Results presented in the presentation has been already published in the following paper:


Please consider referring to the above paper if you find this presentation useful!
Theoretical limits on detection and analysis of small earthquakes

Grzegorz Kwiatek\textsuperscript{1} and Yehuda Ben-Zion\textsuperscript{2}

1. Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Section 4.2: Geomechanics and Rheology, Potsdam, Germany
2. University of Southern California, Department of Earth Sciences, Los Angeles, USA
Study

• Improve understanding of theoretical limits to detection of seismic events
• Clarify limitations for reliable derivation of source characteristics

Can we detect and reliably analyze earthquake in a particular combination of source, path, sensor and noise characteristics?

Can we provide first-order guidelines on designing local/regional seismic networks in various geological environments to reliably estimate the source characteristics?
Simulation parameters

- **Seismic source**
  - size, slip, rupture velocity
  - radiation pattern
  - STF directionality

- **Path effects**
  - geometrical spreading
  - attenuation

- **Noise effects**
  - HF noise

- **Sensor effects**
  - BB, short period
  - Fixed sampling rate and AA filter
Source modelling

- Rupture process described by $M_0$, $\Delta \sigma$, and $V_R$.
- Rupture propagates radially with constant $V_R$ and stops abruptly.
- Radiation pattern: pure shear and pure tensile failure considered.

\[
M_0 = \mu U \pi r^2
\]
\[
\Delta \sigma = \frac{7 M_0}{16 r^3}
\]

$V_R$
Source characteristics and amplitude/frequency content

- RMS amplitude variations averaged over focal mechanisms and observations points vary between -23dB and +14dB w/r to source with $\Delta\sigma = 1MPa$ and $V_R = 0.9V_S$
Influence of attenuation

• Attenuation diminishes the high-frequency content of waves

• Two cases considered: \( Q_P = Q_S \) and \( Q_P = \frac{9}{4}Q_S \)

\[
Q_C(f) = \exp\left(-\frac{\pi f R}{V_C Q_C}\right)
\]

1. Influence of attenuation

2. Examples of attenuation effects on ground displacement

3. Graphs showing attenuation over frequency and time
Noise

- Low frequency noise from *Peterson* (1993)
- High-frequency noise from various sites (surface and borehole sensors)
Sensor characteristics

- Different low-frequency cut-off (100s, 4.5Hz, 15Hz)
Results: Detection limits

- Sample detection limits using $P$-waves, GS11D sensor, $\Delta \sigma = 1\text{MPa}$ and $V_R = 0.9V_S$
Results: Attenuation and distance vs frequency content

- High frequencies suppressed due to attenuation
Results: Should we use P or S wave for detection?

- Amplitude/frequency content of S phases generally more affected by attenuation
- The smaller & further the event, the less preferable is S phase for detection

\[ Q_S = Q_P \text{ (~saturated)} \]

\[ Q_S = 4/9 Q_P \text{ (~Poisson solid)} \]
Summary

• We investigated theoretical limits on detection and analysis of small earthquakes using synthetic seismograms including influence of path, noise and properties of acquisition systems.

• We provide guidelines on designing local-to-regional seismic networks for detection of small events in various geological environments, and information relevant to a reliable analysis of earthquake source properties.
Conclusions

• The amplitude RMS-averaged over focal mechanisms and observations points vary between -23dB and +14dB with respect to the standard shear source. The P-wave amplitudes of a pure tensile source may be enhanced by up to +12dB (unlikely).

• Amplitude/frequency content of waves excited from source is predominantly affected by $M_W$ and $\Delta \sigma$. The rupture velocity and radiation pattern have minor effects. In realistic scenarios, tensile faulting has no significant influence on S/N ratio.

• Distance and attenuation key limiting factors for EQ detectability and analysis of source properties.

• In certain circumstances, stronger attenuation of S waves may favor earthquake detection using P waves.

• Acquisition system characteristics seriously affect the detection and ability to analyze source properties of both small and large earthquakes.
Thank you for your attention!

Questions?
Signal-to-noise ratio calculation

- Bandpass filter 1-1000Hz applied to synthetic trace with superimposed noise

\[
\frac{S}{N} [\text{dB}] = 20 \log_{10} \frac{\max(V(t))}{\text{rms}(N(t), l)}
\]
Results: Source variability vs amplitude

- RMS maximum ground velocity amplitude vary from -23dB to +14dB w/r to the seismic source with $\Delta\sigma = 1\text{MPa}$ and $V_R = 0.9V_S$.
- Pure tensile faulting enhances RMS $P$-wave radiation by +12dB (unrealistic!)
Effects of attenuation and distance on frequency content

- Influence of sensor characteristics on low-frequency part of the spectrum
Detection limits (aggregated source and path characteristics)

- GS11D sensor, $P$-wave

<table>
<thead>
<tr>
<th>Distance</th>
<th>1km</th>
<th>10km</th>
<th>100km</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_p$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta \sigma$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>S/N ratio [dB]</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moment magnitude</td>
<td>-3</td>
<td>-2</td>
<td>-1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

0.5, 0.7, 0.9 $V_s$
Motivation

- Detecting smaller events important
  - Increases resolution of monitoring and analyzing seismic processes associated with natural and human-related activities
- Denser networks closer to target source but...
  - Detection limits in various source/path/instrumental effects not well established