Reviewing Laubscher's empirical method to estimate subsidence limits

C Contreras *The University of British Columbia, and SRK Consulting, Canada*

D Elmo *The University of British Columbia, Canada*

J Jakubec *SRK Consulting, Canada*

A Thomas *SRK Consulting, Canada*

Abstract

The increasing global demand for mineral resources and the depletion of significant high-grade near-surface deposits is driving mining companies to consider cave mining as the ideal method to exploit large low-grade deposits at depth. A key characteristic of cave mining is the formation of a significant surface subsidence crater, which may impact nearby infrastructures, as well as have important environmental impacts. The most used empirical method in cave mining for estimating subsidence damage limits is the Laubscher method (2000). The original dataset at the core of the Laubscher chart does not reflect the conditions of the modern caves (i.e. deeper orebodies, stronger rock masses and higher production rates). In addition, there is a need to review the definition of the cave material factor. This paper explains the limitations related to the method and evaluates new cases from recent cave mining operations for checking the validity of the empirical subsidence chart.

Keywords: *subsidence, empirical method, Laubscher, block caving*

1   Introduction

Subsidence is defined as the lowering of the ground surface following the underground extraction of ore or another resource (Brady & Brown 2004). In the context of underground mass mining methods (i.e. caving mining methods), large scale surface displacements induced by the extraction of the ore eventually result in the formation of a crater and stepped terraces. The ability to characterise the potential extent of surface subsidence is therefore very important for mine planning, operational hazard assessment and evaluation of environmental and socio-economic impacts. According to Lupo (1998) and Van As et al. (2003) surface deformations observed and/or measured at several caving mines can be grouped into three distinctive zones: Caved rock zone, fractured zone, and continuous subsidence zone (Figure 1).
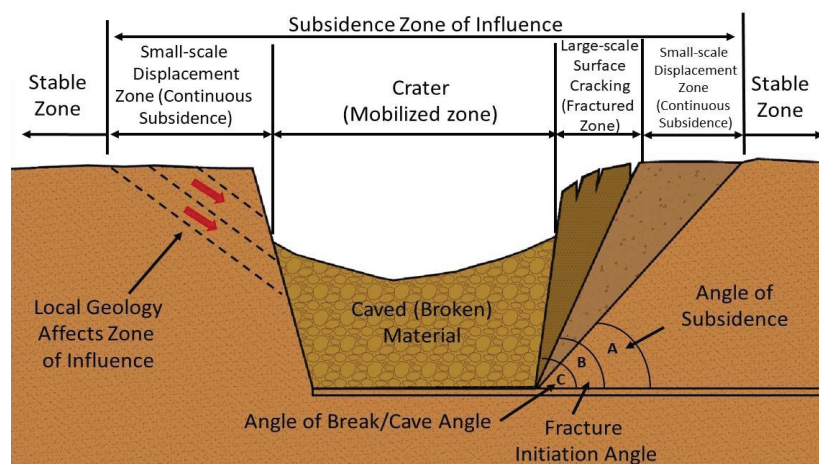

Figure 1   **Block caving subsidence characterisation terminology (modified from Laubscher et al. 2017)**

This paper will focus on the caved rock zone since the Laubscher method is applied to determine the limit of this zone. Caved rock zone corresponds to a zone of active cave movement typically situated above the active caving footprint and manifested as a large crater. The terms 'cave angle', 'break angle' or 'angle of break' have the same meaning in this paper.

The most commonly used empirical method in cave mining for estimating cave rock zone limits is the Laubscher's method (Laubscher 2000), which is based on a design chart that relates the predicted cave angle (angle of break) to the MRMR (Laubscher's Mining Rock Mass Rating), the density of the caved rock, the height of the caved rock and the mine geometry (minimum span of a footprint). Laubscher developed two charts, one less conservative for estimating the break angle or cave angle (Figure 2), and another more conservative, which was originally designed to also estimate the break angle and should be used for siting important infrastructures such as shafts or plants according to Laubscher.
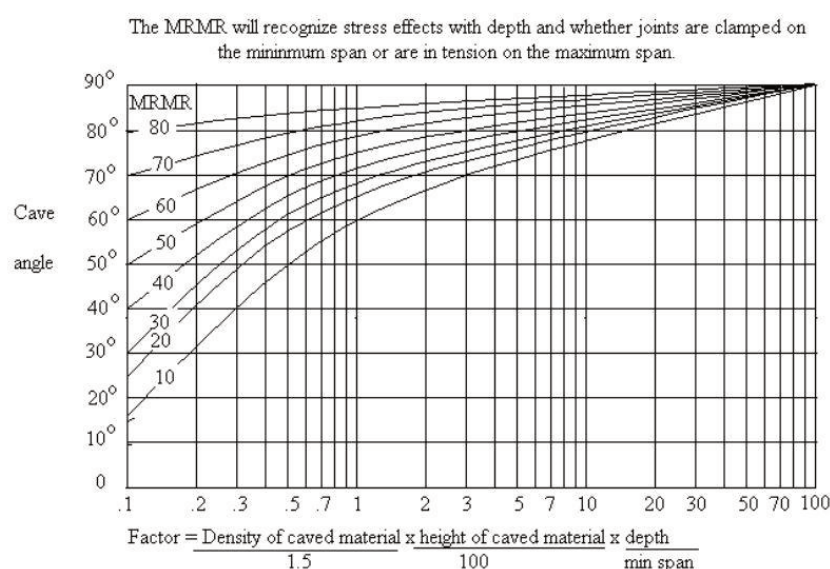

