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Time-lapse target-oriented crosswell full waveform inversion without downhole sources

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Summary

Time-lapse seismics has a wide range of application in different scales, from near-surface to resource exploration. Crosshole seismics is used to characterize fluid reservoirs and to obtain highly resolved rock/soil-dynamic parameters e.g., elastic moduli and Poisson ratio. Developments in distributed acoustic sensing shows the potential of deploying permanent downhole receivers at low costs. In order to achieve an efficient and accurate time-lapse seismic measurement in such scenarios, we have developed a nonlinear waveform inversion to reconstruct velocity structure between boreholes using VSP data with source located only at the surface, and no downhole sources. The new approach formulates the forward modelling using wavefield representation theorem, which enables directly estimating the velocity structure by minimizing data residuals and calculating the gradient from the adjoint state problem. We test the approach using numerical modelling of time-lapse VSP data to detect layer-specific temporal changes. A heterogeneous shallow vadose zone represents a low-velocity layer. The results show that the new approach provides more stable and more accurate temporal velocity profiles than conventional full waveform inversion, when the initial velocity model does not include the shallow low-velocity layer. The new approach is robust and highly advantageous as it does not require downhole seismic sources.

Introduction

Time-lapse seismic measurements have been developed for many applications spanning over a wide range of scale, from monitoring tectonic stress changes to detecting fluid-flow effects at landfill sites, in CCS fields, and in water/geothermal/hydrocarbon reservoirs. Electrical and electromagnetic methods have proven efficiency in monitoring changes in shallow subsurface properties related to water. However, they can be ineffective in highly electrically conductive or resistive environments and over massive or fractured rocks (Hubbard and Linde, 2011). Borehole seismic measurements (VSP and crosswell seismics) provide more accurate, higher resolution images than surface seismic measurements due to the location of the receivers and/or sources close to the target and due to relatively lower sensitivity to near-surface heterogeneities. Time-lapse crosswell seismic traveltime tomography and waveform inversion have been used, for instance, to monitor changes in rock/soil-dynamic properties (e.g., Fehler and Pearson, 1984), to enable dynamic interpretation of shallow hydrosystems (e.g., Kamei et al., 2017), and to detect velocity changes due to CO2 injection (e.g., Saito et al., 2006; Luth et al., 2011; Ajo-Franklin et al., 2013).

In realistic terms, time-lapse seismic measurements need to be performed in a cost-effective manner. Although a crosshole acquisition geometry is promising to resolve subtle time-lapse changes, it requires special downhole sources which emit seismic waves in a borehole. The source needs to be repeatedly installed at multiple depths in order to cover the survey depth interval. Wavefields are efficiently recorded at multiple depths using a receiver array. Recent developments in distributed acoustic sensing (DAS) offers the possibility of deploying permanent receiver system at a relatively low cost (Daley et al., 2013).

Considering such benefits, a unique crosswell imaging technique was proposed by Minato et al. (2011), where VSP data using two vertical boreholes were transformed into crosswell seismic data. The approach adopted seismic interferometry (e.g., Wapenaar et al., 2011). Seismic interferometry estimates the Green's functions between boreholes by crosscorrelating the VSP data, or solving the inverse problem. Minato et al. (2011) successfully imaged the reflection structures between boreholes using retrieved crosswell seismic data. Almalki et al., (2013) applied this idea coupling traveltime tomography for characterizing water reservoirs system in acquirer storage and recovery.

In this study, we consider the same acquisition geometry as before (Minato et al., 2011), but propose a conceptually new, nonlinear waveform inversion scheme to reconstruct the velocity structure and detect the temporal changes. The wavefield representation theorem (e.g., Wapenaar et al., 2011) is exploited in a similar manner as that in seismic interferometry, but we directly estimate the velocity structure without explicitly resolving the Green's functions in the inversion. We calculate the sensitivity of the velocity structure to data residual using the adjoint state method. Although the proposed approach is, in principle, similar to full waveform inversion or FWI (e.g., Pratt, 1999), it has few distinct differences; (1) estimating the source wavelet is not required, and (2) velocities at only the target zone (between boreholes) is reconstructed. Otherwise, the new approach offers the same advantages as crosswell seismics: less sensitive to near-surface environments and more sensitive to velocities and their changes at a target zone between boreholes. We test the approach using numerical modelling of realistic time-lapse VSP data, considering a heterogeneous vadose zone with random velocity distribution varying in time and space as the target zone.

