Caving 2026 – A van As, D Cumming-Potvin & J Wesseloo (eds)

doi:10.36487/ACG_repo/2645_56

A new software-based methodology for applying Laubscher's empirical charts to estimate caving angles and evaluate subsidence surfaces in caving mining projects

Juan Montoya [a,*], Julián Morales [b], Emrich Hamman [c]

[a] *Minera de Cobre Quebradona, Colombia*

[b] *CIG2 Ingenieros SAS, Colombia*

[c] *AngloGold Ashanti, Australia*

Abstract

Laubscher's empirical charts for the estimation of cave angles are widely used in caving mining as a straightforward method for estimating the extension of the zone affected by caving. This method is usually applied in two vertical sections (e.g. north–south and east–west) and considers a simplified geometry of the planned mine. In this article a new methodology for the application of Laubscher's empirical method is proposed, based on a 3D block model with detailed information of rock mass (RMR_{90}) and mine geometry. The use of the block model makes it possible to identify the zones potentially affected by the mining process, and to define in detail the adjustments required for the calculation of mining rock mass rating (MRMR) due to water, weathering, joints orientation, mining-induced stresses and blasting. The representation of the mine inside the block model allows one to explicitly consider the effects of geometry changes between sublevels in the shape and extension of the final caving surface. Laubscher's methodology was automatised using R programming language, making it possible to perform the analysis in multiple vertical sections (e.g. 180 sections every 1° azimuth) and to evaluate the sensitivity of the results to the input parameters in a fast and efficient way. The main results of the proposed methodology are the 3D empirical caving surface and the subsidence area associated with the planned mine. The methodology was applied during the feasibility study of a sublevel caving mining project in Colombia, with very good agreements between the empirical estimation of the caving surface and the results of subsequent numerical modelling. The proposed methodology could become a powerful tool in the planning of caving mining projects, including the design of critical infrastructure and the evaluation of environmental impacts.

Keywords: *cave angles, subsidence, block model, RMR_{90}, MRMR, mine geometry, Laubscher's empirical charts*

1 Introduction

Caving is a low-cost, high-productivity, unsupported underground mining method suitable for extensive, low-grade ore bodies. This technique involves creating an undercut – or void – beneath the orebody, causing gravity and the redistribution of stresses to fracture the overlying rock, which triggers their collapse and facilitates ore extraction through drawpoints. The caving of the materials causes surface impacts, primarily subsidence or lowering of the ground surface located above the mine (Brown 2002). Based on observations from various caving mining projects worldwide, three main zones of surface impacts can been defined, as illustrated in Figure 1: the caved zone itself, located directly over the mining footprint and characterised by significant disturbances (a crater with broken and irregular blocks), the zone of discontinuous subsidence or zone with fracture development, and the zone of continuous subsidence, which determines the maximum limit of observable ground deformations (Woo et al. 2013).

[*] Corresponding author. Email address: jdmontoya@aga.gold

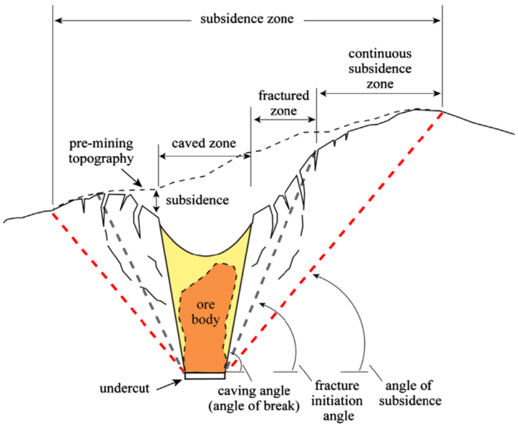
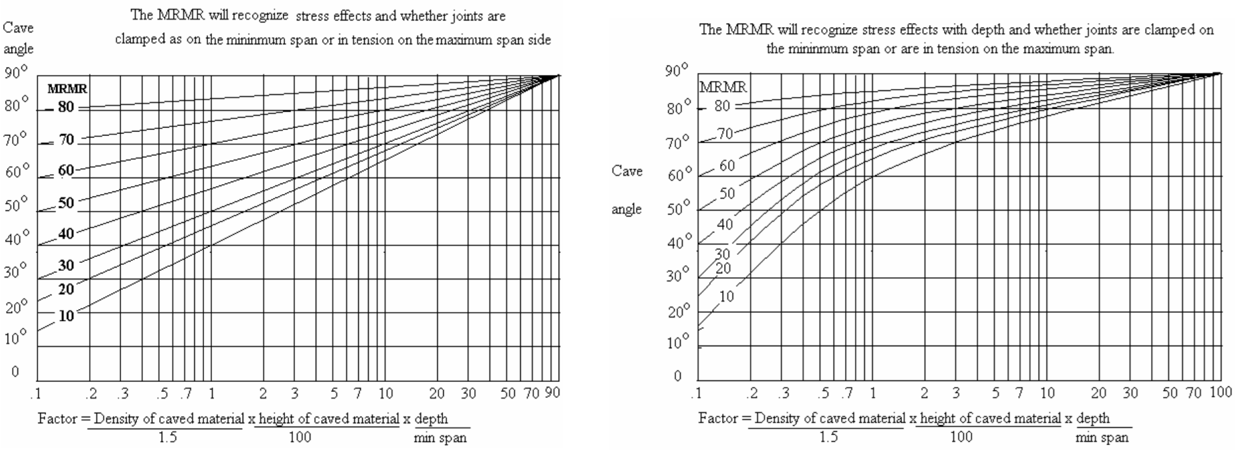