Figure 2   Empirical chart relating MRMR and cave (break) angle (Laubscher 2000)

Laubscher charts are still used in mining projects today. However, the method requires sound engineering judgement and experience in similar geotechnical settings, and it is not intended as a replacement for more complex analyses. While numerical models clearly have a visualisation advantage over empirical methods, they generally share the same problem in terms of the availability of reliable and spatially variable input parameters (e.g. rock mass quality estimates). In addition, these models are unreliable until they have been calibrated to specific conditions and mining approach. As discussed, in Elmo et al. (2017), large-scale numerical models often fall into the paradox of having to use empirical formulae to define acceptable ranges of modelled rock mass strength and deformability. The non-prototypal nature of rock engineering problems and the need to constrain the results of numerical analysis at a scale that cannot be validated using laboratory surrogates reveal an opportunity to better integrate experience-based design charts and numerical models.

To achieve this integration, there is a need to update existing empirical methods to better reflect the evolution of cave mining over the past 20 years, with caving operations facing deeper orebodies, extracting taller ore columns in stronger and massive rock masses while at the same time targeting higher production rates. For instance, the original dataset at the core of the Laubscher chart (2000) is not well defined in the literature, and there is the need to review the definition of the cave material factor. In addition, Laubscher's method does not consider the effect of major geological structures (e.g. faults), which may influence the dip of the cave angle.

2   A review of Laubscher's chart to estimate subsidence

A large number of mines have used and are using the Laubscher chart to estimate subsidence limits. Cave angles are a function of MRMRs of different geotechnical domains, density of caved material, height of the caved material and minimum span. The method is founded on the premise that the stronger the rock mass (higher MRMR) the steeper the cave angles. In addition, the broken rock within the cave is assumed to offer confining support to the cave walls and thus allows steeper angles than the angles observed on the crater surface, where an unconfined zone allows flatter angles unless the structural condition or excellent geotechnical quality of the rock prevents it (Figure 3).
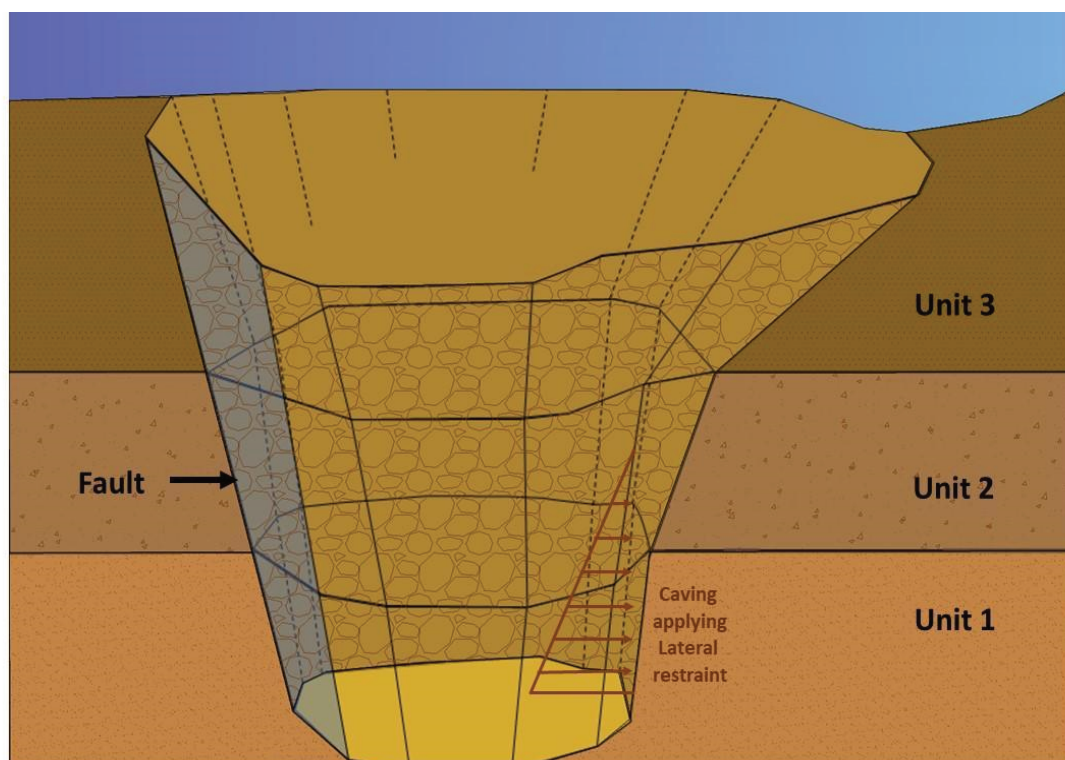

Figure 3   Influence of structures and geotechnical quality of the units. Effect of lateral restraint of caved material

Reports were reviewed where this method has been applied (Table 1). One of the findings was that in some cases a single MRMR value is applied to the entire cave wall when the methodology suggests that a division is required considering different values for each interval. The interval closest to the surface is generally expected to have a lower MRMR value due to direct exposure to environmental conditions (i.e. weathering and alteration). In addition, many reports use an empirical method to estimate subsidence, but they do not specify if it is Laubscher's method or the parameters, and they only show the results, without showing calculations.

