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The Role of Pillars in Raise Caving

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Abstract: Mining advances to greater depth, where the control of rock pressure is central for a successful operation. To handle the increasing rock pressure at LKAB's Kiruna iron ore mine, LKAB and Montanuniversität Leoben develop a novel mining method called "raise caving". Raise caving is based on an active stress management approach. De-stressing slots, which are separated by substantial pillars, are developed first and provide stress shadows for stope development and subsequent large-scale mineral extraction. At an advanced stage of extraction, these pillars are extracted, too. The pillars are decisive for the success of the raise caving method. They are responsible for the control of stresses, the stability of the hanging wall, and the control of seismic energy release. Hence, studies on pillars have a high importance. This contribution investigates the effect of pillar behavior on the overall extraction system by means of numerical simulations. Two different types for pillar behavior are examined, namely infinitely strong pillars and pillars which yield or crush in the process of extraction. In the second case, pillar stress strain curves are created and replicated numerically. The investigated behavior of pillars is based on available studies on the pillar stress strain behavior. Results show the importance of intact (not overloaded) pillars in the initial de-stressing phase in raise caving. These pillars are essential for controlling the stress levels at the position of the raise bore holes for the initial slot development. Pillar overloading results not only in an increase of the spatial extent of the stress shadow but also in a growth of stresses in the abutment areas and neighboring not yet overloaded pillars. It has been found that this instance can endanger the mining activities in the de-stressing phase. Furthermore, it has been found that the layout of the slot-pillar system together with the extraction sequence is decisive for ensuring that pillars are not overloaded in the de-stressing phase.

Keywords: Raise caving, Pillars, Deep mining, Numerical simulations

Die Rolle von Bergfesten im Raise-Caving Verfahren

Zusammenfassung: Der Bergbau dringt in immer größere Teufen vor, wobei die Kontrolle des Gebirgsdruck eine zentrale Rolle für einen erfolgreichen Abbaubetrieb spielt. Um den steigenden Gebirgsdruck im LKAB Eisenerzbergbau in Kiruna in den Griff zu bekommen, entwickeln LKAB und die Montanuniversität Leoben ein neues Abbauverfahren. „Raise-Bruchbau“ basiert auf aktiven Gebirgsdruckmanagement. Entspannungsschlitze, welche durch mächtige Gebirgsfesten unterteilt sind, werden zu Beginn geschaffen, um der Errichtung der Kammern und der folgenden großmaßstäblichen Mineralgewinnung Spannungsschatten bereitzustellen. Bei vorangeschrittenem Abbau werden auch die Gebirgsfesten entnommen. Die Gebirgsfesten sind für den Erfolg der Raise-Bruchbau-Methode entscheidend. Diese Festen kontrollieren Spannungen und Seismik und sind weiters für die Stabilisierung des Hangenden verantwortlich. Forschungstätigkeiten zum Thema Gebirgsfesten haben deshalb auch höchste Priorität. Diese Arbeit untersucht mit Hilfe von numerischen Simulationen den Einfluss des Festenverhaltens auf das gesamte Abbausystem. Zwei verschiedene Typen von Festenverhalten werden untersucht. Diese sind intakte unendlich belastbare Festen und Festen, welche während des Abbaus versagen können. Bei zweiteren werden Spannungs-Dehnungskurven von Festen erstellt und numerisch repliziert. Das Festenverhalten wurde aufgrund vorhandener Studien über das Spannungs-Dehnungsverhalten von Gebirgsfesten erstellt. Ergebnisse zeigen die Wichtigkeit von intakten (nicht überlasteten) Gebirgsfesten während der Entspannungsphase im Raise-Bruchbau. Die Gebirgsfesten sind für die Kontrolle der Spannungen im Bereich der Raise-Bohrlöcher, welche dem Abbau der Entspannungsschlitze dienen, essenziell. Ein Festenversagen ist einerseits für eine Ausdehnung des Spannungsschattens sowie andererseits für einen Anstieg der Spannungen in den Auflagerbereichen und in den noch nicht versagten, benachbarten Festen verantwortlich. Dieser Umstand kann die Bergbauaktivität

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täten in der Entspannungsphase gefährden. Weiters ist das Layout des Schlitz-Festen-Systems gemeinsam mit der Abbausequenz dafür verantwortlich, eine Überbeanspruchung der Gebirgsfesten in der Entspannungsphase zu verhindern.

