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Application of empirical methods to estimate crown pillar failure in caving mines

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Abstract

Crown pillar in cave mines corresponds to the solid rock pillar located between the cave and the surface in the early stages of the caving process. A correct estimation of the failure time may provide valuable assistance in planning underground and surface activities.

While modelling has shown important advances in the simulation of the breakthrough process, empirical tools may provide an early warning of the pillar failure process, delivering early guidelines about when to isolate surface infrastructure or change draw velocities due to the change in the mined column height.

This paper reviews empirical methods to estimate crown pillar stability and their application in the breakthrough process in block cave mines, evidenced by a case study in Chuquicamata underground mine.

Keywords: *caving, crown pillar, subsidence, empirical method, breakthrough*

1 Introduction

As described by Flores (2019), breakthrough is an important stage in the cave establishment process for caving mines. Breakthrough corresponds to the connection between the growing cave and surface or upper level. This process is preceded by the crown pillar failure (Glazer 2016) corresponding to the loss of load capacity of the rock bridge above the cave. This failure process manifests itself as increases in rock permeability or in seismic softening inside the failed volume.

Crown pillar failure (CPF) and breakthrough initiate a major geotechnical condition change in cave mines, with important implications in stress distributions around the cave and in draw strategy. It is therefore important to have an accurate estimation of the time when CPF will occur in order to anticipate surface and underground planning and stability issues.

In the following sections, several methods to estimate crown pillar stability are described and the seismic monitoring of CPF and breakthrough is provided. Finally, there is a case study to illustrate the differences between different methods to estimate crown pillar stability.

2 Crown pillar failure and breakthrough

Crown pillar stability (Figure 1) is important as it defines the start of the breakthrough process. From a planning point of view, it also defines the moment when draw rates can be increased, incrementing ore productivity. Considering these aspects, it is important to have an estimation of the time frame of pillar failure and consequent breakthrough to upper level. While numerical methods can provide these estimations, modelling processes may be quite demanding in time and resources whilst being useful for design engineering. However, a faster response may be achieved using empirical methods for early stages in project engineering or to check stability during mine operation with real data obtained from the mine.

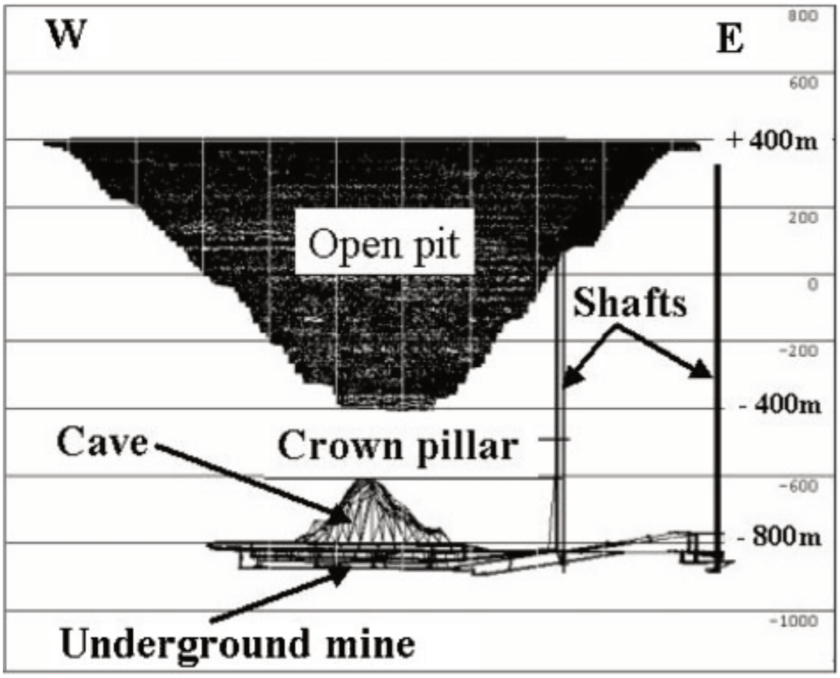

Figure 1 Crown pillar in cave mines as described by Glazer & Hepworth (2005)

3 Empirical tools for crown pillar stability

Evaluation of crown pillar stability is an important matter in underground mines, specifically in stope mines. The main empirical method to evaluate crown pillar stability was proposed by Carter (1992) as a stability chart and was upgraded by Carter (2014) with the scaled span concept which is commonly used in stope mines. However, these methods are not used to evaluate block cave mine crown pillars, with most of the analysis based on numerical modelling and in the comparison between the broken rock column and the existing rock pillar.

The most used methods to calculate the minimum thickness of the crown pillar are:

- Thumb rule (anonymous).
- Scaled span (Carter 2014).