Velocity reconstruction using waveform inversion coupling representation theorem

We consider the source-receiver configuration (Figure 1(a)) where two vertical boreholes (right borehole or RB, left borehole or LB) are used to record the wavefield due to sources at the surface, located on the right side of RB. In this geometry, the wavefield recorded at LB can be written as,

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

where p denotes scalar wavefield recorded in the VSP measurements, and $\bar{G}$ the Green's function in the reference medium. Equation (1) is derived from the convolution-type representation theorem (e.g., Wapenaar et al., 2011) with the following assumptions: (1) physical sources (x_S) for the measured wavefield (p) are located right to the integral boundary ∂D, (2) receiver x_R is located left to the integral boundary ∂D, (3) ∂D has an infinite radius and is coincident at the location of RB (Figure 1), and (4) the reference medium has the same velocity structure as the actual medium, although ∂D is a free-surface boundary. Equation (1) states that the measured wavefield $p(x_R)$ at LB is represented by $p(x)$ at RB and the Green's function in the reference medium. Earlier studies of seismic interferometry by multidimensional deconvolution or MDD (Wapenaar et al., 2011; Minato et al., 2011) use equation (1), but with different boundary condition at ∂D. The MDD requires separating measured wavefield p at ∂D into incoming and outgoing waves so that the representation theorem can be simplified. In the context of retrieval of Green's functions using MDD, equation (1) was recently tested to be true and effective (Weemstra et al., 2017). Contrary to these studies, in this research, we estimate velocity structure which is constrained by equation (1) through the Green's functions between the boreholes.

Once we establish the forward modelling equation (equation (1)) with a given velocity model and measured wavefield at two boreholes, we can formulate the nonlinear waveform inversion to estimate the velocity structure between the boreholes. The framework for solving FWI (e.g., Pratt, 1999) is useful to solve the proposed inversion where data residual (data at the left borehole in this study) is minimized through nonlinear inversion, with the gradient calculation from the adjoint state problem. A similar idea, but using a horizontal borehole and conventional MDD formulation (i.e., requiring wavefield separation at ∂D) was recently tested by da Costa et al. (2018). We solve the nonlinear problem using the preconditioned *l*-BFGS method (Metivier and Brossier, 2016).

Note that the Green's function $\overline{G}$ does not depend on the heterogeneity between the surface source x_S and RB (Figure 1(b)), and wave path of the calculated Green's functions changes from surface–borehole into inter-boreholes (Figure 1). This shows the potential of velocity reconstruction and monitoring much sensitive to the target zone (i.e., between boreholes) than conventional FWI where the velocity structure and its temporal changes along the path connecting surface sources and receivers affect the inversion results. Finally, contrary to the conventional FWI, the forward modelling of data $p(x_R)$ using equation (1) does not involve estimating the source wavelet; the effects is implicitly taken into account by the recorded data at the right borehole, i.e., $p(x)$ on the right-hand side of equation (1).

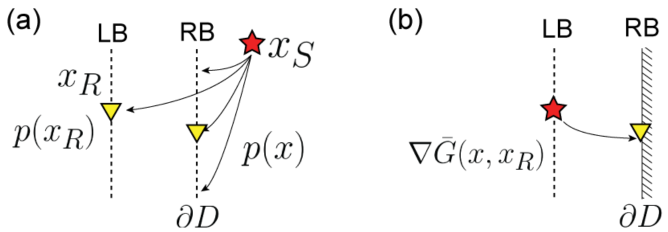

Figure 1 *Source-receiver configuration (a) in the actual medium, and (b) in the reference medium. Hatch represents free-surface boundary.*