Schlüsselwörter: Raise-Bruchbau, Gebirgsfesten, Tiefer Bergbau, Numerische Simulationen

1. Advancing to Greater Depths with a Novel Mining Method

1.1 Deep Mining

The demand for mineral resources is growing with the increase in the world's population. The easily accessible deposits near the surface are getting mined-out, and so the mines need to move to greater depths. One consequence of this development is the rise in rock pressure related mining problems [1]. This rise is the result of increasing stresses but a constant rock mass strength:

- As mining goes deeper, the primary vertical stresses increase. Depending on the location of the mine, the primary horizontal stresses vary in a broad range. The primary horizontal stresses are calculated with the k-factor, which is the ratio of the primary horizontal stresses to the primary vertical stress. Fig. 1 visualizes the development of the vertical stress and k-factor depending on the depth for an average rock weight of 27 kN/m^3 [2]. Additional to the primary stresses, mining causes additional stress changes.
- As the rock mass strength does generally not increase with depths, rock pressure problems become more likely and more severe with increasing depths. Typical rock pressure related problems are excessive spalling and rockbursts.

An appropriate mine layout and mining sequence are decisive for the control of rock pressure at great depth [3].

1.2 Raise Caving

The LKAB's iron ore mine in Kiruna has been experiencing rock pressure problems. The current mining method sublevel caving induces considerable stresses in the lower abutment where active mining areas are. Due to the prevailing high stresses, ore passes which are situated in this area are damaged heavily. Moreover, rockbursts cause significant damage to the infrastructure [4–6]. The main haulage level in Kiruna mine is in a depth of 1365 m and a depth extension of up to 2000 m is planned in the future [7]. In cooperation with the Montanuniversität Leoben, a novel mining method called raise caving is developed, which aims at controlling the rock pressure situation whilst enabling a high productivity [8, 9]. Furthermore, the application of raise caving is of interest for other LKAB mines as well. Fig. 2 gives a schematic overview of the method. There-

fore, this new method is based on de-stressing slots, which are not emptied and hence always filled with blasted rock mass, in combination with substantial pillars to ensure favorable stress conditions for the establishment of the raise bore holes where modern remote-controlled or automated machinery is installed to excavate the de-stress slots.

The method is further separated in a de-stressing phase and a production phase. The main idea is to create de-stressing slots with a minimum amount of pre-developed infrastructure in the de-stressing phase, where, in the later production phase, large-scale stoping can take place in the de-stressed ground behind these slots. Pillars between the de-stressing slots control the stresses in the mining layout, provide support to the hangingwall, and control the release of seismic energy. In the subsequent production phase, the pillars are also mined and a redistribution of stresses on a regional scale as well as regional energy changes are the result. Hangingwall caving is initiated in the production phase. If pillars are not able to fulfill the above outlined tasks in the de-stressing or production phase, the pillars fail from a functional perspective. A functional failure of pillars might lead to considerable operational and safety issues in raise caving. So the pillars play an important role for the success of raise caving [9].

Pillars are formed between the slots in the de-stressing phase. Currently planned pillar dimensions in the de-stressing phase range between 30–70 m in width, between 5–10 m in height, and up to several hundred meters in length. Due to the inclined orientation of the pillar, the term "pillar length" describes the dip extension of the pillar and the terms "pillar width" and "pillar height" refer to the pillar extension in a cross-section perpendicular to the pillar length (Fig. 3). Hence, pillars in the de-stressing phase are planned to have a width to height ratio of about 2.5–10. The knowledge about hard rock pillars with such dimensions and geometry is rather limited [3], which impacts on the development of the raise caving method. Furthermore, the massive pillars, which transfer considerable stress magnitudes in the de-stressing phase, need to be crushed and extracted in the production phase in a safe manner. For this reason, the following investigations are necessary:

- Improving the understanding of pillar strength and stress-strain behavior of pillars utilized in raise caving
- Analyzing the impact of pillar strength and stress strain behavior on the raise caving method, in particular their impact on the regional stress and energy changes

Addressing both points is necessary in order to design an implementable layout and sequence for raise caving. For the first point, fundamental studies are conducted, which comprise conceptual and numerical investigations as well as an in-situ test of a pillar in a large-scale test site. These studies and their results will be outlined elsewhere. For the second point mainly, numerical simulations are conducted. As the pillar strength and stress strain behavior are not well known at this stage, they are replicated based on literature, and parameter studies will be conducted to consider uncertainty and to investigate the impact of different

Fig. 1: Relation between depth and a Vertical stress [MPa] and b k-factor [2]

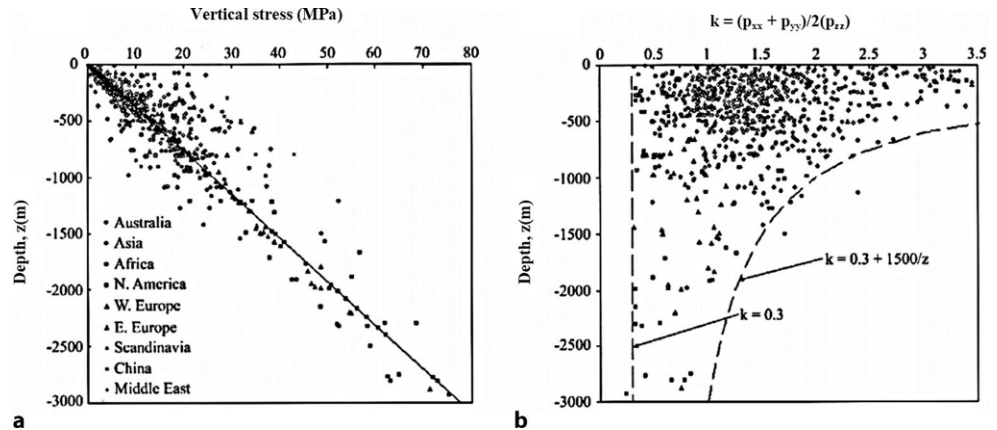
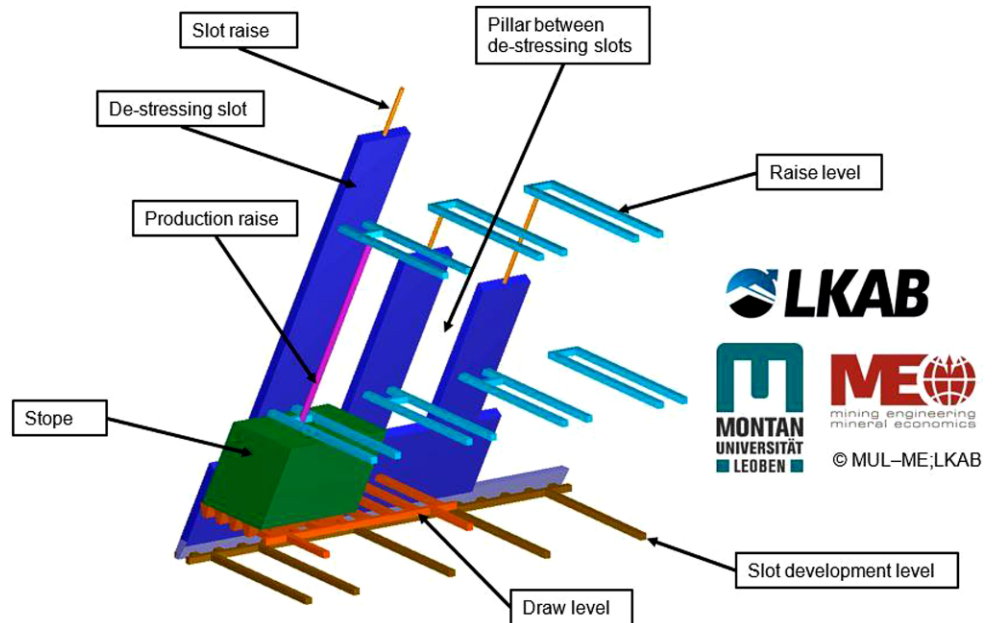


