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Analysis of caving and ground deformations in Malmberget using a coupled CAVESIM-FLAC3D model

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Abstract

Large-scale sublevel cave mining (SLC) remains the mining method of choice for efficient underground mining of iron ore at the Luossavaara-Kiirunavaara AB (LKAB) mines in Kiruna and Malmberget, northern Sweden. However, SLC mining ultimately results in ground deformations above active mining areas, thus necessitating relocation of surface infrastructure and/or residential areas within the locations containing large and damaging deformations. Moreover, caving may also affect underground infrastructure and a prediction methodology for both surface effects and underground infrastructure is warranted. A coupled CAVESIM-FLAC3D model was developed for the LKAB Malmberget mine. Initially, a mine-scale model with the centrally located major orebodies was set up for detailed analysis of critical infrastructure. This was followed by an extended model in which all orebodies and production areas (approximately 20 of them) were included. Large-scale geological structures were included in the model, as well as the local geology. The coupled modelling approach enables simulating production and material flow, as well as the rock mass response outside the caved volumes. Production was simulated from the start of mining up until today and the model calibrated against observed cave cratering on the ground surface and inferred cave shapes from seismic monitoring, followed by model validation against measured ground surface deformations. The calibrated model was then run for future mining and a planned production increase, up until the year 2070. The results were evaluated with respect to: (i) surface cave cratering, (ii) ground surface deformations, (iii) strains on the ground surface and (iv) cave shapes and deformations around critical underground infrastructure.

Alternative re-locations of underground infrastructure were compared and stability conditions quantified, as input for planning decisions made by the mine. For the ground surface, the model results provided a quantitative prediction of which areas will be affected, both spatially and temporally. For areas within the Malmberget township, these predictions are critical for planning and execution of the ongoing urban transformation. Moreover, the model provided predictions of ground surface affects within and near the industrial area, as input to future location of planned new surface infrastructure. The coupled modelling approach and the extensive calibration process was instrumental in developing reliable and accurate predictions for the continued mining at the Malmberget mine.

Keywords: *sublevel cave mining, mining-induced ground deformations, coupled flow-mechanical modelling*

1 Introduction

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 1,200 km north of Stockholm. The mine comprises 20 orebodies (with 14 currently in production) of varying size, shape and orientation, over an area of 8 km^2 (Figure 1). The ore reserves were first discovered in the middle of the 17th century, but mining in the area did not start until the 18th century. Industrial-scale mining commenced in the late 19th century. Initially, all ore was mined in open pits but a gradual switch to underground mining took place during the early 20th century. At first, mining with waste rock backfilling was used, but this was later replaced with shrinkage stoping. In the mid-1960s, sublevel caving was decided upon as the standard mining method, which has been used ever since. The total annual production amounts to 16 million metric tons of iron ore. The current main haulage level is denoted M1250 and located at Level 1,250 m. The ground surface is between Levels 50 and 250 m in the mine coordinate system, with the zero-level at the top of the Välkomma Mountain in northwestern Malmberget (at 616.4 mamsl). Currently, the deepest active production area is Level 1122 m (Figure 1).

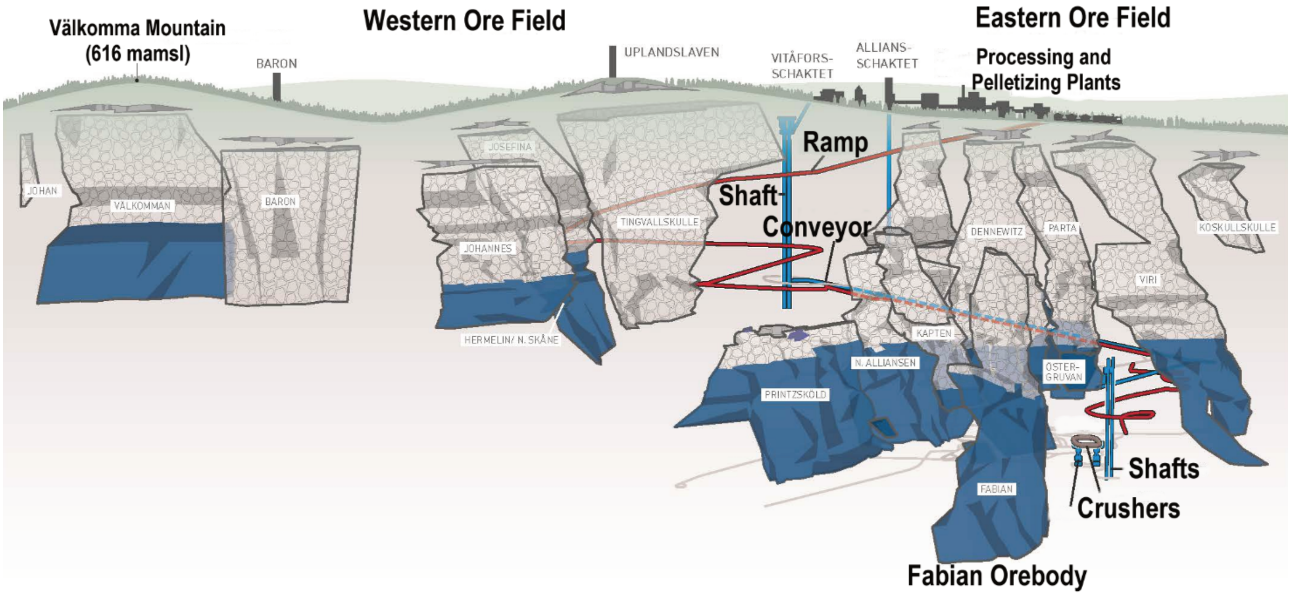

Figure 1 Orebodies and transport and haulage system in the LKAB Malmberget mine (blue colour shows unmined portions)

The ore in the Malmberget ore field is primarily magnetite of fairly high strength and stiffness, with hematite occurring in some orebodies, most notably in the western portion of the ore field. The host rock comprises igneous felsic-intermediate fine-grained rock types, with varying degree of mica (mostly biotite) content. Generally, the rock is of good quality and competence, but a weak biotite schist also exists, primarily near the orebody contacts in some of the production areas. The rock mass is jointed with two to three dominating joint sets oriented subparallel to the orebodies and vertically. A structural-geological model of the area has revealed several potential large-scale deformation zones, as interpreted from topography and geophysical data. Some, but not all of these, have been verified through field observations and core drilling.

Utilisation of large-scale sublevel caving (SLC) allows a high degree of mechanisation and improvements over the years have resulted in high productivity and (comparably) low costs, making it possible to mine iron ore underground at large depths. In addition to the challenges associated with underground cave mining, SLC mining also results in mining-induced ground deformations, caused by the required caving of the hanging wall rock mass. In the long-term perspective, this makes it impossible to have any residential buildings or infrastructure within the fracture zone and cave zone, where discontinuous deformations develop. Thus, relocation of surface infrastructure and/or residential areas has been a long-time accompanying aspect of mining at Malmberget. In recent years this process of 'urban transformation' has increased in scale and the requirements on control and follow-up of ground deformations have become increasingly important.

Monitoring of ground deformations on a regular basis is necessary to be able to plan for this urban transformation accordingly. GPS-monitoring has been the major tool for this, with a measurement network of 260 measurement hubs at the Malmberget site, with measurement campaigns every quarter. The results are primarily evaluated against an 'environmental criterion' for allowable mining-induced ground deformations, regulated through a ruling in the Environmental Court in Sweden. The environmental criterion states that the ground outside the mining industrial area cannot be affected by more than 0.3% strain (horizontally) and 0.2% tilt (vertically). These limits are based on investigated sensitivity of critical infrastructure.