Figure 1 Definition of block caving deformation zones (van As et al. 2003 in Woo et al. 2013)

The characterisation of subsidence is essential for any caving mining project, particularly for mine planning, assessment of operational risks and evaluation of environmental and socio-economic impacts (Contreras et al. 2022). The estimation of subsidence extension can be performed using empirical models, analytical solutions and numerical simulations (Ding et al. 2020), depending on the project's stage and the quality and quantity of available information. Each of these approaches has its own advantages and limitations, and all are affected by various sources of uncertainty. Although there have been significant advances and improvements in the development of numerical models for subsidence estimation, the use of empirical methods remains a recommended and even necessary step prior to any detailed numerical modelling of a mining operation (Brown 2002).

2 Overview of Laubscher's empirical method

Using data from various mining projects around the world, Laubscher (Laubscher 2000) developed an empirical method for estimating the subsidence angles associated with underground mining, based on the characteristics of the rock mass and the mine geometry. This method is widely used in mining projects today and provides an initial estimate of the shape and extent of the area affected by subsidence. Laubscher's method is summarised in two design charts: a more conservative one used for the location of critical infrastructure such as shafts and processing plants, shown in Figure 2a, and a less conservative one used for draw control and water influx calculations, shown in Figure 2b.



(a) (b)

Figure 2 Laubscher's empirical charts for estimation of cave angles in sublevel mining. (a) Conservative chart for infrastructure siting; (b) Less conservative chart for draw control and water inflow calculations (from Laubscher 2000)

To apply Laubscher's empirical method, it is necessary to know the rock mass rating (RMR_{90}) value of the rock mass and to adjust that value according to the expected effects of the mining process and estimate the mining rock mass rating (MRMR) (Laubscher 1990). The value of another factor known as F must also be calculated using the following expression (modified from Laubscher 2000):

$$F = \frac{rho_b * z_b * z_u}{150 * b_u} \tag{1}$$

where:

rho_b = density of caved material

z_b = height of caved material

z_u = depth of the undercut

b_u = minimum span of the undercut.

Using the MRMR and F values, it is possible to determine the subsidence angle along the vertical axis of each of the charts. Laubscher (Laubscher 2000) further notes that the zone of discontinuous subsidence (with fractures) extends 10–100 m beyond the subsidence zone, depending on the quality of the rock mass. This range of values is purely empirical, and the author does not present additional methodologies for estimating the extent of the zones of discontinuous and continuous subsidence in detail.

In practice, it is common for Laubscher's empirical method to be applied to two perpendicular vertical sections, in which the geomechanical properties of the rock mass and its possible subdivisions, as well as the geometry of the mine, are represented in a simplified manner. This study proposes a new methodology for applying Laubscher's design charts which allows for the precise and objective definition of the adjustments to the RMR_{90} necessary for calculating the MRMR, provides a detailed representation of the mine geometry and the spatial variations in the rock mass properties, and automates the estimation process to quickly obtain the caving angles in multiple vertical sections.

