Detailed three-dimensional stress analysis of complex orebody geometry – model setup and results for the Malmberget Mine

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ABSTRACT: This paper presents a mine-scale model of several orebodies of varying size, shape, and orientation. The complex ore geometry requires a three-dimensional modeling approach, but the model generation is challenging. A model for stress calibration was built in 3DShop. Using KUBRIX, a tetrahedral mesh was created for FLAC3D where nodal mixed discretization was utilized. A refined model to predict stress conditions near the actively mined orebodies was built using Rhino. This permitted controlling mesh density, with finer discretization in and near actively mined orebodies. The approach taken enabled varying levels of discretization and the degree of detail in the model could be controlled to a much better extent than previously possible. The results were evaluated with respect to possible interaction between the orebodies and possible effects from mining on hoisting shafts. Stress conditions at the location of observed seismic events were also evaluated to assess the seismic potential of large-scale structures.

1 INTRODUCTION

The LKAB Malmberget iron-ore mine in northern Sweden comprises several orebodies of varying size, shape, and orientation, see Figure 1, in an area of 8 km². Mining of these orebodies using sublevel caving is ongoing on different levels with an annual production of 14 million metric tons, as of 2010. Mining is currently between the 650 and 1000 m levels, which correspond to 550–850 m depth below the ground surface.

Figure 1. City of Malmberget (left), mine plant (right), orebodies and transportation systems in the LKAB Mine in Malmberget (LKAB 2010).
Due to the complex geometry and geology together with the effects of the mining, it has been difficult to establish a reliable stress model for the overall mine. The purpose of the initial model was therefore a stress calibration and stress analysis of the mine. However, this mine-scale model proved to be too coarse to accurately predict stress conditions in the close vicinity of the actively mined orebodies. To further study the stress situation in the vicinity of the two orebodies; ViRi and Parta, including possible causes of seismicity, a detailed mine-scale model was required. The purposes of the detailed model were several: (i) to assess stress conditions and causes for mine-induced seismicity near the two orebodies; ViRi and Parta, (ii) to investigate the possibility for stress interaction between the two orebodies and (iii) to study the effect of mining-induced stresses on a hoisting shaft.

2 METHODOLOGY

The complex ore geometry required a three-dimensional modeling approach. Only continuum modeling was conducted in this work, using the FLAC3D computer code (Itasca 2006). The complex geometry necessitated the use of a pre-processor to assist with grid generation. The stress calibration model was setup in 2008; at that time Itasca supported the use of 3DShop (Simulation Works 2006) and KUBRIX (Simulation Works 2008) for pre-processing. Tetrahedral elements and NMD (“Nodal Mixed Discretization”) were used in the FLAC3D analysis. The stress calibration was carried out through regression analysis, following the methodology of McKinnon (2001).

For the detailed model, a refined model geometry was constructed, in which the two studied orebodies (ViRi and Parta) were represented in more detail. The other, surrounding orebodies, were also included in this model, but with the same, coarser, geometry as in the stress calibration model. At this time (2009) Itasca no longer supported the use of 3DShop, but instead recommended the use of Rhino (McNeel 2007). For future needs it was decided to use Rhino in combination with KUBRIX to setup the model grid.

3 MODEL DESCRIPTION

3.1 Geometry

3.1.1 Stress calibration model

The mine comprises of about 20 orebodies, but only the 17 largest orebodies were included in the model. The mining sequence was simplified into three mining steps, see Table 1. Several simplifications of the real mining geometry were necessary, e.g. the geometry was simplified to horizontal polylines for the mining levels/steps simulated in the model. Files in dxf-format were imported into 3DShop and a solid model was created for each of the orebodies and mining steps, see Figure 2. The ground surface was created from topography and triangulated. The total model size was 10,300 by 6400 by 2400 m. Discretization into tetrahedral elements was conducted using the KUBRIX (Simulation Works 2008) mesh generator.

Table 1. Mining steps in initial model.

<table>
<thead>
<tr>
<th>Step</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Initialization</td>
</tr>
<tr>
<td>1</td>
<td>Mining to 2006/2007 year level</td>
</tr>
<tr>
<td>2</td>
<td>Mining to 2015 year level</td>
</tr>
<tr>
<td>3</td>
<td>Mining to 2020 year level (new main haulage level at 1250 m)</td>
</tr>
</tbody>
</table>

3.1.2 Detailed model

The geometry from the stress calibration model was converted from 3DShop, and imported into Rhino, and used to build the new model. In the conversion process, the polysurfaces were exploded into surfaces and had to be joined. After joining there were some remaining geometrical problems, e.g. naked edges that had to be solved manually, by moving vertices, splitting and rebuilding surfaces, etc.
More mining level for the two orebodies ViRi and Parta were added to the model through simplified polylines and converted to solids, Figure 3. In the detailed model ten new steps were added (steps 2-11) to the mining sequence, see Table 2.

