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Crosswell nonlinear seismic waveform inversion without downhole sources and its application to time-lapse monitoring

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Summary

Crosswell seismic measurements enable obtaining high resolution, high accuracy images of the subsurface between boreholes. They are, however, generally expensive considering the need of deployment of special downhole sources. In this study, we develop a novel nonlinear waveform inversion to estimate velocity structures between two vertical boreholes using VSP data without downhole sources. Contrary to the conventional full waveform inversion (FWI), the effect of wave propagation between surface sources and one of the vertical boreholes is appropriately cancelled using representation theory. Furthermore, it enables us to calculate partial derivatives of the cost function without explicitly resolving the Green's functions in seismic interferometry. We test numerically this new approach of time-lapse monitoring of a deeper target layer, considering also the effect of changes in the complex, shallow vadose zone. We assume that the temporal changes in velocity in the vadose zone are larger than those at the deeper target layer. Our results show that in contrast to conventional FWI, the newly developed approach has the advantages of expensive crosswell seismics involving downhole sources. The estimated velocity is robust against spatiotemporal changes in the near-surface. The approach will be very useful when accurate time-lapse seismic measurements are needed in a cost-effective manner.

Introduction

Monitoring dynamic changes in elastic properties of the subsurface due to tectonic stress and fluid flow finds many applications. Crosswell seismic measurements provide very high resolution images with high accuracy because both sources and receivers are installed in depth close to the target and seismic signals are less affected by near-surface heterogeneities. Time-lapse traveltome tomography and full waveform inversion (FWI) are, among others, applied to detect temporal changes of subsurface properties between boreholes (e.g., Saito et al., 2006; Luth et al., 2011; Ajo-Franklin et al., 2013; Kamei et al., 2017).

Efficiency and accuracy in time-lapse measurements are crucial in monitoring experiments. Recording wavefield is efficiently performed by an array of receivers and/or permanent receiver system, e.g., via distributed acoustic sensing (DAS). However, the acquisition cost of using special downhole sources, e.g., mechanical sources or piezo-electric transducers, is generally high because the sources need to be repeatedly installed at multiple depths to cover the survey depth interval. Installing special downhole sources at multiple depth levels and simultaneously exciting random signals was earlier proposed in order to reduce the acquisition cost (Takanashi et al., 2016).

In this research, we develop a novel acquisition and processing technique for efficient and accurate time-lapse monitoring between two boreholes. The approach does not require downhole sources but uses VSP data with surface seismic sources and only receivers located in the borehole. Flexible choices are available for surface seismic sources (e.g., airguns, vibroseis, explosives, sledge hammer). Furthermore, data can also be obtained during standard walk-away VSP measurements for reflection imaging and velocity logging.

We formulate nonlinear waveform inversion in order to estimate velocity structure between the boreholes using VSP data. Contrary to conventional FWI, effects of near-surface heterogeneities in the recorded VSP data are appropriately cancelled through use of representation theory. We consider that one borehole measures the reference wavefield including information of wave propagation through near-surface heterogeneities, and the other borehole measures wavefield which is represented by the combined effect of the propagation of reference wavefield and the velocity structure between the boreholes. There is similar approach proposed earlier which retrieves crosshole Green's function from VSP data through seismic interferometry by crosscorrelation or least-squares inversion (Minato et al., 2011). This approach enables estimating the wavefield as if the sources would be located in the borehole, and the retrieved crosshole wavefields are used for further processing, e.g., reflection imaging (Minato et al., 2011) and travel time tomography (Almalki et al., 2013). Contrary to these studies, in the present research we formulate a nonlinear waveform inversion using representation theory as basis for the forward modelling operator. This enables directly estimating the velocity structure between boreholes without explicitly retrieving Green's function using seismic interferometry. We test this new approach numerically considering time-lapse measurements in the presence of a shallow heterogeneous layer with temporally changing properties.

