Addressing rock engineering challenges faced in the development of a novel, deep mining method

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ABSTRACT: Raise Caving is a novel mass mining method utilizing an active stress control approach for the foresighted, strategic and systematic control of rock pressure. The active stress control approach is based on a slot-pillar system, which is established prior to large-scale mineral extraction. From a rock engineering point the challenge is to design initially strong pillars, which are required to provide and maintain a favorable stress environment for establishing the de-stress slots. As large-scale mineral extraction commences, the pillars have to be weakened stepwise to create a regional de-stressed area for mineral extraction. The critical issue is to manage this process such that pillar strength degradation takes place in a stable controlled manner. The paper discusses rock engineering considerations related to pillars. The investigations show that the design of pillars and the regional extraction sequence are crucial and that design criteria for infrastructure and mining-induced seismicity need to be developed.

Keywords: Deep mining, Rock Mechanics, Cave Mining, Raise Caving, Stress Control, Pillars.

1 INTRODUCTION

Raise caving is a novel mass mining method, which relies on two well-established principles, namely an active stress control approach and modern large-scale raise mining. The raise caving method and its principals are discussed by Ladinig et al. (2021) and Ladinig et al. (2022a, 2022b). The main objective of raise caving is to enable low-cost, mass mining at great depth. For this reason, raise caving is considered for mining at great depth in ore bodies owned by LKAB and the technological development of the method is driven by LKAB.

Figure 1 provides a conceptual layout of a raise caving operation in steeply-dipping tabular ore bodies. Table 1 outlines typical dimensions of excavations and pillars. For pillars it is mentioned that for the outlined steeply-dipping tabular deposit, the pillar width is the extension in strike direction, the effective pillar height is the extension of the pillar in transverse direction and pillar length is the dip extension of the pillar. The actual dimensions must be designed according to the prevailing rock engineering environment.

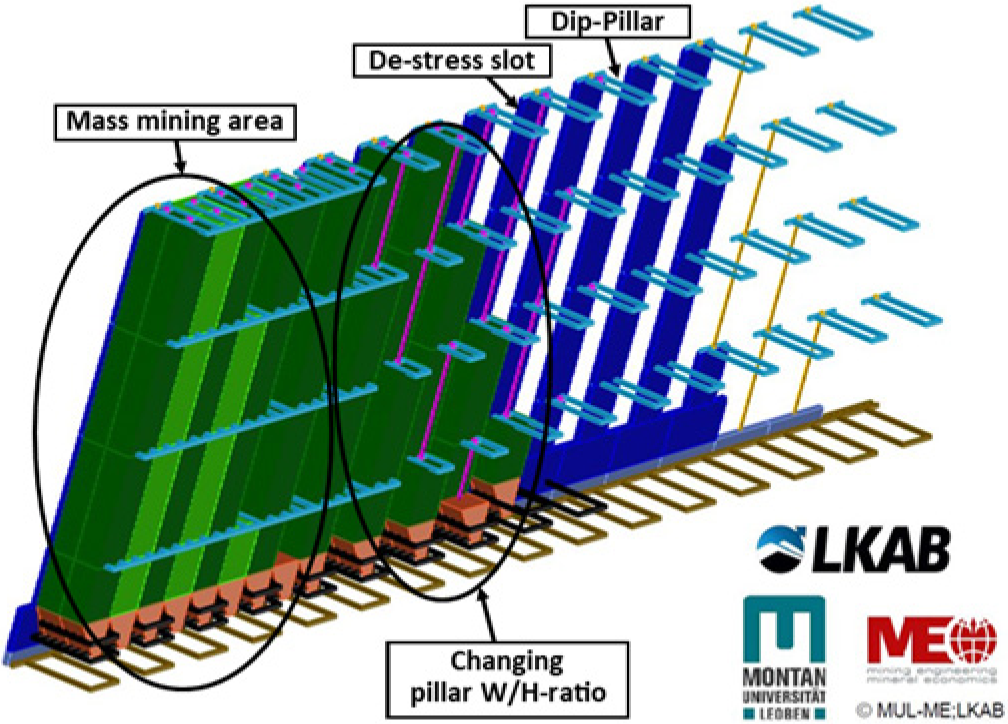

Figure 1. Conceptual layout of the raise caving mining method in a steeply-dipping tabular deposit.

Table 1. Typical dimensions of central excavations in the raise caving mining method.