Numerical modelling tests

We consider simple but realistic numerical modelling experiments for monitoring a subtle change of velocity at a specific layer between the two boreholes (Figure 2(a)). A shallow subsurface layer (6 m thickness) is modelled as a low-velocity layer with random fluctuation, which simulates complex shallow heterogeneities introducing natural noise in the modelled data due to scattering. Furthermore, we assume different shallow heterogeneities between the baseline and the monitor surveys, which simulates the possible temporal changes of elastic properties in the vadose zone by precipitation (e.g., Lu and Sebastier, 2009). 1D velocity model, the geometry of the 8 surface sources, and that of the receivers (2 m spacing between 2 to 170 m depth at each borehole) are shown in Figure 2(a). The velocity at the layer with 10 m thickness around 100 m depth temporarily decreases by 5 % or 90 m/s (an arrow in Figure 2(a)). The temporal change of shallow heterogeneities is bigger than that in the target layer, i.e., random fluctuation by 10 % centered around 1000 m/s ($\pm$ 100 m/s, Figure 2(b)). Figure 3(a) shows the example of a modelled shot gather recorded at LB in the baseline survey. The complex waveform difference between the baseline and monitor surveys (Figure 3(b)) shows that the changes in the waveform are associated with velocity changes both at the target and the shallow layers. This gives an additional difficulty in resolving the temporal changes at the target layer.

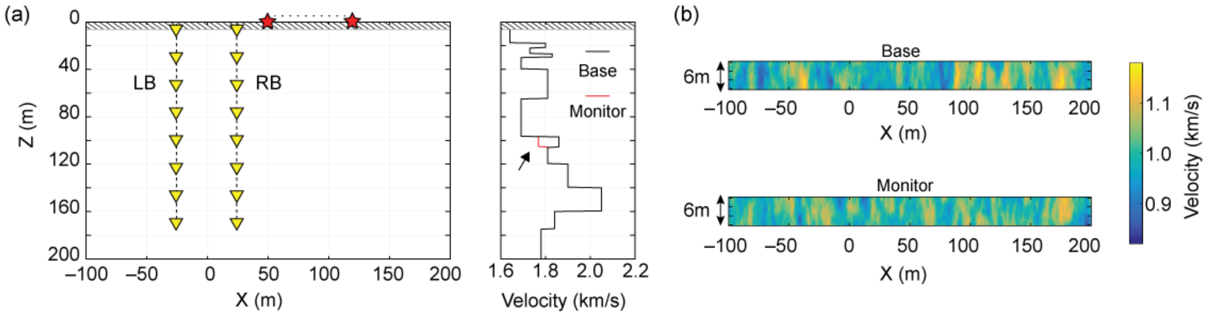

Figure 2 *(a) Configuration and velocity model in the numerical tests. Hatched area shows a shallow subsurface layer. (b) Velocity structure at the shallow layer in the baseline and monitor surveys.*

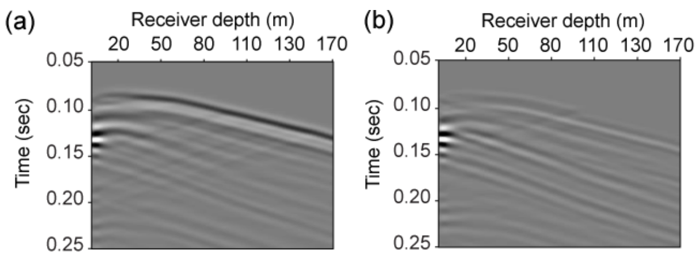

Figure 3 *(a) Example of modelled shot gather at LB due to the source at x = 80 m, and (b) difference section between the baseline and monitor surveys. The gray scale is same as (a).*

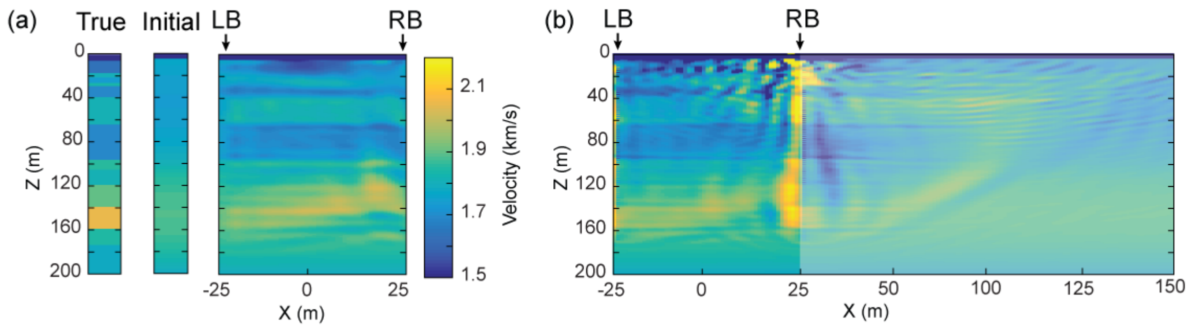

Figure 4 *(a) True, initial and inverted velocity models using the newly developed approach. (b) Result using the conventional FWI. See (a) for the colour legend.*

