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Retrieval of the P- and S-velocity Structure of the Groningen Gas Reservoir Using Noise Interferometry

W. Zhou* (Utrecht University), H. Paulssen (Utrecht University)

Summary

The Groningen gas field in the Netherlands is the world's 7th largest onshore gas field and has been producing from 1963. Since 2013, the reservoir has been monitored by two geophone strings at reservoir level (3 km). For borehole SDM, 10 geophones with a natural frequency of 15-Hz are positioned from the top to bottom of the reservoir. We used seismic interferometry to determine, as accurately as possible, the inter-geophone P- and S-wave velocities from ambient noise. Cross-correlations were stacked for every 1 hour and 24(hours)*33(days) segments were obtained for each station pair. The cross-correlations show both diurnal and weekly variations reflecting fluctuations in cultural noise. The apparent P-wave travel time for each geophone pair is measured from the maximum of the vertical component cross-correlation for each of the hourly stacks. We used Kernel density estimations to obtain the maximum likelihood travel times of all the geophone pairs which were subsequently used to determine inter-geophone P-wave velocities. A good agreement was found between our estimated P velocity structure and well logging data. The S-velocity structure was obtained from the east-component cross-correlations. Because of the interference with P wave in east-component, the inferred S-velocity structure is less accurate.

Introduction

The Groningen gas field (Fig. 1 left) in the Netherlands is one of the world's largest onshore gas fields and has been producing from 1963. As a result of gas extraction, subsidence and induced seismicity occur, causing damage and concern in the area. Since 2013, which was the year with the highest level of induced seismicity, two geophone strings have been placed in two boreholes to monitor the reservoir. For borehole SDM (Fig. 1 right), 10 geophones are positioned almost vertically from the top to the bottom of the reservoir with a geophone spacing of 30 m. We used the ambient noise data recorded in this borehole to determine the 1D P and S wave velocity structure within the reservoir.

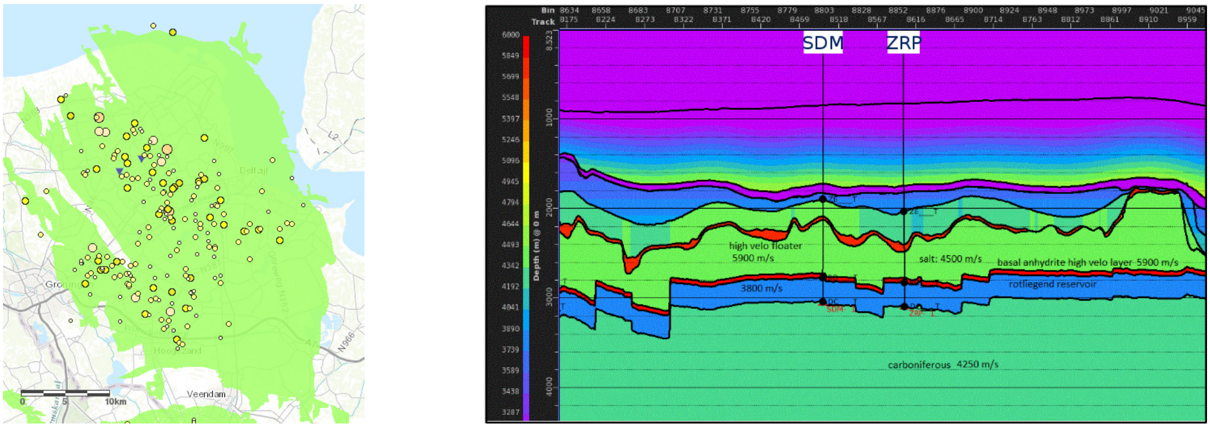

Figure 1: *Left: Groningen gas field (green) with seismicity (M_L 0.1-3.5; 2013-2014), and two borehole locations (blue inverted triangles). Right: P wave velocity model and borehole monitoring system.*