Nonlinear waveform inversion coupling representation theory

We consider VSP measurements with two vertical boreholes (Figure 1(a)). The wavefield due to the surface seismic source at x_S is measured at right borehole (RF) and left borehole (LF). Considering this geometry, we use the following representation theory in the frequency domain:

$$p(x_R) = (-i\omega\rho)^{-1} \int_{\partial D} (\nabla G(x, x_R) \cdot \mathbf{n}) p(x) dx, \quad (1)$$

where $p(x_R)$ is the recorded wavefield at LF, $p(x)$ is the recorded wavefield at RF, $\nabla G(x, x_R)$ is the spatial derivative of the Green's function between the boreholes, and \mathbf{n} is the normal vector at the

integral boundary ∂D or the geometry of RF (Figure 1b). Equation (1) can be derived from convolution-type representation theory (e.g., Wapenaar et al., 2011) where we assume 2D acoustic wavefield, surface sources x_S located on the right side of RF, and free-surface boundary condition at RB in the Green's function G .

Equation (1) states that the recorded wavefields at RF and LF are related through the Green's function G which is a function of velocity structure between the boreholes. We formulate the nonlinear waveform inversion, where we search for the velocity structure between the boreholes which satisfies equation (1) through Green's function G . To this end, we use the framework in FWI to calculate the partial derivatives of the misfit function (e.g., Pratt et al., 1998). The misfit function is the waveform difference between recorded wave at LF, i.e., $p(x_R)$ and synthetic wave at LF given by equation (1) using the recorded wavefield at RF and the Green's function G calculated using the current velocity model. Additional matrix multiplication corresponding to the evaluation of equation (1) is performed using the frequency-domain formulation in Pratt et al. (1998). The Green's functions are calculated using finite-difference approach (Jo et al., 1996). The velocity model is iteratively updated by nonlinear inversion where we use l -BFGS method (Metivier and Brossier, 2016).

As one can see from Figure 1(b), the calculation of the partial derivatives does not require knowledge of the velocity structure between the surface source x_S and RF. In other words, this approach effectively cancels the wave propagation between the surface source x_S and RF including those due to near-surface heterogeneities. Note that the conventional seismic interferometric studies (Minato et al., 2011; Almalki et al., 2013) have the same characteristics. However, an important difference of the newly developed method compared to seismic interferometry is that here we do not perform additional least-squares inversion to estimate the Green's functions; the Green's functions retrieved by seismic interferometry are assumed perfect or the errors in the estimated Green's functions are additionally considered when they are used in the existing processing methods, e.g., traveltime tomography or conventional FWI. In contrast, the proposed approach finds the optimum velocity structure satisfying the representation theory (equation (1)), and therefore, additional interpretation of the estimated Green's function is not necessary.

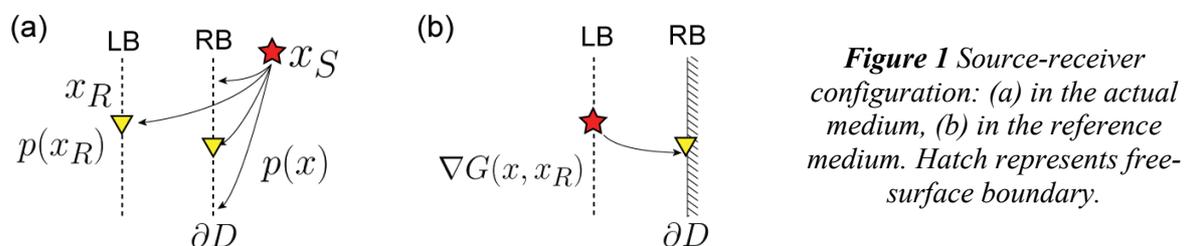


Figure 1 Source-receiver configuration: (a) in the actual medium, (b) in the reference medium. Hatch represents free-surface boundary.

Numerical modelling example

We test the new approach using a 2D acoustic model as shown in Figure 2. We assume an 1D velocity model (see right figure in Figure 2(a)), with a shallow layer (6 m thick) having a random distribution of velocity (Figure 2(b)) and a complex vadose zone. The target layer that we address in time-lapse monitoring is located at 100 m depth (dashed lines in Figure 2(a)). Velocity changes in the target layer by 5% between the baseline survey and the monitor survey. The random velocity fluctuation in the top shallow layer is significantly different between baseline and monitor surveys (Figure 2(b)), representing dramatic changes in the vadose zone due to, e.g., rainfall (Lu and Sabatier, 2009).

