Made to Measure: On the Performance and Limitations of Seismic Instrumentation

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September 2016
Introduction

• Appropriate instrumentation selection is one of the most critical aspects of the seismic monitoring system design

**GOAL:** Accuracy of ground motion measurements, and resulting data products, is not impacted by the sensing technology used.

• Focus on the induced seismic monitoring (ISM) use case
  • Global earthquake seismology and microseismic use cases well understood
• Each sensing technology has a use case – one size does not fit all
• Presentation summary
  • Outline seismic instrumentation selection process
  • Apply the selection process to ISM use case
  • Comment on common instrumentation types
  • Highlight instrumentation-related data accuracy issues in ISM data sets
The Seismic Instrumentation Selection Process

**STEP 1:** Identify application and monitoring objectives.

**STEP 2:** Express the monitoring objectives in terms of desired seismic data products.

**STEP 3:** Determine the target ground motion range at the receiver that will result in accurate desired data products.

**STEP 4:** Identify the key instrumentation performance specifications linked to the target ground motion range.

**STEP 5:** Select the instrument with the best performance in the target ground motion range.
Effective induced seismic monitoring (ISM)

- Meet regulations
  - Accurate source parameters for M2.0> events (AER)
  - Accurate ground motion measurements PGA, PGV, RSA >0.02g (BC OGC)
- Manage induced seismicity risk
  - Richest seismic catalog to compute seismicity rate and b-value in real-time
- Provide inputs into emergency response
  - Accurate real-time shake maps
  - Structural integrity warnings if PGA/RSA exceeds a design threshold
- Facilitate research
  - Accurate amplitudes over a wide magnitude and distance range to …
    - calibrate magnitude equations
    - calibrate ground motion attenuation models (GMPEs)
  - Update seismic hazard
Event Spectra Modeling

Ground motion spectrum at the receiver (sensor)

Target ground motion range

Path modeling parameters:
- Source – receiver distance
- Geometrical spreading
- Anelastic attenuation (Q)

Source forward modeling inputs:
- Magnitude
- Stress drop
- Source velocity and density
- Radiation pattern

Path: represents the decay of ground motion amplitudes.

Site: site amplification (surface geology)

Source: describes amplitude and frequency content of waves radiated from an earthquake source assuming a point source approximation.

Describes amplitude and frequency content of waves radiated from an earthquake source assuming a point source approximation.
Importance of Spectral Analysis

Able to identify amplitude and frequency range of interest …

Seismic moment

\[ M_0 = \frac{\Omega_{\text{low}}}{R_{\phi}} \left( \frac{4\pi \rho \beta^3}{F V} \right) \]

Moment magnitude

\[ M_w = \frac{2}{3} \log(M_0) - 10.7 \]

Corner frequency

\[ f_0 = \sqrt{\frac{\Omega_{\text{high}}}{R_{\phi}} \left( \frac{4\pi \rho \beta^3 f^2}{F V} \right)} \]

Stress drop

\[ \Delta \sigma = M_0 \left( \frac{f_0}{4.9 \times 10^6 \beta} \right)^3 \]

Source radius

\[ r = 7.59 \times 10^{-8} (M_0/\Delta \sigma)^{1/3} \]

Ground motions

\[ PGA, PGV, RSA \ (at \ Xs) \]
Earthquake Receiver Spectrum

With increase in event magnitude:
- Amplitude at the receiver increases
- Corner frequency shifts to lower frequencies

With increase in hypocentral distance:
- Amplitude at the receiver decreases
- Corner frequency shifts to lower frequencies
• Induced seismicity characteristics:
  – Recorded at hypocentral distances \(\sim 4\) to \(30\) km
  – Aim for events in magnitude range \(\sim -0.5\) to \(4.5\)
• Corresponding frequency range of interest:
  – Passband \(\sim 0.1\) Hz to \(\sim 80\) Hz

Shaded area represents the target ground motion range for ISM
Key Instrumentation Selection Criteria
(Step 4)

Measurement Bandwidth
• Ground motion frequency range that can be adequately measured by the instrument
• Bandpass filter analogy
• Must encompass GM passband

Dynamic Range

- Broadband instruments
- Geophones

Clip Level
• Determines the largest signal instrument can measure before it saturates
• Must meet target GM max amplitudes