In addition to predictions of cave cratering and associated ground deformations, there is critical infrastructure located in areas likely to be affected by caving in the near future, most notably an air heating plant, which warrants prediction of underground caving and deformations. Both of these aspects are addressed in this paper through the use of a coupled *CAVESIM-FLAC3D* mine-scale model that allows simulation of material flow and associated deformations, caving and stress redistribution. The model was calibrated against observed cave cratering and validated against measured ground deformations and then applied for future production and mining up until the year 2070.

2 Numerical model

2.1 Methodology

The two main aspects of cave mining, i.e. production and material flow and rock mass response outside the cave column, were addressed in this study using a bi-directional coupling between *FLAC3D* Version 7 (Itasca 2019) and *CAVESIM* Version 6.5 (Sharrock 2021). *CAVESIM* is a multi-threaded general purpose cellular-automata code for the simulation of gravity flow of caved rock in cave mines (Hebert & Sharrock 2018). *FLAC3D* is a three-dimensional explicit finite difference program for geotechnical analysis.

In this methodology, two sets of models are prepared; a mechanical model in *FLAC3D* featuring all geomechanically relevant parameters, such as elastic and strength parameters for the rock mass for included entities (different rock types or geomechanical regions) as well a block model in *CAVESIM* including (as a minimum) material densities. Every lattice cell in *CAVESIM* is mapped to a zone in *FLAC3D* at the corresponding coordinates. Several *CAVESIM* lattice cells may be mapped to the same *FLAC3D* cell depending on the resolutions of the two models (Figure 2). Through this mapping, information about the rock mass behaviour can be shared between the two models.

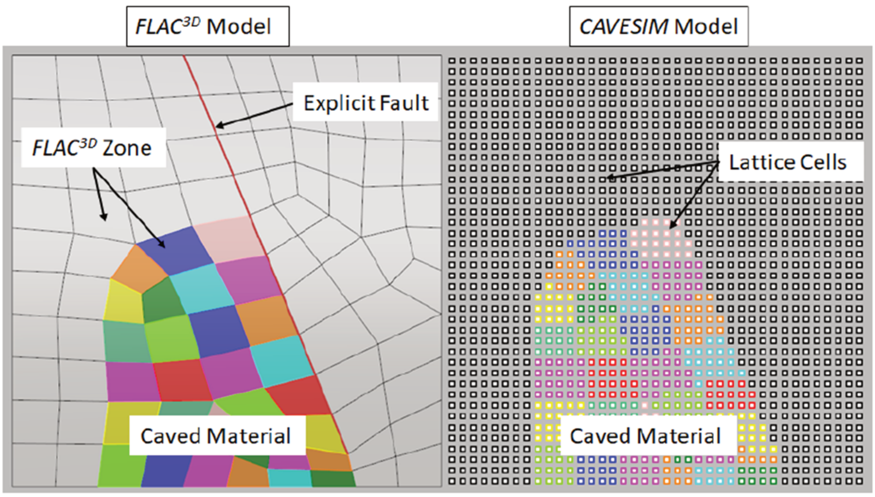

Figure 2 Conceptual cell mapping between *FLAC3D* and *CAVESIM* (Hebert & Sharrock 2018)

Production is simulated in *CAVESIM* by the removal of material from the model based on prescribed tonnages. The material is removed using a ring-by-ring principle with the material draw initiating displacement in the overlaying material to fill the void formed from extraction. The displacement within the flowing material is then recorded by *CAVESIM* as volumetric flow rates for each lattice cell. Following this, the flow rate and void formation information is passed to *FLAC3D* and the flow rates from *CAVESIM* are translated into a reduction in support pressure at the boundary of the cave zone in *FLAC3D*. Boundary areas adjacent to lattice cells reporting high accumulated flow rates are being prescribed larger support reduction while areas with negligible or no accumulated flow rate are subjected to no reduction in support pressure.

In this context the term 'support pressure' is synonymous to vertical compressional stress – meaning that volumes of rock that are flowing due to extraction below offer reduced support to the overlaying rock mass. The rock mass response to the reduction in support pressure is calculated in *FLAC3D* as deformation, stress redistribution and material yielding. *FLAC3D* passes information of yielded zones back to *CAVESIM*, which unlocks the corresponding lattice cells allowing them to be part of the next round of flow calculations. The bi-directional coupling means that no strength properties need to be known by *CAVESIM* and *FLAC3D* only need to consider (intermittent) static loads and stress changes. The coupling also allows airgaps to develop inside and on top of the cave column. The airgap from *CAVESIM* is interpreted by *FLAC3D* as caved rock which offer (basically) no support pressure.

All geological entities were modelled with the strain-softening *IMASS* (Itasca Constitutive Model for Advanced Strain-softening; Ghazvinian et al. 2020) material model. The required inputs are the following intact rock properties:

1. Geological Strength Index, *GSI.*
2. Hoek–Brown constant m_i for intact rock.
3. Uniaxial compressive strength, σ_{ci}.
4. Young's modulus for intact rock, *Ei.*
5. Density of the rock, ρ.

Initial values on each parameter were determined based on core logging and laboratory tests on intact rock from the Malmberget mine. The model was then calibrated against observed cave cratering and caving, with revised and representative material properties being determined.

2.2 Geology and large-scale structures

Initially, a mine-scale model with the centrally located major orebodies was set up for detailed analysis of critical infrastructure. This was followed by an extended model in which all orebodies and production areas were included. The orebodies included in the extended model were Gunilla, Printzsköld, Hoppet, Alliansen, Dennewitz, Parta, Kapten, Fabian, Baron, Hens, Johannes, Josefina, Koskullskulle, Tingvallskulle, ViRi, Välkomman and Östergruvan, as shown in Figure 3. A geological model existed for the area around the orebodies, from about 250 m below the ground surface. For the areas of the numerical model that are not covered by this model, the most dominant rock type (red-grey-leptite) was assumed for the host rock. Moreover, six large-scale structures were 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 above and underground, see Figure 4.

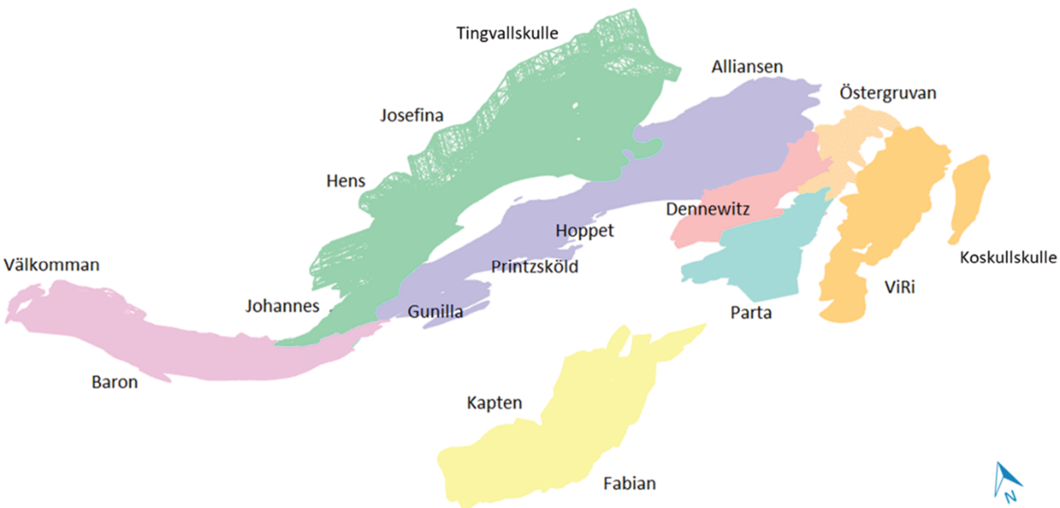

Figure 3 Perspective view showing orebodies included in the model of the Malmberget mine

