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# Infrastructure Restriction Volumes for Future Mining at the LKAB Malmberget Mine

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**ABSTRACT**

Large-scale sublevel cave mining unavoidably results in the rock mass around the orebodies being affected by caving and stress redistribution. Knowledge about the extent of areas that will not allow safe placement of infrastructure is essential for the planning process for deeper mining. This paper presents a case study from the LKAB Malmberget iron ore mine in which "infrastructure restriction volumes" were developed for guidance of where mining infrastructure such as ramps, shafts, etc., should not be located for future mining at depth. The methodology used involved simulating historic and future production in a mine-scale numerical model, containing relevant geology but no infrastructure. The mine-scale model simulates caving and material flow together with mechanical (stress and deformation) calculations in a coupled process. Stresses were extracted from the mine-scale model and applied to local models, built based on case areas with observed and documented damages from the mine. The local models were constructed with detailed geology and explicit infrastructure. Several criteria for predicting damage were tested and compared with mapping data from multiple locations in the mine. The most suitable criterion for prediction of damage that corresponds to infrastructure function being compromised was the Strength-Stress Ratio (SSR), which describes the "margin capacity" of the rock mass. This criterion was then applied to the mine-scale model to create restriction volumes for each year of mining down to a depth of 1900 m, corresponding to the depletion of currently known orebodies in the mine. The restriction volumes consider static (aseismic) loading only. Development of infrastructure inside the restriction volumes should be avoided or minimized, but in cases where developing infrastructure inside the restriction volumes is necessary, this should be done in a way allowing for future rehabilitation. For current infrastructure located inside the restriction volumes rehabilitation or alternative infrastructure plans should be developed.

**KEYWORDS**

Sublevel caving; numerical modelling, global-local modelling; strength-stress ratio

## 1. INTRODUCTION

Large-scale sublevel cave (SLC) mining is a cost-efficient bulk mining method, allowing a high degree of mechanization. Constant improvements over the years have resulted in high productivity and (comparably) low costs, making it possible to mine iron ore underground at large (currently up to 1000 m) depth. However, SLC mining inevitably results in the rock mass volume around the orebodies being significantly affected by caving and stress redistribution. For planned continued mining towards depth it is important to gain knowledge about the extent of regions that will not allow safe placement of mine infrastructure, such as ramps, shafts, etc.

This paper presents a case study for the LKAB Malmberget iron ore mine in which "infrastructure restriction volumes" were developed for guidance of where mining infrastructure should preferably not be located for future mining at depth.

The Malmberget iron ore mine is owned and operated by the Luossavaara-Kiirunavaara Aktiebolag (LKAB) mining company. The mine is situated in the municipality of Malmberget in northern Sweden, some 70 km north of the Arctic Circle and 1200 km north of Stockholm. The mine comprises 20 orebodies of varying size, shape and orientation, over an area of 8 km$^2$. Annual production is around 16 million metric tons (Mton) of crude ore with mining currently ongoing between the 475 and 1123 m mining levels, corresponding to approximately 400–900 m below ground surface. The ore is transported by front loaders to ore passes at the production levels, and then through the ore passes to chutes at the main haulage level. From these, the ore is transported by trucks to underground crushers, and subsequently by conveyor belt and skip to the concentrator plant on the ground surface, (see also Figure 1). The current main haulage level is located at the 1250 m level, denoted M1250.