Fig. 2: Schematic overview of the raise caving mining method [9]



pillar strength and stress strain behavior. This contribution highlights the ongoing investigations on the impact of pillar strength and stress strain behavior.

2. Research Approach

2.1 Numerical Simulations with FLAC3D

To investigate the impact and importance of pillars in the raise caving process, several situations have been analyzed by means of numerical simulations using FLAC 3D [10]. The first investigation examines the stress situation resulting

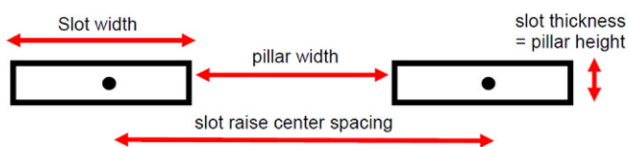


Fig. 3: Cross-section perpendicular to the pillar length showing used terms for describing pillar and slot dimensions [3]

from the development of a number of narrow de-stress slots separated by 50m wide squat pillars. A linear elastic material model is used, and it is assumed that the squat pillars do not fail.

The linear elastic model is able to outline the regional stress changes sufficiently. However, the linear elastic model cannot be utilized directly for modelling pillar overloading, yielding, and crushing. In order to simulate pillar overloading, yielding, and crushing, the approach outlined in Sect. 2.2 has been implemented in the simulations.

2.2 Numerical Replication of Pillar Overloading and Crushing

Pillar overloading and crushing is simulated as follows. The simulation is still solved with a linear elastic material behavior. As long as pillar overloading does not occur, the pillar is modelled as linear elastic (Fig. 4a). However, in case of a pillar overloading the original pillar is removed and instead a stress is applied at the previous pillar bound-

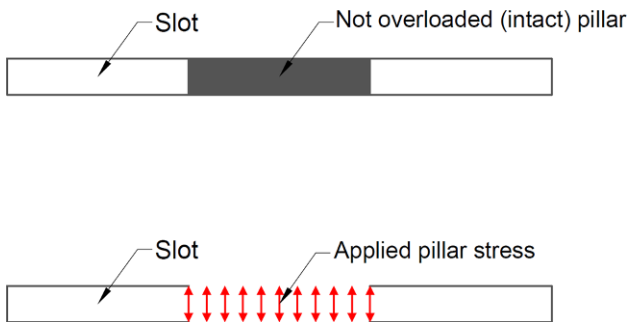


Fig. 4: Conceptual sketch of sequenced overloaded pillar

aries (Fig. 4b). This applied stress replicates then a defined post-peak behavior of the pillar, which is a function of pillar compressive strain. Pillar overloading and crushing can occur gradually over the pillar length, which means that certain portions of the pillar can already be overloaded, whilst other portions are still intact. For the implementation of this approach, the Python interface in Flac3D is utilized.

