Monitoring and Numerical Modelling of Induced and Triggered Seismicity in a Deep Sublevel-Stoping Mine

Francesca De Santis (1,2), Yann Gunzburger (2), Vincent Renaud (1)
Isabelle Contrucci (1), Pascal Bernard (3)

(1) Institut National de l’Environnement Industriel et des Risques (Ineris); (2) GeoRessources, Université de Lorraine; (3) IPGP
### Objective of the study

**Why compare seismic and model data?**

**Microseismic Monitoring**  
Real-time monitoring for short-term prevention

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global in site measurements</td>
<td>Precision of detection and location</td>
</tr>
<tr>
<td>Real time monitoring</td>
<td>No detection of aseismic deformation</td>
</tr>
<tr>
<td>Insight into fractures dynamic</td>
<td>Local measures</td>
</tr>
</tbody>
</table>

**Numerical modelling**  
Optimization of future excavations

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long-term prediction</td>
<td>Needs lots of geo-mechanical information</td>
</tr>
<tr>
<td>Simulation of different excavation sequences</td>
<td>High computational requirements</td>
</tr>
<tr>
<td>Global view of stress changes</td>
<td></td>
</tr>
</tbody>
</table>

**Finding possible links**

- Better understanding of interactions between stress changes and seismic activity generation
- Gaining additional insights into failure processes
- Improving long-term and short-term prevention
Garpenberg mine

Geographic and Historical context

- **Sweden's oldest mining area still in operation**
- Deposits first mined in the 13th century
- Acquired by Boliden in 1957 (300,000 tonnes/year)
- Discovery of Lappberget orebody in 1998
- Production moved in Garpenberg North in 2004

Extracted ore in 2016
2,622,000 t

- Zinc
- Lead
- Copper
- Silver
- Gold

Schematic vertical profile of Garpenberg mine

Lappberget monitoring network

- Acquired by Boliden in 1957 (300,000 tonnes/year)
- Discovery of Lappberget orebody in 1998
- Production moved in Garpenberg North in 2004
**Garpenberg mine**

**Production & Injuries**

*Amount of produced ore [kt] (1957-2014)*

*Number of injuries (1996-2014)*

**Mass mining methods**

**Improve automation and digitalization**

**Microseismic monitoring**
Lappberget orebody

Mining method and sequence

Sublevel stoping method with backfilling

Plan view

Drift excavation: Development Blasts

Foot-wall drift

Secondary drift

Primary drift

Orebody profile

Vertical section

Stope excavation: Production Blasts

2014

2015 - 2016

25 m

Stope 13

2014

2015 - 2016

25 m

Stope 13

3D view between 2 levels

Drift excavation:

Development Blasts

November 2015

December 2016

Mining sequence
Lack of data:

- Characteristics of fractures, joints or faults
- Mechanical properties of rock types
- No 3D information except for the orebody
Analysis of Lappberget Microseismic Activity between 2015 and 2016
Mining Production & Microseismic Activity

Space-time distribution

**Microseismic swarms**

Extracted rock mass volume:
- 1000-3000 m³
- 3000-4000 m³
- 4000-5000 m³
- 5000-6000 m³
- ≥ 6000 m³

**Mined Stopes**

Stope 13
Mining Production & Microseismic Activity
Cluster of MSE

First period
- Central Cluster
- Right Cluster

Second period
- Central Cluster
- Right Cluster

Cumulative MSE number over time:
- First period
- Second period

Time [year-month]:
- 15-03
d- 15-06
- 15-09
- 15-12
- 16-03
- 16-06
- 16-09
- 16-12

Cumulative CC events:

Cumulative RC events:

Stope 13

X [m]:
- 3600
- 3650
- 3700
- 3750
- 3800
- 3850
- 3900

Y [m]:
- 450
- 550

Z [m]:
- 1050
- 1100
- 1150
- 1200
- 1250

Cum. MSE number:
- 0
- 50
- 100
- 150
- 200
- 250
- 300
- 350
- 400

Stope 13 coordinates:
- 3
- 4
- 5

MSE: Microseismic Event
Seismic source characteristics
Fracture size and Apparent Stress

Fracture dimension

- Source radius: from 0.3 m up to 32 m
- Median RC radius = 0.9 m
- Median CC radius = 3 m

Source radius $[m]$ vs Cumulative [%]

$\begin{align*}
  f_c &= k_c \frac{V_S}{r} \\
  k_c &= \text{constant} [-] \\
  r &= \text{source radius} [m] \\
  V_S &= \text{S wave velocity} [m/s]
\end{align*}$

Moment magnitude

- Apparent stress $\Rightarrow$ measure of stress release at a seismic source
- Bigger stresses in the Right Cluster area