In Rhino a triangulated mesh was constructed on all surfaces of the model (orebodies, ground surface, boundaries, etc). This permitted controlling mesh density, with finer discretization in and near actively mined orebodies. The density of the mesh for the host rock was chosen to a maximum zone edge length of 250 m. For the surrounding orebodies 100 m edge length was chosen, and for the orebodies ViRi, Parta and Dennewitz 20 m edge length was specified, see Figure 4. The different polygon meshes were sewn together to one polygon mesh.

The triangulated model was then fed into the KUBRIX (Simulation Works 2009) mesh generator for volume discretization into a FLAC3D finite difference mesh. KUBRIX was set to use density from the Rhino-file. Tetrahedral elements and nodal mixed discretization were utilized. The approach that was taken enabled varying levels of discretization and controlling the degree of detail in the model to a much better extent than previously possible. The detailed model has 1.5 million zones, which is twice as many as the stress calibration model, see Figure 5.

<table>
<thead>
<tr>
<th>Step</th>
<th>Area</th>
<th>Step</th>
<th>Area</th>
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<tbody>
<tr>
<td>0</td>
<td>Initialization</td>
<td>7</td>
<td>Parta level 906</td>
</tr>
<tr>
<td>1</td>
<td>Mining to year 2006/2007 including ViRi level 858 and Parta level 826</td>
<td>8</td>
<td>ViRi level 930</td>
</tr>
<tr>
<td>2</td>
<td>ViRi level 882</td>
<td>9</td>
<td>ViRi level 954</td>
</tr>
<tr>
<td>3</td>
<td>Parta level 846</td>
<td>10</td>
<td>Parta level 926</td>
</tr>
<tr>
<td>4</td>
<td>Parta level 866</td>
<td>11</td>
<td>ViRi level 978</td>
</tr>
<tr>
<td>5</td>
<td>ViRi level 906</td>
<td>12</td>
<td>Mining to year 2015</td>
</tr>
<tr>
<td>6</td>
<td>Parta level 886</td>
<td>13</td>
<td>Mining to year 2020</td>
</tr>
<tr>
<td></td>
<td>(new main haulage level at 1250 m)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.2 Input data

Initial stresses were determined using the stress calibration model and data from stress measurements in the mine. To prevent translation and rotation of the model, four points in vicinity of the outer edges were fixed (in x-, y-, z-direction). Roller boundaries were used on the bottom boundary and the upper boundary (ground surface) was simulated as a free surface. Stresses were applied to the vertical model boundaries.

There is little data available on the rock properties in the mine; hence, the input data were chosen based on experience, see Table 3. Caved rock has much lower stiffness than surrounding rock and for that reason very little influence on the stresses in the mined area. Thus the caved rock was simulated as empty space.

Table 3. Elastic properties.

<table>
<thead>
<tr>
<th>Rock type</th>
<th>E [GPa]</th>
<th>υ</th>
<th>ρ [kg/m³]</th>
</tr>
</thead>
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<tr>
<td>Orebodies</td>
<td>70</td>
<td>0.27</td>
<td>4700</td>
</tr>
<tr>
<td>Host rock</td>
<td>70</td>
<td>0.27</td>
<td>2700</td>
</tr>
</tbody>
</table>

4 RESULTS

4.1 Stress calibration model

Data from the stress calibration model were used to determine virgin boundary stresses for modeling. The methodology presented by McKinnon (2001) was used, in which unit boundary stresses for each of the stress tensor components are applied and the unit stress response
calculated. By repeating this for all stress components, a set of unit response tensors are obtained, which can be freely combined using the principle of superposition, to fit the results to conducted stress measurements. Each response tensor is thus multiplied with a factor, whose values can be determined by solving a system of equations. These factors (multiplied by the unit stress) are then the calibrated boundary stresses for the model.

For the Malmberget mine, the stress measurements conducted by Ask et al. (2009) were used for the calibration. It was further assumed that the virgin stress field was oriented horizontally-vertically, and that the vertical stresses equal the pressure of the overburden material. Using the above methodology, the following calibrated boundary stresses were obtained:

\[
\sigma_H = 0.0356z, \quad (1) \\
\sigma_h = 0.0172z, \quad (2)
\]

where \(\sigma_H\) is the maximum horizontal stress, \(\sigma_h\) is the minimum horizontal stress, \(z\) is the depth below the ground surface in meters, and \(\sigma_H\) is oriented 130.6 clockwise from local north. The vertical stresses are solely due to gravity (\(g = 9.81 \text{ m/s}^2\)). The calibrated boundary stress differs somewhat from the measured stress, indicating an influence from mining, differences in density, and topography, which all have been accounted for in the numerical model. A more detailed description of the stress calibration is given in Sjöberg (2008).