Empirical Green's function and data processing

In this study ambient noise interferometry was used to determine the velocity profile along the borehole. Under the assumption that ambient seismic noise is isotropically distributed, cross-correlation of records at two sensors provides an estimate of the Green's function between them (Snieder 2004; Wapenaar et al. 2010). For deep borehole data, the assumption can be satisfied for noise distributions mainly above or below the vertically aligned sensors. Previous studies have shown that body waves along borehole can be extracted by stacking noise cross-correlations over certain time (Miyazawa et al. 2008; Grechka and Zhao 2012; Vaezi and Van der Baan 2015; Behm 2016). Here we calculated the normalized cross-correlation $C_{sr}(t)$ (Richter et al. 2014; Durand et al. 2011):

$$C_{sr}(t) = \frac{S(t)}{\parallel S(t) \parallel} \star \frac{R(t)}{\parallel R(t) \parallel}.$$

Where $S(t)$ is the record at the reference geophone, $R(t)$ the record at receiver geophone, $\star$ stands for correlation, and $\|\|$ for the L^2 norm.

Continuous data from 21st November to 23rd December 2013 was used. A bandpass filter from 3 to 400 Hz was applied. After filtering, we used 1-bit normalization, setting all positive amplitudes to 1 while negative amplitudes were set to -1. This is a treatment to remove amplitude bias in the time domain. Spectral whitening was also applied to remove frequency bias. The normalized cross-correlations were calculated for 6 second segments with 4 second overlap. These segmented cross-correlations were stacked over 1 hour. Further processing was based on these stacks.

Figure 2 displays cross-correlation functions (CCFs) with the top geophone as a virtual-source for a 24-hour stack. In the left panel of Fig. 2, CCFs of vertical components of the 10 geophones are shown. A strong signal with an average velocity of about 3800 m/s is interpreted as the direct P wave. In the right-hand panel, CCFs of east components are shown. The two signals with apparent velocity 3800 m/s and 2200 m/s correspond to the direct P and S wave, respectively.

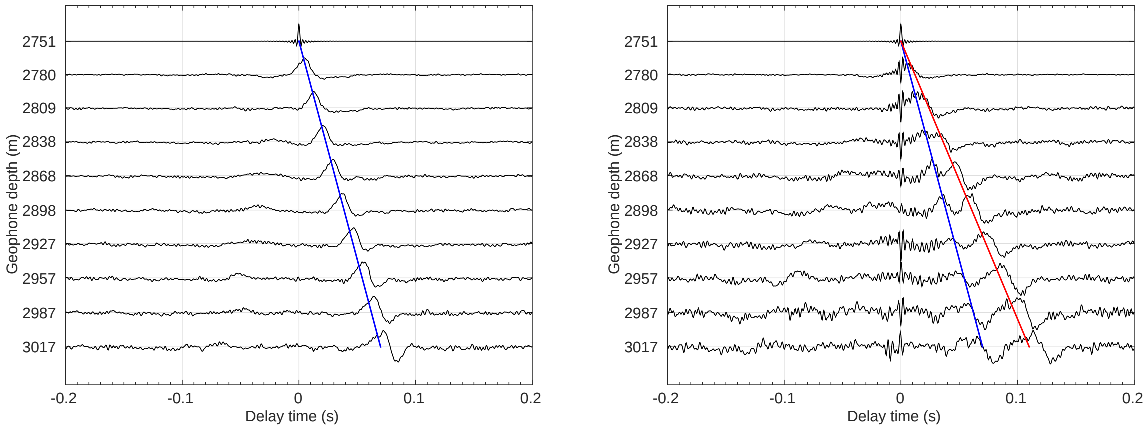

Figure 2: *Left: Vertical component cross-correlations with top geophone. Right: East component cross-correlations. Blue and red lines indicate P and S wave arrivals, respectively*

The causal parts of the hourly CCFs between the top and the bottom geophone are shown in Fig. 3 for the entire period of over 1 month of data. For each hourly stack an estimate of the travel time, given by the maimum of the CCF, is marked with a black dot. Figure 3 shows diurnal and weekly variation of the CCFs for both vertical and horizontal components. This indicates that the noise is dominated by cultural noise from the surface.