Seismic moment $[J]$ vs Seismic energy $[J]$
Seismic source characteristics

Apparent stress

Contour maps of apparent stress

First period
February 2015 - May 2016

Second period
June 2016 - December 2016
Conclusions on seismic data analysis

<table>
<thead>
<tr>
<th>Central Cluster</th>
<th>Right Cluster</th>
</tr>
</thead>
<tbody>
<tr>
<td>In agreement with production in the area</td>
<td>Linked with remote blasting in stope 13</td>
</tr>
<tr>
<td>Active since the beginning of the monitoring</td>
<td>Activated at final stages of stope 13 exploitation + Influenced by local geology</td>
</tr>
<tr>
<td>Bigger fractures</td>
<td>Smaller fractures</td>
</tr>
<tr>
<td>Lower apparent stress values</td>
<td>High apparent stress values</td>
</tr>
</tbody>
</table>
Numerical Modelling

Simulation of the exact mine sequence between 2015 and 2016
1. Galleries & Stopes
2. Weak & Very weak zones
3. Orebody
Upper levels mesh = 5 m

Ore extension

Upper levels

Limits of the model

Box mesh = 20 m
Numerical Model  
Boundary Conditions & Mechanical Parameters

**Initials & Boundary Conditions**

\[
\sigma = f(z) = \rho g \left( \frac{k_X}{k_Y} \right) z \quad \begin{cases} 
\sigma_X = 44.3 \text{ MPa} \\
\sigma_Y = 47.3 \text{ MPa} \\
\sigma_Z = 34 \text{ MPa} \end{cases}
\]

**Failure criteria**

*Hoek-Brown failure criteria*

\[
\frac{\sigma_1}{\sigma_C} = \frac{\sigma_3}{\sigma_C} + \sqrt{m \frac{\sigma_3}{\sigma_C} + S}
\]

*Brittle failure criteria*

\[
\sigma_1 = \sigma_3^{b-d}
\]

**Elastic parameters**

<table>
<thead>
<tr>
<th>Materials</th>
<th>Young modulus E [MPa]</th>
<th>Poisson’s ratio $\nu$</th>
<th>$m$</th>
<th>$s$</th>
<th>$\sigma_c$ [MPa]</th>
<th>Density $\rho$ [kg/m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore</td>
<td>66000</td>
<td>0.2</td>
<td>10</td>
<td>0.112</td>
<td>188</td>
<td>3030</td>
</tr>
<tr>
<td>Limestone</td>
<td>57000</td>
<td>0.18</td>
<td>10</td>
<td>0.112</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>Weak</td>
<td>20000</td>
<td>0.3</td>
<td>1</td>
<td>0.001</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Very weak</td>
<td>2000</td>
<td>0.4</td>
<td>0.63</td>
<td>0.00024</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Paste</td>
<td>500</td>
<td>0.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2000</td>
</tr>
</tbody>
</table>

**Brittle failure criteria parameters**

<table>
<thead>
<tr>
<th>Materials</th>
<th>$m_r$</th>
<th>$\sigma_3^{b-d}$</th>
<th>$s_r$</th>
<th>$\xi_r$</th>
<th>$\beta_m$</th>
<th>$b_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore</td>
<td>2</td>
<td>$\sigma_c^{*}(s)^{1/2}$</td>
<td>$s*1e^{-5}$</td>
<td>0.0025</td>
<td>tan(15°)</td>
<td>750</td>
</tr>
</tbody>
</table>

(Souley et al., 2018)
Numerical Model

Model Results

Step 15 – 2015/03/15
Level 1182

Step 25 – 2016/02/09
Level 1182

Step 41 – 2016/08/03
Level 1182

Step 52 – 2016/12/28
Level 1182

Deviatoric stress $^*$ [MPa]

$q_{ini} = 12.1 \text{ MPa}$

$\sigma_{x_{ini}} = 44.3 \text{ MPa}$

$\sigma_{y_{ini}} = 47.3 \text{ MPa}$

$\sigma_{z_{ini}} = 34 \text{ MPa}$

\[
q = \sqrt{3J_2} = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_3 - \sigma_2)^2]}
\]
Numerical Model

Model Results

\[ q^{ini} = 12.1 \text{ MPa} \]
\[ \sigma_x^{ini} = 44.3 \text{ MPa} \]
\[ \sigma_y^{ini} = 47.3 \text{ MPa} \]
\[ \sigma_z^{ini} = 34 \text{ MPa} \]

Deviatoric stress \(^* \text{[MPa]} \):

- 5.0000E+01
- 4.7500E+01
- 4.5000E+01
- 4.2500E+01
- 4.0000E+01
- 3.7500E+01
- 3.5000E+01
- 3.2500E+01
- 3.0000E+01
- 2.7500E+01
- 2.5000E+01
- 2.2500E+01
- 2.0000E+01
- 1.7500E+01
- 1.5000E+01
- 1.2500E+01
- 1.0000E+01
- 7.5000E+00
- 5.0000E+00
Seismic Data and Model Data comparison
Seismic Data & Model Data