For block caving situations, the following methods have been proposed:

- Stability charts based on numerical results (Flores 2005).
- Analytical solutions (Bakhtavar et al. 2010).

These methods will be briefly described in the following sections.

3.1 Thumb rule

As described by Carter (1992), one of the first attempts to generate a criterion to evaluate crown pillar stability corresponds to the plot of the thickness to span ratio versus rock mass rating or Q NGI rock mass index (Figure 2), obtained through discussion with old miners and classic textbooks. These relations provide the basic guidelines for design, however, the behaviour of the rock mass is scale dependent and therefore a design based on this chart was very limited.

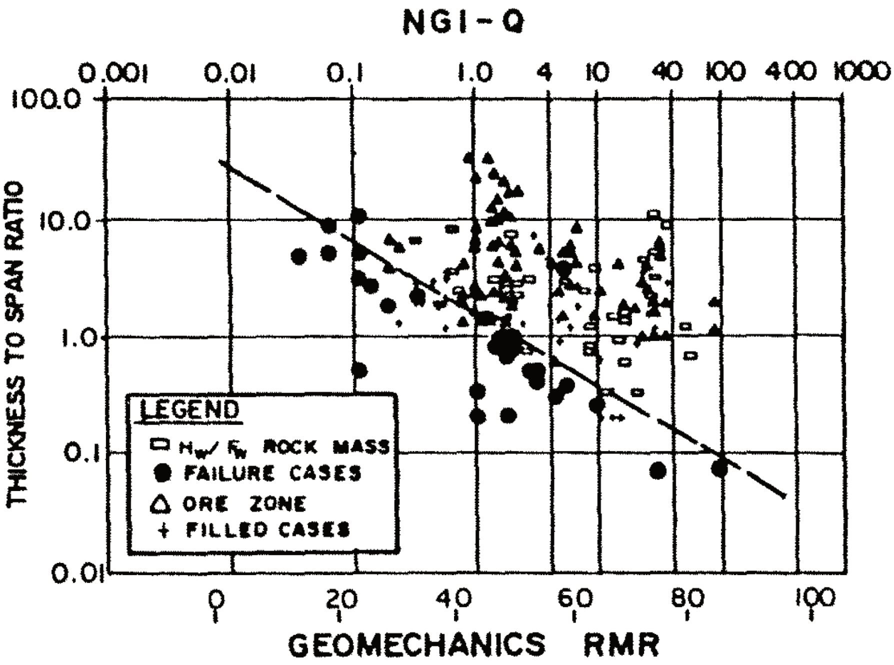

Figure 2 Empirical data from Canadian crown pillars (Carter 1992)

3.2 Scaled span method (Carter 2014)

As described, thumb rule has an important gap because the relations between thickness and span are scale dependent variables, constraining the applicability of the relations. Because of this, Carter developed the scaled span method, considering the complete geometry of the stope and the pillar along with geotechnical parameters (Figure 3).

The scaled span Cs is defined as

$$Cs = S\left(\frac{\gamma}{T(1+S_R)(1-0.4\ cos\theta)}\right)^{0.5} \tag{1}$$

where:

S = crown pillar spam (m).

γ = specific gravity.

T = corresponds to the thickness of the crown pillar (m).

θ = orebody/foliation dip.

S_R = span ratio given by crown pillar span/crown pillar strike length.