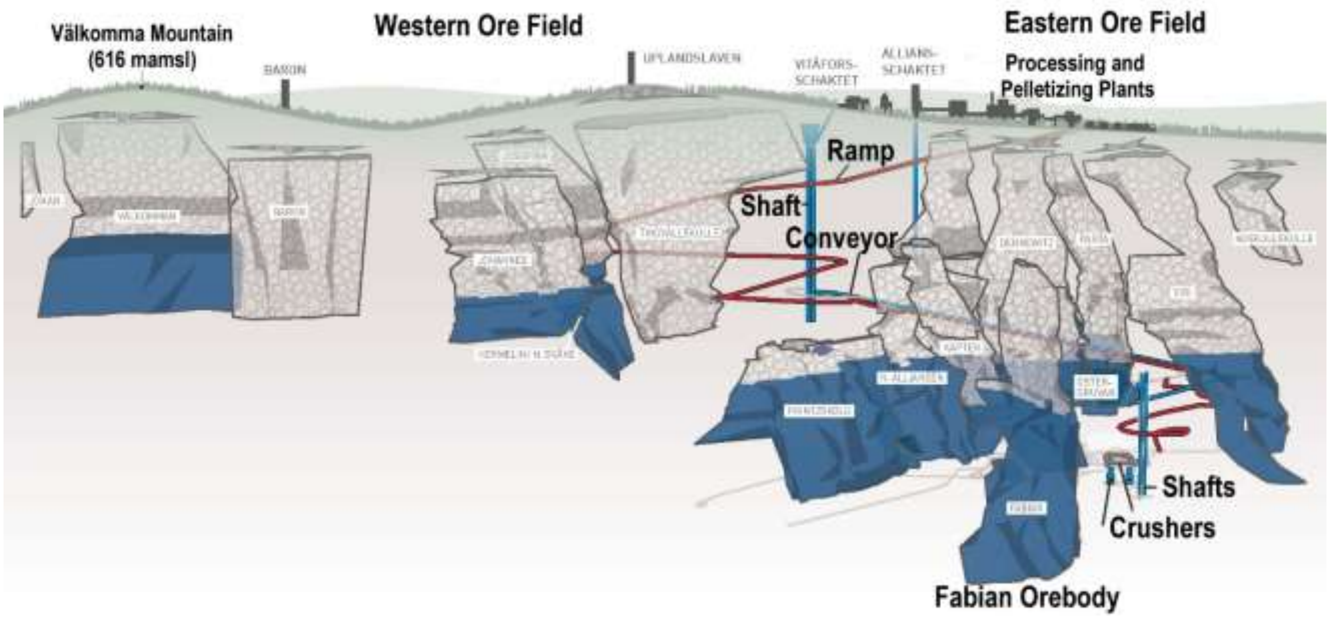


*Figure 1. Schematic figure showing major orebodies and mine infrastructure at the Malmberget mine. Grey areas are mined ore and blue areas are unmined ore, view towards north.*

## 2. METHODOLOGY

### 2.1. Approach

The methodology used involved simulating historic and future production in a mine-scale (global) numerical model, containing relevant geology but no infrastructure. The mine-scale model simulates caving and material flow together with mechanical (stress and deformation) calculations in a coupled process, see e.g., Sjölander et al. (2022).

Local models were then built based on case areas with observed and documented damages from the mine. The local models were constructed with detailed geology, explicit infrastructure, and with the option to include surface support. The stress states for relevant years (noted time of damage occurrence) were retrieved from the mine-scale model and superimposed on the local model. The infrastructure in the local model was then excavated and the areas containing damage observations were evaluated with respect to stresses from the mine-scale model, drift convergence, support loads, and secondary stresses to define criteria identifying conditions likely to lead to infrastructure damage. The criteria developed using one local model were then applied to a second local model from a different location. If the criterion holds true the definition can be carried through to the mine-scale model for prognosis, if not, then the criterion is scrapped.

The methodology is seemingly straight-forward but does necessitate iteration between the mine-scale and the local models. The criteria must be based on data available in the mine-scale model used to do prognosis, but must also be proven to be associated with numerical damage indicators in the local models. The observed damage from the field cases must be contained in the parts of the local model where the numerical results indicate that damage is plausible. This step was essential to verify that (i) the damage is controlled by static loading (aseismic), and (ii) the resolution of the mine-scale model is acceptable for adequate stress differences to occur on local scale during mining.

Following this, the criteria that can be successfully applied over the different local models were then applied in the mine-scale model. The criteria were used to create restriction volumes for each year of mining down to a depth of 1900 m, corresponding to the depletion of currently known orebodies in the mine. The "target" level of damage indicated by the criteria will mimic the level of damage contained in the calibration cases, i.e., the level of damage in the field observations will determine the level of potential damage related to the restriction volumes.

## 2.2. Damage Observations

Several observed and documented damages in mine infrastructure were provided by LKAB and used for purpose of developing a damage criterion. The documented cases contained a selection of damages on the infrastructure along with their location, a brief description, photos, and the date that they were mapped. Only specific cases were used for the development of criteria that could predict higher-risk areas for the location of future infrastructure. The exclusion of certain cases was based on the type and location of a certain damage or failure. Specifically, cases located in the proximity of production areas were not considered suitable for the development of criteria that was later to be applicable to areas where permanent mining infrastructure is going to be located. Additionally, damages on the rock support that could not be associated to rock movements were excluded. An example of documented damages is shown in Figure 2.

Two sets of damage observations were used – one with minor damages, e.g., cracking of shotcrete, minor rockfalls and minor damage to installed reinforcement, and one with more severe damages resulting in infrastructure function being compromised. Calibration of the developed criterion against the second category of data enhanced its precision in identifying areas where permanent infrastructure development could potentially result from rock failures of similar severity.


Figure 2. Example of damage observations in the LKAB Malmberget mine.

