



Study of the Impact of Hard Rock Pillar Behavior on the Raise Caving Mining System

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Received August 8, 2023; accepted August 9, 2023; published online September 25, 2023

Abstract: Raise caving is a novel mining method with an active stress control approach, which is suitable for deep mining environments. The application of raise caving is investigated for LKAB's Kiruna mine. This mining method consists of two different phases. In the de-stressing phase, inclined de-stressing slots are created with a minimum amount of infrastructure and long-raise bore holes. The de-stressing slots provide stress shadows for subsequent large scale mining activities. These slots are separated by massive pillars, with width to height ratios of up to 10 and a length of several hundreds of meters, which are required to control stresses and seismicity and prevent hangingwall caving. Due to the stress redistribution in the mine, pillars and abutment areas become highly stressed. In the so-called "production phase", which follows the de-stressing phase, large scale mineral extraction is conducted. As pillars are highly stressed after the de-stressing phase, it is important to de-stress them in a safe manner. Overall, pillars play a decisive role for the success of the raise caving mining method. Hence, studies on pillars and their impact on the raise caving mining method are of great importance. The first part of the contribution outlines the importance of pillars in the raise caving mining method on a conceptual basis. Numerical simulations for different mine layouts and different pillar behavior are then conducted to study the impact of pillar behavior on the system. The stress redistribution in the mining system and the infrastructure stability, with the help of the RCF-value, are analyzed. For this purpose, simulations with a linear elastic material behavior are a well-suited method. Consequently, the de-stressing of the pillar due to crushing cannot be analyzed with a linear elastic model. To do so, a method for de-stressing the pillar has to be implemented into the simulation. The behavior for

pillars with a different width to height ratio is implemented with the help of pre-calculated stress-strain curves from available knowledge on pillar strength and behavior. Since mining is a progressive process, the sequence of mining plays an important role for the stress development in pillars and abutment areas and is also included in the simulations. Different ways for pillar de-stressing are outlined and discussed. Furthermore, the influence of stoping in the production phase is discussed in this contribution.

Keywords: Pillar, Raise caving, Numerical simulation, Deep mining, Rock mechanics

Studie über den Einfluss von Hartgesteinsfesten auf das Raise-Bruchbau-Verfahren

Zusammenfassung: Das Raise-Bruchbau-Verfahren ist ein neuartiges Abbauverfahren, welches mit Hilfe von aktiver Spannungskontrolle auch unter tiefen Bergbaubedingungen eingesetzt werden kann. Die Anwendbarkeit des Raise-Bruchbau-Verfahrens wird für das LKAB Bergwerk in Kiruna betrachtet. Diese Abbaumethode wird grundsätzlich in die „Entspannungsphase“ und die „Produktionsphase“ eingeteilt. In der „Entspannungsphase“ werden mit Hilfe von geneigten Schlitzen, welche mit Hilfe von minimaler Infrastruktur und langen Raisebohrlöchern aufgeföhren werden, Spannungsschatten erzeugt die großflächige Abbaaktivitäten ermöglichen. Diese Schlitze werden von massiven Bergfesten, mit Breiten zu Höhenverhältnissen von bis zu 10 und einer Länge von mehreren hundert Metern, voneinander getrennt. Diese Festen haben die Aufgabe, Spannungen und Seismizität zu kontrollieren und den Bruch vom Hangenden zu verhindern. Durch die Umverteilung der Spannungen im Bergwerk werden die Festen und Auflagerbereiche stark beansprucht. In der „Produktionsphase“ wird Bergbau im großtechnischen Stil betrieben. Durch Spannungsumverteilung im Bergwerk werden Festen und Auflager stark beansprucht. Die Gebirgsfesten spielen daher eine tragende Rolle für die Umsetzbarkeit des Raise-Bruchbau-Verfahrens. Da Festen nach der Entspannungsphase hochbelastet sind, müssen sie in der Produktionsphase

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wieder entspannt werden, um auch hinter den Festen Abbau betreiben zu können. Daher sind Studien über Festen und ihre Auswirkungen auf das Raise-Caving-Bergbauverfahren von großer Bedeutung. In diesem Artikel wird die Bedeutung von Festen für das Raise-Caving-Verfahren zunächst auf konzeptioneller Basis dargestellt. Es werden numerische Simulationen für verschiedene Bergbauszchnitte und unterschiedliches Festenverhalten durchgeführt. Die Spannungsumlagerungen im Grubengebäude, sowie die Stabilität der Infrastruktur mit Hilfe des RCF-Wertes werden analysiert. Für diesen Zweck sind Simulationen auf der Basis eines linear elastischen Materialverhalten eine bewährte Methode. Dies hat zur Folge, dass die Entlastung der Festen aufgrund von Überbeanspruchung und Rissbildung nicht analysiert werden kann. Hierfür muss eine Methode zur Entlastung der Festen in die Simulation implementiert werden. Das Verhalten von Festen mit unterschiedlichem Breiten zu Höhen Verhältnissen wird mit Hilfe von vorberechneten Spannungs-Dehnungs-Kurven aus verfügbaren Festenfestigkeitsformeln untersucht. Darüber hinaus spielt die Abbausequenz eine wichtige Rolle für die Spannungsentwicklung in Festen und Auflagerbereichen und wird ebenfalls in die Simulationen einbezogen. Es werden verschiedene Möglichkeiten, um die hochbelasteten Festen zu entspannen, aufgezeigt und diskutiert. Weiterhin wird der Einfluss von Abbau großer Kammern in der Produktionsphase analysiert.

Schlüsselwörter: Festen, Raise-Bruchbau, Numerische Simulation, Tiefer Bergbau, Gebirgsmechanik

1. Raise Caving—A Novel Mining Method

Raise caving is novel mining method for large scale operations in highly stressed ground based on an active stress control approach combined with raise mining. The application of raise caving is investigated for Kiruna Mine as the mine is advancing to greater depths [1]. So called de-stressing slots, which are created from raises and special machinery, provide stress shadows for subsequent large scale mineral extraction. Those slots are separated by massive pillars, which are fulfilling several functions for the success of the mining method. A brief description of the raise caving method is provided below. An emphasis is therein put on the role of pillars in the raise caving system. More information on the method can be found in [1, 2]. Figure 1 shows an idealized layout of a raise caving operation in a steeply-dipping, massive tabular deposit.

1.1 De-stressing Phase

In the so called “de-stressing phase”, steeply inclined slots (dark blue in Fig. 1) are created with a minimum amount of infrastructure. Those slots have a width between 20 and 100m, a thickness between 5 and 10 m, and a length of several hundreds of meters. For that reason, “slot raises” (yellow) are developed between two raise levels (light blue) by raise boring. The slots are located at the boundary between

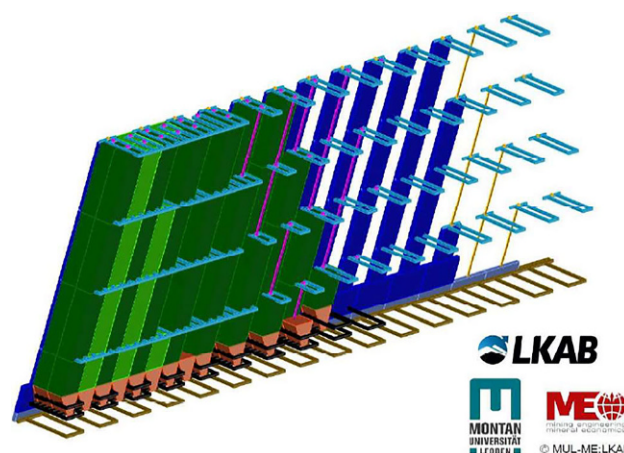


Fig. 1: Sketch of the raise caving mining method [3]

the hangingwall and the ore body, and they are parallel to the striking direction of the ore body. Those slots are always filled with blasted rock mass. The slots provide de-stressed zones in the ground, in which the infrastructure for the subsequent large scale mining operation is going to be developed. Massive pillars, with a width between 20 and 100m and an effective height, which is the pillar extension in transverse direction, of 5 to 10 m, separate the slots. The functions of pillars in the de-stressing phase are [4]:

- Control of stresses
- Control of seismicity
- Control of hangingwall caving

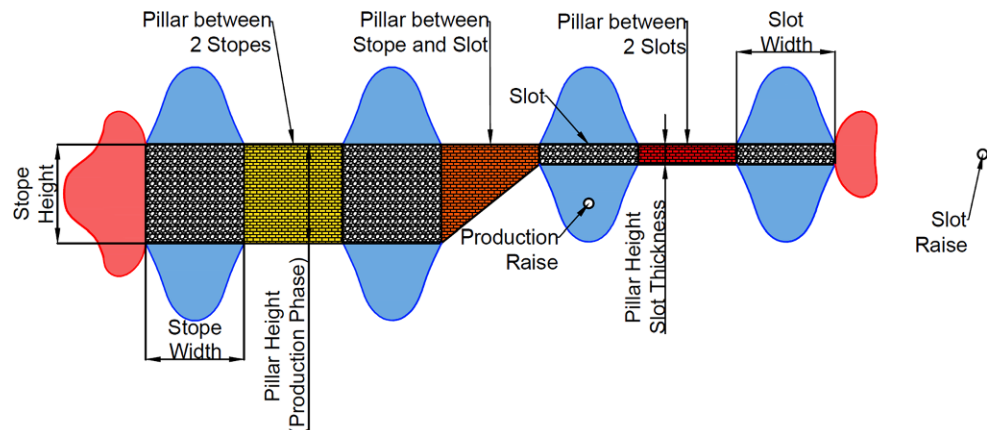
Hence, pillars play an important role for the success of the raise caving mining method. In the initial mining phase, the pillars have to be able to withstand high stresses. The impact of pillar behavior is investigated further in this contribution.

1.2 Production Phase

The de-stressing phase is followed by the production phase. In this phase large scale mineral extraction commences. Infrastructure for the production phase are production raises (pink in Fig. 1) and draw levels (black). The production raises are situated in the de-stressed zones provided by slots and are used to mine large stopes. Inclined rings are drilled, and ore is blasted in a bottom-up sequence. The ore is extracted from draw levels, where initially only the swell is drawn to provide a free surface for blasting. In some instances, ore could also be drawn from intermediate draw levels, which are the levels the production raises were developed from. After the stope reaches its designed height, it is drawn empty. At this point, the caving of the hangingwall commences and the stope is filled with caved rock successively.

To achieve an economic extraction ratio, it is also necessary to extract at least some of the pillars. As pillars are highly stressed after the de-stressing phase, they must be de-stressed prior to their extraction in the production

Fig. 2: Cross section of a schematic raise caving layout where the dynamic of system is shown. Pillar in different stages of stope extraction. Pillar between two slots (large W/H ratio, high pillar strength, red), Pillar between stope and slot (orange), Pillar between two stopes (lowered width to height ratio, low pillar strength, yellow). De-stressed zones are in blue [4]



phase. Different possibilities for pillar de-stressing and extraction are discussed in [3] and [4]. These possibilities comprise:

- Extraction by active drilling and blasting from a production raise being situated in a stress shadow of an adjacent slot
- Pillar crushing and de-stressing by decreasing of the pillar width to effective height ratio due to stope extraction behind adjacent de-stressing slots
- A combination of the above-mentioned possibilities
- Pre-conditioning of the pillar could be used to facilitate pillar crushing
- Pillar crushing could also be facilitated due to high abutment stresses near stoping areas

Basically, a method where the width to height ratio of the pillar is reduced by stoping seems to be most appropriate to de-stress pillars. By a change of the width to height ratio, the pillar behavior changes, and, as a result, the load bearing capacity is progressively reduced and the pillars get de-stressed. When the pillar is de-stressed, it is also possible to place production raises into the pillar for stope extraction.

1.3 Dynamic System

The raise caving mining method is a dynamic system. Once stoping has commenced, there is a significant change in the system. When stopes are extracted in the production phase, the shape of the pillar (width to effective height ratio) and, as a result, the strength and behavior of the pillar are strongly influenced. Due to stoping, the cross-section of the pillar changes at the beginning from rectangular (large width to height ratio) to trapezoid when one stope is excavated and in a later step back to rectangular (small width to height ratio) when the second stope is extracted (compare Fig. 2). Accordingly, the strength of the pillar decreases and the pillar post-peak behavior becomes markedly strain-softening. Furthermore, pillars are crushed, de-stressed, and extracted causing regional stress and energy changes. Another aspect with a further impact on the system is that the hangingwall starts to cave due to stope extraction and

consequently the regional loading system is altered. These regional stress and energy changes and loading system changes must not endanger the further extraction activities. It is of particular importance to ensure that pillar crushing is non-violent and pillars still control the regional stresses and seismicity. The regional abutment stresses and energy changes should not prevent the extraction of de-stressing slots and stopes, and pillars should be able to control hangingwall caving to avoid early dilution.

1.4 Advantages of Raise Caving

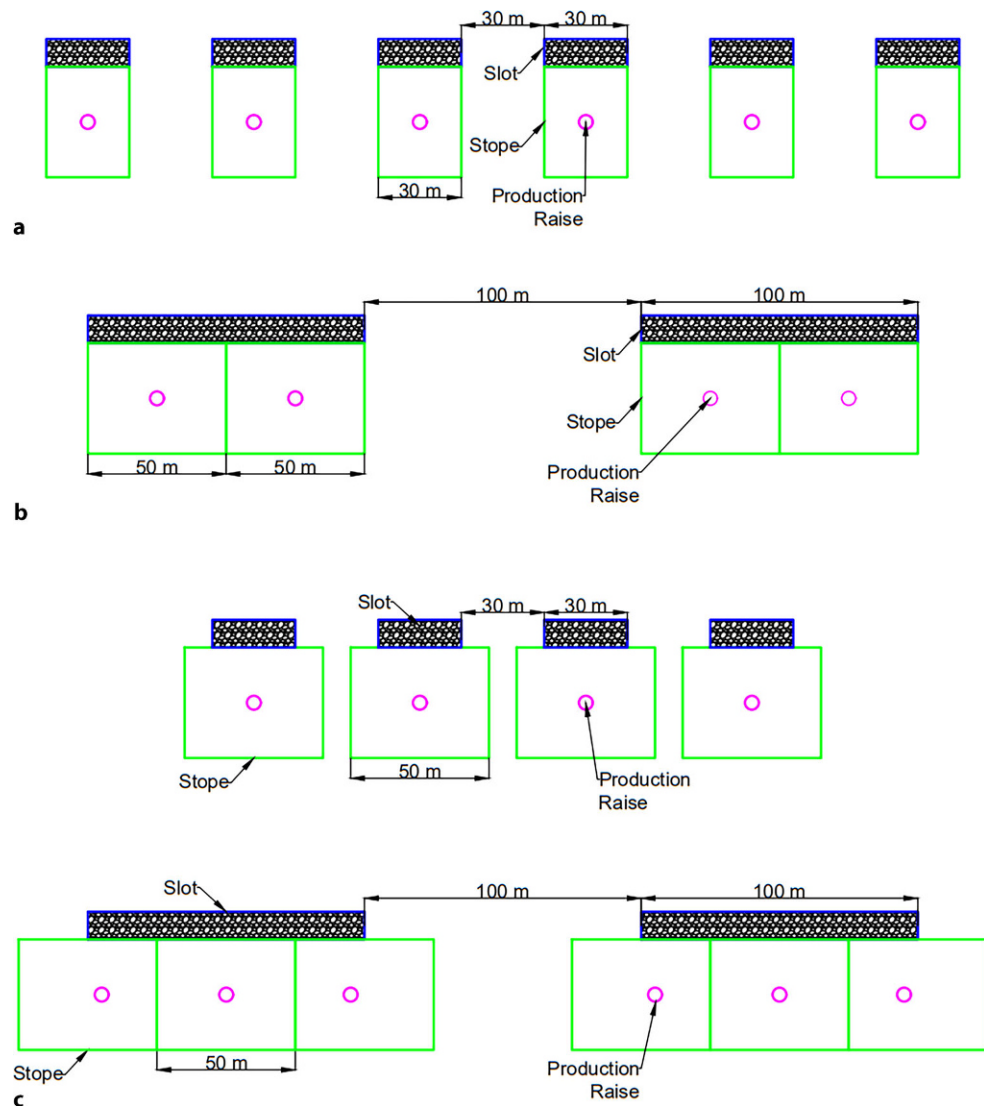
Raise caving combines several advantages, namely [3, 4]:

- Active stress control approach
- Modern raise mining techniques
- Potential for automation and remote control
- Potential for just-in-time infrastructure development
- Flexibility on short to medium term
- Adaptability to different conditions and requirements

1.5 Generic Layout Options in Raise Caving

Generally, raise caving is based on long slots and pillars which are located along the boundary between orebody and hangingwall. The thickness of the slots is given by machinery and ore flow considerations, and the length is given by the geometry of the orebody. The design parameters which can be varied are therefore the width of the slots and pillars. Slots and pillars are categorized as wide and narrow. The definition of wide and narrow is based on the number of slot raises or production raises necessary to create the slot or to mine the stope behind the slot or pillar. In case of narrow slots and pillars, the number of production raises is limited to one. In case of wide slots and pillars, more than one slot and production raise are necessary. Additionally, the extension of the stress shadow also plays a role because it must have a considerable size to provide enough free space for two or more slot raises in case of wide stopes. Based on operational considerations (e.g. length of drill holes), the limit between wide and narrow slots and pillars is considered to be 50 m. Figure 3 displays

Fig. 3: Layout with (a) narrow pillars and narrow slots, (b) wide pillars and wide slots, (c) demonstrates the high flexibility of the system



two different layouts with future stopes (green) and production raises (pink) where (a) shows the situation for narrow pillars and narrow slots, (b) shows wide pillars and wide slots, and (c) demonstrates the flexibility of the system in terms of pillar extraction. The position of production raises can be varied to be able to de-stress the pillar with drill and blast operations. The impact of the behavior of pillars on the raise caving system in different generic layouts is studied.

2. Modelling Approach

The main purpose of this contribution is to analyze the impact of pillar behavior for the raise caving method. The different generic layouts are analyzed. Moreover, due to the uncertainty of the behavior of the massive pillars being used in the raise caving method [5], the effect of different possible pillar strengths and behaviors is investigated. Therefore, the usage of numerical simulations is an appropriate way because results can be gained quickly and in-

put parameters can be varied to replicate different pillar strengths and behaviors.

2.1 Numerical Simulation Approach

The numerical simulation is intended to be a simplified representation of the reality. Therefore, it is easy to highlight important factors which influence the pillars in raise caving. 3D models are created with the software FLAC3D [6] to receive data for the subsequent analyses. The 3D model follows an approach with a linear elastic material behavior. A special procedure to replicate different types of pillar behavior in the simulation is implemented. The advantages of this simplified approach are [4]:

- Easier interpretation of results
- Fewer and simpler input parameters
- Quick results of stress and deformations
- Simple implementation of pillar behavior (stress-strain curves)

The applicability of linear elastic simulations in deep mining is discussed in [7, 8].

2.2 Model

The simulation model is based on a raise caving layout with 6 slots and 5 pillars. A linear elastic material behavior is taken for the simulation. For the simulation several input parameters are necessary which are taken from [1], who studied the application of raise caving in Kirunavaara mine.

Table 1 gives an overview of the input parameters for the conducted simulations.

To analyze the influence of pillar and slot geometry and, as a result, the overall extent of the mine layout, different geometry parameters are necessary. Table 2 gives an overview on the chosen geometry parameters for the simulations.

Moreover, the model is built from blocks with different block size to reduce calculation time. As a result, the inner model has a finer grid to provide a sufficient resolution, whereas the outer part of the model is meshed coarser. The same primary stresses as used by [1] are taken. These primary stresses represent the stress situation in 2000 m depth in LKABs Kirunavaara mine, which is a possible depth for a new main haulage level in case of the application of raise caving in the mine, and they are calculated after [9] and are 58 MPa for the vertical component, 74 MPa for the horizontal stresses in East-West direction, and 56 MPa for the horizontal stresses in North-South direction. Moreover,

TABLE 1 Material parameters for numerical simulations	
Input parameter	Value
Young's modulus [GPa]	53
Poisson's ratio [-]	0.32

TABLE 2 Geometry parameters for numerical simulations	
Geometry parameter	Value
Pillar Width W_p [m]	20, 30, 50, 70, 100
Pillar height = Slot thickness $H_p = H_s$ [m]	10
Slot width W_s [m]	20, 30, 50, 70, 100
Inclination I_n [m]	65°
Stope width W_{st} [m]	20, 30, 50, 70, 100
Stope height H_{st} [m]	50
Slot length = Pillar length = Stope length L [m]	400

TABLE 3 Primary stress situation for numerical simulations		
Stress direction	Primary stresses – Sandström 2003 [MPa]	Primary stresses – LKAB 2022 [MPa]
σ_v	58	58
σ_{HEW}	74	74
σ_{HNS}	56	74

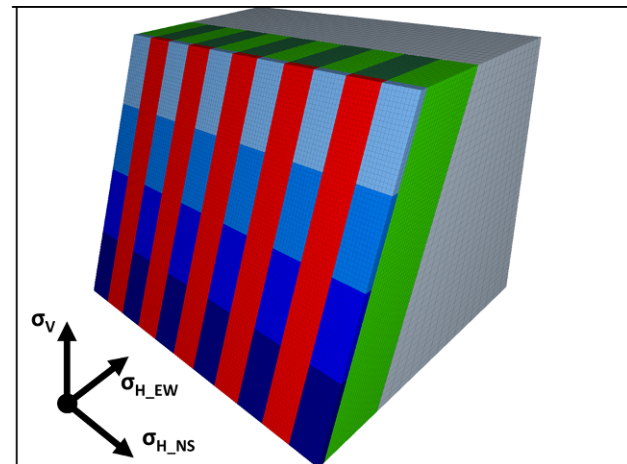


Fig. 4: Model of raise caving in FLAC3D

recent studies indicate that the stress situation changes in greater depths. It is assumed that the magnitudes of the primary horizontal stresses are equal to 74 MPa. This stress situation is also considered in the analyses. A simplification is to exclude the stress gradient in the simulation. As the main haulage level is planned to be situated approximately at 2000 m depth and hence the slot pillar system is mostly extending above this depth, this approach can be seen as a conservative approach because the real primary stresses will be lower than in the simulations. The considered primary stresses are summarized in Table 3.