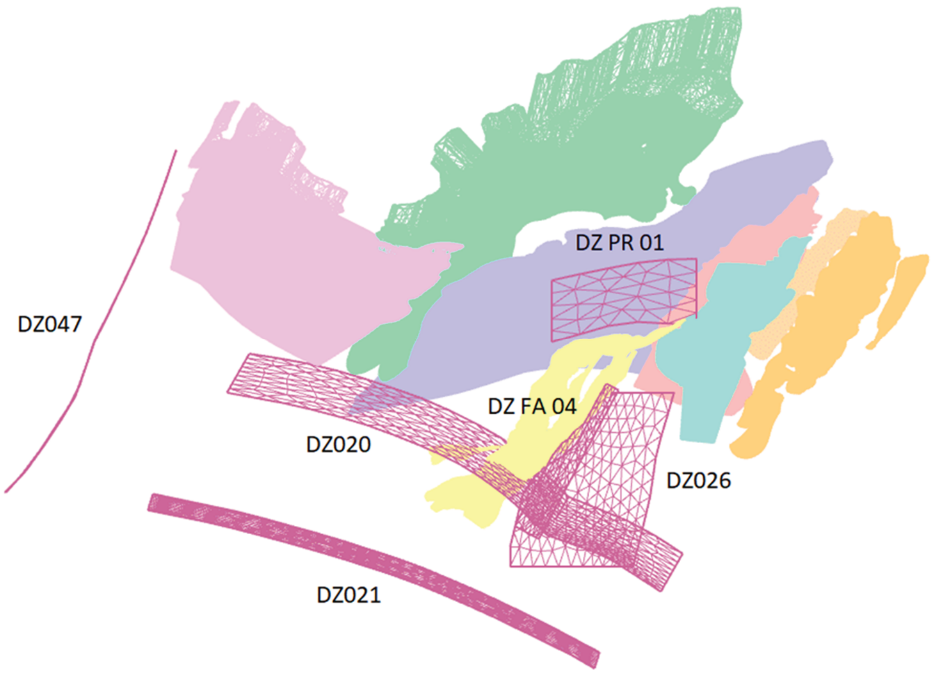

Figure 4 Plan view showing included large-scale structures in the numerical model and major orebodies as per Figure 3

2.3 Model geometry

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 for 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 undulation of the structures. 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 increasing in size out to the outermost part of the model where the element size is 96 m (Figure 5). The outer dimensions for the extended model were set to 9,650 × 9,550 × 3,480 m. Here, 3,480 m is the depth of the model from level 0 m of the mine coordinate system (the top of the Välkomma Mountain). Initially, large-scale structures were modelled in two different ways – as discrete planes and zones with a finite thickness. For the final calibrated rock properties, the model with structures simulated as discrete planes generally provided a better agreement with monitoring results.

2.4 Production and mining sequences

The mining in the numerical model can be divided in four parts:

1. Mining with shrinkage stoping in the beginning of 20th century.
2. Mining with sublevel caving before 1995.
3. Mining with sublevel caving between the years 1995 and 2019.
4. Future mining with sublevel caving until the 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, ore is extracted using a ring-by-ring principle in *CAVESIM*. The actual tonnage per ring were used for mining from the year of 1995 to 2019. For the years before that, a fictitious value for each ring was used that corresponds to the mined tonnage per year and orebody. For future production, a draw schedule was obtained from LKAB with a planned increase in annual production of 25%.

The production rings were grouped in one-year production blocks except for levels mined prior to 1975, which are mined in two- or three-year production blocks. For the period 1995 to 2019, the levels are excavated according to LKAB's production database. From 2020 and onwards, levels are mined according to the long-term production plan provided by LKAB. Each ring was individually extracted in *CAVESIM* with the coupling to *FLAC3D* being activated every year of equivalent production for each orebody.

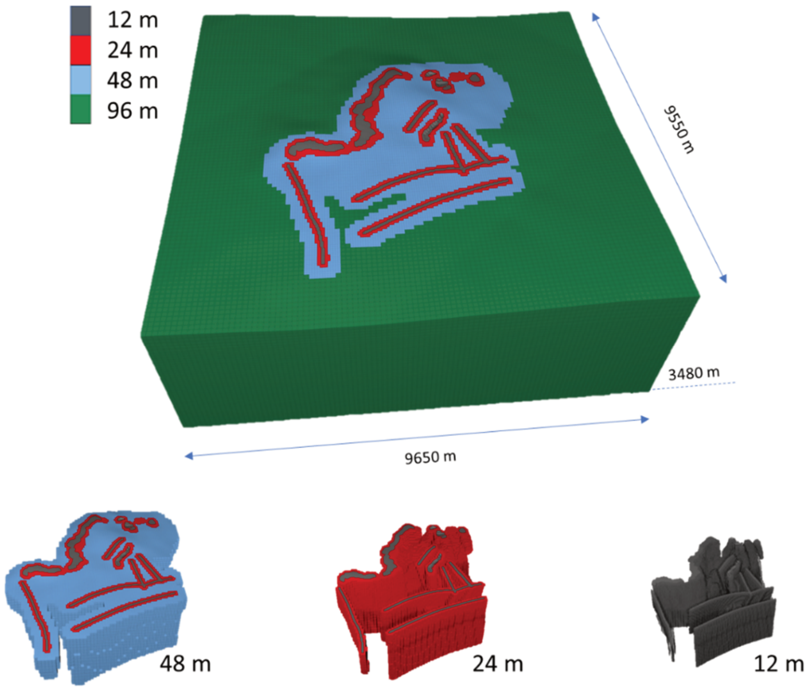

Figure 5 Grading and design of the computational mesh (element size) in the area of evaluation

2.5 Input data

2.5.1 Stresses and boundary conditions

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, yielding the following initial stress state:

$$\sigma_H = 0.0396\, z \tag{1}$$

$$\sigma_h = 0.0161\, z \tag{2}$$

$$\sigma_v = \rho g h/10^6\ (\approx 0.0265\, z) \tag{3}$$

where:

σ_H = maximum horizontal stress in MPa.

σ_h = minimum horizontal stress in MPa.

σ_V = vertical stress in MPa.

ρ = density in kg/m^3.

g = gravity, 9.81 m/s^2.

h = depth below surface in metres.

z = the *z*-coordinate in the mine, measured from the top of the Välkomma Mountain in Malmberget.

The orientation of the maximum horizontal stress (σ_H) is 132° clockwise from the North in the mine coordinate system. The model was rotated to have the boundaries aligned parallel and perpendicular to the initial rock stresses. The boundary conditions were set to roller boundaries for the sides and the bottom of the model and the top was simulated as a free surface.

2.5.2 *Rock mass properties*

The properties from the final calibrated model are presented in Table 1 for the different types of rock included in the model. These values were used for the *IMASS* material in the models. For rock that has caved in the model the material model is changed to Mohr–Coulomb by the coupling algorithm. The properties assigned to the caved Mohr–Coulomb material are presented in Table 2.

