Supplementary materials for “Detecting Elevated Pore Pressure due to Wastewater Injection using Ambient Noise Monitoring”

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Figure S1: Daily peak ground acceleration (PGA) versus daily peak ground velocity (PGV) in all three seismic stations, with linear fitting in the log space, $\log(PGA) = a \times \log(PGV) + b$. We follow other studies to establish that the regime of ground motion is largely linear during this sequence (Guéguen, 2016; Chandra et al., 2015; Viens et al., 2018).

Figure S2: Processing steps starting from raw data to $dv/v$ measurements.
1 Text S1: On the relation between $dv/v$ and pore pressure

According to Ostrovsky and Johnson (2001), we can write the relation between the change of seismic velocity and isotropic strain $\epsilon_{kk}$:

$$dv/v = \beta \epsilon_{kk}.$$  \hfill (1)

Previous studies have reported estimates for $\beta$ using empirical data and measured or estimated isotropic strain ranging from $5 \times 10^3$ and $5 \times 10^4$ (Hillers et al., 2015a; Wegler et al., 2009; Ueno et al., 2012; Takano et al., 2017; Hillers et al., 2015b; Takano et al., 2019; Mao et al., 2019; Sens-Schönfelder and Eulenfeld, 2019). In following Rice and Cleary (1976) to write the constitutive relations of a poroelastic medium, and the definition of the Skempton’s coefficient $B$, $\Delta p = -B/3\sigma_{kk}$ (Skempton, 1954), the pore pressure is related to the dilatational strains:

$$p = -\frac{2GB}{3} \frac{1 + \nu_u}{1 - 2\nu_u} \epsilon_{kk},$$ \hfill (2)

$$dv/v = -\frac{3}{2GB} \frac{1 - 2\nu_u}{1 + \nu_u} \beta p,$$ \hfill (3)

$$dv/v = C p,$$ \hfill (4)

where $G$ is a rigidity of about $30 \times 10^9$, $B$ is on the order of 1, $\nu_u$ is the undrained Poisson ratio that could be taken as 0.25. This leaves a range of values for the constant $C \sim 10^{-7} - 10^{-6}$. 

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Table 1: Studies of coseismic velocity changes and peak ground accelerations (PGA).

<table>
<thead>
<tr>
<th>Earthquake sequence(s)</th>
<th>Coseismic velocity drop(%)</th>
<th>PGA (m/s²)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mogul, Nevada, U.S. Tocopilla, Chile Hokkaido, Japan Four areas in Japan</td>
<td>0.5 -1.0 1.1 2- 3 0.77 -0.85</td>
<td>5.9-11.67 0.4 9.6 1.0 -29.4</td>
<td>von Seggern and Anderson (2017) Richter et al. (2014) Ikeda and Takagi (2019) Hobiger et al. (2016)</td>
</tr>
<tr>
<td>M 4.1 2010/10/11</td>
<td>2</td>
<td>2</td>
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</tr>
<tr>
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<td>1</td>
<td>2</td>
<td>ARK2</td>
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<tr>
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<td>WHAR</td>
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<td>2.5</td>
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<td></td>
<td>7.5 (5)</td>
<td>0.1</td>
<td>WHAR</td>
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</tbody>
</table>

References


Figure S3: Day-stacked auto-correlations of Z-Z component pair at the ARK1 station filtered between 0.2-1 Hz. (a) shows the auto-correlations with lag time from 2 to 20 s where we select our phase lag measurements. (b) shows the reference auto-correlation (blue) and the example of one day-stacked auto-correlations, within the lag times between selected for our $dv/v$ measurements (2 and 12 s).


Figure S4: Day-stacked auto-correlations of N-N component pair at the ARK1 station filtered between 0.2-1 Hz. (a) shows the auto-correlations with lag time from 2 to 20 s where we select our phase lag measurements. (b) shows the reference auto-correlation (blue) and the example of one day-stacked auto-correlations, within the lag times between selected for our $dv/v$ measurements (2 and 12 s).


Figure S5: Day-stacked auto-correlations of E-E component pair at the ARK1 station filtered between 0.2-1 Hz. (a) shows the auto-correlations with lag time from 2 to 20 s where we select our phase lag measurements. (b) shows the reference auto-correlation (blue) and the example of one day-stacked auto-correlations, within the lag times between selected for our $dv/v$ measurements (2 and 12 s).


Richter, T., Sens-Schönfelder, C., Kind, R., and Asch, G. (2014). Comprehensive observation and modeling of earthquake and temperature-related seismic velocity changes in northern chile with passive image interferometry. Journal...
Figure S6: Daily peak ground acceleration (PGA) versus seismic velocity drops in all three seismic stations, with linear fitting $PGA = G \cdot (-\frac{dv}{v})$ and nonlinear fitting $PGA = G \cdot \frac{(-\frac{dv}{v})}{(1 - \frac{dv}{v} \cdot \alpha)}$. The more transparent dots represent the daily velocity variations which are smaller than the standard deviation of $\frac{dv}{v}$ in the first and a half months at each station.


Figure S7: Time-frequency crosscorrelation coefficients of Z-Z component at three stations.

References:


Figure S8: Station ARK1 $\Delta v/v$ of E-E (a), N-N (b) and Z-Z (c) components. (d) shows the relative velocity changes ($\Delta v/v$) at 0.4 Hz, 0.8 Hz, and the average $\Delta v/v$ from 0.4 to 1 Hz. Data on 2010-07-12 only has a small portion of frequency with $cc_{after} > 0.9$ (as shown by Figure S7), therefore, it was not included in Figure 2 but is shown here.
Figure S9: Station ARK2 $dv/v$ of E-E (a), N-N (b) and Z-Z (c) components. (d) shows the relative velocity changes ($dv/v$) at 0.4 Hz, 0.8 Hz, and the average $dv/v$ from 0.4 to 1 Hz. Data on 2010-07-12 only has a small portion of frequency with $cc_{after} > 0.9$ (as shown by Figure S7), therefore, it was not included in Figure 3 but is shown here.
Figure S10: Station WHAR $dv/v$ of E-E (a), N-N (b) and Z-Z (c) components. (d) shows the relative velocity changes ($dv/v$) at 0.4 Hz, 0.8 Hz, and the average $dv/v$ from 0.4 to 1 Hz.
Figure S11: Similar to Figure 5b but for ARK1 (a) and ARK2 (b).