The stresses are initiated in each calculation cell, and the model is fixed at its outer boundaries. Figure 4 displays the part of the simulation model for a raise caving layout with 6 slots and 5 pillars in FLAC. The outer regions of the model are not shown so that slots and pillars are visible. The slots are split in parts and are shown by the different shades of blue in Fig. 4. The pillars are displayed in red. Furthermore, the stopes behind slots (light green) and pillars (dark green) are displayed. The hanging wall has the same grid size as the pillars and stopes to get the same resolution of stresses and is displayed in brown. The foot wall has a coarser grid and is shown in grey. The black axes visualize the direction of the primary stresses.

2.2.1 Implementing Pillar Yielding and Crushing

A drawback of the linear elastic constitutive model is that pillar yielding and crushing cannot be modelled in a straightforward way. For this reason, it is necessary to implement a method to simulate pillar yielding and crushing with a linear elastic model. As pillars can have different width to height ratios in the simulations, also the behavior of pillars may differ. Pre-calculated stress-strain curves for the pillars are implemented. To define a stress strain curve for a pillar, several points are necessary to describe the curve:

- Young's modulus
- Pillar strength

TABLE 4 Behavior and parameters for the stress-strain curves of pillars						
Parameter set	Behavior	W/H	Young's modulus [GPa]	Peak strength [MPa]	Post peak modulus [GPa]	Residual strength [MPa]
Low Residual Strength	Strain softening	2	40	88	-25	4
Medium Residual Strength	Strain softening	2	40	88	-22	6
High Residual Strength	Strain softening	2	40	88	-19	9
Low Residual Strength	Strain softening	3	40	108	-21	8
Medium Residual Strength	Strain softening	3	40	108	-17	13
High Residual Strength	Strain softening	3	40	108	-13	23
Low Residual Strength	Strain softening	5	40	187	-13	31
Medium Residual Strength	Strain softening	5	40	187	-7	72
	Yielding	5	40	187	0	187
	Yielding	7	40	330	0	330
Low Residual Strength	Strain softening	7	40	330	-6	138
	Yielding	10	40	679	0	679

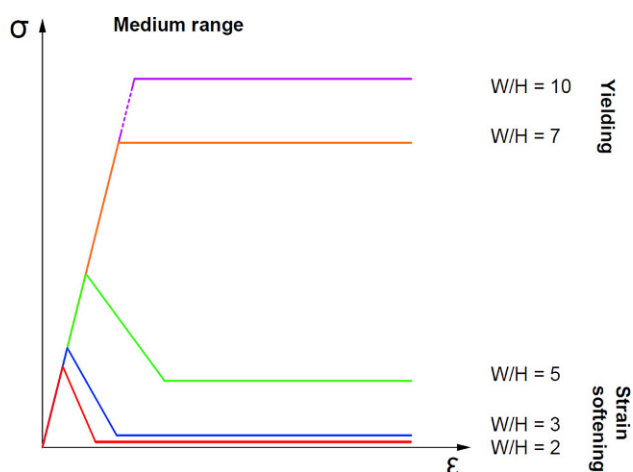


Fig. 5: Pillar behavior for a medium value range for residual strength [4]

- Post peak modulus
- Pillar residual strength

The stress strain curves are calculated after [10–13]. A detailed description of the calculation of the pillar stress strain curves can be found in [4]. The values for the curves which are taken for the simulations are summarized in Table 4:

Figure 5 gives an overview of the different stress-strain relationships of pillar material used in the simulations for pillars with a “Medium Residual Strength”.

Figure 5 and Table 4 show that pillars with a smaller width to height ratio (2, 3, or 5) have a strain softening behavior. Pillars with a larger width to height follow a yielding behavior. Normally, pillars with that high width to height ratios tend to follow a strain hardening behavior. To follow a conservative approach in this study, pillars, which would

follow a strain hardening behavior, are simulated as yielding pillars.

To implement the pillar stress strain curves a suitable approach in the simulation is defined. In this approach the pillar is split into several parts along its length. The length of such a pillar part is 50 m. After a pillar is created by mining of slots or stopes, it can crush in case the pillar stress exceeds the pillar strength. The different parts of the pillar are independent, which means that a part of a pillar can crush, whilst another part of the pillar does not crush. The utilized method must be able to represent different pillar behavior as well as the yielding or crushing process of a pillar. In order to implement the pillar behavior in the linear elastic model, the following steps are necessary:

- Crushing check
- Decrease of load bearing capacity
- Application of residual strength

The steps of the simulation are shown in Fig. 6.

1. First an excavation (part of an excavation) is extracted. After this extraction, the simulation is solved to a static equilibrium with a linear elastic material behavior. After equilibrium is reached, it is checked if the pillar (part of the pillar) crushes by comparing the average pillar stress with the pillar strength. The pillar crushes if the average pillar stress exceeds the pillar strength.
2. If crushing does not occur, the next excavation (part of an excavation) is extracted and the simulation is calculated to equilibrium and so on.
3. If a pillar (part of the pillar) crushes, its load bearing capacity is decreased and the simulation is solved to static equilibrium. Further excavations are not created at this stage. After equilibrium is reached, it is again checked if

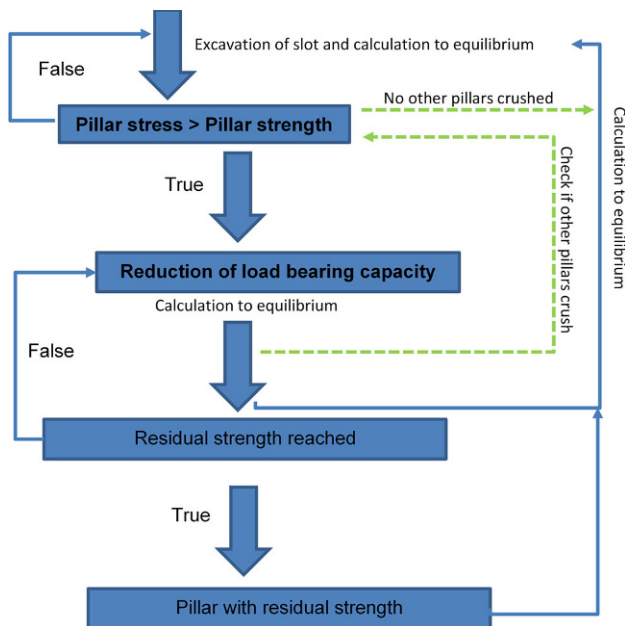


Fig. 6: Overview of the solving process for simulations with crush pillars [4]

a pillar (part of the pillar) crushes. If yes, the load bearing capacity of the pillar (part of the pillar) is decreased and the simulation is solved to static equilibrium and so on. If pillars (part of the pillar) do not crush further after equilibrium is reached, the next excavation (part of an excavation) is extracted and the loop starts from the beginning.

- If a pillar (part of the pillar) reaches its residual strength, the load bearing capacity cannot be decreased further. From this point onwards, the pillar (part of the pillar) stays on the residual strength for the whole ongoing simulation.