Table 1 Rock mass properties from the final calibrated model, used for the *IMASS* material

Rock type	Density (kg/m³)	Intact Young's modulus (GPa)	Intact UCS (MPa)	*GSI*	*mi*	Residual friction angle (°)	Dilation angle (°)
RGL – Host rock	2,800	66	93.5	56	25	30	10
BSF	2,800	47	38.5	30	13	30	10
GLE	2,800	57	72.0	47	20	30	10
GRA	2,800	62	127.5	57	29	30	10
RLE	2,800	72	119	48	34	30	10
SKN – PR, AL	2,800	70	63.5	46	28	30	10
SKN – FA, PA, DE	2,800	70	80	39	28	30	10
MGN – Ore	4,700	62	45	46	24	30	10
HEM – Ore	3,600	62	45	46	24	30	10

Table 2 Rock mass properties used for Mohr–Coulomb material

Rock type	Density (kg/m³)	Young's modulus (GPa)	Poisson's ratio	Friction angle (°)	Cohesion (MPa)	Tensile strength (MPa)	Dilation angle (°)
Caved rock	2,622	0.2	0.28	43	0	0	0

2.5.3 *Properties for large-scale structures*

The strength and stiffness properties for the large-scale structures are shown in Table 3. All structures were assumed to have zero cohesion. DZ026 and DZ FA 04 both have an assumed friction angle of 25° due to having chlorite on the surfaces.

Table 3 Properties of the large-scale structures

Structure	Cohesion (MPa)	Friction angle (°)	Normal stiffness (MPa/m)	Shear stiffness (MPa/m)	Character
DZ020	0	35	1e11	1e10	Crushed zone
DZ021	0	35	1e11	1e10	Unknown
DZ026	0	25	1e11	1e10	Fault
DZ FA 04	0	25	1e11	1e10	Fault
DZ PR 01	0	35	1e11	1e10	Unknown
DZ047	0	35	1e11	1e10	Crushed zone

3 Model calibration and validation

3.1 Calibration

Observations of surface cave crater growth in Malmberget were available for the Kapten-Fabian orebody complex for over 50 years. In addition to surface observations, there are also information from seismic monitoring using the mine-wide seismic network at Malmberget as well as probe drilling, thus enabling inferring cave volumes underground. The calibration was focused on the caving around the Kapten and Fabian orebodies, as the longest historical record of surface cratering was available in this area. Results were also compared with caving observations in the Printzsköld, Alliansen, Dennewitz and Parta orebodies.

A large number of calibration runs (>50) were conducted, in which *GSI* and σ_{ci} were varied. Minor adjustments to historic drawpoints and tonnages (which were highly uncertain) were also made. An example of calibration results are shown in Figure 6. The grey-coloured area shown in the figure represents caved material in the numerical model, which can be compared to the observed cave cratering (coloured lines) for different years.

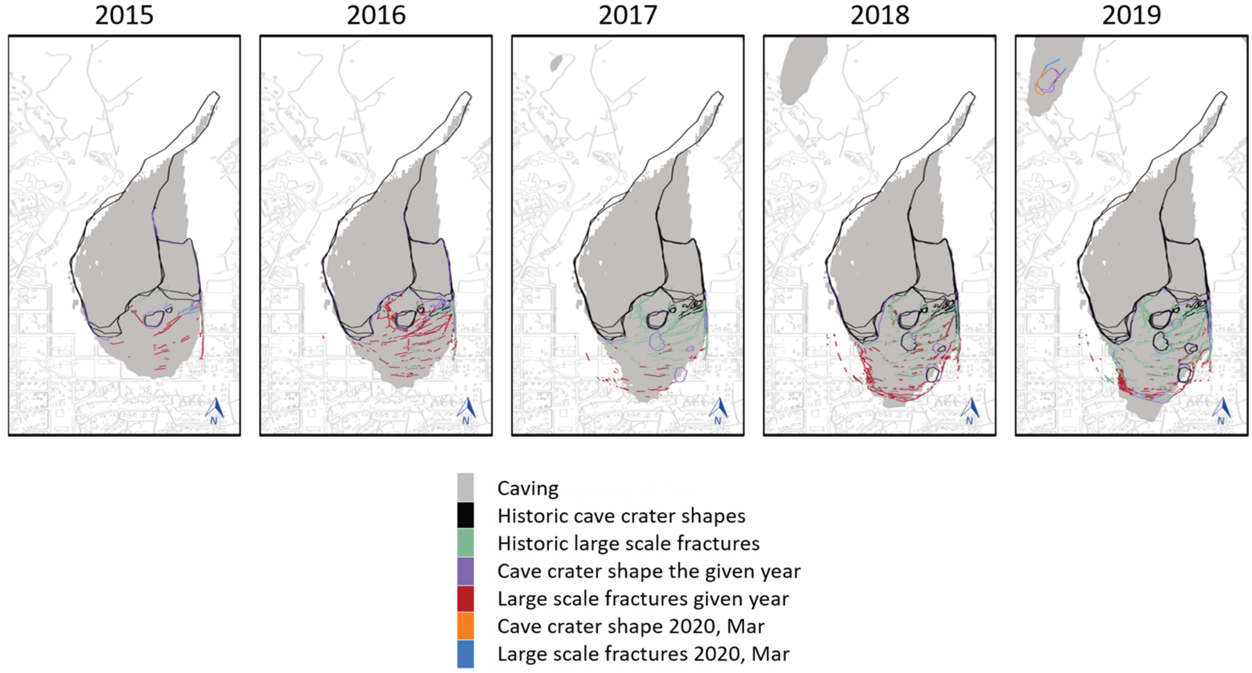

Figure 6 Comparison of model output and surface cave crater observations for the calibrated model

Overall, a good agreement between model output and crater observations was found in the final calibrated model. Underground caving and cave progression towards the surface were also compared with model output and the model results showed similar caved shapes for all studied orebodies. However, for the Printzsköld orebody, in the northwestern portion of Figure 6, cave breakthrough to the surface occurred slightly earlier in the model, in 2018 rather than 2019, but at the correct location. The cave crater was also larger in the model compared to observations for this area, which may be due to locally different rock conditions that was not captured in the model.

The calibration of the model resulted in the *GSI* values reduced by 15 units and the σ_{ci} value reduced to 50% of the intact rock's properties, to properly reflect this large-scale behaviour. It should be noted that the calibration was primarily conducted for the Fabian and Kapten surface cratering, with rock mass properties then being changed in the same manner for all rock types in the entire model. The comparison with underground caving observations in other orebodies nevertheless showed fair agreement between model prediction and field data. The final properties are judged to be a fair representation for the entire ore field and for the purpose of coupled *CAVESIM-FLAC3D* modelling of caving and ground deformations. Moreover, the resulting *GSI*-values are in good agreement with recent and more detailed results from underground mapping, thus further confirming the rock mass characteristics used in the model.

3.2 Validation

Using the ground surface displacement data from GPS-monitoring at Malmberget enables performing an independent validation of the numerical model results. The calculated deformations from the numerical model were compared with the corresponding measured deformations for the period of 2010 to 2020, focusing on the vertical displacement component. There was a fair agreement for most monitoring points, with a few exceptions. An example of the development of the measured and calculated deformation for a selected number of monitoring points is shown in Figures 7 and 8.