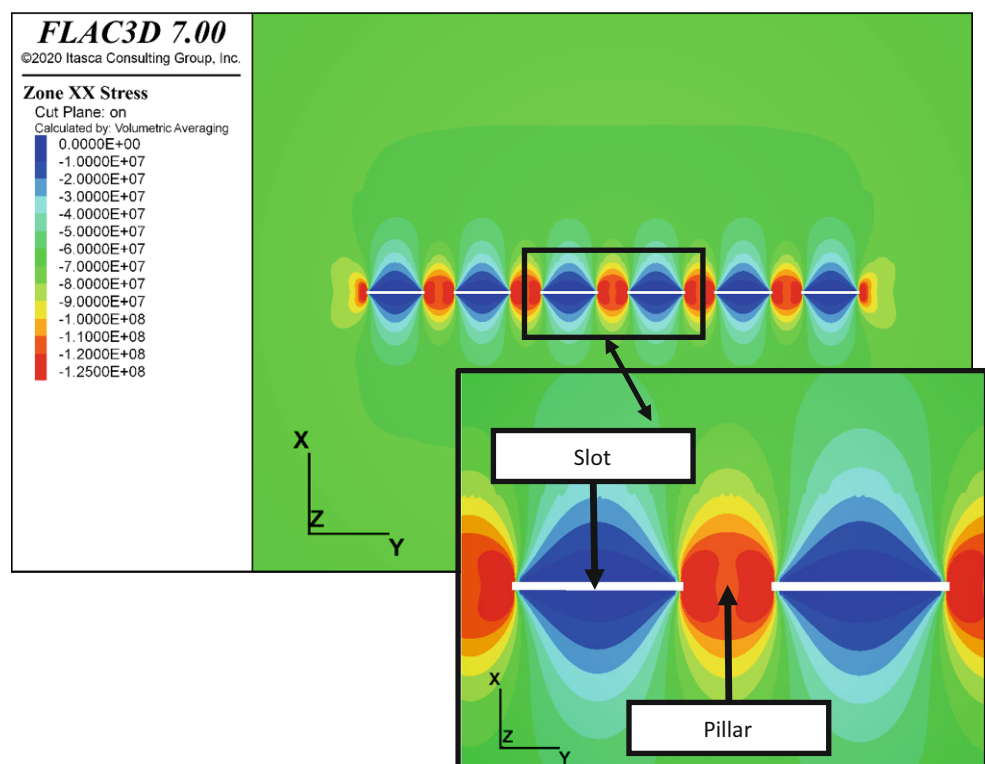
This simplified modelling approach of pillar overloading and crushing makes it possible to analyze the impact of different pillar geometries and dimensions as well as of different rock mass properties efficiently. Furthermore, maintaining a linear elastic material model facilitates the interpretation of the modelling results and reduces the calculation time.

2.3 Types of Numerical Simulations

Two different types of simulations are made:

1. In the first type, the pillars are not modelled with the above-outlined approach. Instead pillars are modelled as linear elastic, too, and hence these pillars are infinitely strong. Pillar overloading, yielding, and crushing cannot occur. The purpose of the model with an infinitely strong pillar is to show the situation in the mining layout when no pillar failure occurs. This has the advantage of getting knowledge on the pillar stresses by a variation of the dimensions. Particularly the extraction ratio in the slot-pillar system, which is a function of the slot and pillar width, has a strong influence on the pillar stresses. Additionally, the influence of the dimensions on the stress redistribution in the slot-pillar system can be interpreted easily. Furthermore, this model allows to determine the stress situation in the abutment area of the de-stress slots, i.e. the area where the next raise bore holes will have to be established. These simulations are less complex and are used as a base case for the interpretation of results.
2. In the second investigation, the pillars are modelled with the above-outlined approach. Pillar overloading, yielding, and crushing can occur. The sequence of slot and stope extraction becomes central because pillar overloading is a gradual process. The results of the second type of simulations represent the situation in raise caving more realistically. They are used for outlining possible layouts and sequences and for highlighting the impact of pillar strength and stress strain behavior.

Fig. 5: Example for stress analyses for a horizontal cut through the model comprising six slots and five pillars. Pillars are infinitely strong



2.4 Interpretation of Results

The following three different approaches are used for analyzing the situation in raise caving:

1. Stress situation and stress changes
2. Infrastructure stability

2.4.1 Stress Situation and Stress Changes

The first approach is to analyze the stress redistribution in the mine layout with the help of color plots as shown in Fig. 5. Furthermore, stresses are displayed and compared along specific measurement lines. These plots and diagrams are used to evaluate the overall stress distribution.