1st approach of comparison: individual measures

Seismic parameters
Punctual measures at seismic events locations

⇔

Model parameters
Measures within the whole space

Model parameters calculated inside meshes at the position of MSE location

<table>
<thead>
<tr>
<th>Seismic parameters</th>
<th>Model parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>E – seismic energy</td>
<td>Stress variables</td>
</tr>
<tr>
<td>M₀ – seismic moment</td>
<td>σ₁ – max. principal stress</td>
</tr>
<tr>
<td>Mₖ – moment magnitude</td>
<td>σ₁ – max. principal strain</td>
</tr>
<tr>
<td>fₖ – corner frequency</td>
<td>σ₂ – inter. principal stress</td>
</tr>
<tr>
<td>σ’app – apparent stress</td>
<td>σ₂ – inter. principal strain</td>
</tr>
<tr>
<td>Vₐ’app – apparent volume</td>
<td>σ₃ – min. principal stress</td>
</tr>
<tr>
<td>Δσ – stress drop</td>
<td>σ₃ – min. principal strain</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stress variables</th>
<th>Strain variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ₁ – max. principal stress</td>
<td>ε₁ – max. principal strain</td>
</tr>
<tr>
<td>σ₂ – inter. principal stress</td>
<td>ε₂ – inter. principal strain</td>
</tr>
<tr>
<td>σ₃ – min. principal stress</td>
<td>ε₃ – min. principal strain</td>
</tr>
<tr>
<td>σᵢⱼ – stress tensor</td>
<td>εᵢⱼ – strain tensor</td>
</tr>
<tr>
<td>σₐ – Von Mises stress</td>
<td>εₐ – Von Mises strain</td>
</tr>
</tbody>
</table>
Seismic Data & Model Data

Qualitative Analysis

Model parameter

Seismic parameter

Mean deviatoric stress

Mean apparent stress

Stope 13

\[ s_q \] [MPa]

\[ \log_{10}(\text{meanAppStress}) \]
Seismic Data & Model Data

Quantitative Analysis: Principal Component Analysis

- $r = 0.0296$
- $r = 0.0512$
- $r = 0.0441$
- $r = 0.0287$
- $r = -0.0196$
- $r = 0.0126$
- $\sqrt{q}$
Seismic Data & Model Data

2nd approach of comparison: cumulated measures

Seismic parameters
Punctual measures at seismic events locations

Cumulated model parameters calculated inside the spheres of 10 m radius around each seismic events location

Model parameters
Measures within the whole space

<table>
<thead>
<tr>
<th>Seismic parameters</th>
<th>Model parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>E – seismic energy</td>
<td>Elastic</td>
</tr>
<tr>
<td>$M_0$ – seismic moment</td>
<td>Plastic</td>
</tr>
<tr>
<td>$V_a$ – max. principal stress</td>
<td>Volumetric energy</td>
</tr>
<tr>
<td>$A_s$ – Source area</td>
<td>Plastic energy</td>
</tr>
<tr>
<td></td>
<td>Volumetric plastic energy</td>
</tr>
<tr>
<td></td>
<td>Shear elastic energy</td>
</tr>
<tr>
<td></td>
<td>Plastic volume</td>
</tr>
<tr>
<td></td>
<td>Total plastic energy</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Von Mises stress and strain</td>
<td></td>
</tr>
<tr>
<td>Mean of max. shear strain</td>
<td></td>
</tr>
<tr>
<td>Volumetric strain</td>
<td></td>
</tr>
<tr>
<td>Shear strain</td>
<td></td>
</tr>
</tbody>
</table>

Image of 3D model with spheres and axes.
Seismic Data & Model Data

Qualitative Analysis

\[ \text{Apparent volume} \Rightarrow V_a = \frac{M_0^2}{2\mu E} [m^3] \]

\[ \text{Plastic volume} \Rightarrow \text{volume of plastic zones in the spheres} \]
Seismic Data & Model Data

Qualitative Analysis

\[ \text{Source area} \Rightarrow A_s = \pi r^2 \quad [m^2] \]
\[ r \text{ determined from } f_c = k_c \frac{V_s}{r} \]

\[ \text{Volumetric strain} \Rightarrow t_r(\varepsilon) \]

\[ \text{Apparent volume} \Rightarrow V_a = \frac{M_0^2}{2\mu E} \quad [m^3] \]
\[ \text{Von Mises strain} \Rightarrow \varepsilon_q = \sqrt{\frac{4}{3}J_2} \]
Discussion and Perspectives

- Seismic & numerical model shows increasing stresses around the main production area

- Spatialization problem
  - Uncertainties in events location & model uncertainties
  - Reactivation of preexisting structure not taken into account in the model

- Cumulating seismic and numerical parameters in space correlations are improved

  - Improvement of events detection and location
    - Detection: bigger number of seismometers and continuous recordings
    - Location: new location methods based on double difference and multiples analysis

  - Include fractures in the model
    - Bigger fractures of CC may be modeled based on focal mechanism of MSE
    - Smaller fractures of RC cannot be included in the model with the actual mesh
      ⇒ reduce mechanical properties of some meshes?

  - Taking creep into account
    - Seismic swarms are long lasting in time (more than 1 month)
    - Stress measurements have sown a differential response of deformations during time
Questions?

References


Extracted rock mass volume for **Production Blasts**:

- 1000-3000 m³
- 3000-4000 m³
- 4000-5000 m³
- 5000-6000 m³
- ≥ 6000 m³

Extracted rock mass volume for **Development Blasts**:

\[ X \approx 300 \text{ m}³ \]