The MRMR is obtained using adjustment factors (weathering, joint orientation, mining induced stresses, blasting, water/ice). The values of these factors should be chosen by experts in the field, who have worked on similar projects. The lack of detailed guidelines for adjustment factors could lead to subjective misuse. For instance, stress adjustment varies from 60% to 120%. These extreme values are explained (Laubscher & Jakubec 2000) but choosing a value in the middle of the above-mentioned range is a challenging task if someone is not familiar with the system.

Table 1   Mining project where Laubscher's method has been used

Project	Country	Company	Stage	Report year	Density of caved material (t/m³)	Height of caved material (m)	Depth (m)	MRMR (RMR)	Cave angle (°)
Cascabel (Wood Plc 2019)	Ecuador	SolGold plc	PEA	2019	–	–	–	22–37	76
Tres Valles (Wood Plc 2018)	Chile	Sprott Resource Holding Inc.	PFS	2018	2.00	70	200	20	75
Resolution (2014)	USA	Rio Tinto	–	2014	2.00	–	–	50–95	72–85
Oyu Tolgoi (AMC Consultants 2012)	Mongolia	Rio Tinto	–	2012	–	–	–	30–60	63–75

Minimum span value is not mentioned in the reports.

The cave angles obtained in areas close to the surface are considered too conservative in the lower end of the 'factor' and MRMR scale (Figure 2), the chart shows values starting at 15° for an MRMR value of 10. According to Woo (2011), the minimum value observed for the cave angle is 40°, considering an undercut depth lower than 100 m. This value is based on a database that considers 47 direct and indirect subsidence observations from caving mines. On the other hand, Haines and Terbrugge (1991) have developed an empirical chart for calculating stable slopes in an open pit in moderate to low MRMR, where the conditions are similar for the unconfined zone of the crater. This method presented a minimum value of 30°, considering a depth lower than 10 m and MRMR lower than 10, according to their database. In addition, the angles are approximately 20–10° lower in the Laubscher chart than in the Haines and Terbrugge chart for the range of MRMR values between 10 and 40.

Both minor and major structures can influence the subsidence mechanism and development. Although studies have been carried out by Vyazmensky & Elmo (2010), using conceptual modelling to evaluate the significance of geological structure on surface subsidence, there is no guideline that can be applied to caving projects in general because these discrete features depend on their location, characteristics, geometry, and other factors which are difficult to account for in an empirical method. The crater walls that are influenced by this condition should be studied in isolation, especially when major faults affect a wall.
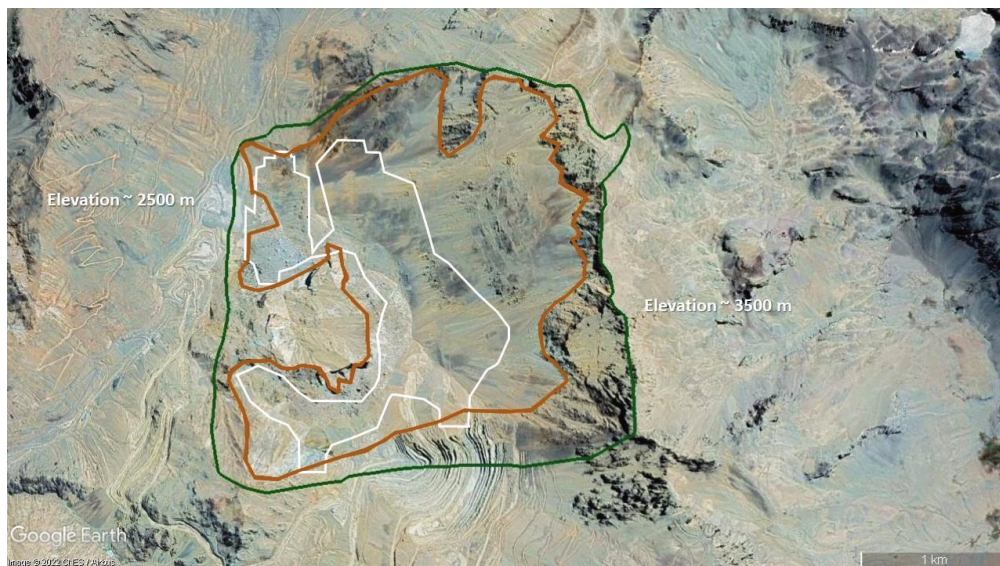
The topography, where the subsidence is developed, could be flat (regular) or irregular (the mine is situated beneath a mountain peak or slope). In general, an irregular topography is seen to result in lower caving angles over the peaks. This is reflected in Google Earth satellite images. For instance, Cadia East tends to show more symmetry in the shape of the caving zone on the surface, for that reason a smaller range in cave angles is expected. The extraction levels for Cadia East are shown in Figure 4a, represented by white lines, the level on the left is a 'mature cave', because the caved rock zone has been developed. On the other side, the level on the right has caving in progress, therefore cracks have been developed on surface that are related to the fractured zone.

