Time-lapse parsimonious refraction interferometry: a field experiment

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Summary

A time-lapse field experiment is conducted to test the effectiveness of parsimonious refraction interferometry for rapidly producing snapshots of subsurface fluid migration in the subsurface. In the field experiment we recorded 90 sparse data sets over a 4.5-hour period of injecting 12-tons of water into the subsurface. The recorded data are then transformed into 90 dense data sets by parsimonious refraction interferometry (PRI). Refraction traveltimes are picked and inverted to generate 90 snapshots of the subsurface velocity distribution. Results show the percolation of water from the ground surface down to a depth of few meters. Here, the P-velocity varies by up to 8% over a 270-minute interval. These snapshots every 3 minutes of rapid velocity changes can be used to estimate the porosity and permeability distributions in the subsurface.

Introduction

The Earth is a dynamic planet where the geological properties change over different time scales. For example, the Earth's properties over small volumes can vary with time scales on the order of a few hours to a few minutes. Examples include eruptions of lava along fissures or volcanic vents (Biggs et al., 2016), geysers that vent steam and hot water every few hours (Jones, 2013; Chiodini et al., 2016), or the recent discovery of ice plumes erupting from Europa (Roth et al., 2014). An engineering example is that of decaying dams, where water leakage into aging dams can lead to disastrous dam failure (Milillo et al., 2016).

One of the main challenges in the seismic method is the long time required to record a large number of shot gathers. For example, to record 240 shot gathers we need around 16 hours of shooting and recording time, where we assume 15 stacks/shot and each shot location requires 4 minutes to be completed (2 minutes shooting time and 2 minutes moving time between shots). Hence, seismic methods cannot be practically employed to monitor subsurface changes if significant velocity variations occur over a period of a few minutes. Ambient noise cannot be used because the data must be recorded over a very long period of time (hours to weeks) in order to enhance the signal-to-noise ratio to an acceptable level. Also active-source data is not practical since recording many shot gathers requires a day or two depending on the required number of shot-gathers and the offsets between them.

To record many shot gathers in less than one hour Hanafy and Schuster (2017) introduced parsimonious refraction interferometry (PRI), where many virtual refraction shot gathers can be obtained from just two reciprocal shot gathers recorded at both ends of the recording line and a few infill shot gathers. For refractions, the assumptions are that the first arrivals mainly consist of head waves and direct waves, where a pair of reciprocal-offset shot gathers and several infill shot gathers are recorded over the line of interest. Refraction traveltimes from two reciprocal and a few infill shot gathers are picked and parsimonious interferometry can be used to compute O($\boldsymbol{N}^2$) refraction traveltimes generated by $\boldsymbol{N}$ virtual sources. Here, $\boldsymbol{N}$ is the number of geophones in the 2D survey. The resulting refraction traveltimes can then be inverted by refraction tomography to produce tomographic snapshots of the subsurface velocity model every few minutes. This enormous increase in the number of traveltime picks and associated rays, compared to the many fewer traveltimes from the two reciprocal and several infill shot gathers, provides for increased model resolution and a better condition number with the system of normal equations (Hanafy and Schuster, 2017). This proposed technique is also valid for surface waves as shown by Li et al., (2018). In our current work we use a field experiment to demonstrate the feasibility of parsimonious refraction interferometry for tracking the fluid flow of water injected into a sand dune.

The next section presents the theory of the PRI method and how it can reduce the recording time of a conventional refraction survey from a few hours to a few minutes. Then, we validate the effectiveness of time-lapse PRI using a field data from a time-lapse experiment. Here, 12 tons of water were injected into a sand dune with an overlying line of geophones. The final section presents the conclusions.