Excavation		Slots	Stopes	Pillars during de-stressing	Pillars during production phase	Slot raises	Production raises
Cross-section	[m]	5-10 x 30-150+	30-50 x 30-50				
Pillar width	[m]			30-70	30-70		
Effective pillar height	[m]			5-10	40-100+		
Length (dip extension)	[m]	150-500+	150-500+	150-500+	150-500+	150-250	150-250
Diameter	[m]					3-4	3-5

De-stressing slots (dark blue in Figure 1) are developed in the so-called de-stressing phase before large-scale mineral extraction commences. De-stressing slots are developed from slot raises (yellow) at the hangingwall contact utilizing raise mining. Massive dip pillars separate neighboring de-stressing slots to control stresses and mining-induced seismicity during de-stressing, which is high stress mining. The production phase follows the de-stressing phase. Production raises (pink) and draw levels (black) are developed in the stress shadows provided by de-stressing slots. Large stopes (dark green) are then extracted from the production raises behind stopes. Large drawbells (orange) are created at the bottom of the stopes to facilitate ore flow. (Koch et al. 2022) Stope extraction changes the geometry of the pillars and initiates pillar crushing. Consequently, stress magnitudes in the pillar decrease and the pillars are eventually extracted with stopes (light green). During the drilling and blasting slots and stopes are always filled with blasted rock mass, as only the swell is drawn. Slots and stopes are drawn empty, once stopes are completely blasted over their full length. As are result hangingwall caving is initiated and caved rock mass from the hangingwall fills up stopes, as they are drawn empty. Raise caving is intended to be used in hard-rock. Hence, the considerations in this paper refer to hard-rock operations.

2 ROLE OF PILLARS

From a rock engineering perspective pillars fulfill a central role in the active stress management approach, which is utilized in RC. (Ladinig 2022), Gams (2022) discuss the required functions of pillars in the de-stressing and production phase. The functions are:

- De-stressing phase:
  - Controlling of regional stress situation
  - Controlling of mining-induced seismicity
  - Preventing of premature hangingwall caving
- Production phase:
  - Controlling of regional stress situation
  - Controlling of mining-induced seismicity
  - Implementing stable pillar crushing
  - Conditioning pillar for subsequent extraction

In order to fulfill the required functions, the design demand on pillars is to provide regional support to the rock mass, to transfer considerable stress magnitudes in the de-stressing phase and to limit convergence. In the production phase, the purpose of pillars and hence the design demand change. Pillars are eventually extracted. In order to extract pillars or in the course of pillar extraction, pillar crushing and associated de-stressing processes take place. The demand on pillar design is to ensure that the pillar crushes in a stable and reliable manner and that stresses in the crushed pillar are at a magnitude, which enables the development of infrastructure and the extraction of stopes in pillars. Furthermore, the position and time of pillar crushing and extraction must be chosen such that the regional stress and energy changes, which take place during pillar crushing and extraction, are manageable. The regional layout and sequence are decisive therefore.

The functions of pillars and the corresponding design demands in the de-stressing and production phase are contrary. Particularly critical is that massive, highly-stressed pillars must be crushed in the production phase. For a successful design of pillars following aspects emerge:

- Strength and behavior of large, massive (crush) pillars
- Position and time of pillar crushing and extraction

3 STRENGTH AND BEHAVIOR OF LARGE, MASSIVE (CRUSH) PILLARS

The strength and behavior of hard-rock pillars is influenced by several parameters. Central parameters are the rock mass forming the pillar, the size of the pillar and the geometry of the pillar, especially the width-to-height ratio; compare Salamon & Munro (1967), Hedley & Grant (1972) or Esterhuizen et al. (2011). Equation 1 shows a basic equation for pillar peak strength (σ_P), where K is a measure for rock mass strength, W_P is the pillar width, H_P is the pillar height and α and β are constants.

$$\sigma_P = \mathrm{K} \cdot \frac{W_P^{\alpha}}{H_P^{\beta}} \tag{1}$$

Indeed, most of the knowledge on the strength and behavior of hard-rock pillars has mostly been derived from pillars with a rather low width-to-height ratio (< 2), from pillars, which are comparatively small in size (width < 10-15 m), or from pillars with very large width-to-height ratios (width-to-height ratio > 10-30). Moreover, knowledge derived from coal pillars has been transferred to the behavior of hard-rock pillars to fill the existing gaps; however, whether the knowledge from coal pillars can be transferred to hard-rock pillars is unknown, as corresponding in-situ experience with hard-rock pillars is largely missing. (Ladinig 2022) Figure 2 provides a summary of in-situ experience related to the strength of hard-rock pillars as a function of width-to-height ratio. Compared to the knowledge of the strength, the knowledge of the stress-strain and fracturing behavior of hard-rock pillars, particularly the post-peak behavior, is considerably smaller. (Ladinig 2022)