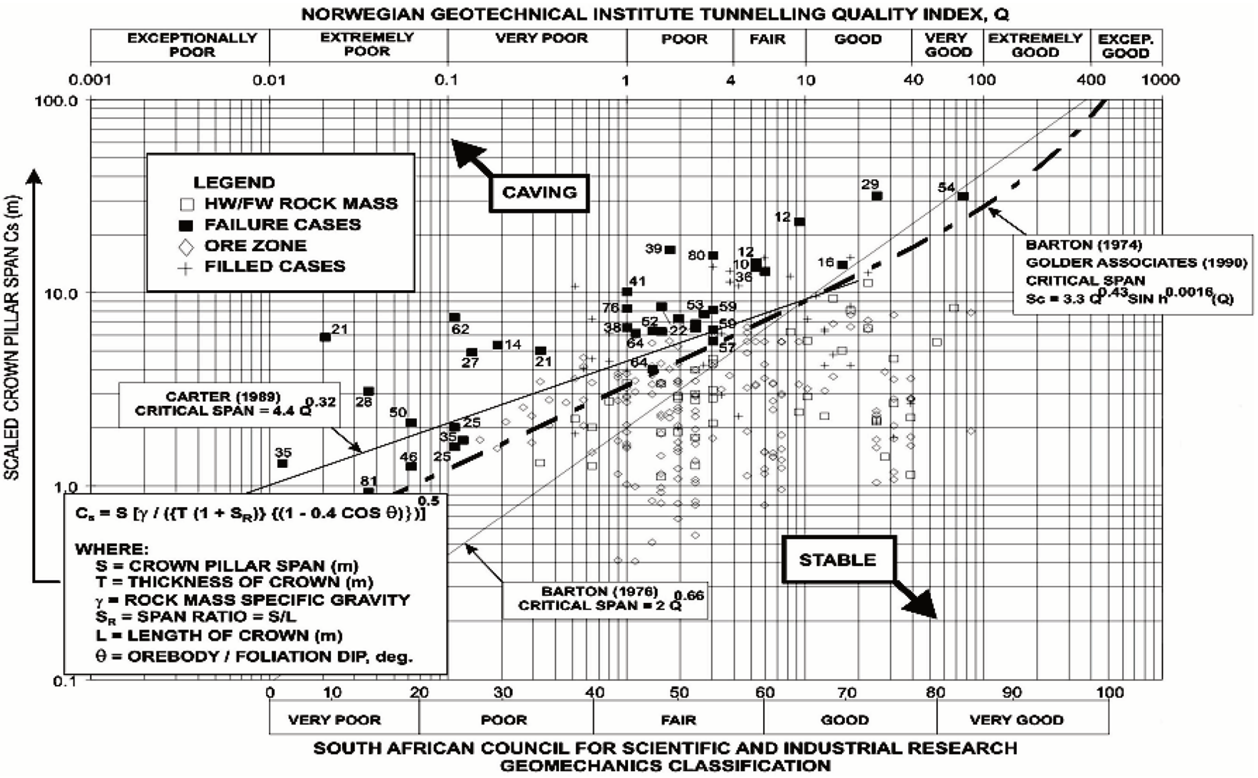

Figure 3 Scaled span method to determine crown pillar thickness (Carter 2014)

This chart allows the estimation of the minimum stable crown pillar thickness based on the scaled span calculated previously and the Q obtained from rock mass mapping.

3.3 Charts based on numerical modelling (Flores 2005)

Based on 2D numerical modelling, Flores (2005) developed several charts that provide guidelines to define the minimum stable crown pillar thickness. These charts are based in simulations of block cave–open pit interactions, considering the mine geometry with the parameters shown in Figure 4 and for different rock mass conditions. The result from this method approximates the minimum permissible crown pillar thickness, where simultaneous underground and open pit operations must cease (Flores 2005).