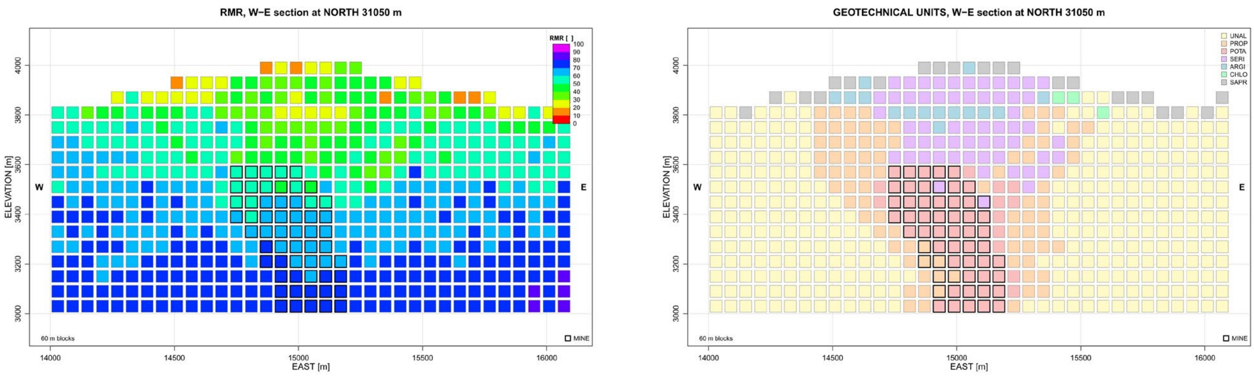
3 Data

The methodology proposed in this study for the detailed and automated application of Laubscher's empirical method requires geological, structural, geotechnical and mining data distributed spatially throughout the area of interest, in order to objectively determine the adjustments to the RMR_{90} associated with the planned mining operation and to accurately estimate the caving angles in all directions and at all levels of the mine. The most appropriate way to represent and process this information is through a block model.

To illustrate the different stages of the methodology, this study uses a synthetic dataset generated for a typical copper-gold porphyry deposit and represented in a 60 × 60 × 60 m block model. The spatial distribution of hydrothermal alteration in this hypothetical deposit follows the model proposed by Sillitoe (2010), which considers six main zones (unaltered, propylitic, potassic, sericitic, argillic and chloritic). In some of the surface blocks, the predominant lithology and alteration are replaced by saprolite to simulate the weathered zone. Different sets of faults are also included to simulate the effects of tectonic activity on the ore deposit after intrusion.

It is assumed that the strength of the rock mass in the hypothetical deposit is determined by the dominant hydrothermal alteration, the vertical depth, and the proximity to faults. Based on this information, values for the intact rock strength (IRS), the joint condition (Jc) and the fracture frequency (FF) are generated on each block of the model. The sum of these three variables allows the RMR_{90} to be calculated following Laubscher's methodology (Laubscher 1990). A mine with 10 levels was designed to extract through caving as much material as possible from the potassic alteration zone, which contains the mineralisation of interest. Figure 3a shows the RMR_{90} values for a west–east section of the synthetic block model, while Figure 3b shows the distribution of hydrothermal alterations in each block. In both figures, the blocks associated with the designed mine are highlighted in black.

For a real-case scenario, the above information is known or can be adequately estimated. The spatial distribution of hydrothermal alterations or geotechnical units, the structural model of the deposit, and the mine design are essential inputs for any pre-feasibility study. The RMR_{90} block model can be obtained through geostatistical techniques, using data obtained from geotechnical core logging, or through methods involving regionalisation, zoning and averaging (Egaña & Ortiz 2013; Eivazy et al. 2017). In the early stages of a mining project, where there might not be enough information for the generation of a detailed block model similar to the one described, a simplified block model can be created using some reasonable values for the required variables, in some general three-dimensional bodies (e.g. horizontal layers of different RMR_{90} values). The most important aspect to be considered here is that the block model allows one to objectively identify the zones affected by the mining process, and to determine the caving angles in multiple vertical profiles as shown in the following sections. Even if the available information is scarce, the proposed methodology aims to improve the current use of Laubscher's empirical charts and to obtain detailed 3D caving surfaces.



(a) (b)

Figure 3 Example of variables in a west–east section of the synthetic block model generated for the application of the proposed methodology. (a) RMR_{90} values; (b) Geotechnical units/alteration zones (bottom). Mine blocks are outlined in black

4 Methodology and results

From the geological, structural, geotechnical and mining data contained in the block model, it is possible to apply the methodology proposed in this study, which consists of two main phases: calculation of the MRMR and estimation of the caving surfaces in all directions and at all levels of the mine. Details are discussed in the following sections.