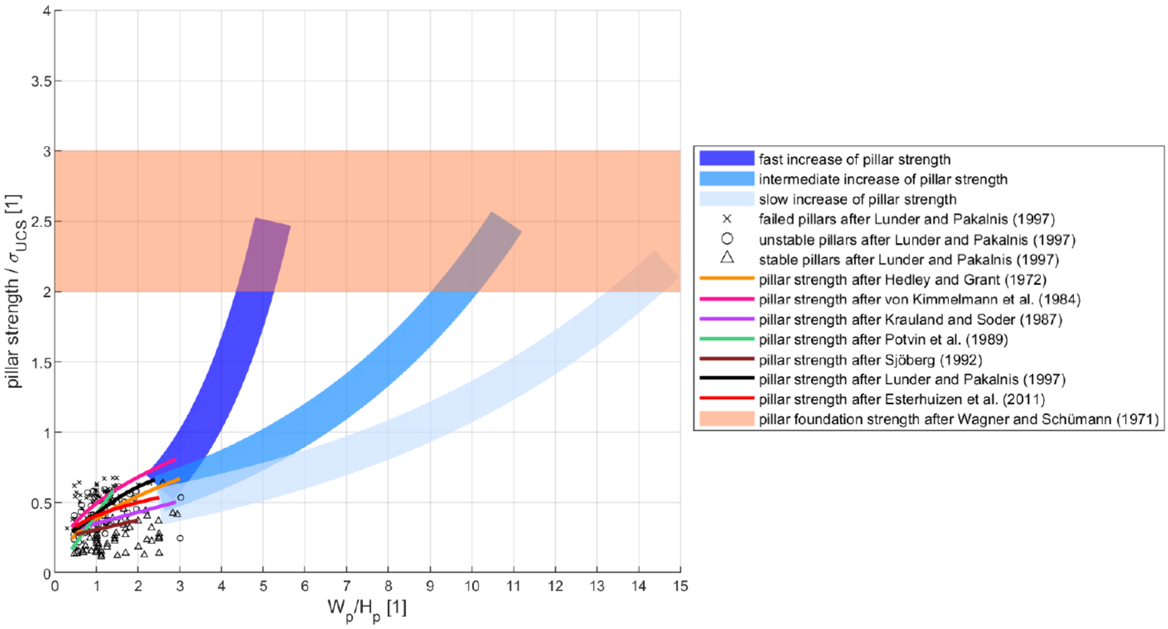

Figure 2. Summary of strength of hard-rock pillars based on mining experience (after Ladinig 2022).

In raise caving pillars have dimensions in the range of several tens of meters. The width-to-height ratio of the pillars in the de-stressing phase is 5 to 10 or even higher, so that pillars can withstand high stress magnitudes and meet the design demand. Investigations have shown that the success of the de-stressing phase is endangered, if pillars are overloaded and crush prematurely, as the abutment stresses increase considerably and the stability of slot raises is at risk. (Gams 2022) However, in the production phase, the stress magnitudes acting in the pillars must be reduced so that pillars can be extracted eventually. Basically, reducing the stresses inside the pillar is only possible by degrading the strength of the pillar and initiating crushing of the pillar. Pillar crushing can be initiated by

- reducing the strength of the rock mass by pre-conditioning methods
- decreasing the size of the pillar by nearby stope extraction (partial pillar extraction)
- decreasing the width-to-height ratio of the pillar by nearby stope extraction

The impact of stope extraction is of particular interest, because stope extraction takes place anyway, whereas pre-conditioning methods are optional. Stope extraction in the production phase, reduces the pillar width-to-height ratio to 1 or even below 0.5. Furthermore, the reduction of the width-to-height ratio is expected to alter the post-peak behavior to a strain-softening behavior, (compare Ozbay 1989), which is required for pillar crushing, whereas the effect of the pre-conditioning on the post-peak behavior is not as well understood. Critical is to ensure the stability of the pillar crushing process. The stope layout and stoping sequence are found to be decisive, as they have a direct impact on the strength and post-peak behavior of the pillar. To design appropriate stope layout and stoping sequences, the strength and behavior of massive pillars, which are subjected to a reduction of the width-to-height ratio and/or size, must be understood well.