Figure 7 Selected monitoring points for time-displacement graphs

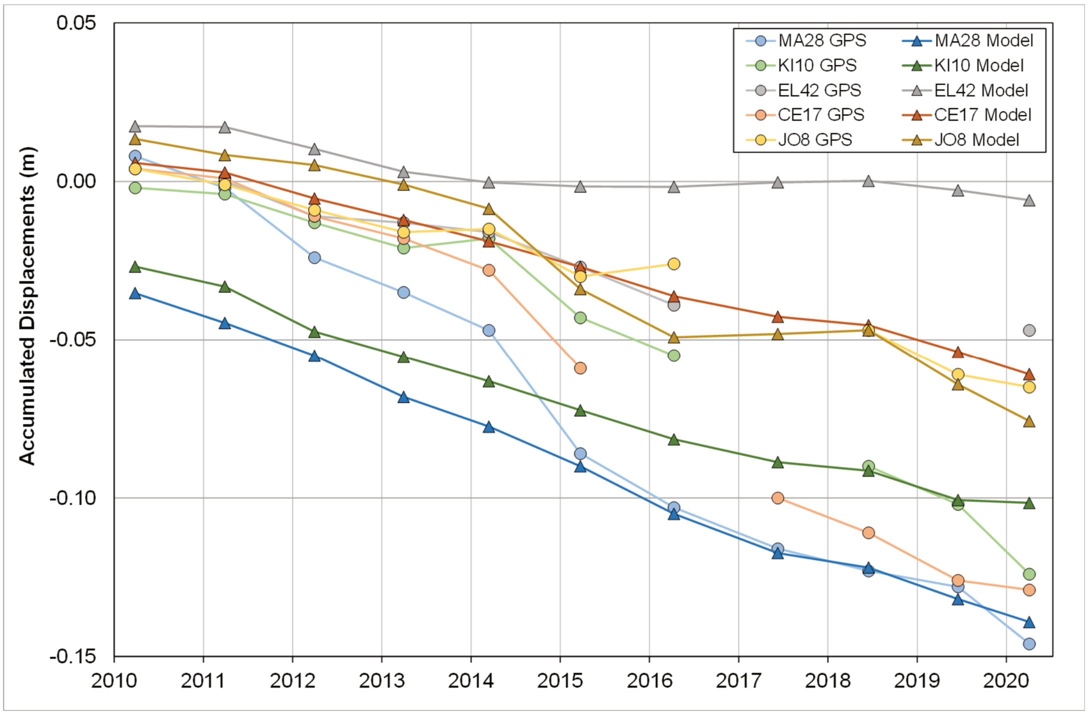

Figure 8 Measured and calculated vertical deformation for five selected GPS-monitoring hubs in Malmberget for the period of 2010–2020

The results show a similar trend in deformation in the model compared to field data and for virtually all monitoring points examined. The temporal evolution of the deformations is thus generally well captured in the numerical model and the model can be said to be reasonably validated.

4 Model prediction

4.1 Caving and surface deformation

The numerical model was used to predict the 3D-volumes of the caved rock between years 2020 to 2070. An example is shown in Figure 9. The results show that, for most of the orebodies, caving is progressive as long as the mining is active and the caved volumes grow all the way to the ground surface. After the mining in an orebody is terminated, a sharp decrease in the growth of the caving volume is found.

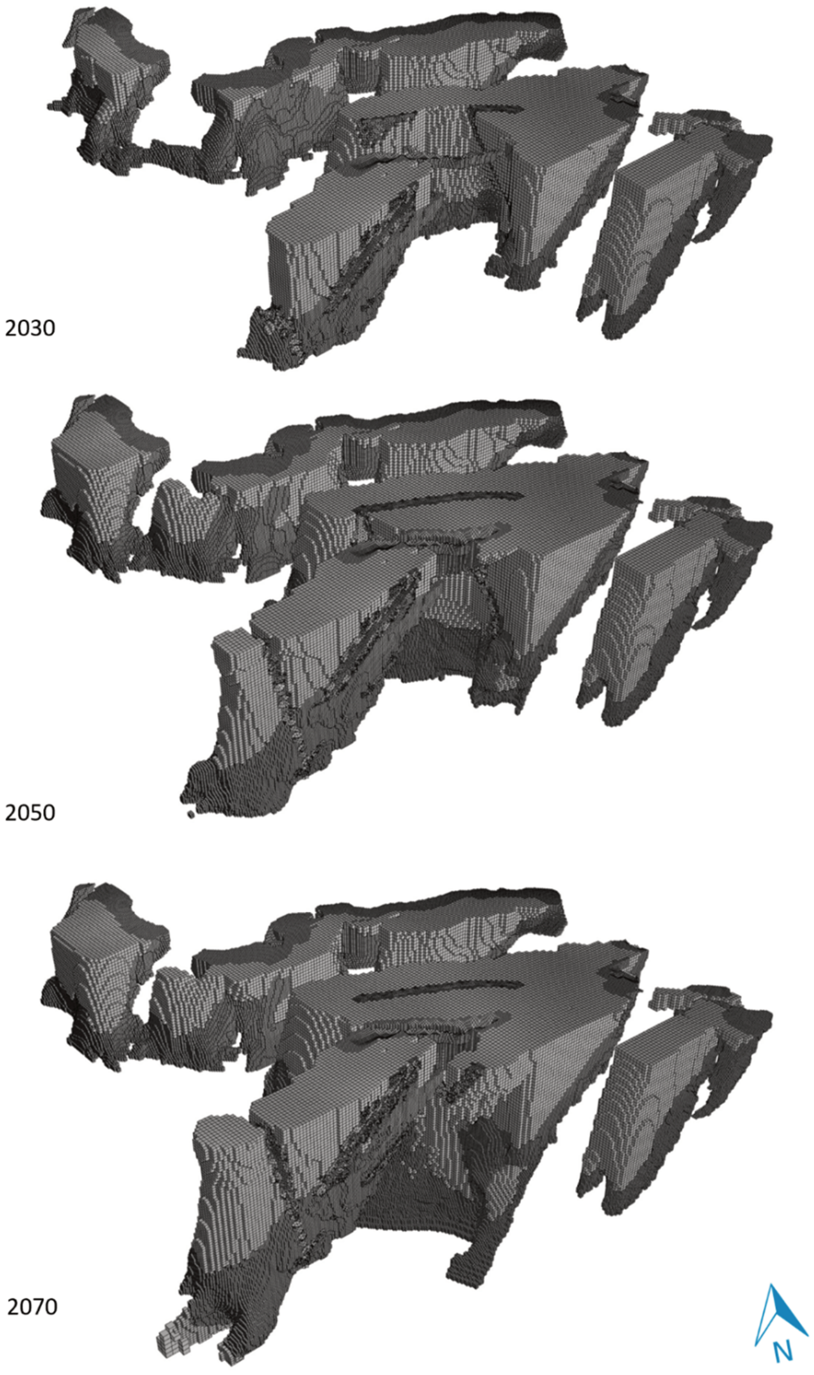

Figure 9 Predicted volumes of caved rock around orebodies for the years 2030, 2050 and 2070

For the orebodies located in the middle of the mining area (Alliansen-Printzsköld orebody complex and Dennewitz orebody), the caving volumes will grow strongly until the year 2070. At the ground surface, this growth seems to be at a steady pace, while the cave growth underground is very marginal from level 1500 m and downwards. This may partly be a model issue, with the downward progression being somewhat exaggerated (same annual production but thinner orebodies) and cave development thus not keeping up with this pace.

For the orebody complex Kapten-Fabian, the caving seems to 're-start' from the mining level when the mining progresses through the structure DZ020. A new cave column is formed that grows to the ground surface between years 2040 and 2050. This may be an effect of how the structure is simulated in the model but can also reflect a real behaviour. Previous analysis of the Kiirunavaara Mine (Svartsjaern et al. 2020) has shown that large-scale structures result in delayed caving and straining behind the structure, as the structure accumulates deformations and strains, thus 'buffering' cave growth temporarily. The 'rock bridge' that is formed near DZ020 will most likely break up and cave, once the cave front extends beyond the geological structure. This 'delay in caving' is also seen near other large-scale structures in the model, but to a lesser extent with mining direction being more parallel to these structures.

The environmental criteria at the ground surface are defined by the allowable tensile ('horizontal' in the criteria) and shear ('vertical' in the criteria) strain caused by the SLC mining. The extent of areas of caved rock and fulfilled environmental criteria was evaluated for each mining step/year in the model. The results obtained for these two criteria (horizontal and vertical) were found to be similar, i.e. the horizontal and vertical strain limits are fulfilled more or less simultaneously. The model results agree very well with the measured values for year 2019, as shown in Figure 10, providing further confidence to the calibrated model.