2.4.2 Infrastructure Stability

The second approach is to focus on the rock wall condition factor (RCF) [11] values for mine infrastructure, such as slot raises or drifts. The rock wall condition factor (RCF) is defined as:

$$RCF = \frac{3\hat{\sigma}_{1RCF} - \sigma_{3RCF}}{F\hat{\sigma}_{UCS}}$$

σ_{1_RCF} and σ_{3_RCF} are defined as the maximum and minimum stresses which are acting perpendicular on the tunnel or raise bore hole axis. The dividend of the equation represents the maximum tangential stress at the circumference of a circular tunnel. The divisor is the strength of the rock. It includes the uniaxial compressive strength of the rock (UCS) and the F-factor, which degrades the intact rock strength considering discontinuities in the rock mass [12].

The corresponding diagram in Fig. 6 shows the observed tunnel conditions as a function of RCF and installed support types. This diagram is calibrated on the experience in deep South African gold mines. Earlier studies with the RCF concept show that the concept and the diagram below is also suitable to describe the conditions of infrastructure in the Kiruna mine [13].

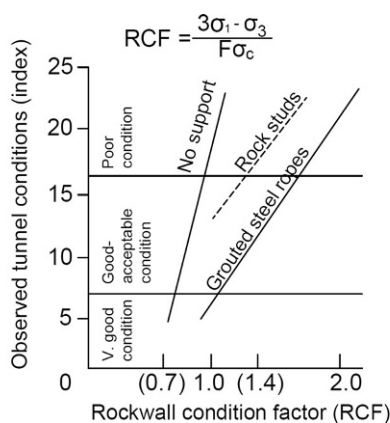


Fig. 6: Correlation of RCF values to tunnel conditions for different rock support types in deep South African gold mines [12]

3. Numerical Modelling

3.1 Model Geometry

The model consists of six inclined slots which are separated by substantial pillars. Fig. 7 displays a typical simulation model. In the back of each slot and in each pillar, stopes can be excavated. These inner parts, the slots and pillars, are surrounded by additional simulation blocks which function as abutments. The area of pillars, slots, and the simulation blocks which are in direct contact to them are built up with a fine mesh. The outer blocks are meshed more coarsely to reduce the calculation time. As the simulations calculate with a linear elastic model, the following input parameters are necessary to solve the simulation:

- Density
- Young's modulus
- Poisson's ratio

The values for the parameters are taken from [13], and they are 4700 kg/m³ for density, 53 GPa for Young's modulus, and 0.32 for Poisson's ratio.

While the input parameters are the same for every simulation, the dimensions of the pillars and slots are varied to generate information on pillar stresses, stress shadow extension, and abutment stresses in different mining layouts.

The model is fixed in velocity in x-, y- and z-direction at the outer boundaries of the model. The primary stresses, which are initiated to the model, are calculated after Sandström [14], who analyzed the virgin stress situation for the Kiruna mine. The investigations in this contribution are done for a depth of 2000m, where the vertical primary stress is 58 MPa, the horizontal stress in west-east direction is 74 MPa, and the north-south horizontal stress is 56 MPa. Furthermore, recent studies which indicate the stress situation in greater depths are also considered in the simulations [15, 16].