However, the knowledge of the strength and behavior of hard-rock pillars used in raise caving is limited. The implications are that the design of pillars for raise caving is associated with high risks at the moment and hence research addressing the strength and behavior of massive, hard-rock pillar is needed. Therefore, intensive studies are conducted. The investigations comprise conceptual considerations, laboratory scale modelling, numerical modelling as well as a full-scale in-situ test of a pillar in one of LKAB's mines.

4 POSITION AND TIME OF PILLAR CRUSHING AND EXTRACTION

Different options for pillar crushing and extraction and their advantages and disadvantages are discussed by Ladinig et al. (2023). Crushing of a pillar alters the regional stress situation considerably, because crushed pillars can only transfer limited stress magnitudes; compare Figure 3. Consequently, regional abutments and stress shadows of regional extent develop. To avoid negative consequences of these abutment stresses on the development of de-stressing slots, de-stressing slots must be developed some distance ahead of stope extraction (position of crushed pillars); compare Figure 1. However, pillars between de-stressing slots must also be able to withstand these regional abutment stresses.

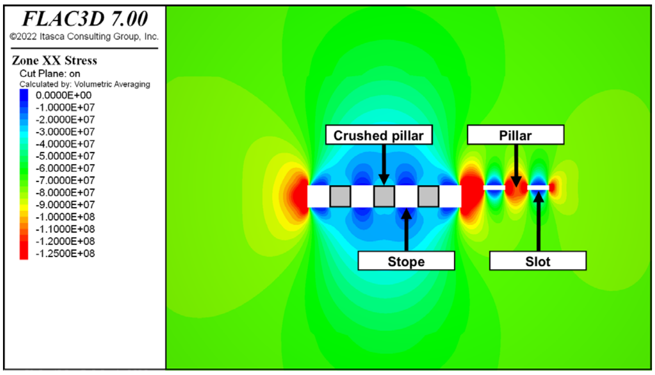

Figure 3. Regional stress situation after pillars between stopes crushed to their residual strength.

Besides regional stress changes, regional energy changes occur due to pillar crushing. Significant amounts of mining-induced seismicity have to be expected. The characteristics of the seismicity is critical. A release with many small events with low magnitudes, which consequences can be managed with support, must be achieved.

The position and time of pillar crushing and extraction and the associated regional stress and energy changes are controlled by the mine layout and mining sequence. In order to design the layout and sequence knowledge related to the response of the crushing pillars and thus related to the strength and behavior of pillars is required. Furthermore, design criteria for the release of mining-induced seismicity in the raise caving situation and for infrastructure, in particular for raises, are needed. For this reason, design criteria are developed for LKAB mines by means of back analyses within the raise caving development project.

5 FULL-SCALE IN-SITU TEST

As the knowledge related to the strength and behavior of massive hard-rock pillars is limited, it is planned to conduct a full-scale in-situ test of a pillar in a LKAB mine. The main objective of the test is to increase the knowledge of the strength and behavior of massive hard-rock pillars. The test comprises the creation of a strong, massive, hard-rock pillar and the subsequent implementation of the crushing process of the pillar by stope extraction. Figure 4 shows the planned test site layout. The pillar will be created in the abutment of the ongoing sublevel caving operation to simulate high-stress conditions. Initially, the pillar will have a width of about 45 m, an effective height of 5 m and a dip extent (length) of about 100 m. The effective height is then step-wise increased through the extraction of so-called “pillar cuts”. Extraction of pillar cuts is continued until the pillar has crushed and de-stressed. The effective height of the pillar at the end of the test can be several tens of meters so that the width-to-height ratio of the pillar can be reduced from about 9 to 0.5 or even lower, similar to the later application of pillars in raise caving. A comprehensive monitoring program will accompany the pillar test. Details about the pillar test are provided by Karlsson et al. (2022). The full-scale in-situ test enables to improve the knowledge on the strength and behavior of massive hard-rock pillars and is thus paramount. Moreover, the test site provides also input for the development of design criteria for infrastructure and mining-induced seismicity.