On the other hand, El Teniente is located under mountainous topography, the difference in elevation is 1,000 m approximately between the zone east and zone west of the crater (Figure 4b). Considering the depth of this mine (the sectors that have produced the subsidence limit in the zone west could have a depth close to 1,000 m) steeper angles are expected based on Laubscher's chart, where the top end shows cave angles greater than 80° (Figure 2). However, angles lower than 80° are observed and measured. This condition is associated with lateral landslides, which are likely to occur when there are large differences in topography,

high extraction rates, and deep mining sectors. Consequently, the cave angles can be lower than the cave angles predicted (Figure 5). For instance, Figure 6 shows the caved rock zone limit in 2011 and 2013 (El Teniente mine). Part of the fractured zone was marked with a dashed line in 2010, the same area is considered part of the caved rock zone in 2013. The variation observed over a period of three years is due to a high rate of extraction from different productive sectors at the same time, which produces instabilities in the crater walls, causing landslides and finally modifying the limits of subsidence (Retamal 2018). A similar situation can be observed in the Grasberg mine (Figure 7), three-block cave mines caused surface ground subsidence in a mountainous area. Surface topography is mentioned among the factors that affect the surface subsidence *"Surface topography although not generally affecting the magnitude of subsidence, it can change the position and the shape of subsidence trough"* (Esaki et al. 2009). A break angle of 65° is shown in Figure 7a (northwest wall), which would be constrained by topography at peaks, showing a lower break angle compared to an angle developed in a regular topography.

(a)

(b)

Figure 4   **Influence of topography observed visually in Google Earth satellite images: (a) Flat topography, elevation near to 850 m. Cadia East mine, Australia (modified from Wilson 2003; Castro & Cuello 2018) and (b) Irregular topography, elevation between 2,500 and 3,500 m at El Teniente mine, Chile (modified from Farloni et al. 2018). The caved rock zone is marked by a brown line, the fractured zone by a green line, and the simplification of the extraction levels by a white line**
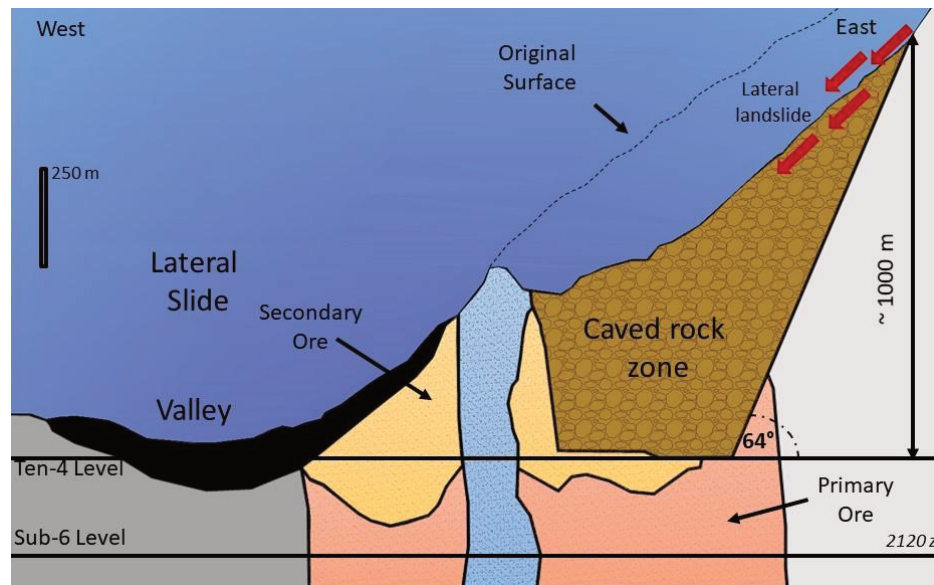
Figure 5   East–west section at El Teniente mine showing the irregular topography and its effects on the limits of subsidence (modified from Brzovic 2010)

Therefore, the actual cave mechanisms (cave mechanics) are not taken into account in Laubscher's chart. The chart considers only the outline of the undercut and surface limit. The processes happening between are neglected completely.

In addition, the sequence of panels and blocks in lateral and vertical directions could have a significant impact. Especially, when the lateral extent of mining is large, where it takes a long period to advance from one boundary to another boundary, or where many areas are brought into production over time due to the large lateral extent. Finally, the percentage of extraction also has an impact, it is expected that the higher the extraction the lower the cave angle.

The limitations mentioned above are summarised below:

- MRMR: The MRMR is part of the parameters to predict subsidence. However, the lack of detailed guidelines for adjustment factors could lead to subjective misuse.

- Unconfined area: The cave angles obtained in areas close to the surface (unconfined area) are considered too conservative in the lower end of the 'factor' and MRMR scale, the chart shows values starting at 15° for an MRMR value of 10.

- Structures: The influence of minor and major structures is not considered.