4.2 Detailed model

4.2.1 Interaction between orebodies

From a production scheduling point it is of interest to investigate whether mining in one orebody affects the stress state in the vicinity of another orebody. The stress interaction between the orebodies ViRi and Parta was evaluated, for mining stages 9-11, i.e. mining of ViRi at 954 m, Parta at 926 m, and ViRi at 978 m.

The stresses were evaluated on three levels: 926, 978 and 1002 m. The model results showed that mining of a level in one of the orebodies did not affect the stress state around the other orebody. An example is shown in Figure 6.

![Figure 6. Example of major principal stress evaluation through a) horizontal stress plot (with stress chart line) and b) stress chart.](image)

4.2.2 Modeled stresses, induced seismicity and large events

Two of the areas that are seismically active in the mine are the western side of the hanging wall of ViRi and the eastern side of the hangingwall of Parta. The question was if this was caused by fault slip in large-scale structures (not identified so far), or if the seismicity could be explained only by the changes of the stress state caused by the mining activity. The calculated stress state in the vicinity of the orebodies is very inhomogeneous and reflects the induced seismicity very well, indicating that the seismicity to a large extent is stress induced (“strain burst”), see Figure 7. This probably also imply that the caving of the side rock does not take place in a uniform pattern along the hangingwall but is stress driven in a certain direction.
Three large seismic events (local magnitude >2) were localized to the vicinity of the cave of Parta, see Figure 8. Stress conditions at the location of the recorded seismic events were evaluated to assess the potential for a fault-slip of potential large-scale structures in the area. The calculated stresses at these locations were moderate. The location is at a relatively large distance from the actively mined orebody, indicating that the observed seismic events are likely to be “fault slips”. These seismic events were most likely neither mining-induced nor stress induced (“strain burst”) events.

Assuming a Mohr-Coulomb strength criterion for the slip planes, it is possible to calculate if slip can occur and which orientations a weakness plane can have (Jaeger & Cook 1969). The results are two angles ($\beta_1=57.3^\circ$ and $\beta_2=66.7^\circ$), corresponding to the angles between the orientation of major principal stress (127-129°) and the normal to the slip plane, which may be illustrated as in Figure 8 b). The analysis showed that slip could occur for future mining, and even for relatively high values of friction angle for the weakness plane (up to 40°). Seismic events in the future can thus not be excluded.

![Figure 7](image1.png)
*Figure 7 a) Calculated major principal stress at 850 m level in the vicinity of ViRi in an horizontal view and b) typical experienced seismicity for a period of eight months, each sphere representing an individual seismic event with local magnitudes of -1.9 – 1.6 (represented by the colors).*

![Figure 8](image2.png)
*Figure 8. a) Location of the seismic events and b) the normal to the slip plane is within the black areas.*
4.2.3 Shafts
Two hoisting shafts to the new main haulage level are under development. In the development phase, seismicity has been experienced fairly frequently. Therefore, the possible effects from mining-induced stresses on the hoisting shafts were evaluated. As no shaft is included in the model, the stresses were only evaluated in the position of the shaft, see Figure 9.

According to the model, the risk for a rock burst is greatest at the top of the shaft at the start of the mining until mining of ViRi at 978 m level (steps 1-11, cf. Table 2). This mining phase is now completed indicating that the hoisting shafts will not experience additional seismicity through its production time.

5 DISCUSSION AND CONCLUSIONS

When building a model, it is recommended to use Rhino to decide the mesh density, and in KUBRIX use the density from the Rhino model. From the same solid model it is possible to produce models for both FLAC3D (zones) and 3DEC (blocks) (Itasca 2007). It should be noted though that FLAC3D needs a dense mesh constructed in Rhino, whereas 3DEC needs a coarse mesh, to minimize the number of blocks (zone generation is to be conducted in 3DEC separately).

The methodology to calculate the overall stress field in a geometrically complex mine turned out to be a successful way to produce initial stresses for further, more detailed analysis and modeling. This was not previously possible with any degree of confidence for the Malmberget mine.

The more detailed model showed that mining of ViRi does not affect the stresses around Parta and vice versa. The change of the stress field occurs only very locally in the vicinity of these two orebodies. This is an important conclusion from two points of view: (i) it has simplified the scheduling of the mine, and (ii) it will simplify further more detailed modeling of different stress and stability problems in other orebodies.

As the calculated stress state in the vicinity of ViRi and Parta agree well with the seismic activity, the determined stress state is regarded as very reliable.

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REFERENCES