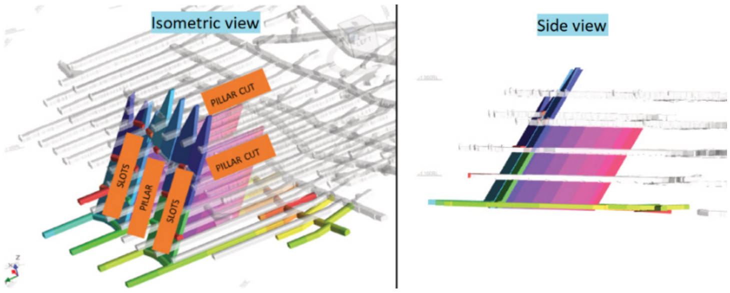

Figure 4. In-situ test site for testing a massive pillar in a LKAB mine (after Karlsson et al. 2022).

6 CONCLUSIONS

Pillars are a central rock mechanics aspect for the success of the raise caving method. The design demands on pillars vary considerably in the de-stressing and production phase. Whilst in the de-stressing phase strong, massive pillars, which can withstand high stresses are required, the pillars in the production phase must be crushed in a stable manner. Due to the limited knowledge on the strength and behavior of massive hard-rock pillars research is needed. Besides the research on pillars, the development of design criteria for assessing the stability of infrastructure and the mining-induced seismicity is necessary. To address these points a comprehensive program has been established.

REFERENCES

Esterhuizen, G.S., Dolinar, D.R. & Ellenberger, J.L. 2011. Pillar strength in underground stone mines in the United States. *International Journal of Rock Mechanics and Mining Sciences* 48 (1), pp. 42-50.

Gams, P. 2022. *The role of pillars in raise caving*. Master's thesis. Montanuniversität Leoben, Leoben, Austria.

Hedley, D.G.F. & Grant, F. 1972. Stope-and-Pillar Design for the Elliot Lake Uranium Mines. *CIM Bulletin* 65 (732), pp. 37-44.

Karlsson, M., Ladinig, T. & Grynienko, M. 2022. Test mining with raise caving mining method: one-time chance to prove the concept? In: *Caving 2022: Fifth International Conference on Block and Sublevel Caving*, Potvin, Y. (ed), pp. 667-682. Australian Centre for Geomechanics: Perth, Australia. DOI: 10.36487/ACG_repo/2205_46

Koch, L.A., Ladinig, T., Wimmer, M., Wagner, H. & Grynienko, M. 2022. Key issues related to oreflow in raise caving. In: *Caving 2022: Fifth International Conference on Block and Sublevel Caving*, Potvin, Y. (ed), pp. 667-682. Australian Centre for Geomechanics: Perth, Australia. DOI: 10.36487/ACG_repo/2205_97

Ladinig, T., Wagner, H., Bergström, J., Koivisto, M. & Wimmer, M. 2021. Raise caving – a new cave mining method for mining at great depths. In: *Proceedings of the 5th International Future Mining Conference*, pp. 368-384. The Australasian Institute of Mining and Metallurgy: Melbourne, Australia.

Ladinig, T. 2022. *A contribution towards the practical implementation of stress management concepts in underground mining*. Ph.D. thesis. Montanuniversität Leoben, Leoben, Austria.

Ladinig, T., Wagner, H., Karlsson, M., Wimmer, M. & Grynienko, M. 2022a. Raise Caving—A Hybrid Mining Method Addressing Current Deep Cave Mining Challenges. *Berg- und Hüttenmännische Monatshefte* 167 (4), pp. 177-186. DOI: 10.1007/s00501-022-01217-3

Ladinig, T., Wimmer, M. & Wagner, H. 2022b. Raise caving: a novel mining method for (deep) mass mining. In: *Caving 2022: Fifth International Conference on Block and Sublevel Caving*, Potvin, Y. (ed), pp. 651-666. Australian Centre for Geomechanics: Perth, Australia. DOI: 10.36487/ACG_repo/2205_45

Ladinig, T., Andersson, M., Wimmer, M. & Gams, P. 2023. Design of raise caving operations in LKAB mines. In: *Underground Operators Conference 2023 Conference Proceedings*, pp. 295-309. The Australasian Institute of Mining and Metallurgy: Melbourne, Australia.

Ozbay, M.U. 1989. The stability and design of yield pillars located at shallow and moderate depths. *Journal of the Southern African Institute of Mining and Metallurgy* 89 (3), pp. 73-79.

Salamon, M.D.G. & Munro, A.H. 1967. A study of the strength of coal pillars. *Journal of the Southern African Institute of Mining and Metallurgy* 68 (2), pp. 55-67.