VSP data are measured using borehole receivers and 8 surface sources (Figure 1(a)). Figure 2(a) shows the example of a modelled shot gather at LB. Figure 2(b) is the difference section in shot gather between the baseline and the monitor surveys when the vadose zone is temporarily invariant; clearly the waveform changes only due to temporal changes in the target layer. Considering the temporal

changes at the shallow vadose zone, its effect obscures greatly the signal from the target layer (Figure 2(c)). The challenge of waveform inversion in this experiment is to correctly isolate the waveform changes due to changes in the target layer from the complex signature as shown in Figure 2(c).

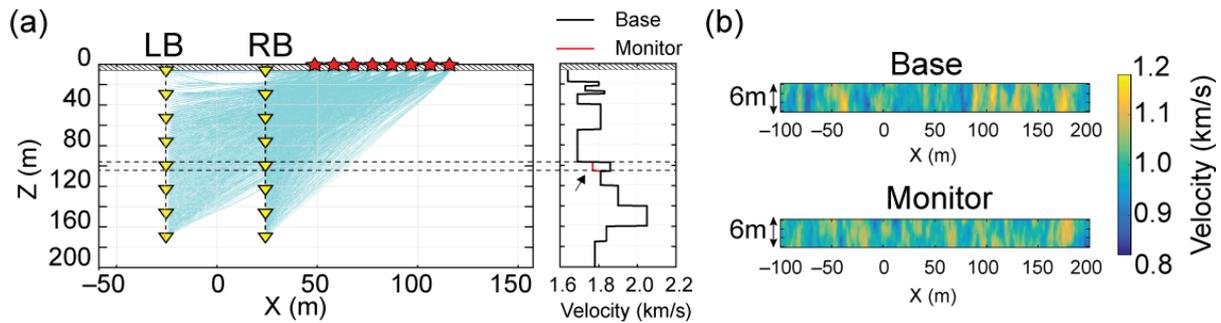


Figure 2 (a) Configuration in the numerical modelling. (b) Near-surface heterogeneity.

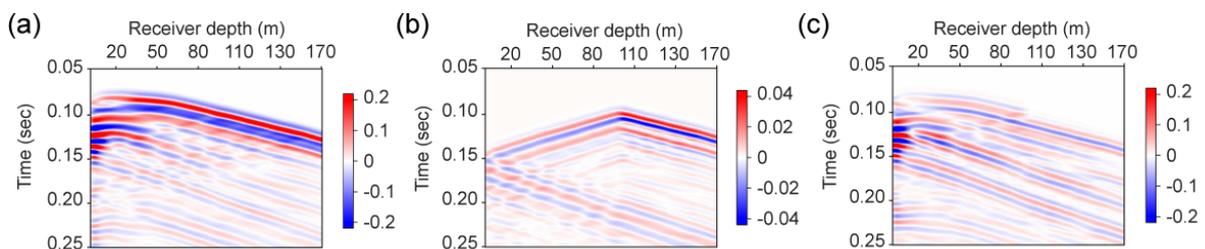


Figure 3 (a) Example of modelled shot gather at LB. (b) Waveform difference in the shot gather between the baseline and the monitor surveys, with time-lapse changes occurring at the target layer only. (c) Same as (b) but with additional time-lapse changes occurring also at the near-surface.

We apply the newly developed approach to the baseline survey (Figure 4(a)). Initial velocity model is obtained by smoothing true model and adding a homogeneous shallow layer with 1000 m/s velocity. We sequentially invert the data in frequency domain from low to high frequencies (from 70 to 200 Hz); we perform 6 nonlinear iterations at each frequency group. The conventional FWI is also performed (Figure 4(b)) using the same initial model and the same frequency-update schedule. For this purpose, we use the FWI code TOY2DAC (Metivier and Brossier, 2016). Note that the conventional FWI estimates the velocity structure in a large area including the area between surface sources and the RB. Also, the conventional FWI shows strong velocity oscillations, mainly due to failure in estimating the velocities in the heterogeneous shallow layer. On the contrary, the new approach estimates the velocity between the boreholes efficiently, and the estimated velocity structure is much less noisy than conventional FWI.