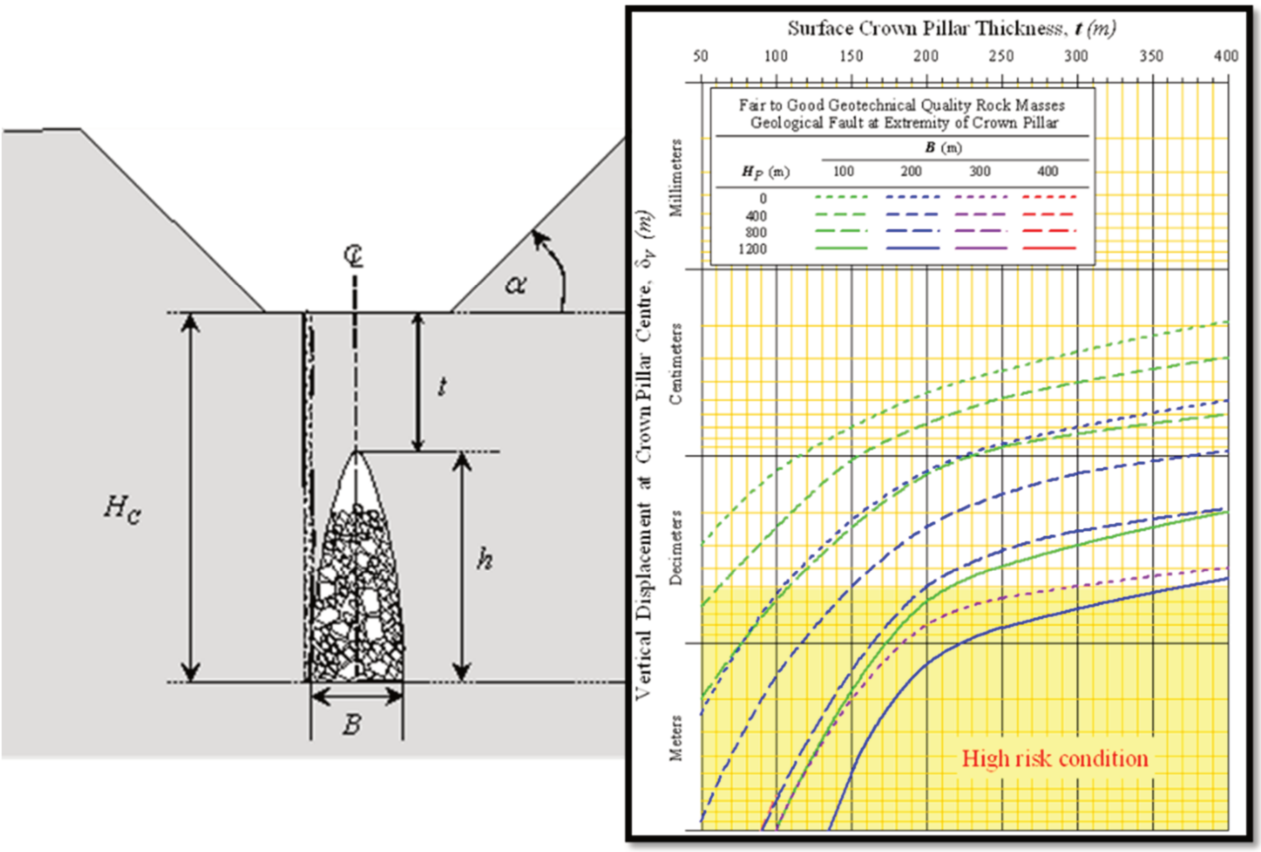

Figure 4 Results obtained by Flores (2005) from numerical modelling of cave propagation

3.4 Analytic solutions (Bakhtavar et al. 2010)

While Flores (2005) provided crown pillar guidelines based on modelling results, Bakhtavar et al. (2010) developed a physic–mathematical model to assess the minimum crown pillar thickness. Using dimensional analysis (a method often used when there is not enough information to set up precise equations), the physical quantities in terms of their fundamental dimensions (in this case, force, length and time) are used as a force dimension system. Using this system, the scaled span equations discussed in previous sections can be reformulated to find the best relations between the variables to define the threshold of stable crown pillars, as defined by Carter (2014) in Figure 3.

Using dimensional analysis, the optimal crown pillar thickness is given by:

$$t = \frac{13.22 * C^{0.03} * S^{0.41} * H^{0.56}}{\gamma^{0.03} * RMR^{0.66}} \tag{2}$$

where:

t = crown pillar thickness.

γ = specific gravity.

C = cohesion of the rock mass.

H = corresponds to the cavity height.

S = cavity span.

RMR = rock mass rating.

The use of this equation provides the optimal crown pillar thickness to operate a mine under combined open pit and underground operations.

4 Seismogenic observations of crown pillar failure

Actual CPF can be monitored in several ways. In this work, seismic monitoring will be used as the main tool to evaluate crown pillar stability based on the energy index parameter, as described by Glazer (2016).

While mine extraction history provides an indication of the volume of rock removed from the ore deposit, seismic data provides a better understanding of the rupture process going on through the caving mechanism. In this case, the energy index, as described by Glazer (2016), will be used as a parameter that indicates stress concentration and relaxation associated with the stress state and stability conditions in the crown pillar. Conclusions about the stability of the crown pillar were obtained by Glazer after analysing several block caving mine breakthroughs in terms of the measured seismic response. These conclusions pointed to seismic pattern characterisation at different stages in the breakthrough process, as shown in Figure 5. The different stages of the caving process are defined as:

- A: start of gravity caving.
- B: start of stress caving.
- C: failure of crown pillar.
- D: initial break.
- E: mature cave.

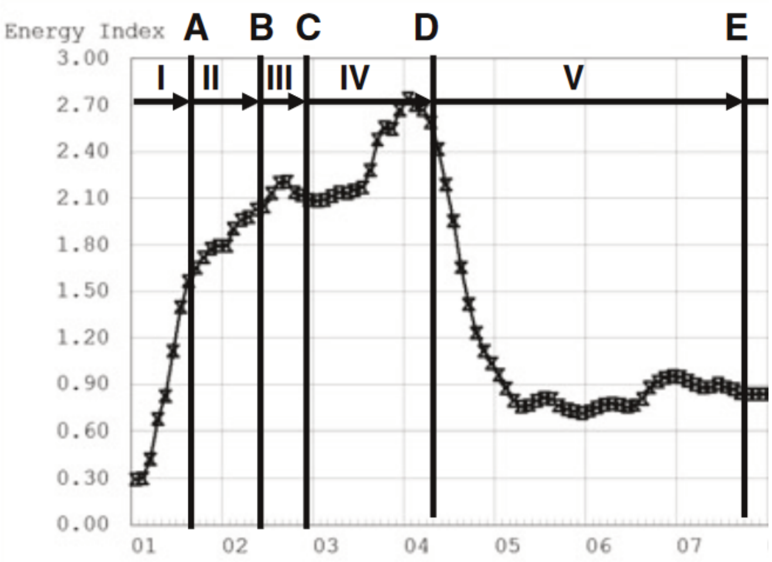

Figure *5* Energy index and different stages in caving mechanism, according to Glazer (2016)

Observations from Glazer at different cave mines has shown that prior to CPF, there existed a considerable increase in the energy index. This may be related to an increase in the pillar stress prior to failure followed by a destressing process with a decrease of the energy index and an increase in the seismic deformation. This seismic deformation is usually estimated from the cumulative apparent volume (CAV) calculated from seismic data (Mendecki 2013).