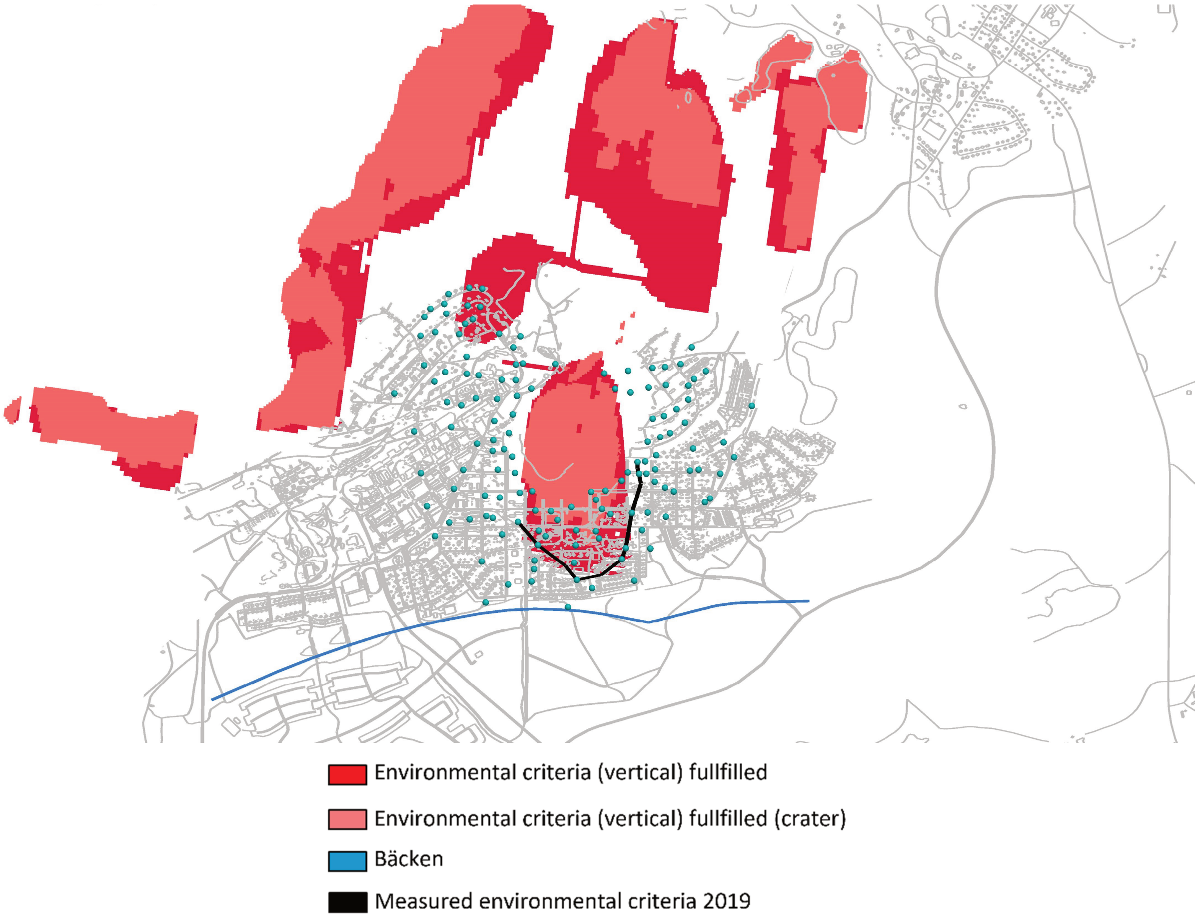

Figure 10 Predicted fulfillment of the environmental vertical strain criteria from the numerical model compared with observed location of the environmental criteria limit on the ground surface

The results of the model obtained for the vertical criteria and the years of 2022, 2030, 2050 and 2070 are presented in Figure 11. The areas in the model with craters are distinguished by using different colour shades. The area with fulfilled environmental criteria increases steadily with future mining. From year 2030, the ground surface area with fulfilled environmental criteria increases in size above the orebodies located north of the Printzsköld-Alliansen orebody complex. There is also some growth towards south, but less extensive due to larger mining depths and buffering of cave growth towards large-scale structures. The thin strain 'bands' shown for years 2050 and 2070 in the south portion (like 'whiskers') is an effect of the strain limit being locally exceeded along a row of elements in the model. The orientation of these bands is thus mesh-dependent, but the strain within the elements is correctly calculated and local straining should be expected in these areas on the ground surface. However, this does not indicate any overall straining of the entire rock mass in this area.

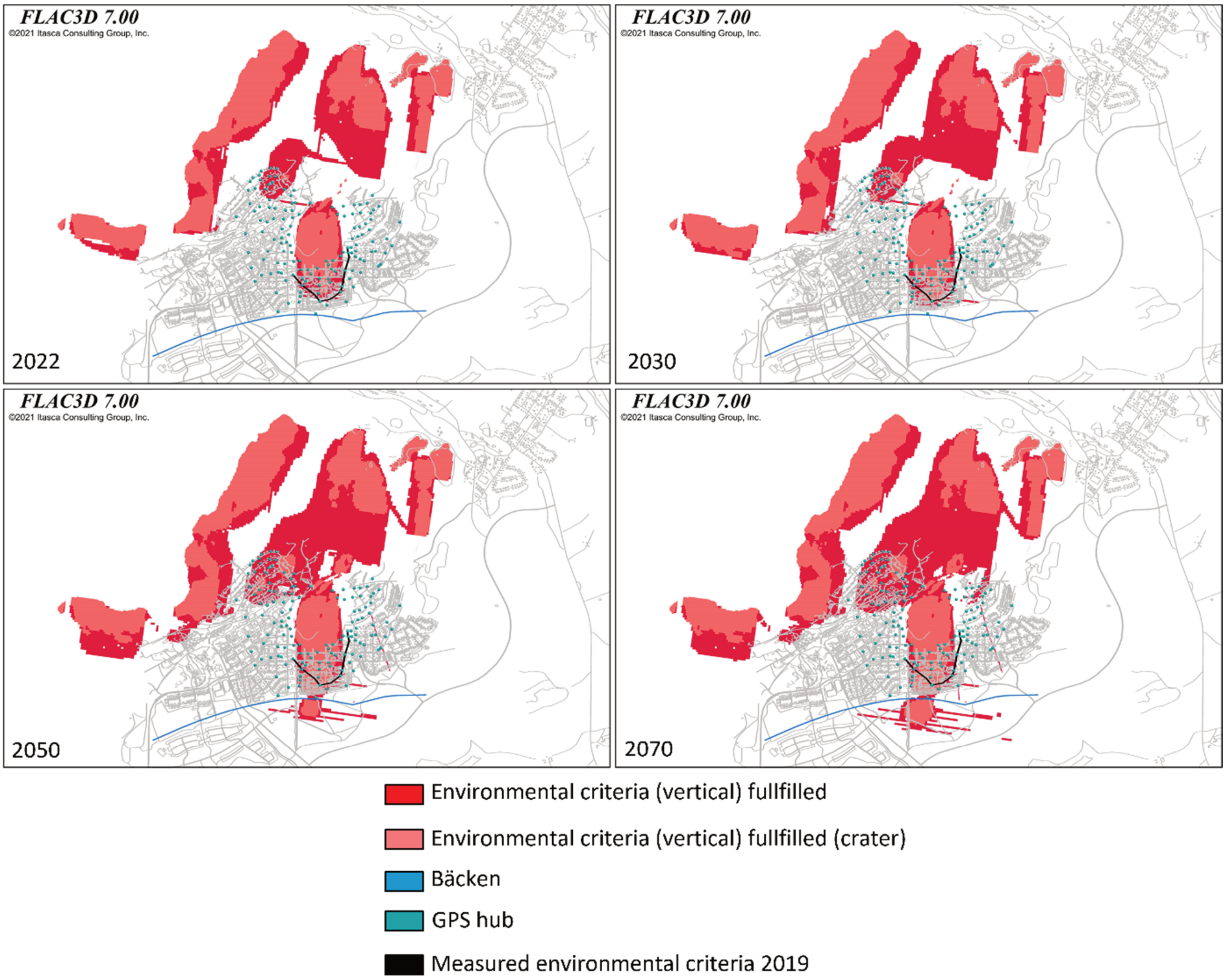

Figure 11 Predicted fulfillment of the environmental vertical strain criteria from the numerical model