- Topography: Irregular topography is seen to result in lower cave angles over the peaks than the cave angles predicted using the method.

- Mining sequence: The impact of the mining sequence is not considered. The effect of a larger extraction or multiple extractions (many areas are exploited at the same time) is neglected. A higher production rate could cause landslides and modify the limits of subsidence. In addition, it is expected that the higher the extraction the lower the cave angle.

(a)

(b)

Figure 6 Influence of topography, deepest productive sectors (below 1,000 m) and high extraction rate observed visually in Google Earth satellite images: (a) El Teniente mine, Chile, date: 06/2010; (b) El Teniente mine, Chile, date: 04/2013. The caved rock zone is marked by a brown line and the sector of interest by a dashed line

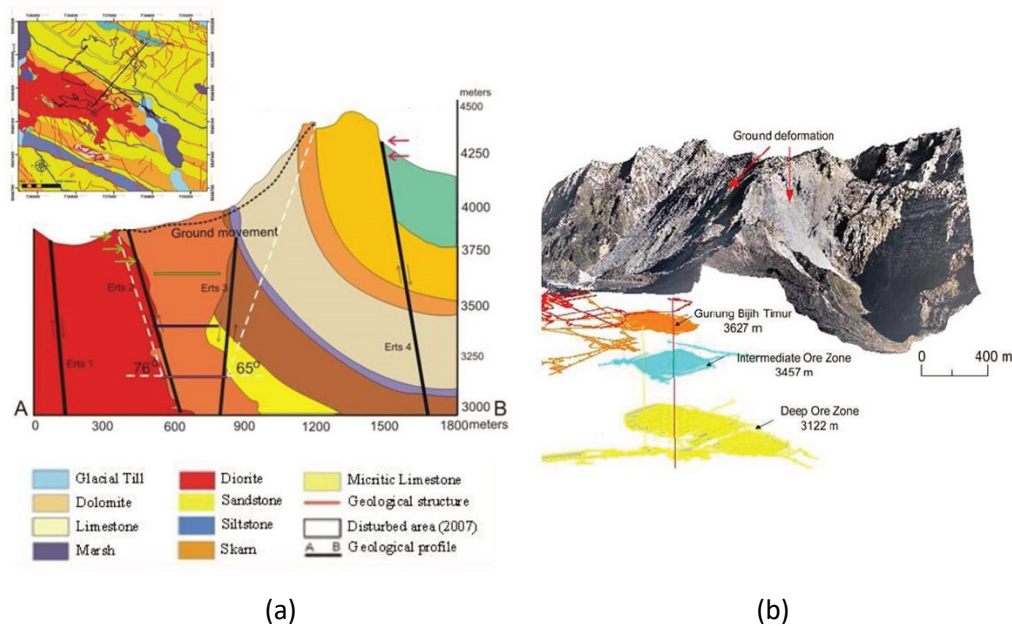(a)   (b)

Figure 7   Influence of topography in constraining the angles of subsidence (a) Schematic cross-section (A-B) of the geological structure showing the lithology, three levels of block caving (b) 3D view of the level of the Gunung Bijih Timur (GBT) Block cave mine, the Intermediate Ore Zone (IOZ) block cave and the Deep Ore Zone (DOZ) block cave that caused surface ground subsidence on the mountainous area (Esaki et al. 2009)

2.1   Why is this method still used despite its limitations?

Laubscher charts are still used in mining projects. However, the method requires a good knowledge of their origin, methodology, parameters, and limitations.

Similar methods to estimate subsidence were developed by Karzulovic (1990), who developed charts to evaluate the break angle based on the geotechnical quality index RMR proposed by Bieniawski (1976) and the height of the crater walls. These methods (Karzoulovic's methods) were developed using information from Andina, and its application is only for this mine as well as El Teniente, where the geology is similar. On the other hand, the method of Laubscher has a broader application. Although the original database is not well defined, it is possible that different mines were considered as in other methodologies developed by Laubscher (e.g. the methodology to estimate the hydraulic radius).

During the preliminary stages of a project, when the information is not available in detail, and there is a high level of uncertainty related to the rock mass, the use of the empirical method is a good point to start. When more information is collected, the study of specific cases could be conducted using numerical analysis, where the geological-geotechnical conditions make the application of empirical methods less reliable.

In general, rock engineering design presented unknown future conditions, and therefore the data to validate the modelling results is not possessed until the construction stage or after the engineering project is complete. Accordingly, empirical assumptions and back-analysis of failure mechanisms are required for the calibration of numerical models.

2.2   Methodology

The methodology to evaluate Laubscher's chart considered the next steps:

- Searching published literature (reports, papers, thesis, etc) from 'new' cave operations (after the late 1990s) to collect information related to caved angle, production rates, depth of the productive sectors, and rock mass geomechanics characteristics in which the mine is located.

- Collecting geographical information from different mine sites using Google Earth satellite images to study the different limits of the caved rock zone.

- Interviewing experts in the field, obtaining information based on the observations.

- Comparing predictions made using Laubscher's method and actual subsidence envelope dimensions.

- Investigating the reasons behind the observed limitations in Laubscher's method.