4.1 Calculation of mining rock mass rating

The RMR_{90} values in each block of the model must be modified according to the effects that the planned mining operation will have on the behaviour of the rock mass; for this purpose, the MRMR classification system is used. According to the authors of the latest update to the MRMR (Jakubec & Laubscher 2000, Laubscher & Jakubec 2001), this system should be flexible and allow geologists, geotechnical engineers and mining planning engineers to adjust the RMR_{90} values according to their judgment and the specific conditions of each project.

The proposed methodology involves an initial zoning of impacts, defining global angles for the continuous and discontinuous subsidence zones. These zones extend in all directions as inverted and truncated vertical cones, the axis of which is located at the centroid of the mine design blocks. Additionally, a block volume balance can be completed considering swelling and dilution factors to identify the potential of a surface block to be part of the possible crater generated by the caving mining process. The initial zoning of impacts for the hypothetical mine is shown in a west–east section in Figure 4.

As a result of zoning, each block in the model is classified into one of the following categories: unaffected by mining, continuous subsidence zone, discontinuous subsidence zone, and possible crater. This allows detailed definition of the adjustments to the RMR_{90} required for calculating the MRMR. The initial zoning angles can be subsequently increased or decreased to ensure that the final caving surface lies within the discontinuous subsidence zone, as shown in Figure 1.

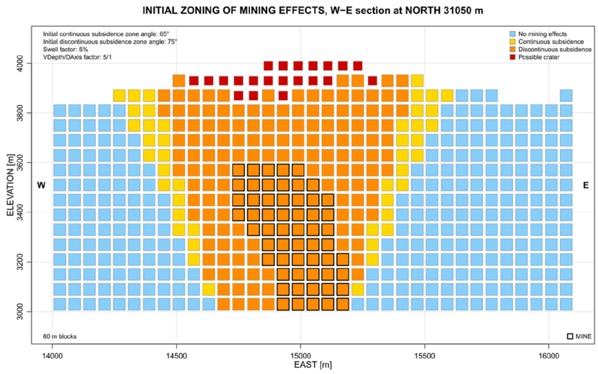


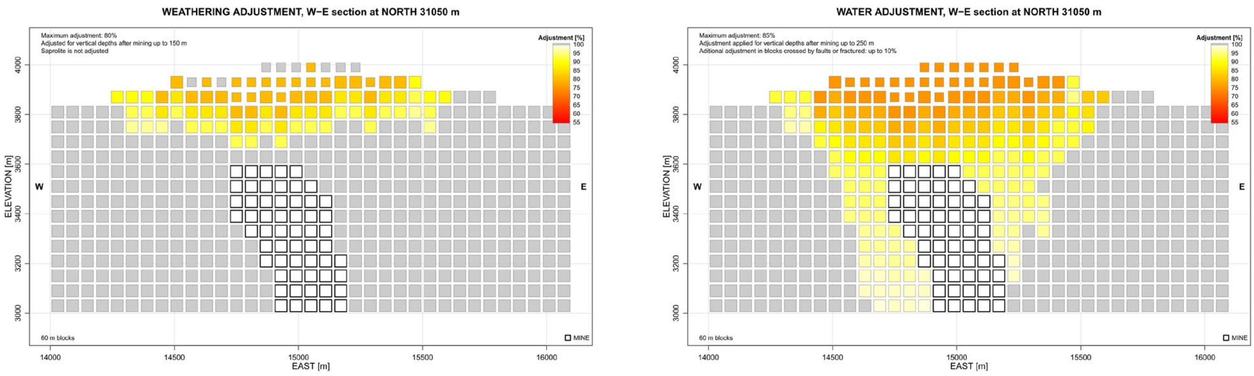
Figure 4 Initial zoning of mining effects in a west–east section of the synthetic block model

The definition of each of the adjustments to the RMR_{90} is explained below:

- Weathering adjustment: refers to the expected changes in the strength of the rock mass as weathering affects surfaces exposed by mining activity (Laubscher & Jakubec 2001). In the proposed methodology, a maximum adjustment value is selected from the MRMR method tables and differentially applied to the blocks, restricting it to depths below a certain limit. Blocks unaffected by mining are not adjusted, nor are blocks where saprolite predominates (since saprolite cannot weather further), while the adjustment is maximum for blocks in the crater zone and surface blocks in the discontinuous subsidence zone as ground deformations are expected to occur, allowing the exposure of the rock mass. Blocks located in the continuous subsidence zone are adjusted with an intermediate to minimum adjustment factor as minimal ground deformations are expected to occur in that zone. Weathering adjustment decreases with the depth of the block and should not be applied beyond the selected limit. Weathering adjustments are shown in Figure 5a.
- Water adjustment: represents the decrease in the rock mass strength caused by the reduction in friction along the structures and decreased effective stresses caused by increased water flow as a result of mining operations (Laubscher & Jakubec 2001). In the proposed methodology, a maximum value is selected from the MRMR method tables and differentially applied to the blocks, restricting it to depths below a certain limit. Blocks unaffected by mining are not adjusted, while the adjustment is maximum for blocks in the crater zone and surface blocks in the discontinuous subsidence zone as ground deformations are expected to occur allowing to increase of water flow into the rock mass. Blocks located in the continuous subsidence zone are adjusted with an intermediate to minimum adjustment factor as minimal ground deformations are expected to occur in that zone. An additional adjustment can be applied to already adjusted blocks that are crossed by faults in the block model as they can allow higher water inflows. Water adjustment decreases with the depth of the block and should not be applied beyond the selected limit. Water adjustments are shown in Figure 5b.
- Joint orientation adjustment: represents the effects that the size, shape and orientation of the excavation have on the behaviour of the rock mass, in terms of the stability of the rock blocks defined by the intersection of various families of discontinuities (Laubscher & Jakubec 2001). In the proposed methodology, a maximum value is selected from the MRMR method tables and is applied only to blocks located in the continuous zone. Blocks located in the discontinuous zone are expected to cave, so no adjustment is considered. Joint orientation adjustment decreases with the depth of the block as the rock mass experiences higher confinement. It also decreases as the value

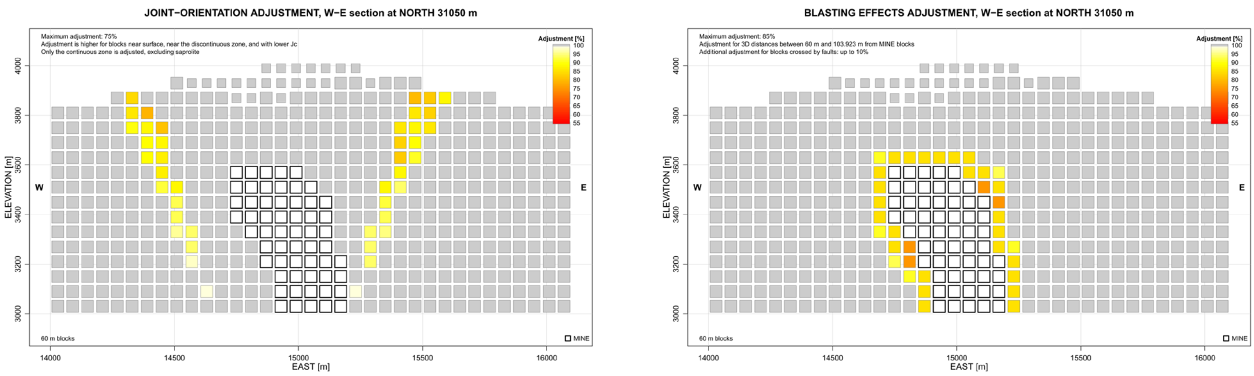
of Jc increases, or as the 3D distance to the discontinuous subsidence zone decreases. Joint orientation adjustments are shown in Figure 6a.

- Blasting adjustment: refers to the redistribution and adjustment of stresses in the rock mass due to blasting processes, which generate new fractures and widen existing ones. Although this effect can be mitigated by implementing good practices, some damage is expected to occur behind the rock walls (Laubscher & Jakubec 2001). In the proposed methodology, a maximum value is selected from the MRMR method tables and applied only to those blocks that share a face, an edge or a vertex with the mine design blocks, regardless of the zone in which they are located. An additional adjustment can be applied to already adjusted blocks that are crossed by faults in the block model as they can be more susceptible to blasting damage. Blasting adjustments are shown in Figure 6b.