2.3 Simulation Types

2.3.1 Stable Pillars

The first set of focus is on infinitely strong pillars. These pillars are simulated in a linear elastic approach. Thus, pillar crushing cannot occur. The focus is on

- Extension of the stress shadow related to the geometry parameters
- Pillars stresses depending on the geometry and layout
- Stresses in the abutments depending on geometry and layout
- RCF depending on geometry and layout.

As there is no pillar crushing possible in that set of simulations, the simulations have to be compared in terms of geometry. Two important geometry parameters mentioned in this contribution are the width to height ratio and the extraction which are calculated after Eqs. 1 and 2. ER is the

extraction ratio. W_s describes the slot width and W_p the width of the pillar. WH is the pillar width to height ratio and H_p the height of the pillar.

Equation 1: Extraction Ratio

$$ER = \frac{W_s}{W_s + W_p} \quad (1)$$

Equation 2: Width to Height Ratio

$$WH = \frac{W_p}{H_p} \quad (2)$$

2.3.2 Crush Pillars

Pillar overstressing and crushing may occur in the de-stressing phase and pillar crushing is an integral part of the extraction strategy in the production phase. Pillars of a certain size and geometry have a specific behavior. The characteristics of the pillars are decisive for their stability and the crushing process. If pillars crush, stresses are redistributed to other parts in the mine. These additional stress redistributions need to be managed. Therefore, it is necessary to analyze them. The strength and behavior of hard rock pillars used in raise caving is quite unknown (compare [5]).

The focus is on:

- The extension of the stress shadow
- Influence on abutment stresses
- Stability of infrastructure

2.4 Analyses Procedure

2.4.1 Stress Analyses

The simulations in FLAC3D are solved according to the process shown in Fig. 6. The results are exported either as a color plot or as a table from measure lines. Color plots are a good tool to analyze and display the stress redistribution in the vicinity of mining excavations and in pillars. With the help of measure lines in simulations, the stress situation for example in pillars or abutments can be shown in numbers. Afterwards the stresses gained from measures lines of different simulations can be visualized in graphs. The stresses in diagrams are normalized to the primary stresses to get a comparison base for different simulations. The normalized stress is calculated after Eq. 3. σ_{norm} describes the normalized stress. It is calculated from σ_{act} which is the actual stress divided by σ_{prim} which is the corresponding primary stress.

Equation 3: Normalized Stress

$$\sigma_{norm} = \frac{\sigma_{act}}{\sigma_{prim}} \quad (3)$$

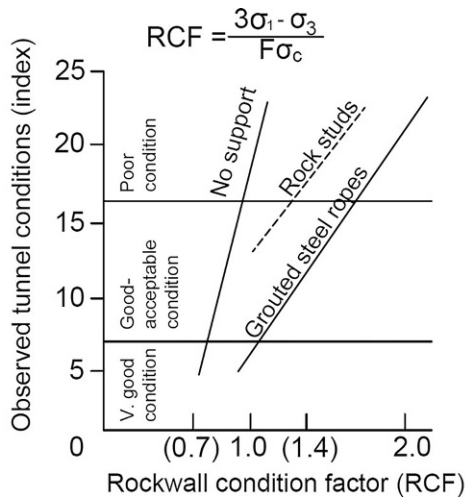


Fig. 7: Correlation of RCF values to tunnel conditions for different rock support types [15]

2.4.2 Infrastructure Stability

The stability for mining infrastructure in this contribution is assessed based on the RCF (rock wall condition factor) [14]. The RCF-value was developed to assess the condition of the rock walls in the deep South African gold mines (Eq. 4).

Equation 4: RCF After [14]

$$RCF = \frac{3 * \sigma_{1RCF} - \sigma_{3RCF}}{F * UCS} \quad (4)$$

σ_{1_RCF} and σ_{3_RCF} are defined as the maximum and minimum normal stresses, which are acting in perpendicular direction to the tunnel axis. UCS is the uniaxial compressive strength of rock, and factor F degrades the intact rock strength to consider discontinuities and more. In the diagram provided by Jager and Ryder [15], the conditions of

Fig. 8: Stress shadow of narrow slots and pillars of 30 m width (blue colors) with future stopes and production raises (black), black arrows indicate stress direction. Horizontal cut of slot pillar system [4]

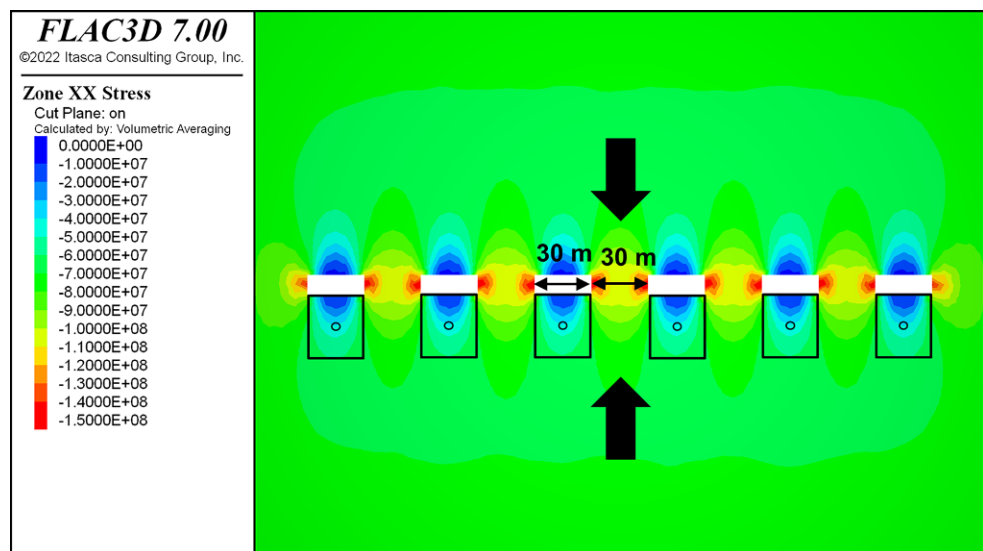


Fig. 9: Stress shadow of wide slots and pillars of 100 m width (blue colors) with future stopes and production raises (black), black arrows indicate stress direction. Horizontal cut of slot pillar system. Horizontal cut of slot pillar system [4]

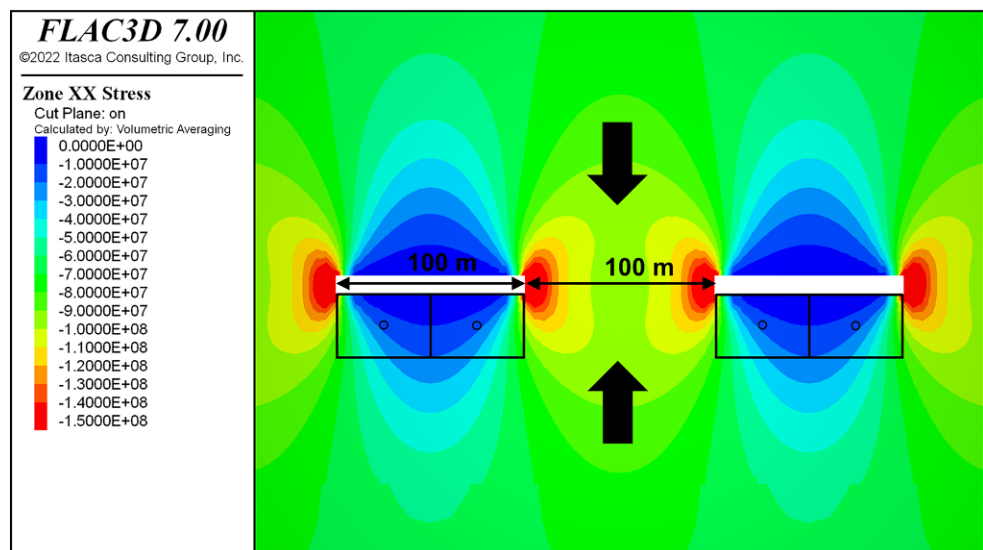


Fig. 10: Plot of E-W-stresses for a vertical cut through slot perpendicular to striking direction [4]