We perform the same processing using data of the monitor survey, and estimate the temporal velocity changes between the boreholes (Figure 5). It is clear that the new approach (Figure 5(b)) provides more stable estimates of the temporal changes than using the conventional FWI (Figure 5(c)).

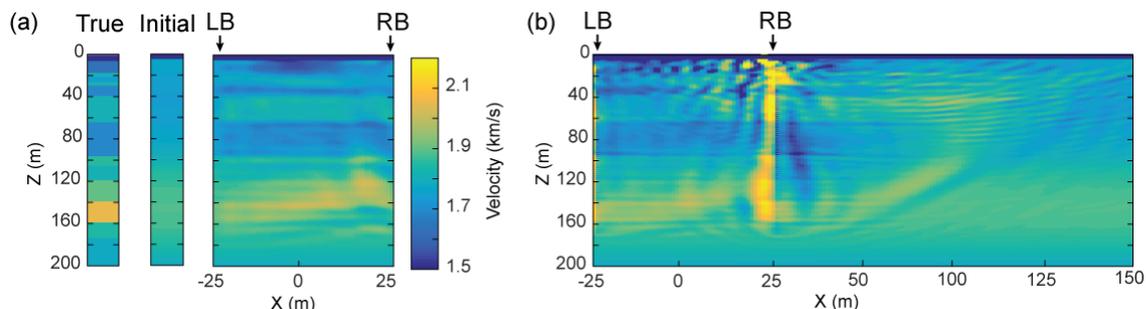


Figure 4 (a) True, initial and final models using the new approach. (b) Final model using conventional FWI.

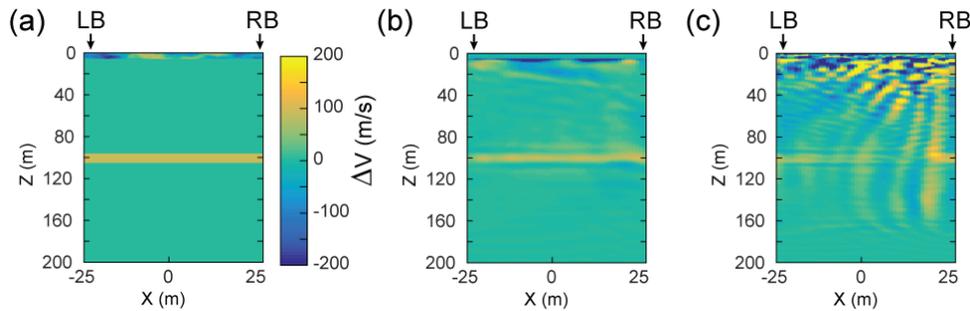


Figure 5 (a) True time-lapse changes in the velocity model. (b) Estimated time-lapse changes in velocity estimated by the new method. (c) Same as (b) but using conventional FWI.

Conclusion

For efficient and accurate time-lapse seismic monitoring between boreholes, we develop a new nonlinear waveform inversion scheme. This new approach uses VSP data from two vertical boreholes where the sources are positioned only at the surface and there are no downhole seismic sources. We formulate a nonlinear waveform inversion scheme using the representation theory to derive the forward modelling operator, which enables directly estimating the partial derivatives of the cost function without explicitly resolving the Green's functions. We numerically test the new approach considering time-lapse monitoring of a relatively deep target layer, but also temporal changes simultaneously occurring in a highly heterogeneous shallow vadose zone. Comparison with the conventional FWI shows the robustness of the new approach in eliminating the effect of changes at shallow depths to monitor correctly subtle changes in the deep target layer, which was so far not possible without using expensive downhole sources.

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