Self Noise Performance
• Determines the smallest signal instrument can measure across its passband
• GM min amplitudes
Matching Targets to Instrument Performance (Step 5)

- Match noise floor, clip level and response to ISM frequency – amplitude content
- Maximize the overlap between instrument performance and target ground motion range

ISM Monitoring application requires broadband (BB) instrumentation

* Quietest Class A accelerometer in the market
Summary

- Instrument selection is the key aspect of seismic monitoring system design
- Identify frequency and amplitude content of the target ground motions and select an instrument with matching performance
- ISM use case overlaps with traditional local and regional seismology and thus requires the use of broadband instruments
- Geophones lack low frequency response
  - Microseismic and active seismic monitoring
- Seismometer – low self-noise
  - Preferred if richer catalog (risk management) is the main objective
  - Magnitude-based regulations
- Accelerometer – high clip level
  - Preferred if emergency response is the main objective
  - Key to near field ground motion characterization – hazard maps
  - Ground motion-based regulations
Thank You

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BB Instrument Selection

- Accelerometer – response proportional to acceleration
- Seismometer – response proportional to velocity
  - Accelerometer at its core
- Often co-located
- Key difference = **low self-noise vs high clip level**
- Both used for ground motion measurement and source parameter computations

Havskov & Alguacil (2002)

Site noise plays a key role in BB instrument selection

- Station noise should be dominated by site noise
- If site is noisy, instrument noise floor may not matter
Selection Criteria (continued)

- **Instrument cost**
  - Primarily driven by instrument bandwidth and noise floor

- **Sensitivity**
  - Active instruments have higher sensitivity

- **Deployment methodology**
  - Vault, surface, direct burial posthole, borehole, cabled or individual node
  - Direct impact on the overall **cost**

- **Tilt range**
  - Trade-off between tilt range and noise floor

- **Power consumption**
  - Active vs passive devices
  - Higher power consumption drives up power system **costs** (if autonomous)

- **Environmental specifications**
  - Level of water resistance
Earthquake Receiver Spectrum

Event A: Record M4.0 event recorded at 40 km
- High amplitude
- Corner frequency at ~0.5 Hz

Event B: Record M-3.0 event recorded at 300 m
- Low amplitude
- Corner frequency at ~300 Hz

- Use cases 1 and 2 require different instruments to adequately characterize
- Induced seismicity characteristics:
  - Recorded at hypocentral distances ~ 4 to 30 km
  - Events in magnitude range ~ 0 to 4.5
  - Frequency range of interest ~ 0.1 to 30 Hz
## Instrument Comparison

<table>
<thead>
<tr>
<th></th>
<th>Accelerometer</th>
<th>BB Seismometers</th>
<th>VBB Seismometers</th>
<th>Geophones</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physical</strong></td>
<td></td>
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<tr>
<td><img src="image" alt="Accelerometer" /></td>
<td><img src="image" alt="BB Seismometers" /></td>
<td><img src="image" alt="VBB Seismometers" /></td>
<td><img src="image" alt="Geophones" /></td>
<td></td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Lower corner f</strong></td>
<td>DC</td>
<td>&gt;40s (&lt;0.025 Hz)</td>
<td>&gt;120s (&lt;0.008 Hz)</td>
<td>1, 2, 4.5, 10, 15 Hz</td>
</tr>
<tr>
<td><strong>Higher corner f</strong></td>
<td>&gt;400 Hz</td>
<td>&gt;100 Hz</td>
<td>&gt;40 Hz</td>
<td>High</td>
</tr>
<tr>
<td><strong>Clip level</strong></td>
<td>High (4g)</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>N/A (Passive)</td>
</tr>
<tr>
<td><strong>Installation</strong></td>
<td>Vault, posthole, direct burial</td>
<td>Vault, posthole, direct burial</td>
<td>Vault</td>
<td>Direct burial</td>
</tr>
<tr>
<td><strong>Application</strong></td>
<td>Structural monitoring, strong motion recording</td>
<td>Surface microseismic, local and regional seismic monitoring</td>
<td>Teleseismic earthquake seismology</td>
<td>Microseismic monitoring, active seismic applications</td>
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