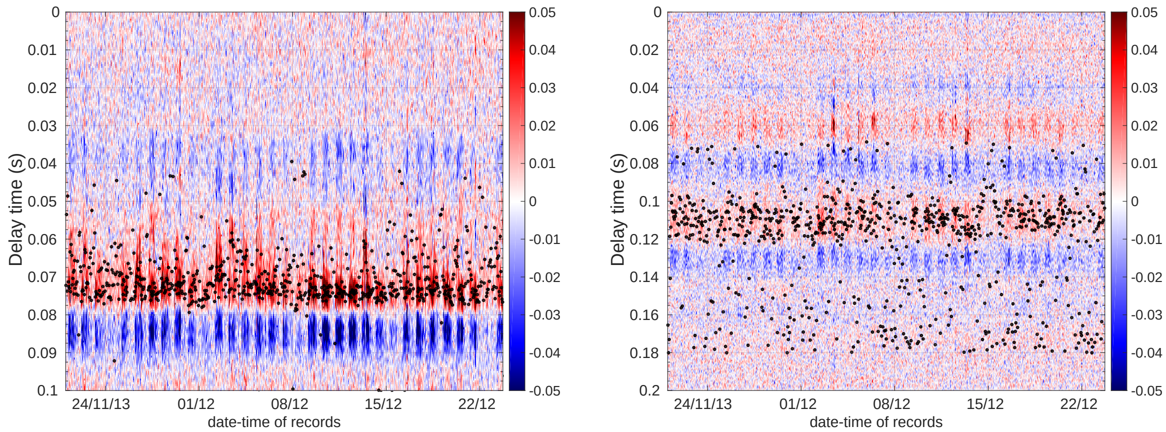

Figure 3: *Causal part of the CCFs between the top and the bottom geophone for the vertical component (left) and the east component (right). Black dots indicate estimated travel times obtained from the CCFs. The colorbar shows retrieved waveform amplitudes.*

Travel time estimation and velocity profile

The apparent P wave travel time for each geophone pair was measured from the maximum of the vertical component cross-correlation for each of the hourly stacks (Fig. 3 left). There are 33 (days) * 24 (hours) hourly stacks, so there are 33*24 P wave travel times for each geophone pair. We did the same for east component CCFs that showed the S arrival. In order to reduce the influence from the early arriving P waves, we set a time window with apparent velocity from 1500 m/s to 3500 m/s for S wave picking.

For each geophone pair, the travel times of the 33*24 hourly stacks were plotted as a histogram. Because the distribution of these apparent travel times is skewed for both the P and the S wave, we used the kernel density estimation (Botev et al. 2010) to obtain probability density functions (PDFs) of the travel times (Fig. 4). The maximum likelihood travel times of all the 45 geophone pairs were subsequently used to estimate the inter-geophone P and S wave velocities.

We treated the 45 maximum likelihood P wave travel times of all geophone pairs with a linear least square method, to determine the best fitting inter-geophone travel times and velocities. We could not use all S wave timings because of the interference of the P with the S wave (Fig. 2 right). Therefore only