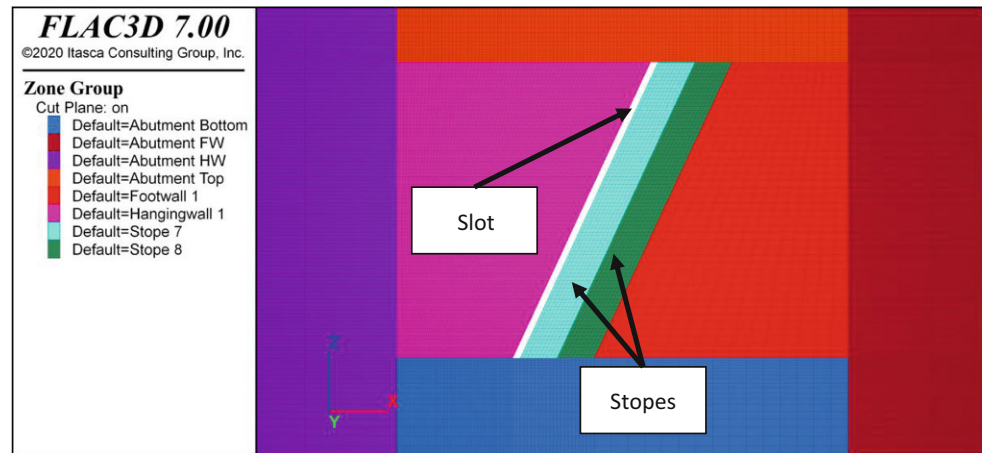
4. Simulation with Pillar Overloading

4.1 Considered Pillar Behavior

A more complex situation occurs in the case of overloading and crushing of pillars. The behavior of pillars is strongly dependent on the width to height ratio of the pillar. Several studies for coal and hard rock pillars outline this dependency [3, 17–22].

As the width to height ratios of the simulated pillars are 2, 3, 5, 7, and 10, replications of the pillar behavior for these width to height ratios must be made. The pillar strength is determined based on the equation of Salamon and Munro [23], as shown in Eq. 1, where K_{rm} is a measure for the rock mass strength, W is the pillar width, and H is the pillar height. As the Salamon and Munro formula was originally designed for coal pillars, where the K_{rm} value is set to 7.2, it requires an adaption for hard rock pillars, namely the rock mass strength constant (K_{rm}) is set to the global rock mass strength after the generalized Hoek-Brown strength crite-

Fig. 7: Vertical cross-section through a slot in the raise caving model



tion [24]. Moreover, the impact of squat pillars is considered according to Wagner and Madden [25], and the impact of pillar length according to Wagner [26]

$$PillarStrength = K_{rm} \dot{\epsilon} \frac{W^{0.46}}{H^{0.66}} \text{ [MPa]} \quad (1)$$

Besides the pillar strength, the pillar post-peak behavior needs to be considered. The required parameters are the post-peak strain softening rate and the residual strength.

- Strain softening rate:** Van Heerden [18] and Wagner [17] conducted in-situ measurements on coal pillars and found a relation between the width to height ratio and the post-failure modulus. Furthermore, Ozbay [27] assessed the post-peak stiffness for pillars by summarizing in-situ measurements and laboratory tests. The relation proposed by Ozbay is used to outline the post-peak stiffness of hard rock pillars, as shown in Eq. 2, where $-\lambda$ is the post-peak stiffness, E the Young's modulus, W the pillar width, and H pillar height. According to Ozbay's equation, pillars with a width to height ratio above 5 do not show a strain softening behavior. Instead pillars of such a geometry show a yielding or strain hardening behavior, where the strain hardening becomes more prominent with increasing width to height ratios. In the simulations, pillars with a width to height ratio of 5 or larger are modelled as yielding pillars. Neglecting the strain hardening effect is a simplification and consid-

ered conservative as it limits the transferred stresses through the pillar, which causes further stress shifts to abutment areas, where the infrastructure is situated.

- Residual strength:** Du Plessis and Malan [28] investigated the pillar residual strength. That study is the basis for the calculation of the pillar residual strength (APS_{res}). Their Eq. 3 is used for determining the residual strength of pillars with a strain softening behavior, namely pillars with a width to height ratio smaller than 5. In Eq. 3 S and m are strength parameters, H is the pillar height, W is the pillar width, and ϕ is the friction angle.

$$-\frac{\lambda}{E} = (0.8 - 0.16\dot{\epsilon}) \left(\frac{W}{H} \right) \quad (2)$$

$$APS_{res} = \frac{S\dot{\epsilon}H}{\tan(\phi)\dot{\epsilon}m\dot{\epsilon}W} \dot{\epsilon} \left[e^{\frac{\tan(\phi)\dot{\epsilon}m\dot{\epsilon}W}{H}} - 1 \right] \quad (3)$$

The pillar stress strain behavior is determined from previously described relations. The smaller pillars with a width to height ratio of 2 and 3 have a strain softening behavior, while the other pillars have a yielding behavior. A combination of the taken assumptions leads to the conceptual stress-strain curves of the pillars shown in Fig. 8. The actual pillar strength, pillar strain softening modulus, and pillar residual strength are a function of the pillar dimensions as well as the prevailing rock mass properties. Typical ranges of rock mass properties in the Kiruna mine are considered in the simulations [29].