Method

For a 2D seismic experiment, assume a point source at each end of a straight recording line and the irregularly layered medium shown in Figure 1, where head waves propagate along the boundary between the first and the second layers. For convenience we assume a two-layer model but the method is valid for a many-layered model with lateral velocity variations. Here, there are $\boldsymbol{N}$ geophones placed at the recording surface between the two reciprocal sources located at $\boldsymbol{A}$ and $\boldsymbol{D}$. The head-wave traveltime from the source at $\boldsymbol{A}$ to a receiver at $\boldsymbol{C}$ is defined as

$$\tau_{AC} = \tau_{Ax'} + \tau_{x'x} + \tau_{xC} \,, \qquad (1)$$

and the opposite traveltime from $\boldsymbol{D}$ to $\boldsymbol{B}$ is given by

$$\tau_{DB} = \tau_{Dx} + \tau_{x'x} + \tau_{x'B} \,, \qquad (2)$$

10.1190/segam2018-2986382.1

where τ_{xy} is the first-arrival traveltime from $\boldsymbol{x}$ to $\boldsymbol{y}$ along the refraction ray. To create virtual sources and receivers within the array in Figure 1, we assume that the geophones located at positions ***C*** and ***B*** are separated at a post-critical distance and both of them record head waves from the same interface. Adding equation (1) to equation (2) and subtracting the reciprocal traveltime τ_{AD} gives the interferometric stationary traveltime for a virtual source (Schuster et. al., 2014) located at ***B*** and a receiver located at ***C***

$$\begin{aligned}\tau_{CB} &= \tau_{AC} + \tau_{DB} - \tau_{AD}\ , \\ &= [\tau_{Ax'} + \tau_{x'x} + \tau_{xC}] + [\tau_{Dx} + \tau_{x'x} + \tau_{x'B}] - \\ &\quad [\tau_{Ax'} + \tau_{x'x} + \tau_{xD}]\ , \\ &= \tau_{x'B} + \tau_{x'x} + \tau_{xC}, \qquad (3)\end{aligned}$$

This PRI formula is used to compute the $\boldsymbol{N^2}$ refraction traveltimes for a virtual source at any of the $\boldsymbol{N}$ geophones using the 2$\boldsymbol{N}$ traveltimes generated by the two reciprocal shot gathers.

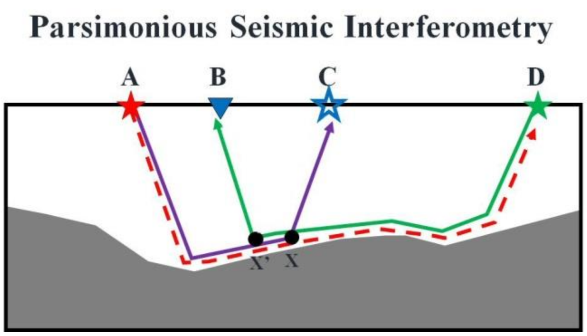

Figure 1: The parsimonious refraction interferometry method for a 2-layer model, where the lower layer has a faster seismic velocity than the upper layer. The ***A*** and ***D*** points are the locations of two reciprocal shot locations and ***B*** and ***C*** indicate the two receiver locations. Solid and dashed lines correspond to positive and negative times, respectively, as shown on Equation 3.

Numerical Example (Field Data Test)

The time-lapse PRI method was tested using synthetic and field-data examples (Fu et al., 2017; Hanafy and Schuster, 2017; Li et al., 2018). We now use field data to test the PRI method in its ability to temporally track the percolation of water through a sand dune after injecting 12 tons of water into the subsurface.

In the field test, seismic data are recorded for a water-injection experiment over a sand dune (Figure 2). The field site is located close to King Abdullah University of Science and Technology (KAUST) as shown in Figure 2. Here, we recorded two conventional data sets, where each one has 72 shot gathers recorded by 72 receivers per shot gather. The shot and receiver intervals of the conventional data sets are 0.5 m and each shot is excited using a 10-kg sledgehammer hitting a metallic plate.

Figure 2: Photos of the field site, where 12-tons of water were injected into the subsurface.