## 2.3. Numerical Models

### 2.3.1. Mine-Scale Model

All analyses in this project were conducted using the three-dimensional finite difference code *FLAC3D* (Itasca, 2019), using a *FLAC3D-CAVESIM* coupling aimed at simulating the progression of caving, see also Hebert & Sharrock (2018). All orebodies in the Malmberget Mine were included in the mine-scale model and six large-scale structures were also included in the model, based on the structural-geological model and an assessment of what the most critical and important structures were from a caving influence perspective with respect to the studied infrastructure (Figure 3). The *FLAC3D* model was built using an "oct-tree" mesh in which the mesh is composed of hexahedral zones arranged in a structured cubic pattern. This applies to the whole model except in the area around the large-scale structures, where the mesh is made up of an irregular hexahedral mesh to follow the fluctuation of the large-scale structure. The outer dimensions of the model were set to 9675 x 9535 x 3480 m. The cubic pattern of the hexahedral elements has a size of 12 m in the near vicinity of the orebodies and the structures, and then gradually increases in size out to the outer-most part of the model where the element size is 96 m. All structures were modeled as continuous discrete planes without any thickness.

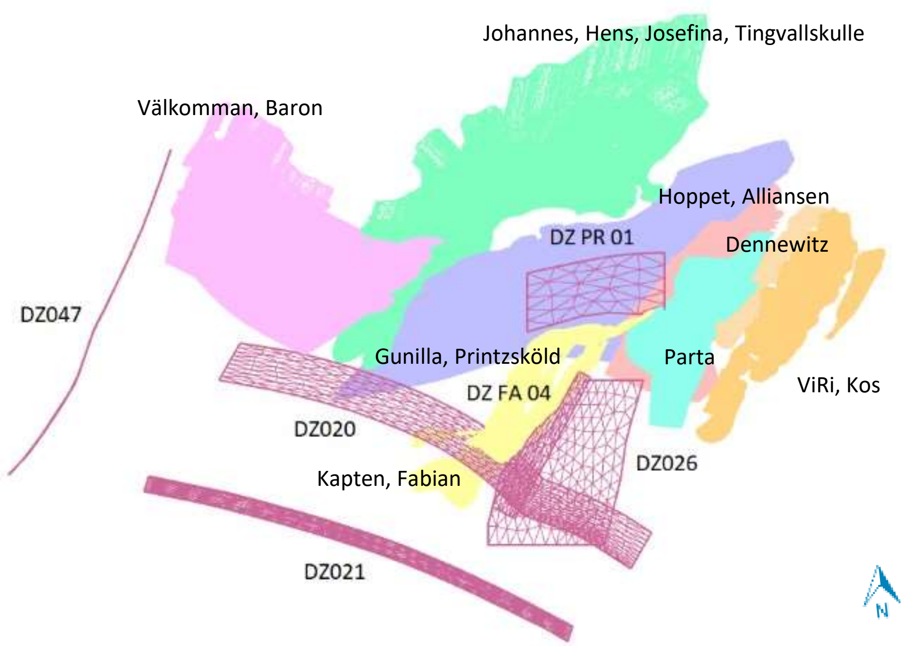


*Figure 3. Plan (projected) view showing orebodies and large-scale structures in the numerical mine-scale model of the Malmberget Mine.*

The rock mass was simulated with the *IMASS* (Itasca Constitutive Model for Advanced Strain Softening) material model (Ghazvinian et al., 2020), and the large-scale structures were modeled with the Mohr-Coulomb plastic model. Material properties were defined through calibration of the model versus caving, surface cratering and surface deformation, and are described in Sjölander et al. (2022). The initial stress state used in the model was based on Perman et al. (2016), who determined the initial stress field in the Malmberget Mine by calibrating a three-dimensional numerical stress analysis model with the results of stress measurements.

Mining in the numerical model can be divided into four parts: (1) mining with shrinkage stoping at the beginning of the twentieth century, (2) mining with sub-level caving before 1995, (3) mining with sub-level caving between the years 1995 and 2019, and (4) future mining with sub-level caving until year 2070 and the mining level 1888 m. For the first part, the ore is extracted the conventional way for numerical analyses in *FLAC3D* and for the three latter parts, the ore is extracted using a ring-by-ring principle in *CAVESIM*. For future production, a draw schedule was obtained from LKAB with an assumed annual production increase of 25 % (to 20 million metric tonnes annually by year 2025 and until year 2037). Each ring was individually extracted in *CAVESIM* with the coupling to *FLAC3D* being activated every year of equivalent production for each orebody.

### 2.3.2. Local Models

Two different local models were created for two selected areas with observed infrastructure damage in the mine, with one example shown in Figure 4. The models were constructed as a hybrid mesh with tetrahedral elements surrounding the infrastructure. Blasted and caved rock volumes were modelled as "caved rock" and correspond to the planned production and the predicted rock caving as they developed in the *FLAC3D-CAVESIM* global model each year. Areas with documented damages to the infrastructure were identified as locations of "higher interest" and a higher resolution zoning was applied to them to increase the precision of the results. The zones at these locations have a maximum edge length of 0.5 m. The maximum edge length of the zones increases gradually further away from these locations with a maximum value of 2.0 m.