Currently, limit angles are used by LKAB for prediction of the location of the environmental criterion on the ground surface. The limit angle is defined as the angle from the horizontal to a line extending from the active production area or drawpoint for a certain year/level and to the location of the environmental strain criterion on the ground surface, see Figure 12. Limit angles were evaluated from the numerical model for selected years of 2020, 2030, 2040, 2050, 2060 and 2070 and for 13 evaluation vertical cross-sections as shown in Figure 13. The results of the limit angle analysis for the Printzsköld-Alliansen orebody complex (cross-section nos. 3 and 5) and the Fabian-Kapten orebody complex (cross-section no. 9) are presented in Table 4.

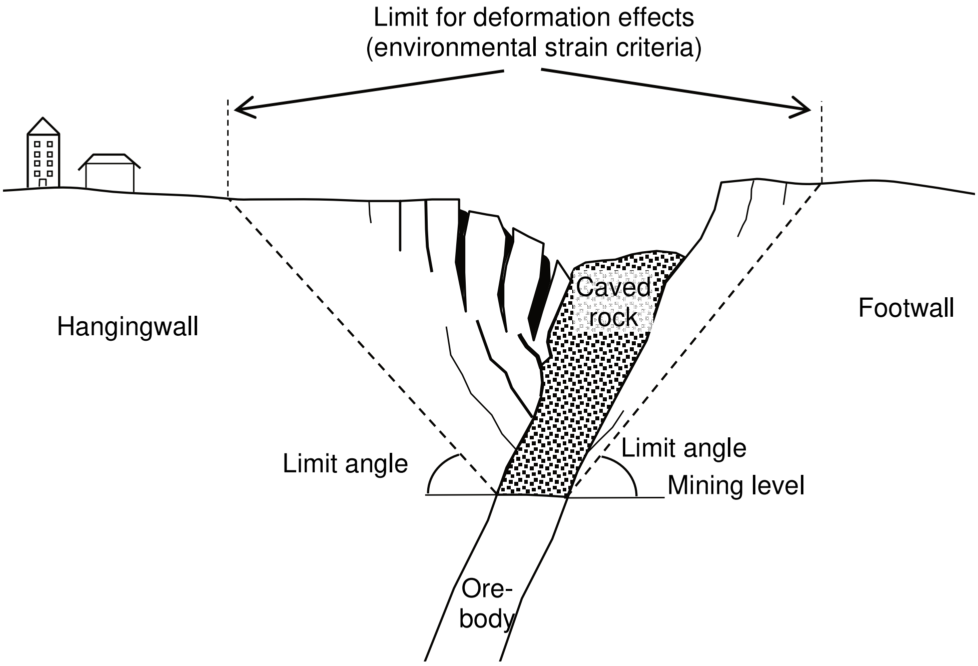

Figure 12 Definition of limit angles

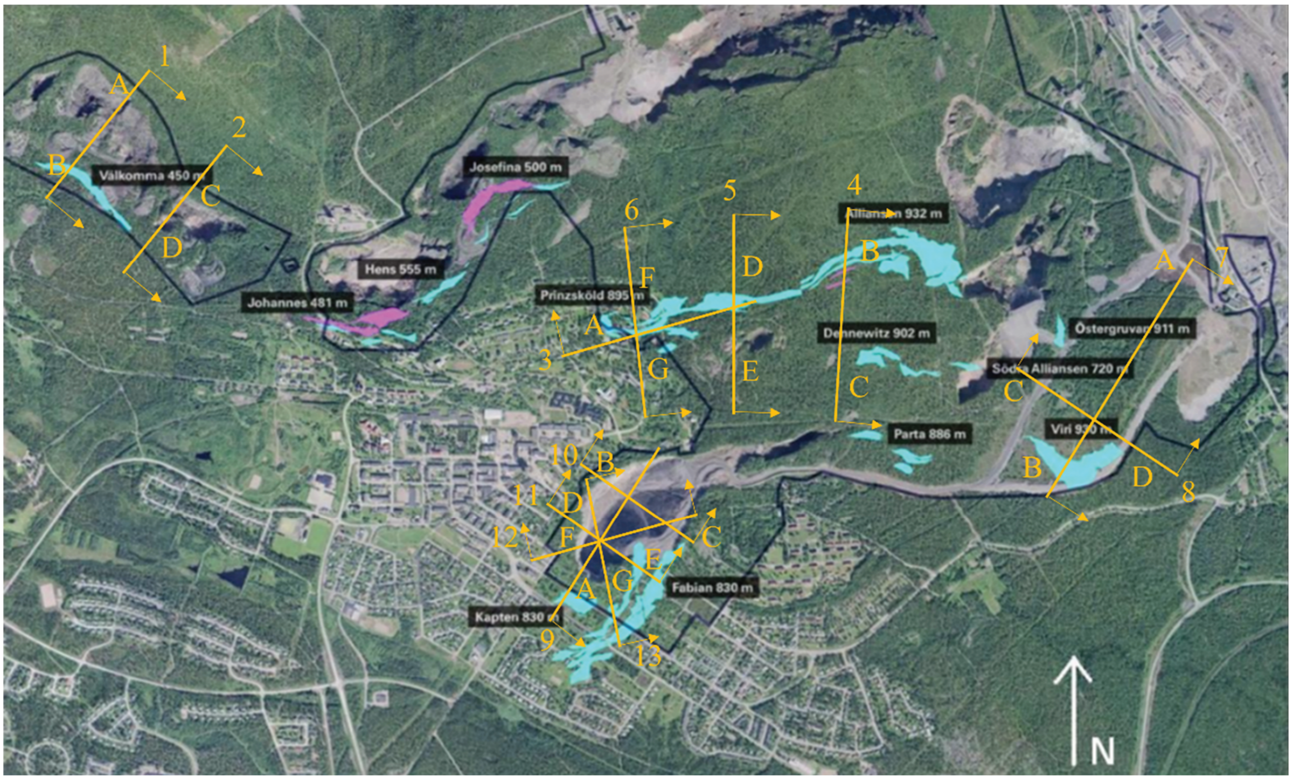

Figure 13 Vertical evaluation cross-sections for limit angles, Malmberget shown on a plan view with the projections of orebodies for selected mining levels

Table 4 Limit angles for vertical evaluation cross-sections. Angles larger than 90° corresponds to an 'overhang', i.e. that the environmental criteria location on the ground surface is 'behind' the horizontal projection of the production drawpoint

Orebody complex	Cross-section	Location	Year					
			2020	**2030**	**2040**	**2050**	**2060**	**2070**
Printzsköld-Alliansen	3	A	78°	83°	94°	107°	102°	101°
Fabian-Kapten	5	E	92°	91°	85°	77°	71°	87°
	9	A	91°	100°	94°	92°	87°	89°

The results show a slight decrease in the limit angle with increasing mining depth except for the cross-section no. 3 where the limit angle for the year 2070 is steeper than that at year 2020. The limit angle is approximately 90° in the regions located south of the Fabian-Kapten orebody complex (cross-section no. 9) and south of the Printzsköld-Alliansen orebody complex (cross-section no. 5). For the Fabian orebody, the large-scale structure in the southern portion temporarily acts as a 'buffer' for the cave development, thus also delaying any surface effects. For the longer time perspective, caving and ground deformations will 'catch up' once the cave front has progressed through the geological structure.