Each of the conventional data sets consisted of 72 shot gathers and required about 2 hours to be completed. Then, 12 tons of water were injected into the subsurface over 4.5 hours, during this time we recorded 90 sparse data sets, where each data set consisted of 6 shot gathers with shots located at receiver numbers 1, 15, 29, 43, 57, and 72. The first-arrival traveltimes from the 6 sparse shot-gathers are picked and used to generate the virtual traveltimes for 63 virtual shot gathers using equation 3. Each sparse data set required an average of about 2 minutes to be recorded, which is less than 2% of the time required to record a conventional data set.

PRI Test of the Conventional Data Set.

The PRI method is now validated by using one of the two conventional data sets. Figure 3a shows the first-arrival traveltimes of the recorded 72 shot gathers. We assumed that only 6 shot gathers (located at receivers 1, 15, 29, 43, 57, and 72) are recorded as shown in Figure 3b, then equation 3 is used to generate the virtual traveltimes from 63 virtual shot gathers (see Figure 3c). The differences between the conventional and virtual first-arrival traveltimes are shown in Figure 3d, which shows a variation of ±5 ms. Figure 3f shows the histogram of the differences between the conventional and virtual traveltimes which agree with one another by about ±3 ms. Figure 3e indicates a good agreement between the conventional and virtual travetimes.

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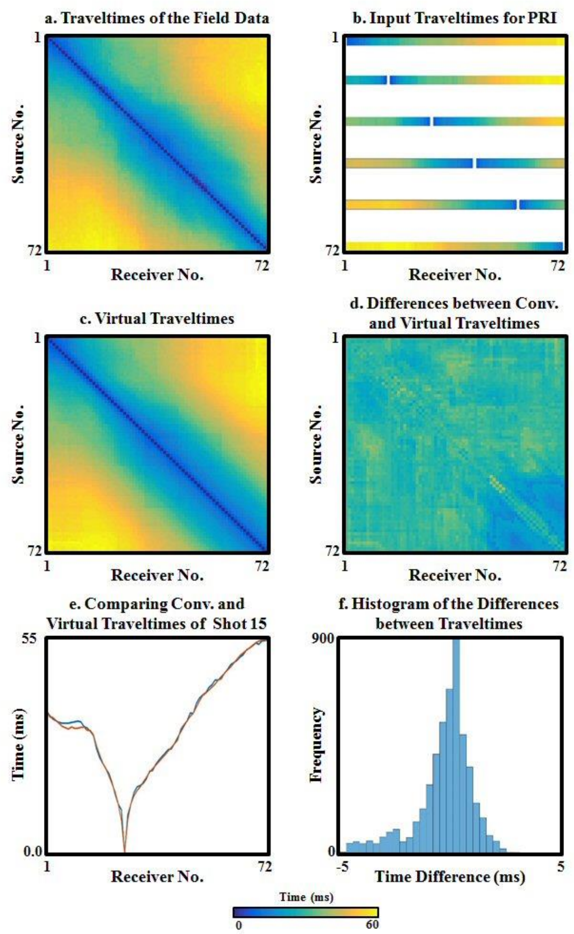

Figure 3: Validation of the PRI method using the conventional seismic data set. a) The traveltimes of the 72-recorded shot gathers, b) the 6-shot gathers used as input to the PRI method, c) the virtual first-arrival traveltimes calculated using the PRI method, d) the difference between the conventional a) and the virtual c) first-arrival traveltimes, e) the comparison between the conventional and the virtual first-arrival travetimes for shot gather No. 23. The blue and red lines indicates the conventional and virtual traveltimes, respectively, and f) the histogram of the differences between the conventional and the virtual first-arrival traveltimes.

Time-lapse Experiment.

The PRI method is now used to calculate the traveltimes of the 63 virtual shot gathers for all 90 sparse data-sets recorded at the field test. The goal is to track the plume of water as it percolates through the sand dune. Tracking is achieved by computing the velocity tomogram from the traveltimes obtained at time steps 1, 11, 21, ..., 81, and 90, where there is a time interval of about 30 minutes between two sequential steps. The tomograms from the other time intervals are also computed but we only show a few of them. First, the virtual traveltimes computed from the virtual shot gathers are inverted to calculate the P-wave velocity tomogram. Then these P-wave velocity tomograms are subtracted from the background P-wave velocity tomogram to get the relative velocity variations shown in Figure 4.