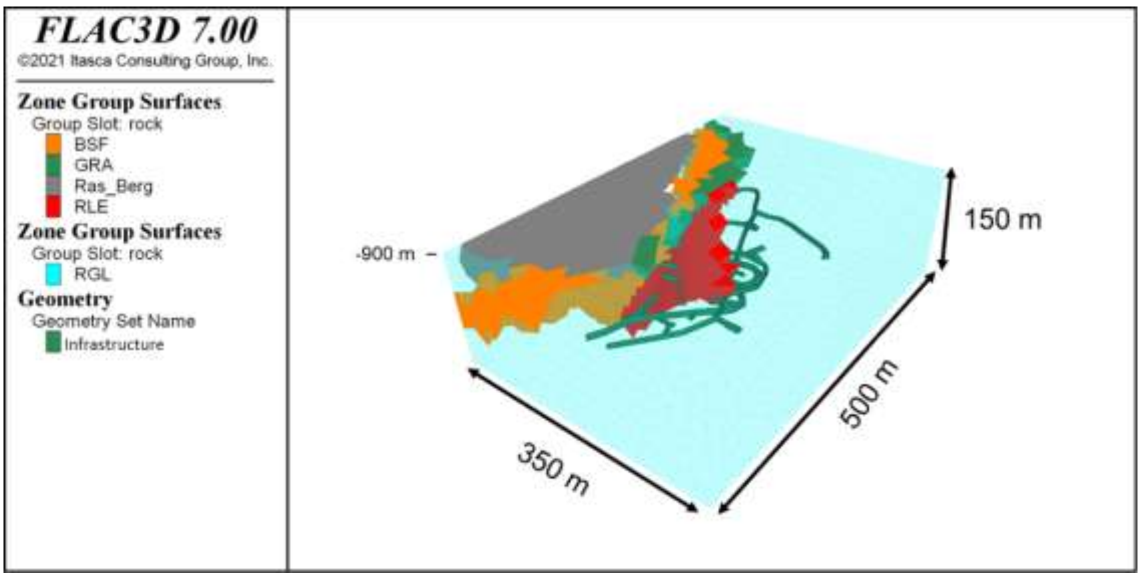


*Figure 4. Example of local model.*

## 3. CRITERIA FOR INFRASTRUCTURE DAMAGE

### 3.1. Development of Criteria

A series of criteria were developed and tested to find a criterion or a combination of criteria that could best explain the documented damages to the infrastructure and subsequently be used for the identification of other risk areas. The following criteria were tested:

– Stresses from the mine-scale model including principal stresses ($\sigma_1$, $\sigma_3$), differential stress ($\sigma_1$- $\sigma_3$), and change in differential stress ($\Delta(\sigma_1$- $\sigma_3)$);
– Stresses in shotcrete in local models;
– Deformations in local models;
– Depth of yielding in local models;
– Stress in areas with large deformations in local models; and
– Stress-Strength Ratio (SSR) for the mine-scale model.

The first two (stresses from the mine-scale model, and stresses in shotcrete in local models) showed none or poor correlation with observed infrastructure damages. None of these criteria could thus be used to replicate the field observations.

The third criterion tested assessed the correlation between the deformations in the local model and the reported damages to the infrastructure. The criterion was tested for all three deformation components (x, y, z) as well as for the displacement magnitude and the differential displacements between mining years, using the local-scale models. The magnitude of displacements provided a fair correlation with the field observations as many of the documented damages on the permanent infrastructure were included in the areas identified as medium or high risk i.e., areas that experience larger deformations. This relation suggests that the stress field retrieved from the global model is the main cause of the damages and therefore it can be used directly for the prediction of other risk areas without the need of constructing additional local models. This criterion, however, also indicates several "false positives" i.e., areas that are classified as medium or high risk but have no documented damages.

To reduce the instances of "false positives" various criteria were tested in combination with the deformations in the local model. One such criterion was the ratio of the maximum yielding depth to the tunnel height, which was used to ensure compatibility across the entire infrastructure. This criterion demonstrated a strong correlation with deformations, as areas classified as medium or high risk consistently had a larger yielding depth to tunnel height ratio. However, the combination of these two criteria did not help reduce the "false positive" cases.

The strong correlation between areas with larger deformations and the location of the field observations led to the conclusion that the initial stress field as this is retrieved from the global model is, together with the infrastructure geometry, a main driver of the damage development. Therefore, the development of a stress related criterion appears to be the best method to identify and predict areas with higher potential for infrastructure damage. Further examination of stresses in areas with large deformations revealed that the calculated major principal stress did not correlate well with observed damages. For the differential stress, a weak correlation between areas classified as medium/high risk and areas with high differential stresses was found. Moreover, the incremental change of the major principal stresses since the excavation of a specific drift was studied. In general, this showed a good correlation between areas that previously had been identified as medium/high risk by the large deformation criterion and areas that experience an even increase in the major principal stress of 3–5%. However, this could not be extended to all local models, thus indicating that there are other differences between the studied areas that were not accounted for.