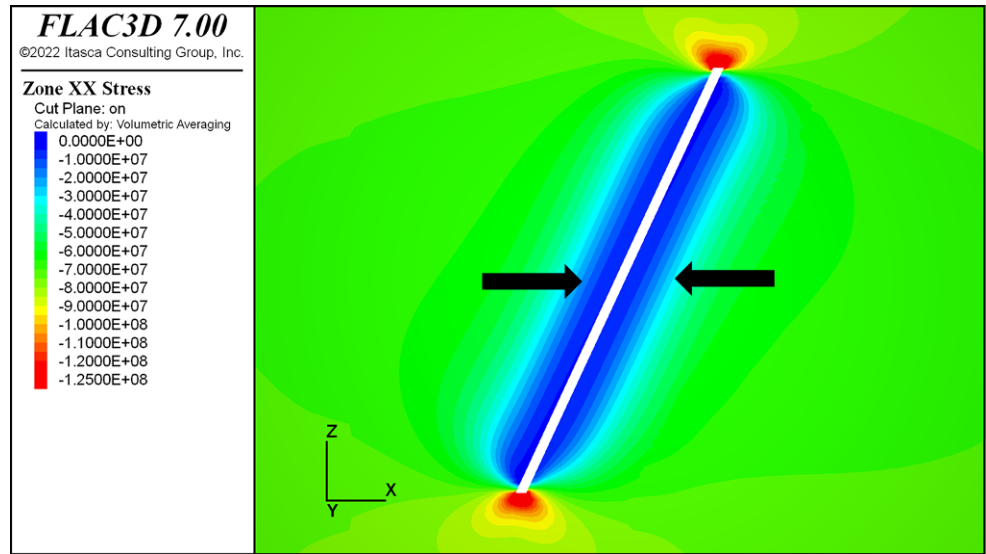
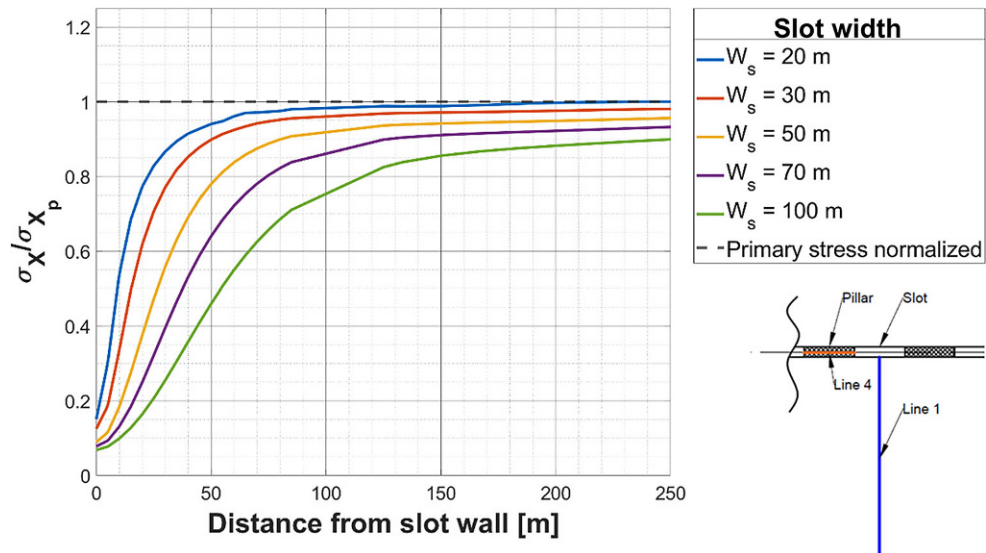


Fig. 11: Extent of stress shadow depending on the slot width for a constant slot thickness of 10 m and a pillar width of 50 m. [4]



the tunnel based on the RCF value and the installed support can be found (compare Fig. 7).

3. Results

The results of the numerical simulations are structured due to specific areas important for raise caving. Diagrams generated from measure lines as well as stress and RCF color plots are used to compare mining sequences and layouts. For raise caving, the following areas are of relevance and are thus analyzed:

- Creation of a layout of slots and pillars, which enable to conduct the high stress mining activities in the de-stressing phase
- Acceptable stress conditions for the creation of mine infrastructure such as

- Slot raises
- Production raises
- Cross cuts
- Striking drifts
- Ore passes
- Selection of most favorable mining sequence for de-stressing and production

3.1 Comparison of Layouts

Slot thickness and the effective height of the pillars are assessed by ore flow and machinery considerations. Hence, the geometry parameters, which can be varied easily, are the slot width and pillar width. Therefore, it is the goal to find the layout which provides the most advantages for mining.

The results of the simulations are presented as color-plots and line diagrams. The stress shadow extent, the

	Narrow slots—narrow pillars	Narrow slots—wide pillars	Wide slots—narrow pillars	Wide slots—wide pillars
Extension stress shadow	Small	Small	Large	Large
Side abutment stresses	Low	Low	High	High
Top abutment stresses	Low	Low	High	High
Pillar stresses	Moderate	Low	High	Moderate
Likelihood of pillar crushing	Moderate	Low	High	Low
Subsequent pillar extraction	Easy	Difficult	Easy	Difficult
Production raise stability	Bad	Bad	Good	Good
Slot raise stability side abutment	Good	Good	Medium	Good
Slot raise stability top abutment	Moderate	Moderate	Bad	Bad

abutment stresses and pillar stresses are analyzed. Additionally, the infrastructure stability is analyzed with the help of the RCF. Color plots give a good overview on the redistribution of stresses around the raise caving layout (Figs. 8, 9 and 10). The color plots are created for different cuts through the mine layout.

The line diagrams are a good tool to compare more simulations (Fig. 11).

The results are summarized in Table 5.

3.2 Pillar Crushing

One of the main tasks of this work is to highlight the impact of pillar crushing in the de-stressing phase. Figures 12 and 13 show the difference of a raise caving layout with stable pillars and with all pillars crushed. The high stresses in the side abutments are visualized in red colors. Early pillar crushing during de-stressing leads to considerable stress redistributions. One consequence is the rise of stresses in the abutments. The simulations show that the RCF values for slot raises multiply in the abutment regions. In the side abutments, the slot raises needed for the development

of the de-stressing slots are created. The high abutment stresses could cause slot raise stability problems, which could influence the advance of mining de-stressing slots. The extent of the stress shadow also increases, which is an advantage, but compared with the rise of stresses in the abutments, that situation must be avoided. In summary, the analyses show that pillars must be able to transfer large stress magnitudes to keep the stresses in the abutment regions on an acceptable level.

Simulations are created for different layouts where the extraction ratio and the pillar width to height ratio differ. One outcome is that only pillars with a width to height ratio smaller than 5 tend to crush, especially when the extraction ratio gets larger, which means that slots get wider for a fixed pillar width. In that case, the stresses in the abutments increase drastically. Pillar crushing in the de-stressing phase can lead to stability problems of the infrastructure, especially of slot raises. Figure 14 shows the RCF values for simulations with the same layout but with different pillar behavior. The black line marks the position of the next slot raise.