The limitations mentioned in Section 2 associated with the empirical method were considered for the analysis, therefore zones that present these limitations were not evaluated.

Each expression of the breakthrough zone on the surface owes its shape to the extraction of the orebody; without extraction using caving methods, there is no crater (or breakthrough zone or caved rock zone). In this context, analysis sections perpendicular to the crater walls and the productive sectors were created (Figure 8a). With this information, an overall angle was measured, considering the limit of the cave rock zone observed on the surface, based on images, and the limit of the productive sector adjacent to the crater wall (Figure 8b). The limit of the productive sector considers production zones where the extraction percentage leads the cave that broke through to the surface. According to Laubscher, the surface will begin to subside between 30% and 40% extraction, considering the extraction percentage of the overall rock mass between the production level and the surface.

On the other hand, an estimated or predicted angle is obtained based on the depth of the undercut level below the surface, the height of caved rock zone, and the density of the caved material (some mines consider a general value, and others consider the density in situ and the 'bulking factor' or 'swell factor'), the minimum span, and the MRMRs (obtained from drill holes or geotechnical models).

Then the 'measured overall' angle is compared with the 'estimated overall' angle to determine the validity of this method. The estimated overall cave angle is calculated using the weighted percentage of the MRMRs intervals.

Laubscher developed two charts; the chart less conservative was considered for this study since the second chart gives extremely conservative results that could be related to the continuous subsidence limit.

There are mines where the caved rock zone has been used as a waste dump, therefore the deformations related to the subsidence phenomenon are hidden. This limitation was considered in the study.

(a)   (b)
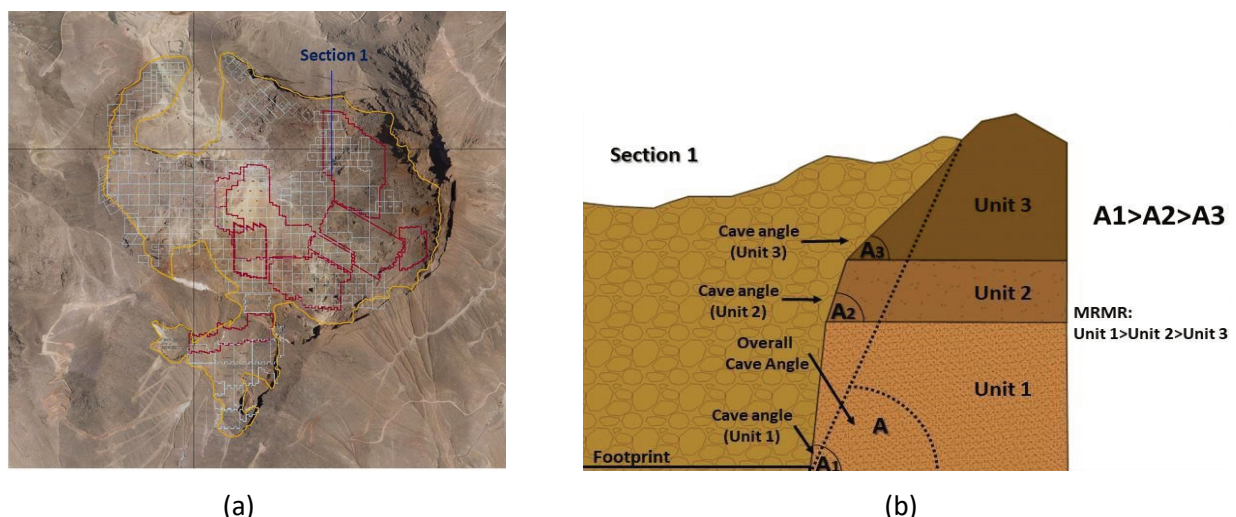
Figure 8   Sketch of the methodology. (a) Caved rock zone limit (yellow line) observed visually in Google Earth satellite images. Block caving productive sectors (grey lines) and panel caving productive sectors (red lines) (modified from Contreras 2016), (b) Predicted break back for Section 1

3   Data

The main database used for the first stage of this investigation corresponds to eight cave mines; most are in their last years of operation (name and location may not be disclosed for confidentiality reasons). Therefore, there are sectors that have already reached 100% of their production and/or are stopped. From these mines, it was possible to study all the parameters related to the Laubscher method.

These cases reflect the deeper, large production, and low-grade ore characteristics of cave mines today in comparison with the mines before 2000 when Laubscher's method was created. The cases have a weighted average of cave factor greater than three (3) in Laubscher's chart, the MRMR in this area has only a comparatively small impact according to Laubscher since the MRMR curves are getting closer (Figure 9). The ranges of cave angle values in the lower end of the chart are from 15° to 80° (factor = 0.1). On the other hand, the range of cave angle values for the upper end are from 85° to 90°, reaching 90° at the end (factor = 100).