5 Case study at Chuquicamata underground mine

To illustrate the application of the methods to define crown pillar stability, these methods will be applied in a case study of a Chilean block cave mine. The case study corresponds to the review of the breakthrough process in Chuquicamata underground mine and is based on the seismological evidence, evaluation of CPF, and comparison with the results of the empirical methods. From an observational point of view, the only reliable indication of pillar failure corresponds to cracks at the bottom of the open pit. Above the cave mine, the rest of the information about the cave rock mass behaviour will be interpreted based on seismic data.

5.1 Chuquicamata underground mine

Chuquicamata underground mine is a block caving mine located 15 km north of Calama, Chile. The century old open pit mine is transitioning to underground mining using the macro block caving method described by Flores & Catalan (2019), as shown in Figure 6. Ore extraction began in early 2019 and during February 2020, large cracks were noted in the bottom of the pit, evidencing the connection between underground mine and surface.

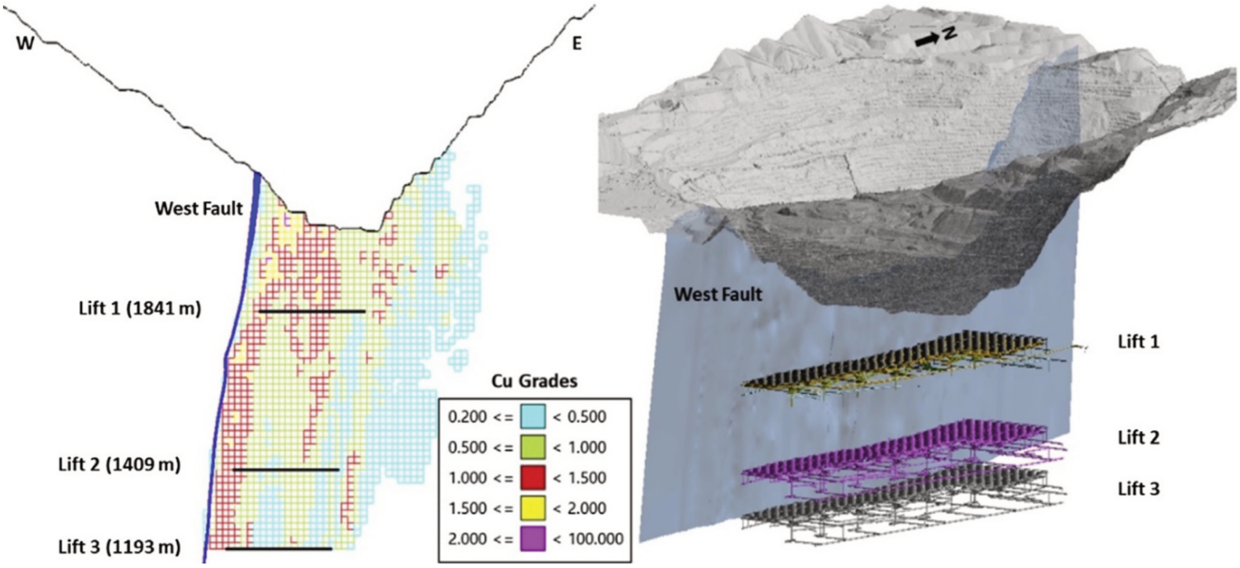

Figure 6 **Chuquicamata underground mine, as described by Flores & Catalan (2019)**

5.2 Application of empirical methods to evaluate crown pillar thickness

As mine extraction increases, the extracted column also increases, which reduces the effective crown pillar. It will eventually fail once the critical pillar thickness is achieved. In this study, the critical pillar thickness corresponds to the last stable state of the crown pillar and is calculated through the previously mentioned empirical methods. Since the cave size grows through time and the critical pillar thickness is a function of cave geometry, the critical pillar also will increase in size (Figure 7).