Fig. 12: Horizontal cut at half length of the slots and pillars. 30 m wide slots and 30 m wide pillars. Infinitely strong pillars. Small stress shadows behind slots (blue color). Black arrows indicate stress direction [4]

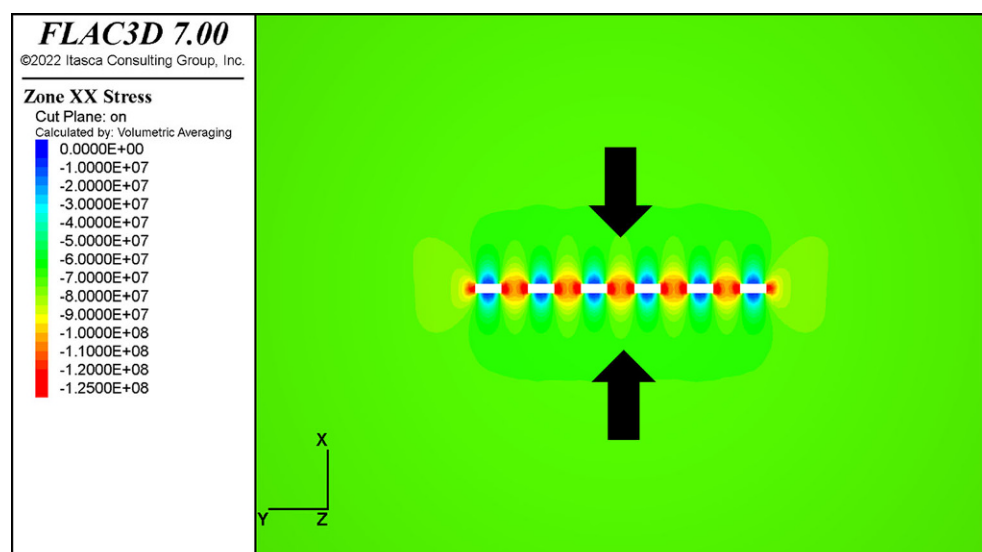


Fig. 13: Horizontal cut at half length of the slots and pillars. 30 m wide slots and 30 m wide pillars. Strain softening behavior with medium parameter set. Small stress shadows behind slots (blue color). Black arrows indicate stress direction [4]

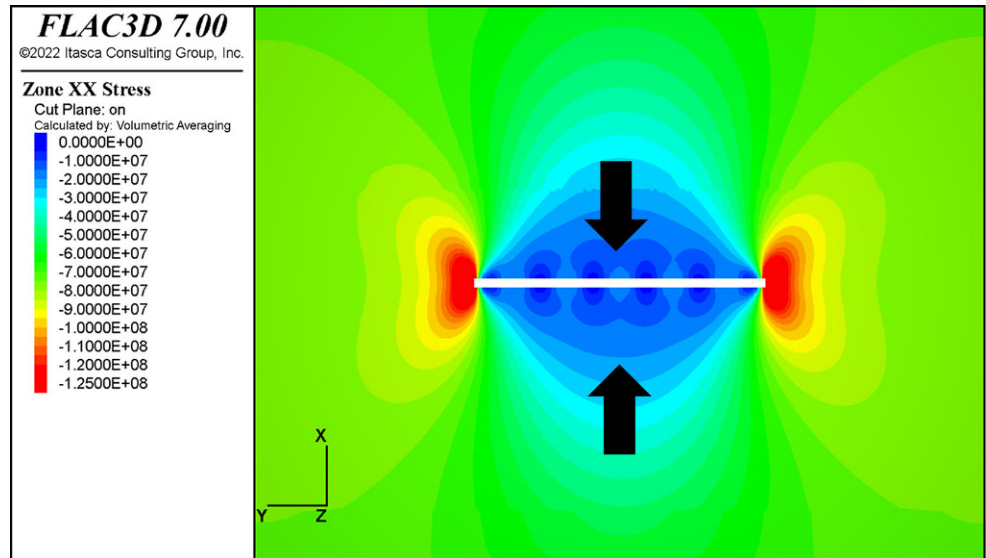
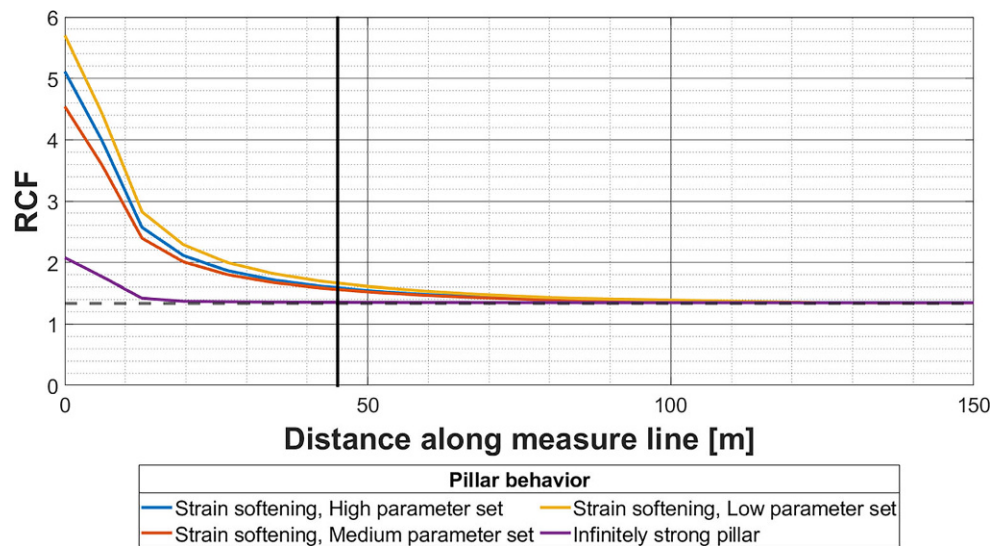


Fig. 14: RCF values in the side abutment in case of pillar crushing. The black line indicates the position of the next slot raise. Pillar width = 30 m, Slot width = 30 m, Slot thickness = 10 m [4]



The definition of the pillar behavior and the different parameter sets can be found in Sect. 2.2.1 and in more detail in [16].

3.3 Mining Sequence

Different mining sequences are analyzed in the studies. Generally, the mining sequences differ in the inclination of the mining front. To focus on the mining sequence, the layout is the same for all simulations, with 50 m wide slots and 50 m wide pillars. In Fig. 15 the different sequences of slot extraction are visualized. The black numbers indicate the order of slot excavation. The green numbers indicate at which step of the excavation process the pillar part is created.

The results show that there is only little difference in the stress magnitude of the next slot raise between the mining sequences in case the pillars are infinitely strong. The situa-

tion changes in case pillars crush, which is simulated in this case by deleting the pillars, which represents an extreme case because the pillars do not have a residual strength in this case. The stresses acting on the next slot raise increase when the pillars crush. By comparing the different mining sequences, it can be found that a mining front with a low inclination can provide advantages. The stresses around such a raise caving layout with such a mining sequence can be seen in Fig. 16. The advantages of this sequence can be found in the shorter length of the slot nearest to the next slot raise.