(a) (b)

Figure 5 (a) Weathering adjustment to RMR_{90} in a west–east section of the synthetic block model; (b) Water adjustment to RMR_{90} in a west–east section of the synthetic block model

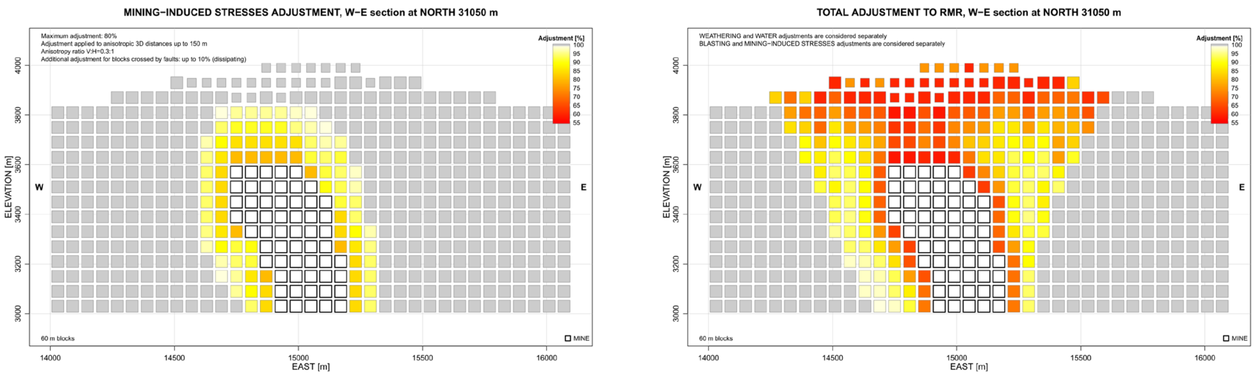


(a) (b)

Figure 6 (a) Joint orientation adjustment to RMR_{90} in a west–east section of the synthetic block model; (b) Blasting effects adjustment to RMR_{90} in a west–east section of the synthetic block model

- Mining-induced stresses adjustment: refers to the stress redistribution effect on the strength of the rock mass due to the geometry and orientation of the excavation. The magnitude, orientation and relationship of the regional stresses must be known in advance, either from direct measurements or from stress analysis and numerical modelling (Laubscher & Jakubec 2001). In the proposed methodology, a maximum adjustment value is selected and applied to the blocks near the mine design blocks regardless of the zone in which they are located. Anisotropic vertical stress ratio is considered to simulate stress concentrations due to geometric changes between mine levels, or directly in the undercut. The adjustment factor can be reduced in already adjusted blocks crossed by faults as fracturing can act as damping to mining-induced stresses. Mining-induced stresses adjustments are shown in Figure 7a.

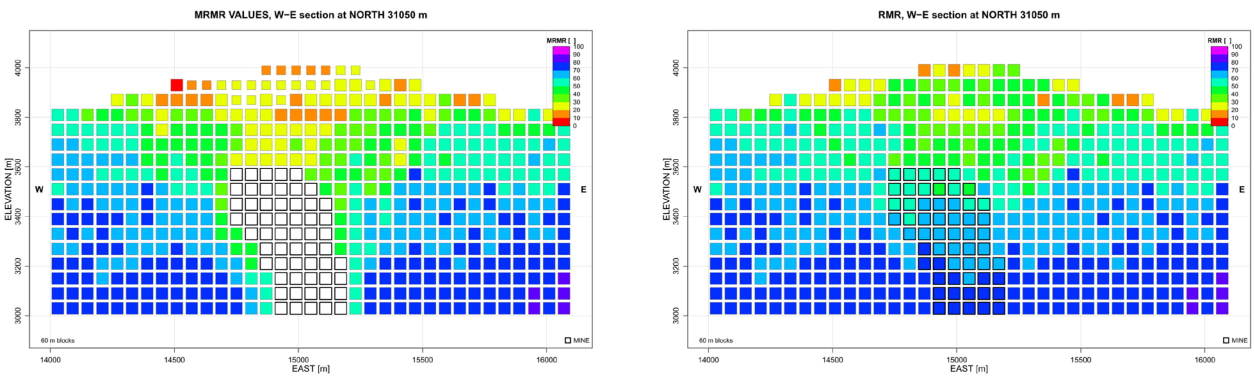
- Total adjustment: total reduction or adjustment to the RMR_{90} as a consequence of mining activities is calculated for each block in the domain as the product of the individual adjustments discussed previously. This approach is considered conservative from a geotechnical perspective, resulting in lower final MRMR values, and subsequently lower caving angles in Laubscher's empirical method. Other combinations of adjustments can be used according to specialist criteria, as it is unlikely that the total adjustment correspond directly to the product of the individual adjustments (Laubscher & Jakubec 2001) and that some of them can be considered together using only the lowest value (e.g. using the lowest value between water and weathering adjustments). Total adjustment is shown in Figure 7b, where it can be noted that blocks with the greatest adjustments are concentrated around the excavation because of blasting and stress concentrations, and also in the surface within the discontinuous subsidence zone as a consequence of weathering and water.