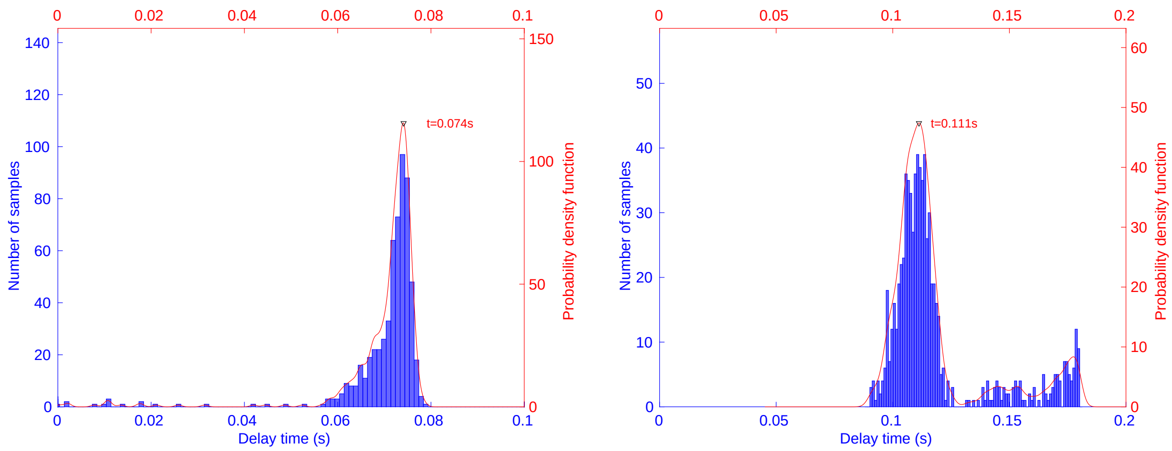

Figure 4: *Histogram (blue) for P wave (left) and S wave (right) travel times obtained from the CCFs between the top and the bottom geophone. Red lines represent PDFs obtained by kernel density estimation.*

geophones with a spacing larger than 3*30 m to the reference geophone were used. The inferred P and S velocity structure is shown in Fig. 5. Errors are estimated as twice the diagonal of the model covariance matrix. We found a good agreement between our P velocity structure and the acoustic logging, with differences less than 5%.

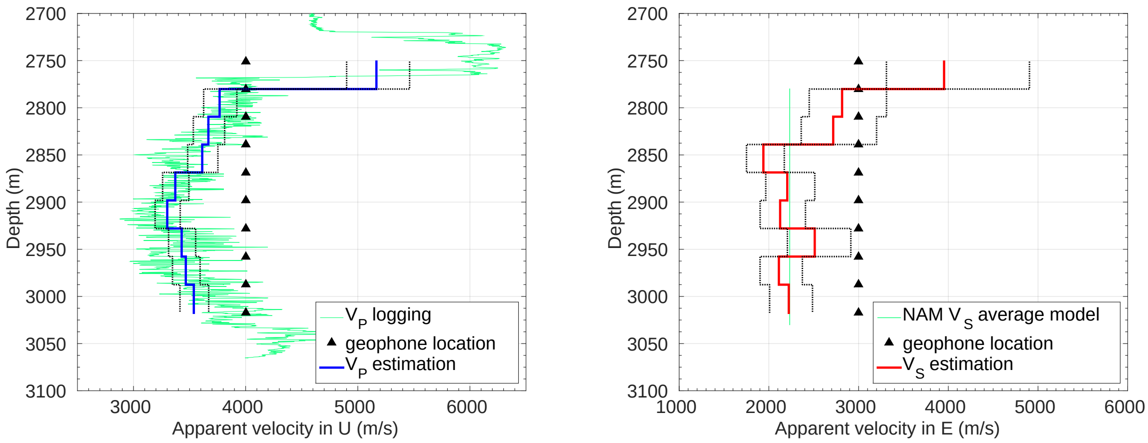

Figure 5: *Left: Estimated P velocity profile (blue) together with well logging data. Right: S velocity profile (red) with average S velocity. Well logging data and average S velocity in the reservoir (green) were provided by the NAM.*

Conclusion

In order to monitor the reservoir of Groningen gas field, we analyzed the data from the 10 vertically aligned geophones in borehole SDM that are positioned from the top to the bottom of the reservoir with 30 m geophone spacing. Using seismic noise interferometry, 33 days of continuous recording was analysed and clear direct P and S wave were obtained.

We found that the CCFs showed both diurnal and weekly variations reflecting fluctuations in cultural noise. Probability density estimations for the distributions of P and S travel times for each geophone pair were used to accurately determine the inter-geophone P and S travel times. A good agreement was found between our estimated P wave velocity structure and well logs, within 5%. S wave velocity was obtained with larger uncertainty. It is concluded that noise interferometry can be used to determine the seismic velocity structure from deep borehole data. In the future we will use this technique to monitor seismic velocity variations in the reservoir.

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