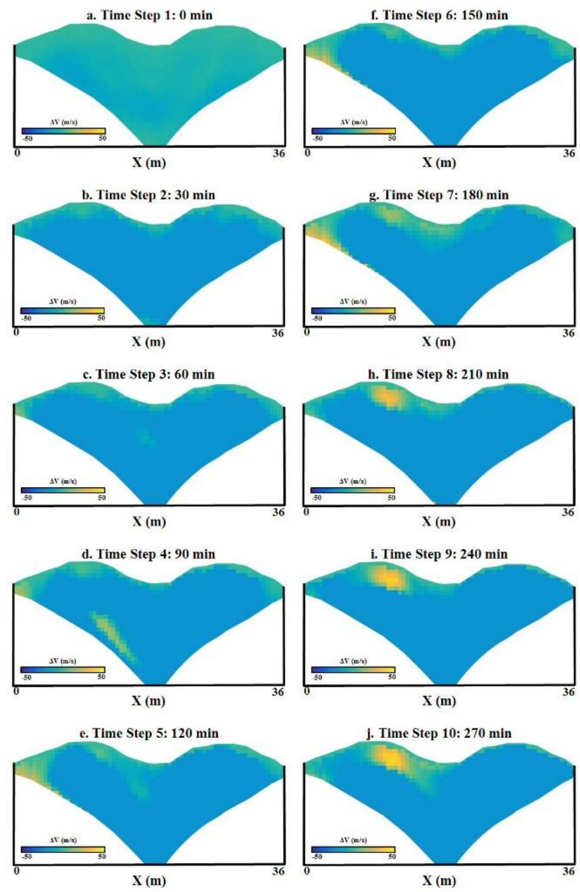

Figure 4: The differences in the P-wave velocities where the background P-wave velocity tomogram is used as a reference. Notice that the effect of the wet zone starts to appears at the experimental time of 120 minutes. The high-velocity anomaly (yellow) corresponds to the water injected from the ground surface, where the ground elevation varies by 1.3 m over the length of the survey line.

Figure 4 shows that velocity variations are very small for the first 180 minutes of the experiment, which does not show the location of the wet-zone. However, after 180 minutes a high-velocity anomaly (shown as yellow in Figure 4) appears at the water-injection zone, where the size of this anomaly increases with increasing experimental time (i.e. increasing amount of water injected into the subsurface). The velocity variations are not noticeable until the changes in the traveltimes are greater than the inherent traveltime error of

±3 ms as shown in Figures 3e and 3f. We believe this error is similar to a statics error associated with the PRI method. In the future we will estimate this statics shift from the reference data and use it to correct the virtual data. Thus, we hope to eliminate the statics errors and increase the accuracy of the tomograms.

Conclusions

The PRI technique is tested on time-lapse field data, where 90 data sets are recorded over 4.5 hours. During this time interval we injected 12 tons of water into the subsurface. Each sparse data set is recorded using only 6 shot gathers, which are then used to calculate the virtual first-arrival traveltimes of 63 virtual shot gathers. This process saves about 98% of the recording time required to record a conventional data set. Results shows that to get a distinguishable velocity variations, the traveltime changes need to be larger than the inherent traveltime picking error (±3 ms). In the future we hope to reduce this inherent traveltime error by estimating the statics shifts from the calibration data and applying them to the PRI data.

The PRI technique can be used as a real-time monitoring tool to characterize the physics of fluid flow in different materials. It has the potential for detecting the pathways, fractures and blockages of injected fluids in structures, such as buildings and dams. The time-lapse PRI technique is the first seismic method that can estimate in almost real time the velocity variations in the earth at intervals of less than a few minutes.

Acknowledgements

We thank the sponsors for supporting the Consortium of Subsurface Imaging and Fluid Modeling (CSIM). We also thank KAUST for the generous support. We also would like to thank the KAUST-IT team for computer time and the support they provided.

10.1190/segam2018-2986382.1

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