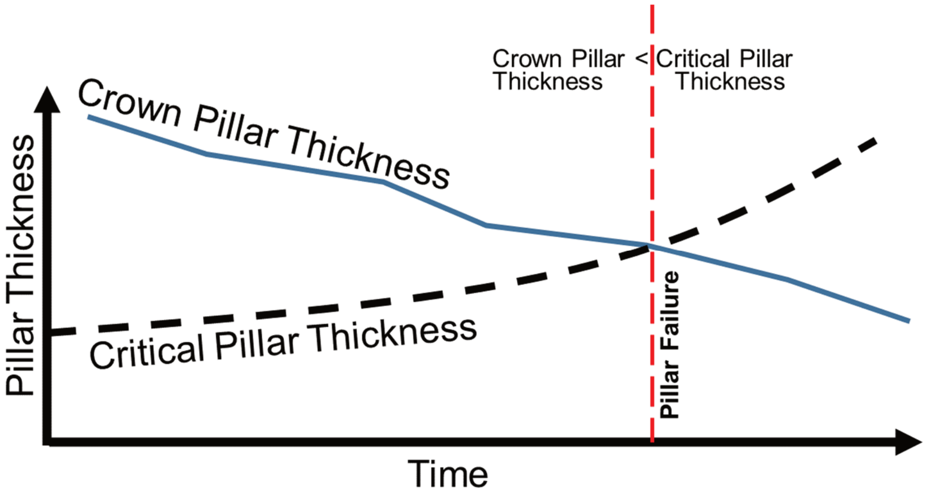

Figure 7 **Relation between pillar thickness and failure. As extraction continues, the cave grows and the crown pillar is reduced. Eventually, the critical pillar thickness is reached and failure occurs**

The calculation of the crown pillar thickness (crown pillar thickness obtained from indirect measurement) is based on the broken column at each drawpoint. Broken rock column is calculated as a factor of extracted column as a result of rock swelling (Laubscher 2000), shown schematically in Figure 8.

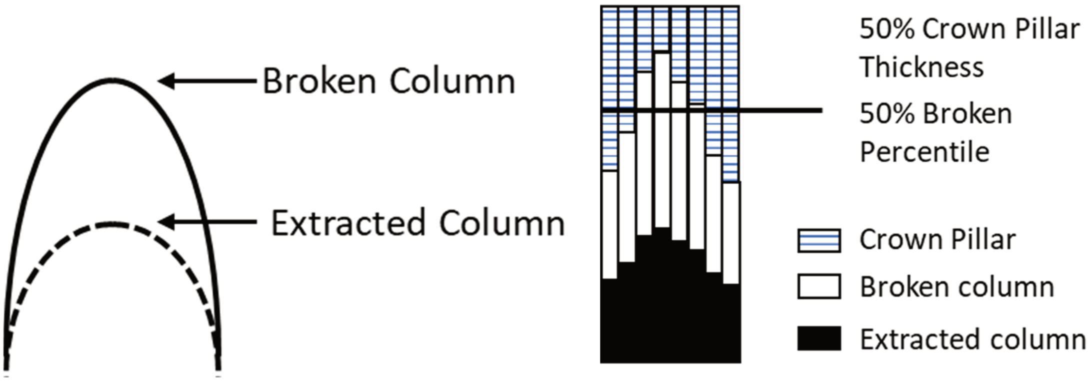

Figure 8 **Relation between extracted and broken rock column and calculation of the 50% of broken column heigh and crown pillar thickness**

Broken rock column is calculated for each drawpoint and considering the distance to the open pit floor, the crown pillar thickness is calculated as the open pit–broken column distance. Since several extraction points exist, the total broken column can be calculated based on the highest extraction points or in those with less extraction. In this paper, the broken column height (and crown pillar thickness) is based in the 50th percentile of the extraction points at any given time (purple line in Figure 9) This allows the calculation of the crown pillar thickness change as the cave grows higher.