Furthermore, the database presents a few cases with a cave 'factor' lower than 1 in one of the MRMR layers and their depth is not significant considering the total depth of the section. Thus, the lower end zone could not be studied using new cases.
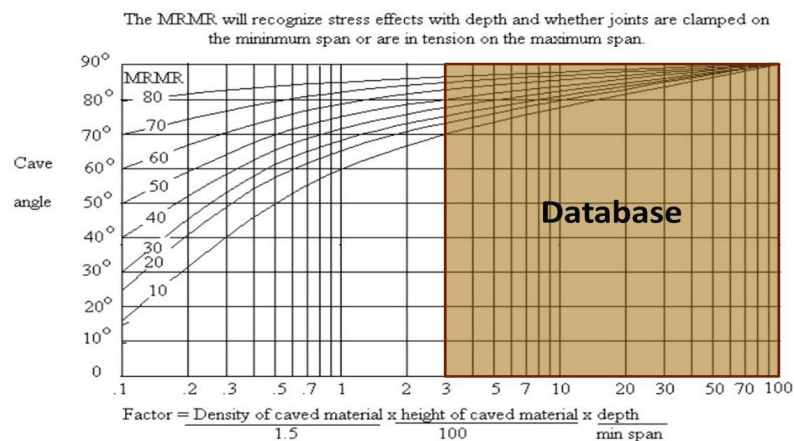

Figure 9   Empirical chart (Laubscher 2000) with a superimposed range of values of different case studies based on the data collected (brown area)

4   Results

The results are illustrated in Figure 10, the values of the overall cave angle are compared with respect to the most sensitive parameters (depth and minimum span) considering the MRMR. The graph (a) of Figure 10 shows the tendency of the measured overall cave angles, cave angles between 200 and 500 m below the surface have a higher scatter than cave angles between 500 and 800 m: with values from 64° to 87° (200–400 m) versus values from 72° to 84° (500–800 m). Therefore, it seems that for depths greater than 600 m the measured overall cave angles tend towards the same range of values (80° ± 4°) regardless of their geotechnical quality. This observation is related to Laubscher's method, the greater the value of the depth, the greater the value of the factor, and the smaller the range of cave angle according to the MRMR. This situation can be explained by the lower extraction ratio when assuming the same height of the ore column being caved, and therefore a less extensive cave developing and daylighting at surface (Woo 2011). Another explanation is the higher stress confinement at depth, which allows a steeper cave angle.

On the other hand, the minimum span and the MRMR do not show a particular trend related to the cave angle.

The graphs shown in Figure 10 present the predicted overall cave angles and the measured overall cave angles, to compare the values. The predicted values have a lower scatter than the measured values. However, the differences are minimal in general, the average distance between the measured data values and the predicted data values is 4° (root mean square error-rmse: 4°), the maximum difference is 9°and the minimum

difference is 0°. Considering these values, the impact that a difference of 4° can have in the caved rock zone limit is small based on the scale of the mining projects. For instance, an overall predicted cave angle of 81° is calculated for a mine at 500 m below the surface, considering a flat topography. Then, the overall cave angle is measured, and the value is 85° (rmse:4). Therefore, the caved rock zone boundary is approximately 36 m larger than the predicted boundary. On the other hand, the caved rock zone boundary is approximately 69 m larger than the predicted boundary considering the same assumptions but a depth of 1,000 m.
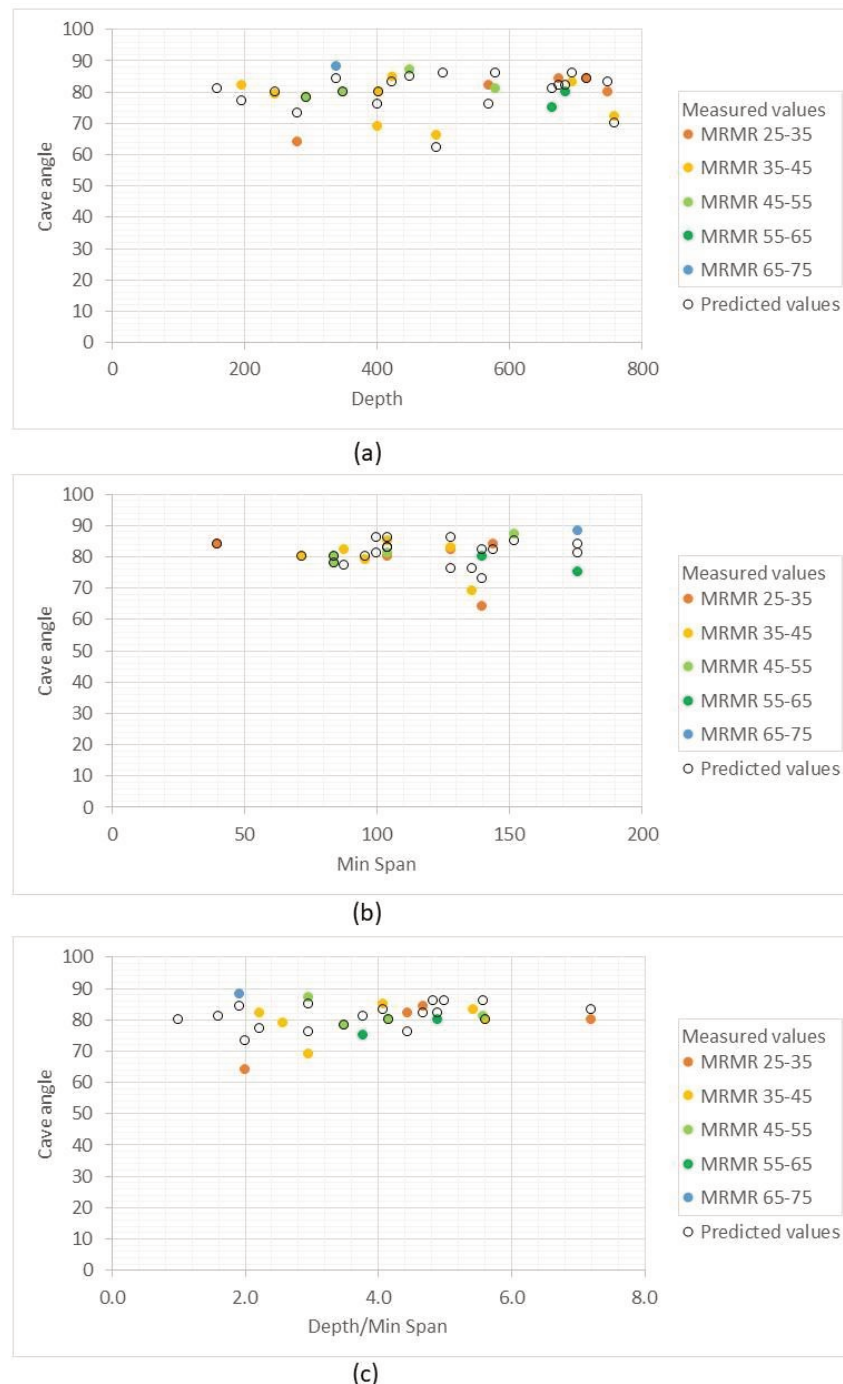