Figure 4(a) shows the results of our proposed waveform inversion for the baseline survey. We use the multiscale approach (e.g., Bunks et al., 1996) for the frequency range 70-200 Hz. The initial model was created by smoothing the true model and adding the shallow layer of 1000 m/s. The conventional FWI (Figure 4(b)) is also performed using the same inversion strategy as the proposed method. Conventional FWI requires the reconstruction of the velocity structure in a larger area than the proposed new approach where the right boundary is a free-surface boundary. The conventional FWI shows large errors in the shallow part of the model due to local minima. Both approaches show oscillations in the reconstructed velocities. These could be improved by introducing Tikhonov regularization, optimizing frequency-update schedule in the multiscale approach, and/or introducing better preconditioning. Nevertheless, the fact that the proposed approach better estimates velocities between the boreholes using the same inversion strategy implies greater robustness of the new approach than conventional FWI. The velocity profiles at the centre of the target zone ($x = 0$ m) for the baseline and monitor surveys (Figure 5(a)) show that the proposed new approach provides accurate and stable estimates of the velocity change at the target layer. The robustness of the proposed approach to the presence shallow near-surface layer is clearly visible when we do not include the shallow low-velocity layer in the initial model in the inversion (Figure 5(b)). This is the same advantage as that of crosswell seismic measurements. Strikingly, we have now achieved this advantage using only surface-source data.

Conclusion

In order to perform efficient and accurate time-lapse seismic measurements, we have developed a nonlinear waveform inversion to estimate velocity structure between the boreholes using VSP data with two vertical boreholes and no seismic source in the borehole. The proposed approach exploits the

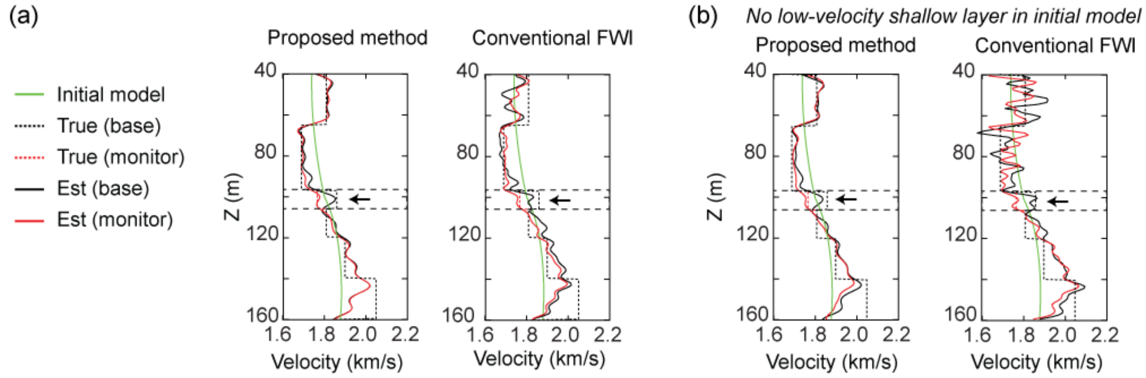

***Figure 5** (a) Velocity profiles at x = 0 m. (b) Same as (a) but using the initial velocity model where the shallow low-velocity layer is absent. The target layer is highlighted.*

representation theorem to mitigate the effect of near-surface heterogeneities and a framework of FWI to solve the gradient-based nonlinear inversion. Numerical modelling tests mimicking time-lapse VSP experiments including a shallow heterogeneous layer show that the proposed approach is more stable and more accurate than conventional FWI in estimating the temporal changes at the target zone between the boreholes. The new approach should find wide applications in fields where characterizing temporal velocity changes is important and where boreholes are deployed, among others, to monitor and perform injection experiments in fluid reservoirs.

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