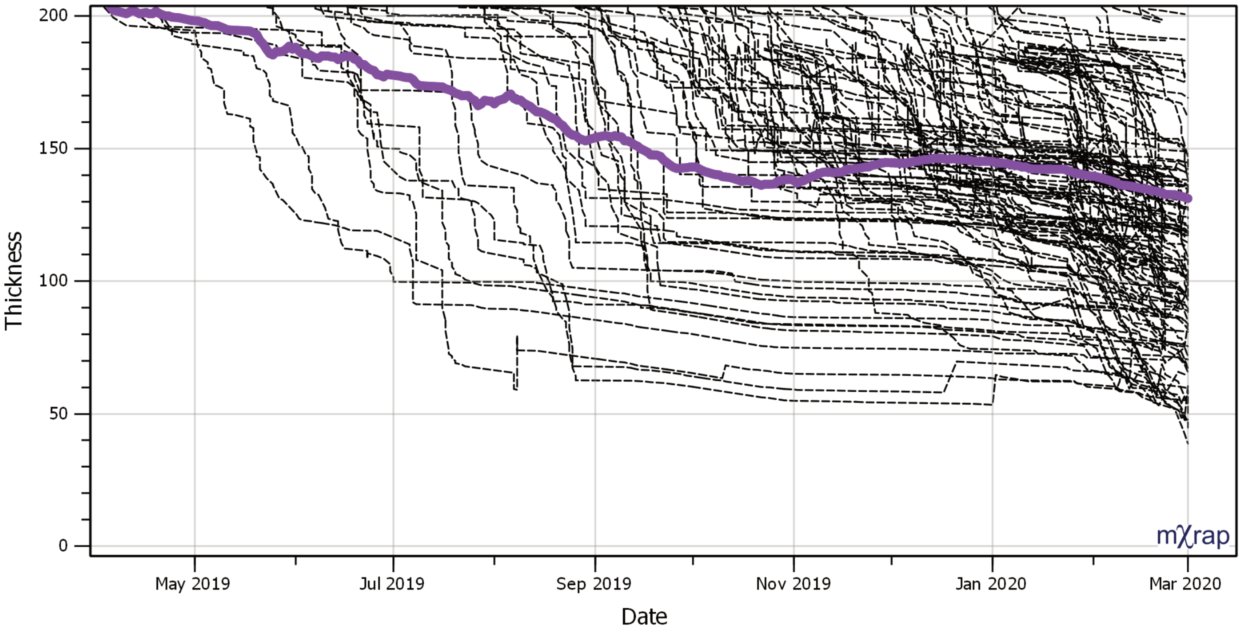

Figure 9 **Crown pillar thickness calculated for each drawpoint (dashed lines) and the median crown pillar thickness (purple line)**

As the caving process evolves towards breakthrough, changes in the geometry of the cave occur in the height, length and width. These geometrical changes generate variations in the calculation of the critical crown pillar thickness and, as the cave becomes larger, the critical crown pillar also becomes larger (as shown in Figure 7). Calculation of the critical pillar thickness according to the different empirical methods are described in Section 3 and these are shown in Figure 10. The method proposed by Flores (2005) includes two variants: one considering a vertical fault near the cave (similar to the real condition observed in Chuquicamata mine) and one case without faults in a homogenous rock mass.

From this analysis, it can be extracted that:

- Pillar failure occurs when the crown pillar thickness line intersects the critical crown pillar thickness obtained from each of the empirical methods described earlier.
- Carter-Miller and Bakhtavar provided the earlier estimation of CPF (October, early November 2019).
- Flores (2005) with fault and Carter (1992) provided the latest CPF (February–May 2020).
- Flores (2005) without fault provided an intermediate solution in December 2019.

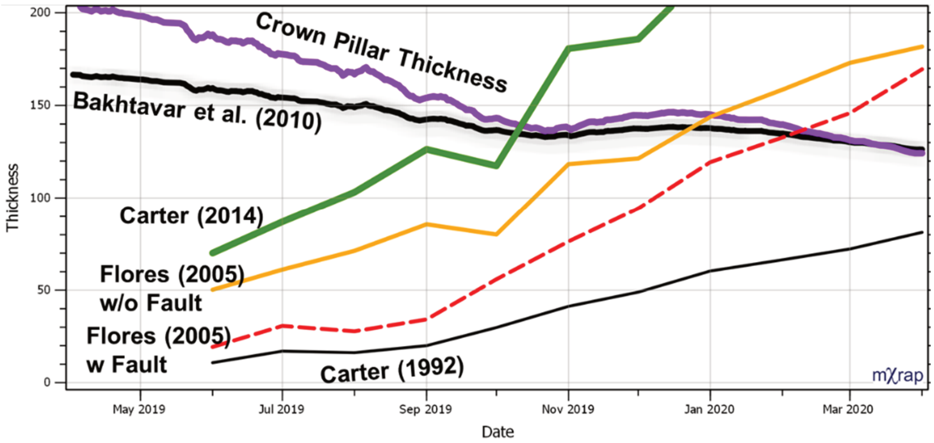

Figure 10 **Crown pillar thickness obtained from cave size estimation and critical crown pillar thickness obtained from the different empirical methods described earlier in this paper**

5.3 Seismological observations of pillar failure

According to the seismological description of the physical process occurring in cave mines described by Glazer (2016), an increase in the energy index signals the initiation of stress caving and pillar failure. Also, from the interpretation of the energy index and CAV as a simile of stress and deformation on the mine, a softening process is indicative of rock mass failure characterised by an excessive stress being dissipated through rock mass fracturing (indicated as an increase in CAV), generating a stress drop that is visualised as a decrease in the energy index. This signals the failure of the pillars in terms of a complete loss of pillar capacity to sustain load.