The next parameter examined was the Strength-Stress Ratio (*SSR*), which quantifies the "margin capacity" of the rock mass, i.e., an *SSR*=1.0 implies that stresses and strengths are equal, while a higher SSR means that the strength is higher than the current acting stress on an element. SSR is calculated using the Mohr circle, starting with the actual stress state, $\sigma_1$ and $\sigma_3$, at a point (a zone) in the model, see Figure 5.

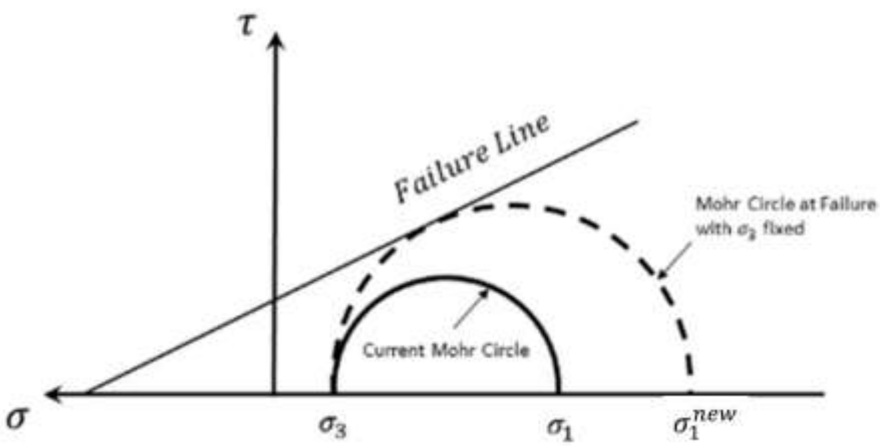


*Figure 5. Schematic figure showing the definition and calculation of SSR.*

The minor principal stress, $\sigma_3$, is fixed and the Mohr circle enlarged until it is tangent to the failure line, with a new major principal stress, $\sigma_1^{new}$, thus determined. The Strength-Stress Ratio is then defined as:

$$\mathrm{SSR} = \left|\frac{\sigma_1^{\mathrm{new}}-\sigma_3}{\sigma_1-\sigma_3}\right|. \quad (1)$$

The SSR criterion thus accounts for both the acting stresses and the variation of strength in the different geological units in the rock mass. An upper limit of SSR ≤ 10 is used in *FLAC3D*. If the current stress state is in tensile failure, then SSR is set to 0.

The value of *SSR* is calculated for every zone of the numerical model using the current major and minor principal stresses retrieved from the global model and the corresponding strength of the rock at the particular zone considering the current stress confinement. *SSR* as a prediction parameter was tested for the two local models used. The results showed a good correlation between the field observations; in particular, it was observed that the majority of the damages under examination were taking place in areas where SSR had a value of 2.5 or less, with only a small deviation of 10–20 m (Figure 6).

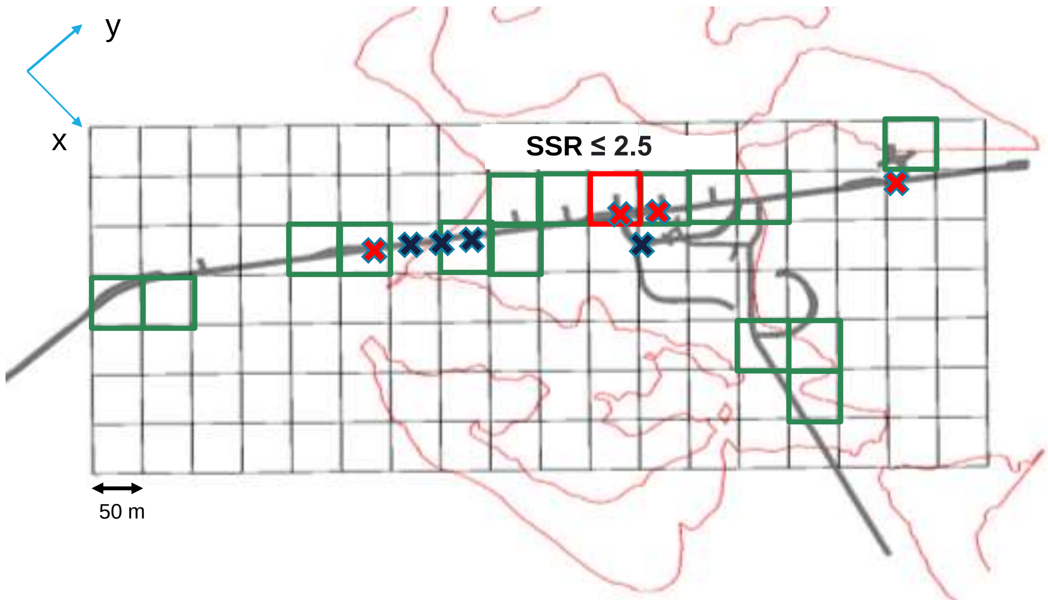


*Figure 6. Example of application of the large deformation results on top of the Strength-Stress Ratio plot for a local model and year 2019, with red crosses showing the location of the observed infrastructure damages and dark blue crosses showing past damages (previous years).*