4. Outcome

The mining layout and especially the massive pillars are superior for the success of the raise caving method. The pillars control the stresses, the seismicity, and the hanging-wall caving in the mine. These pillars should have a width

Fig. 15: Different mining sequences for de-stressing phase, where the inclination of the mining front is (a) 0°, (b) 30°, (c) 45°, (d) 60° and (e) 90° [4]

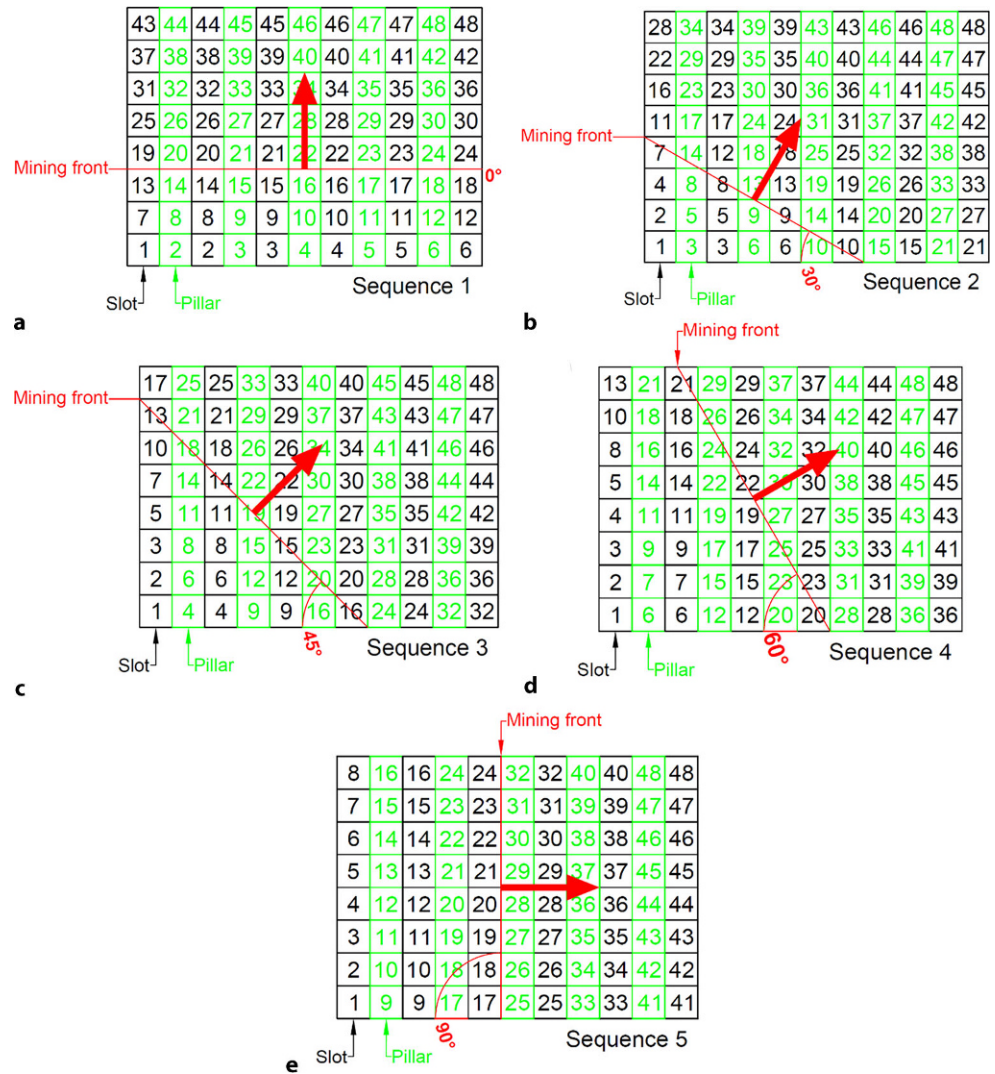
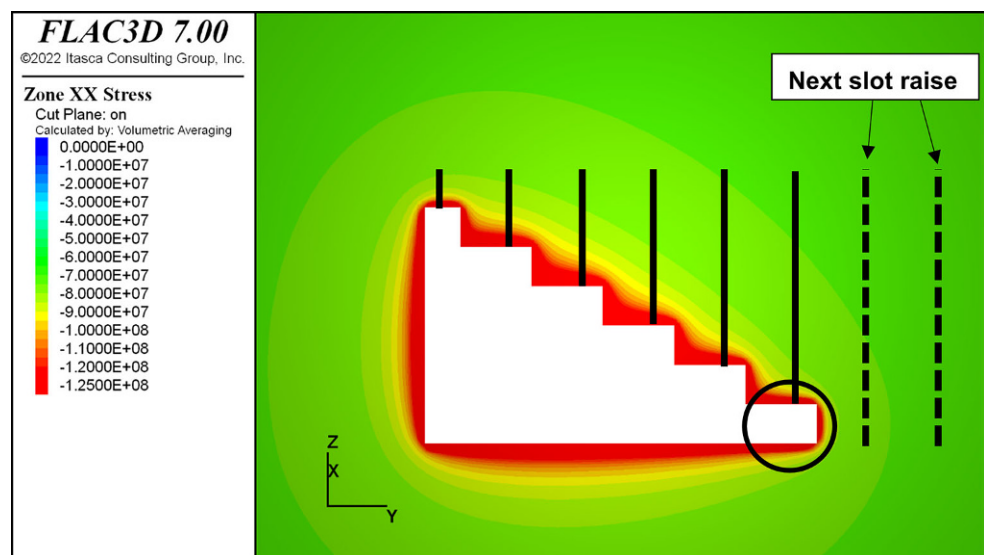


Fig. 16: Dip parallel cut through a raise caving system with mining sequence 2 after 24 steps mined completely crushed pillars. The black full lines display the active slot raises. The dotted lines represent the slot raises where no slots are mined yet [4]



to height ratio between 2.5 and 10 to fulfill their tasks in the de-stressing phase. In the production phase, the highly stressed pillars must be de-stressed and extracted to achieve a high extraction ratio to fulfill the task in mining.

The following points are important for the success in raise caving:

- The interaction between pillars and slots and the overall extent of the mining system
- The influence of the layout in the de-stressing phase on the stress situation and stability of infrastructure (slot raises, production raises)
- The influence of the mining sequence in the de-stressing phase on the stress situation and stability of infrastructure (slot raises, production raises)
- The influence of pillar crushing on the stress situation and stability of infrastructure (slot raises, production raises)
- The influence of different pillar behavior on the stress situation and stability of infrastructure (slot raises, production raises)
- The influence of stope extraction on the stress situation and stability of infrastructure (slot raises, production raises)

With the help of numerical simulations where stresses and the RCF values from several simulations are analyzed, conclusions are made. By the combination of all analyzed points, a possible layout for raise caving could be

- A layout with wide slots and wide pillars
 - Wide slots:
 - Large extension of the stress shadow
 - Flexibility in positioning of production raise
 - Wide pillars:
 - Stability during de-stressing phase due to high pillar strength
- A mining sequence with an inclined mining front
- A combined method for pillar de-stressing
 - Active blasting of stopes, also behind pillar
 - Decrease of width to height ratio results in decrease of pillar strength

There are several open points which need further investigations:

- The actual behavior of massive hard rock pillars with a considerable width to height ratio
- The influence of the broken rock mass inside the stopes on the slot stability
- The impact of hangingwall caving
- Ore flow considerations for the slot design

In conclusion, the novel mining method of raise caving is suitable for mining in great depths situations where high horizontal stresses occur. The designing of the mine layout and especially of pillars is an important task to be successful with raise caving.

Funding. Open access funding provided by Montanuniversität Leoben.

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