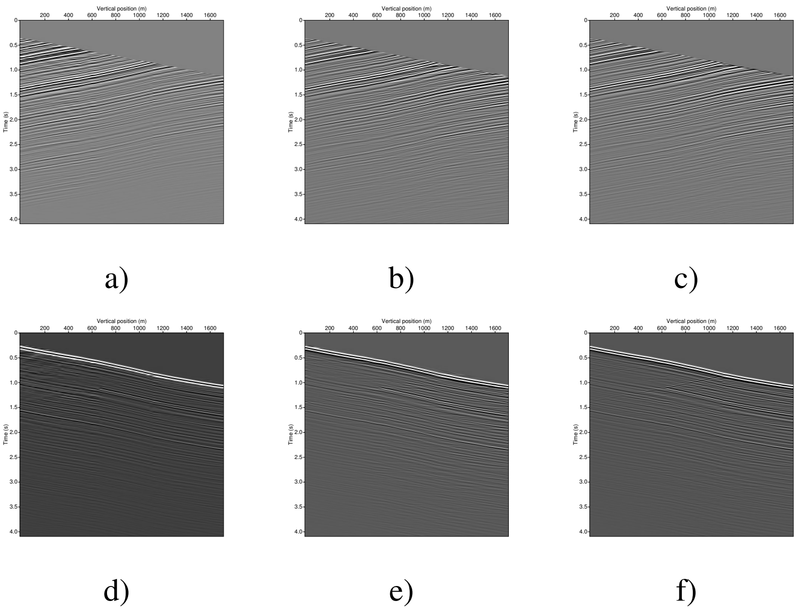
Figure 4 *The comparison of reconstructed up-down wavefields for the model with the deviated well (Fig. 3a). The first row shows the common-source gather at* $x_1 = 2500$ *m. a) & b) The upgoing fields. c) & d) The downgoing fields. a) & c) are the reconstructed results from the surface data. b) & d) are those obtained by PZ summation with angle-dependent filters. The second row shows the zero-offset comparison. e) & f) are the upgoing fields, g) & h) are the downgoing fields. e) & g) are those by this method. f) & h) are by multi-component (p and vz) approach.*

Discussion

For field application, a few considerations are the following. First, the method requires a good surface reflection response, as the one-way wavefields in the borehole are essentially reconstructed from the surface data. This means that source signal deconvolution and surface multiples removal need to be applied successfully to the data prior to use this method. However, the surface multiples can be accounted for by adapting the method according to Singh et al. (2017). Second, the reconstructed up-down wavefield has a smaller illumination angle to steep reflectors compared to the actual decomposed data from the borehole, because the source-receiver angle to those reflectors are smaller from the surface than from the borehole. But the small-offset results are not affected. Third, a complete surface reflection response with source positions regularized as in the borehole data is required. The price for skipping any medium property information is that a wide source coverage at the surface is needed. However, unlike the multi-component decomposition approaches that either reply on vertical wave propagation (such as PZ summation) or require an receiver array, this method can be applied with a single receiver as long as a full set of surface reflection response is available.

Conclusions

We show a new approach to reconstruct the up-down wavefields in boreholes using surface reflection responses. The method requires only the acoustic pressure measured at the surface and in the borehole. No medium parameter is needed. The application of this method to a general borehole geometry is shown with numerical examples. The results using only single-component data show good agreement with those by conventional decomposition methods. Although multi-component data are commonly available now, the possibility of reconstructing the up-down wavefield using existing single-component data without any extra field cost is nevertheless attractive. The method is robust and not affected by any velocity uncertainties in the model.



a) b) c)

d) e) f)

Figure 5 *The comparison of the reconstruction of the up-down wavefields of a source at* $x_1 = 3000$ *m for the model with the vertical well (Fig. 3b). a) , b) & c) are the upgoing fields, d), e) & f) are the down-going fields. The left column shows the reconstructed results from the surface data, the middle column shows those from the borehole data by f-k dip filtering, and the right column shows those from the borehole data by PZ summation. Both the left and the middle results are obtained using only single-component data.*

Acknowledgements

We like to acknowledge the sponsors to the ROSE consortium at NTNU, Jan Thorbecke at TUD for the Open Source modelling package, and Alexander Kritski at Statoil for the velocity model.

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