### 3.2. Application and Calibration

As described above, the *SSR* criterion emerged as the most suitable fit to the field observations being able to replicate the location of damages on the permanent infrastructure with sufficient precision in both local models. Therefore, it was deemed as a robust criterion that can be applied globally to define higher-risk areas where the development of future infrastructure should be avoided or minimized. The *SSR* criterion can be applied directly to the mine-scale model, resulting in the identification of all the zones with a *SSR* value equal to or lower than the cut-off value selected (SSR=2.5). The restriction volume obtained is the product of the merging of those zones into one unified volume. The number of zones with an *SSR* value equal to or lower than the cut-off value, and subsequently the overall restriction volume varies annually, depending on the caving process and stress redistribution occurring during mining at deeper levels.

However, when developing the resulting volumes for SSR=2.5, very large volumes result for deeper mining, as illustrated in Figure 7. Since the damages used for the development of the criterion were exclusively minor damages on the infrastructure, the value of 2.5 was considered overly conservative and the rock volumes produced by its application too large for the purposes of this work. To enhance the precision of the produced "restriction volumes" further calibration of the selected criterion was undertaken using the additional data with more severe observed damages. The refined calibration validated that the preliminary value of 2.5 was too conservative and that a new lower value should be used to increase the precision of the criterion. Hence, a series of different *SSR* values were tested against all the calibration data. Example results are shown in Figure 8. The majority of the locations with severe damages in the calibration data were located in areas with an *SSR* value of 1.5 or less, within a spatial deviation of around 10–20 m.