(a) (b)

Figure 7 (a) Mining-induced stresses adjustment to RMR_{90} in a west–east section of the synthetic block model; (b) Total adjustment to RMR_{90} in a west–east section of the synthetic block model

- Calculation of MRMR: once the magnitude of the total adjustment to the RMR_{90} has been determined, the MRMR in each block of the domain is estimated as the product of the RMR_{90} and the total adjustment. The MRMR values calculated for the application example are illustrated in Figure 8a. When comparing the calculated MRMR values with the original RMR_{90} values, shown in Figure 8b, a clear decrease in the strength of the rock mass is observed in the blocks located within the zones of continuous and discontinuous subsidence as a result of mining activities. Blocks representing the mine design are not adjusted as it is expected those blocks will disappear during mining and the estimated caving surfaces will not cross through them.



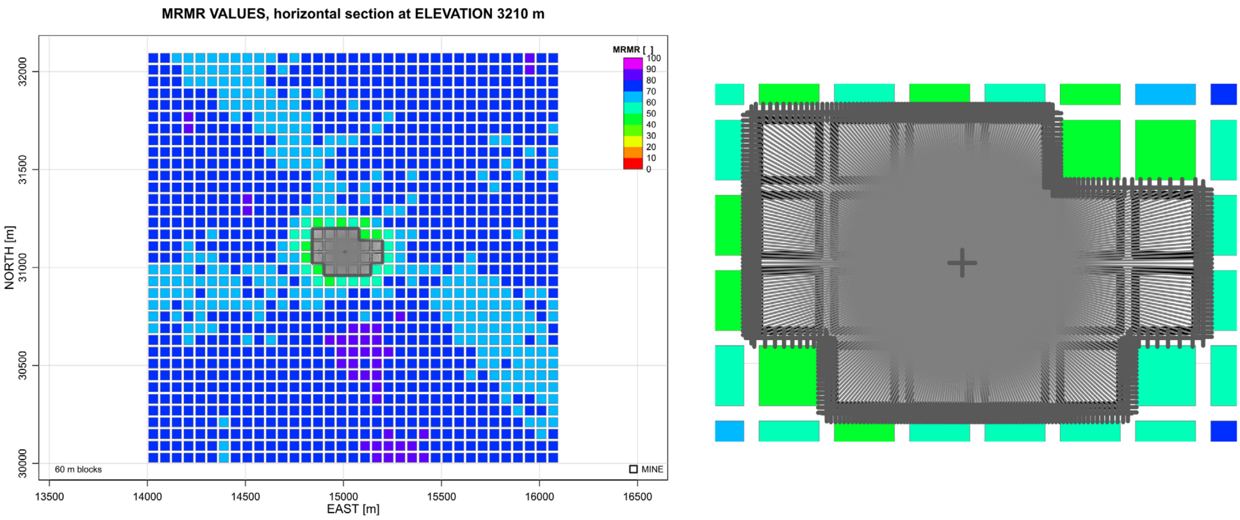
(a) (b)

Figure 8 (a) Calculated MRMR values in a west–east section of the synthetic block model; (b) Original RMR_{90} values in a west–east section of the synthetic block model

4.2 Estimation of caving profiles and caving surfaces

Based on the MRMR value calculated for all blocks in the domain, it is possible to estimate the caving angles, profiles and surfaces by applying Laubscher's empirical method using the software-based methodology proposed in this study. The main objective of the methodology is to extend the analysis of caving angles in all directions, capturing spatial differences in the quality of the rock mass, and representing the mine geometry effects caused by changes between different levels, which potentially generate 'steps' and 'shadow zones' as mentioned by Karzulovic et al. (1999). Additionally, by automating the estimation process, it is possible to analyse different final scenarios efficiently by making changes to parameters such as the swelling and dilution factors, and the magnitudes of the adjustments to the RMR_{90}, among others. The detailed application of the proposed methodology is discussed in this section.

As a starting point, each level of the mine is analysed individually. The east–north coordinates of the centroid of all mine design blocks at the specific level are determined, and from this point a set of 'rays' is extended, with azimuths ranging from 0° and 359° at 1° increments. The caving angle is calculated for each of those rays using the desired Laubscher chart by extending the ray from the centroid to the nearest adjacent block in that specific direction. The ray is then projected upwards to the next block, and the process is repeated until the ground surface is reached. Figure 9a shows a horizontal section of the block model at elevation 3,210 m, with its respective calculated MRMR values. The mine design blocks at that elevation are highlighted in black and their centroid and the 360 rays, along which the caving angles and profiles are estimated, are superimposed on them. Figure 9b shows a detail of the central area of Figure 9a, where the density of the profiles in which Laubscher's empirical chart is applied using the proposed methodology can be seen more clearly.