4.2 Influence on underground infrastructure

Of particular interest was the underground air heating plant, located between the Kapten-Fabian and Alliansen-Printzsköld orebodies and how this was possibly to be affected by the cave mining. The model was used to study the development of caving, as well as yielding and deformation at the location of the underground air heating plant, associated shafts and its connecting infrastructure. The model showed that over the past 5–10 years, yielding and deformation in the area has increased, mainly at the top of the ventilation shaft but also in connecting infrastructure, see Figure 14. Moreover, a significant increase in the extent of yielding and the magnitude of displacements is predicted over the next 5–10 years. These results strongly suggest a relocation of this infrastructure in due time.

Several relocation alternatives were investigated using the numerical model. An initially proposed alternative proved to have a predicted life of only 10–20 years; hence, other alternatives were developed and studied further. Five separate locations were investigated with the aim of achieve at least a life of 30 years for the air heating plant. Deformations were evaluated for the five locations, with an acceptance criterion of 0.2–0.4 m of total induced deformation applied. Moreover, the extent of yielding in the area of the ramp, ventilations shafts and connecting infrastructure, was evaluated and the five alternatives ranked in priority. One alternative was collectively judged to be the most favourable, with small deformations and small to moderate areas of yielding in the rock mass over the expected life of 30 years.

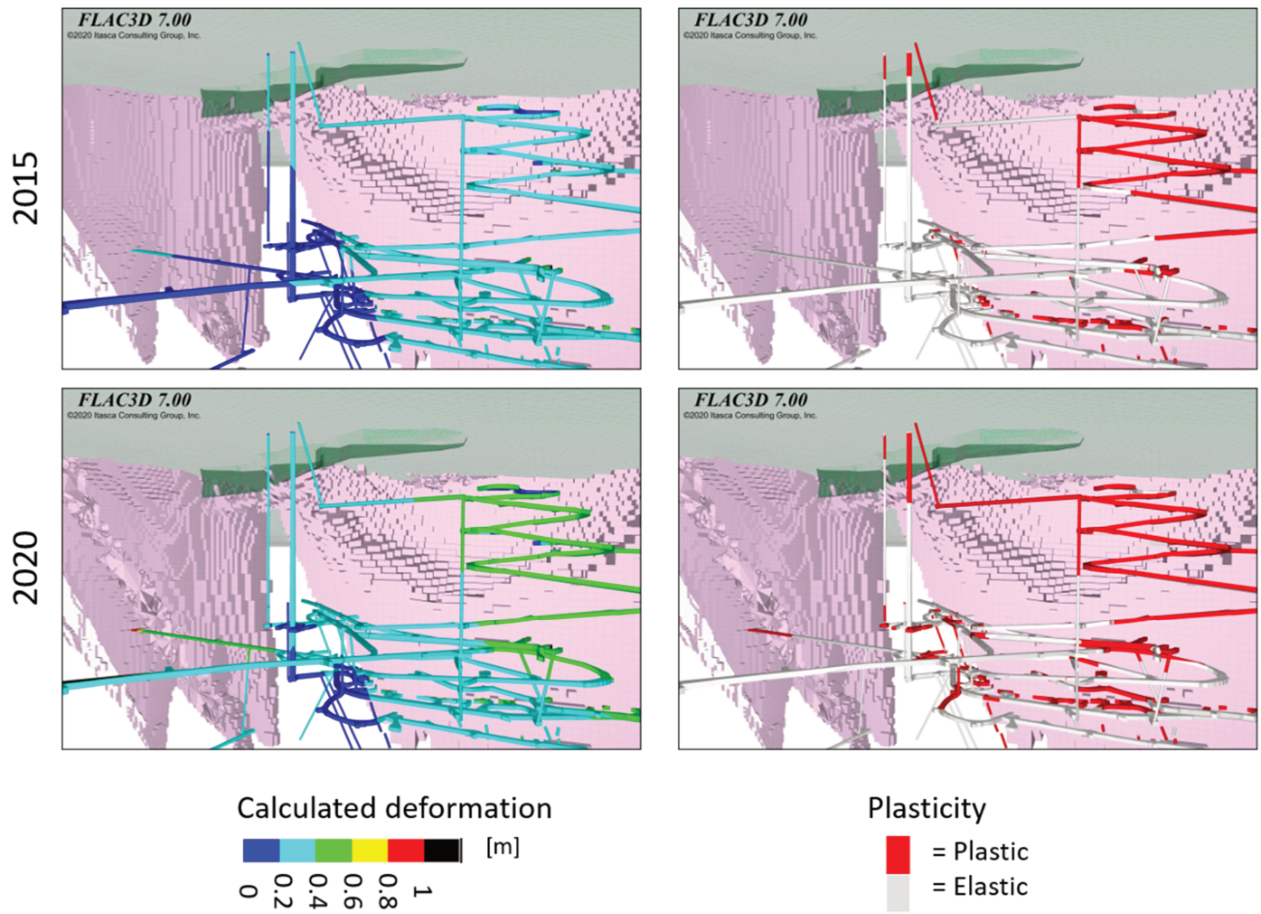

Figure 14 Effect of cave mining on the underground air heating plant for years 2015–2020

5 Discussion

The calibration of the rock properties was conducted through the comparison of observed and calculated cave cratering on the ground surface. Cave propagation towards the surface develops a bit faster in the model compared to reality for some of the orebodies. A contributing factor to this may be that the upper part of the model has no variation in the rock mass properties, due to lack of mapping data. On the other hand, it cannot be stated with certainty that the model is consistently conservative, since it is possible that the ground has displaced more in reality but without visible cracking or surface cratering.

The model also shows a delay in caving and ground deformations when mining progresses towards a large-scale structure. This can partly be a model effect, but it is likely that it also reflects a true behaviour, with the structure accumulating deformations and strains, thus temporarily halting cave growth. This behaviour is most evident when the direction of mining is perpendicular to the strike of the structure, but is also seen, to a lesser extent, for other structures in the model.

There is some yielding around the infrastructure in the area of interest and some of it could be reinforced depending on the depth of yielding. The interpretation of yielding and deformations in this model only show what it looks like in the area of the infrastructure, not an actual analysis for that particular drift or shaft. For the underground infrastructure, it is important that the different levels of calculated deformation in the model is linked to observations. It is only when a link is made between a certain deformation value and the damage that occurs in reality, that an assessment can be made of how much the drift can take. Additional work, using field observations and measurements, where available, is recommended to provide this link.

6 Conclusion

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

- Caving on the ground surface predicted from the numerical model up until today is generally consistent with the observations made in the field. There are indications that cave predictions in some areas are slightly conservative (larger areal extent and earlier in time), but it is also possible that larger ground movements have developed (over time), without observable cracking and surface cave cratering. It cannot thus be stated with certainty what the level of conservatism is.
- The limit angles evaluated for prognosis of the location of the environmental criteria on the ground surface showed a general trend of decreasing angles with the future mining. This implies that the prognosis methodology should be re-evaluated and possibly revised going forward.
- There is clear influence on caving and mining-induced ground deformations from the included large-scale structures in the numerical model. It should be noted that properties and characteristics of the structures are largely assumed; more detailed investigations are required to further characterise these structures. This may also involve supplementary modelling with refined properties and/or more structures included, to assess the influence to ultimately increase reliability in predictions.

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