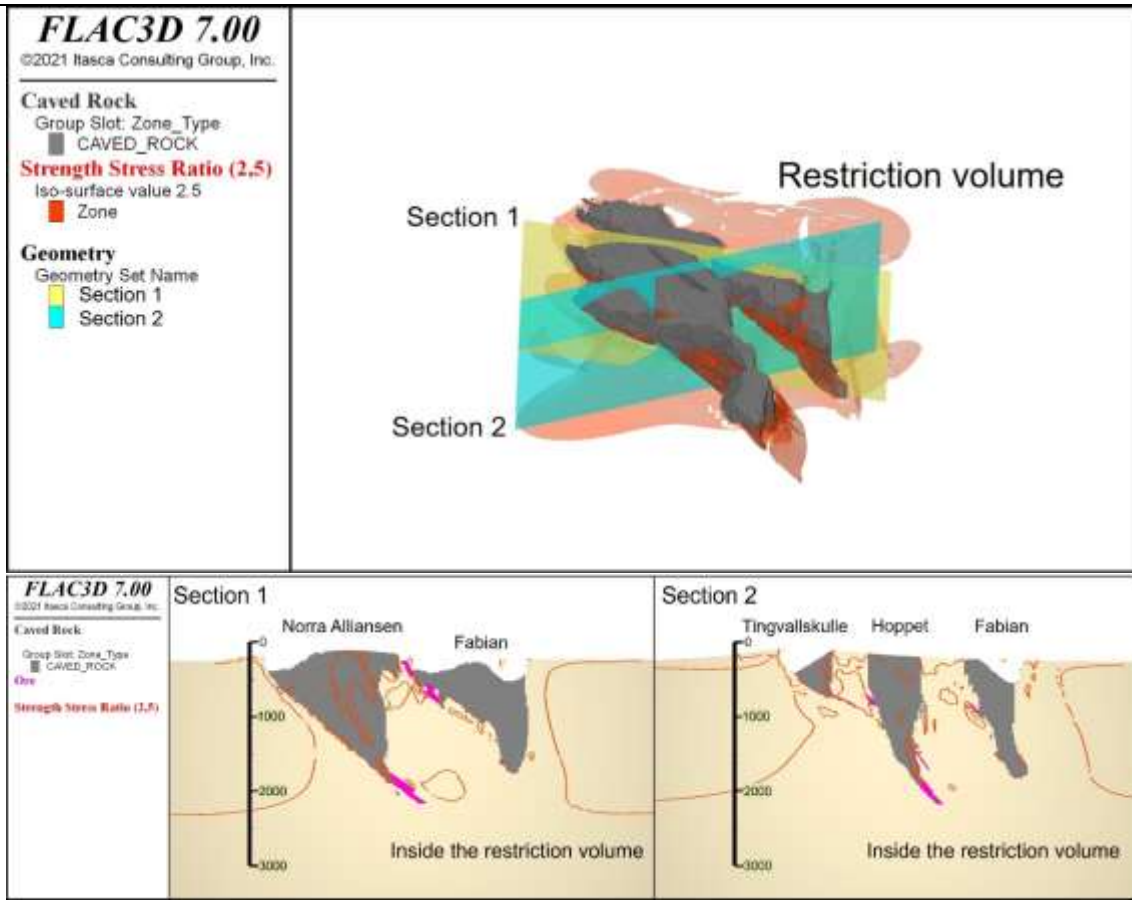


*Figure 7. Development of "infrastructure restriction volumes" shown in 3D view (top) and selected cross-section views (bottom) for the year 2070 and SSR value of 2.5.*

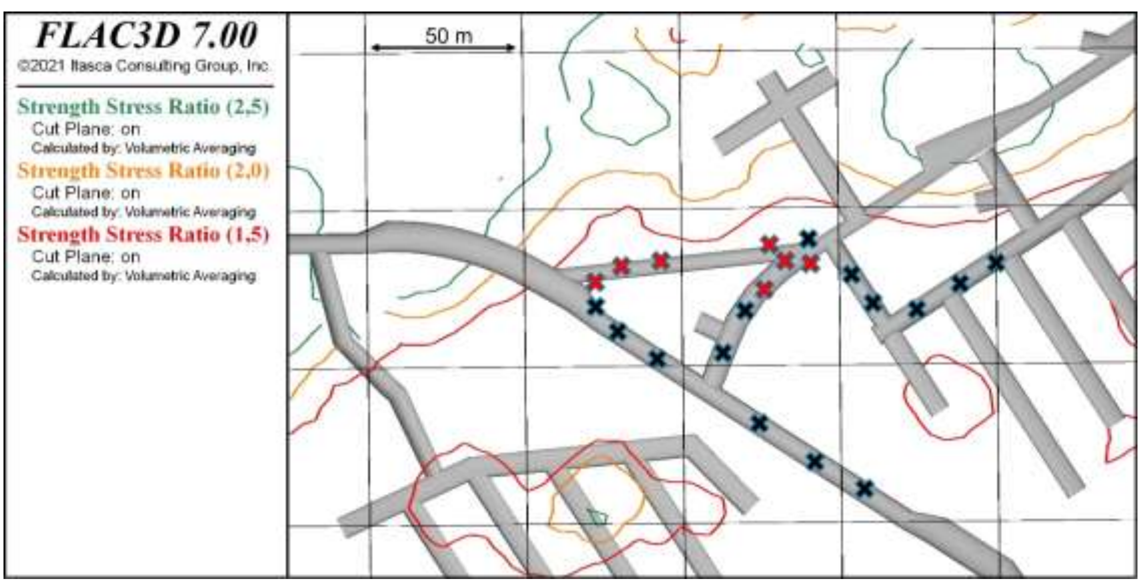


*Figure 8. Example of testing of different SSR values for a selected area in the mine with infrastructure damage for year 2021, with red crosses showing the location of the observed infrastructure damages and dark blue crosses showing past damages (previous years).*

## 4. INFRASTRUCTURE RESTRICTION VOLUMES

### 4.1. Final Restriction Volumes

The final application of the criterion resulted in considerably smaller restriction volumes, which were more precise in targeting areas with higher potential to develop stability problems, similar to those used for the calibration. The revised restriction volumes for year 2070 can be viewed in 3D and in the two selected sections in Figure 9. Developing infrastructure within the restriction volumes, or in areas that will later be included in the volumes, should be done with ability of rehabilitation in mind. For infrastructure that have already been developed in areas that will be included in the restriction volumes during the expected service time, rehabilitation plans should be created.