(a)

(b)

(c)

Figure 10 Relationship between cave angles measured, cave angles estimated and Laubscher's parameters to estimate subsidence. (a) Comparison between cave angles measured, and cave angles estimated for different depths; (b) Comparison between cave angles measured and cave angles estimated for different min span; (c) Comparison between cave angles measured and cave angles estimated for different ratios (depth and minimum span)

5   Conclusion

The review of the Laubscher caving chart indicated that the method is still used to calculate the cave angles and estimate the limits of the cave rock zone, especially in the early stages of a caving project (scope, pre-feasibility) which are associated with a high level of uncertainty in the database, therefore the application of empirical methodologies is acceptable.

Although there is a general optimism towards computer models, numerical models are much more expensive and take much longer than empirical methods. Furthermore, the uncertainty associated with the numerical models will be the same as that related to the empirical methods at the beginning of the project.

Laubscher's method, like any empirical methodology, has limitations. For that reason, it is necessary to consider and evaluate them. The limitations found and reviewed can be divided into the following categories:

- MRMR: The MRMR is part of the parameters to predict subsidence. However, the lack of detailed guidelines for adjustment factors could lead to subjective misuse. Expert advice is crucial to define MRMR values as well as a robust database. In addition, a future study that considers a review and update of the MRMR adjustments is recommended to reduce the subjectivity in its application.

- Unconfined area: The cave angles obtained in areas close to the surface (unconfined area) are considered too conservative in the lower end of the 'factor' and MRMR scale, the chart shows values starting at 15° for an MRMR value of 10. The database only presents a couple of cases that show this situation; therefore, it is not significant enough to update this zone in the chart. However, these cases could be compared with the values given in the chart developed by Haines and Terbrugge.

- Structures: The influence of minor and major structures is not considered.

- Topography: Irregular topography with a greater difference in elevation (> ~500 m) is seen to result in lower cave angles over the peaks than the cave angles predicted using the method.

- Mining Sequence: The impact of the mining sequence is not considered. The effect of a larger extraction or multiple extractions (many areas are exploited at the same time) is not considered either. A higher production rate could cause landslides and modify the limits of subsidence. In addition, it is expected that the higher the extraction the lower the cave angle.

- The scenarios related to the three last limitations could be studied using a numerical model, considering the inputs, their relationship, and the limitations associated. The modelers should be aware that numerical analysis is affected by the uncertainty related to the input parameters, and sometimes inputs are calculated using empirical analysis. In view of that, reviewing, understanding, and improving the application of empirical methods seems to be the key to improving rock engineering design processes.

The evaluation of new cases from recent cave mining operations showed that Laubscher's method performs well. It is observed that for depths greater than 600 m the measured cave angles tend towards the same range of values (80° ± 4°) regardless of their geotechnical quality. This observation is related to Laubscher's method, the greater the value of the depth the greater de value of the factor, and the smaller the range of cave angles according to the MRMR. This situation can be explained by the lower extraction ratio when assuming the same height of the ore column being caved, and therefore a less extensive cave developing and daylighting at surface (Woo 2011). Another explanation is the higher stress confinement at depth, which allows a steeper cave angle.

In general, the predicted values have a lower scatter than the measured values. However, the differences are minimal, the average distance between the measured data values and the predicted data values is 4° (root mean square error-rmse: 4°).

Due to a paucity of reliable data, the Laubscher method remains only partially reviewed but may be useful as a first approximation.

Acknowledgement

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