Observation of the seismic data from Chuquicamata underground mine using mXrap (Harris & Wesseloo 2015) in Figure 11, shows that an increase in the energy index occurred in mid-November, indicating the initiation of the stress caving process with a CPF occurring during January 2020. Breakthrough to surface occurred in March 2020, as evidenced by large fractures in surface and radar monitored deformations. These observations also correlate well with the sudden increase in seismic deformation expressed though CAV, reflecting stress relaxation through rock mass plastic deformation.

Based on the previous analysis, complete CPF is evident in March 2020, with minor failure occurring also in February 2020 (indicated by changes in energy index and CAV). A decrease in the energy index indicates that stress is being dissipated as plastic deformation through the pillar, indicating pillar failure. This process starts in January 2020, where energy index starts to decrease.

Also, based on the criteria proposed by Glazer (2016) and shown in Figure 5, pillar failure may have happened during December 2019.

This analysis implies that crown pillar is stable before December 2019 and therefore, any empirical method that predicts a critical crown pillar before December 2019 provided a conservative estimation of the crown pillar stability (Bakhtavar et al. 2010; Carter 2014). Empirical methods that conclude that critical crown pillar thickness is achieved during early 2020 (Flores 2005) provide a good approximation of the estimated CPF. Finally, the method proposed by Carter (1992) estimated CPF after real crown pillar fail and is therefore not suitable for this case.

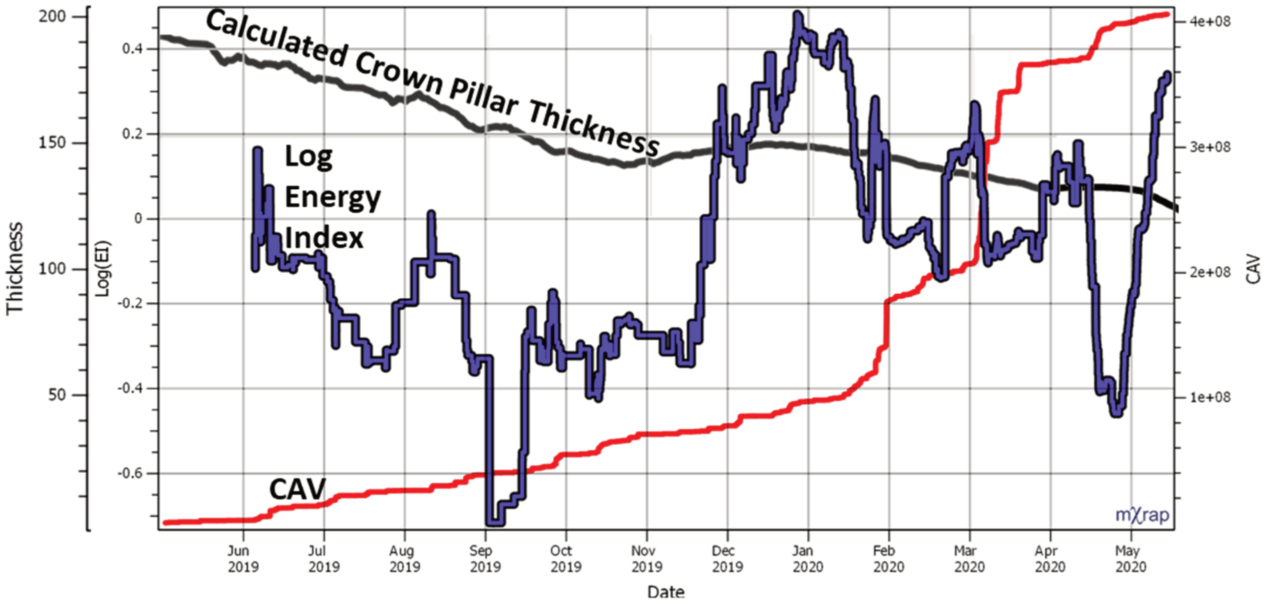

Figure 11 Energy index time history for Chuquicamata underground mine

5.4 Conclusions from the comparison between empirical methods, crown pillar thickness and seismic measurement

When comparing the results from the empirical methods and the seismic record, the following conclusions can be stablished:

- From a seismic point of view, according to the guidelines published by Glazer (2016), CPF must have happened during December 2019.
- Empirical methods to estimate pillar thickness in cave mines propose failure between November 2019 (Bakhtavar et al. 2010) until February 2020 (Flores 2005).
- The results from the Flores (2005) method provided an estimation of the pillar failure between the end of December 2019 and February 2020, much closer to the seismicity-based estimation of the pillar failure.

6 Conclusion

Empirical methods provided different estimations of the CPF time. Methods developed for caving mines provided early warning of CPF. The Carter (2014) method also generates a good warning of the CPF. Older methods to estimate crown pillar thickness as thumb rule described in Carter (1992) provided a late estimation of pillar failure.

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