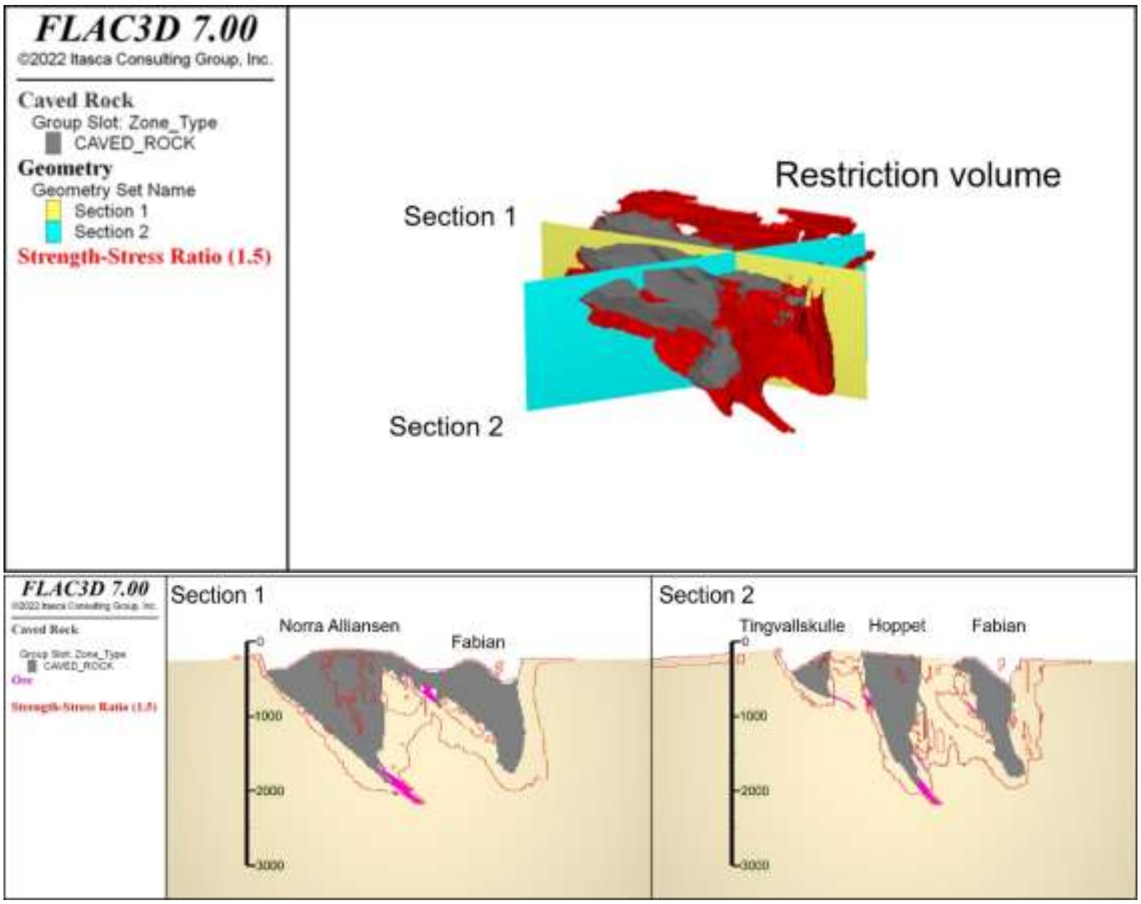


*Figure 9. Development of "infrastructure restriction volumes" shown in 3D view (top) and selected cross-section views (bottom) for the year 2070 and SSR value of 1.5.*

The infrastructure restriction volumes represent volumes of the rock mass within which the potential for damages to the infrastructure, similar to the damage in the calibration cases, is increased. The damage potential within the volume is uniform, meaning that damage is not more likely to occur deeper into the volume compared to close to the boundary. In general, however, the closer the position is to the orebody the more likely it is to be damaged. However, there are exceptions to this rule; developing in rock already yielded might be more beneficial than developing through rock that is expected to yield after development, thus, the lack of gradient in the volumes.

### 4.2. Discussion

The criteria for the development of the volumes were based on pre-existing damage (observed failures and fall-outs) observed in the mine. Only specific damages were used while others had to be excluded since they either could not be associated to failure mechanisms related to rock movements or were situated in proximity to production areas. Apart from the damage mapping, the geological model can be a source of uncertainty. The current geological model starts at 250 m depth and extends to some distance from the orebodies, thus lacking information near the surface and farther from the orebodies. The material parameters used for the different rock types were defined through previous calibration (Sjölander et al., 2022), and do not account for possible variations of the material properties within the same rock unit volume.

The infrastructure restriction volumes have been developed in relation to specific mining years. The mining years are based on the conceptual 20 Mton annual production plan. Deviations from this mining plan might affect the reliability of the restriction volumes, in particular when mining levels in different order or using a different mining method. Finally, the restriction volumes are based on static (aseismic) loading. The volumes have not been correlated to seismic risks and any attempts to cross-reference the restriction volumes to seismicity should be performed with great care.

## 5. CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this study, the following conclusions can be drawn:

– The infrastructure restriction volumes represent rock mass volumes with higher potential of occurrence of damages corresponding to infrastructure function being compromised.
– Development of infrastructure inside the restriction volumes should be avoided or minimized. In case of developing infrastructure inside the restriction volumes, this should be done in a way allowing for future rehabilitation. For current infrastructure lying inside the restriction volumes rehabilitation or alternative infrastructure plans should be developed.
– The reliability of the restriction volumes can be affected in case of a revision of the conceptual mining plan or change of the mining method. A complementary analysis and a potential update of the restriction volumes is required in these cases.
– The yearly development of the restriction volumes should be considered during the mine design process to account for areas of volume contractions.
– The general methodology applied is judged to be suitable also for non-mining applications, provided that suitable observations are available for calibrating the criteria.

## 6. ACKNOWLEDGEMENTS

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