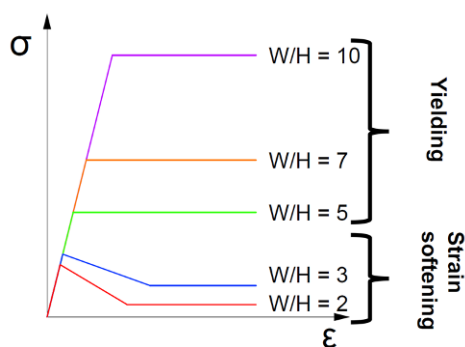


Fig. 8: Pillar stress strain behavior used in simulations for different width to height ratios

4.2 Mining Sequence

As described in the previous chapters, the mining sequence is, in combination with the mine layout, decisive for the spatial and temporal occurrence of pillar overloading, yielding, and crushing. Different mining sequences of slots and stopes are tested to gain knowledge on the stress development the slot-pillar system.

5. Analyses

The analyses are currently ongoing, and the majority of simulations has not been finished yet. Hence, the final re-

sults are not available at this stage. The analyses are done by color plots and data measure lines. Additionally, a script for plotting the RCF values is used. A brief summary of the initial results found from numerical models is given below. Further simulations and detailed analyses will be done in future; these results are planned to be published in subsequent papers.

- An increase in slot width results in an increase of the spatial extent of the stress shadow
- An increase in extraction ratio leads to higher stresses in the pillar
- Pillars are highly stressed in the de-stressing phase
- Placing mining infrastructure in or directly behind highly stressed pillars should be avoided
- The width to height ratio is decisive for the observed pillar behavior
- Pillar height and pillar width have less influence on the de-stressing effect than slot width, presupposed that the pillar is not overloaded
- An overloading of pillars has a considerable impact:
 - stresses in the abutments increase
 - stresses are shifted to not yet overstressed neighboring pillars, increasing of likelihood to overstress these pillars, too
 - stability of required infrastructure for de-stressing is affected adversely
 - stress drop in and spatial extent of stress shadows increase
 - the above outlined points depend on the pillar stress-strain and the degree of pillar overloading and crushing
- The mining layout and sequence have an influence on the location and time of a potential pillar overloading
- In summary, pillar overloading during the de-stressing phase has impacts on:
 - Creation of future slots
 - Further mining sequence
 - Stability of infrastructure

6. Conclusions

This contribution describes the tasks of pillars in raise caving and the way of simulating pillar overloading for pillars with a different width to height ratio. The focus of the analyses is on the stress situation, stress changes, and infrastructure stability. Numerical simulations in FLAC 3D are made therefore.

Pillars are decisive for the success of raise caving. Early results underline this issue. An overloading of pillars in the de-stressing phase must be prevented to guarantee suitable stress conditions for the needed infrastructure such as slot raises. A stress redistribution from the pillar to the abutment areas results in a degradation of the excavation stability in the de-stressing phase. A well-planned mining sequence and mine layout is the basis to prevent premature pillar overloading in the de-stressing phase. Furthermore, the mining layout and mining sequence are decisive in the

production phase for the extraction of pillars and the associated regional stress and energy changes.

Further investigations relating to energy changes and seismicity are planned to be done with the model. The analyses for the situation in the production phase are part of further investigations. For this, the model provides the base for simulating different stoping layouts and sequences as well as pillar extraction in the production phase. Of particular interest are the resulting regional stress and energy changes in the production phase. Moreover, the stability of pillar crushing needs further investigations and is not considered in this contribution.

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