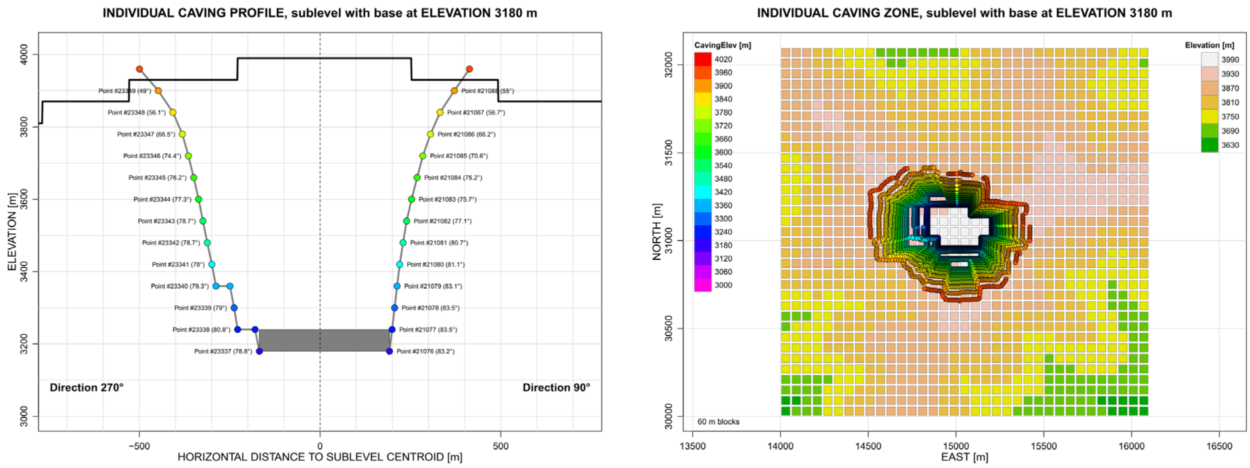
(a) (b)

Figure 9 (a) Horizontal section of the block model at elevation 3,210 m, with MRMR values and the rays used for the estimation of the caving angles; (b) Detail of the centre of Figure 9a showing the centroid of the mine design blocks and the rays

For each block intersected by a ray emerging from the centroid of the level, all the information necessary for calculating the caving angle using equation (1) and Laubscher's empirical charts is known: MRMR; density of the caved material (rho_b), which corresponds to the density of the rock column above the block under analysis; height of the caved material (z_b), which corresponds to the height of the rock column or the number of blocks above the analysed block; depth of the undercut (z_u), equal to the height of the rock column above the analysed level, which is constant for each level and trajectory; and minimum span of the undercut (b_u), which is calculated as the horizontal distance between the centroid of the level and the intersection of each ray with the first non-mined block, and is constant for each level and trajectory.

Each trajectory is traced starting from its origin, successively calculating the 3D coordinates of all points where it intersects a block in the model, along with the corresponding caving angle. When the trajectory intersects a mine design block at any point along its route, it is forced to advance horizontally at a caving angle of 0° until it reaches a non-mined block, from where the process of tracing the path to the surface continues. The process described previously is summarised in Figure 10a, where the calculated caving angles for the mine level with base level elevation 3,180 m are shown in a west–east section (azimuths 270° and 90°). Each of the points shown and numbered along the east trajectory (azimuth 90°) corresponds to the ray's pass from one block of the model to another, where the respective caving angle is calculated using Laubscher's conservative chart (Figure 2a) and the information of the blocks. For the ray in the west direction (azimuth 270°) direction, two horizontal sections with caving angles 0° are observed, at elevations of 3,240 m and 3,360 m, which correspond to the intersection of the trajectory with the upper levels of the mine, where the ray is forced to advance horizontally.

Figure 10b illustrates the topography of the block model and the associated cloud of 3D points cloud for the individual caving surface at the 3,180 m mine level. The caving zone shown in this figure contains a total of 5,200 points, distributed across 360 individual profiles. The level of detail achieved in estimating caving angles and profiles using the proposed methodology is clearly reflected in the density and shape of this cloud of points, which also reflect changes in the mine's geometry or steps between the different levels above the analysed level.

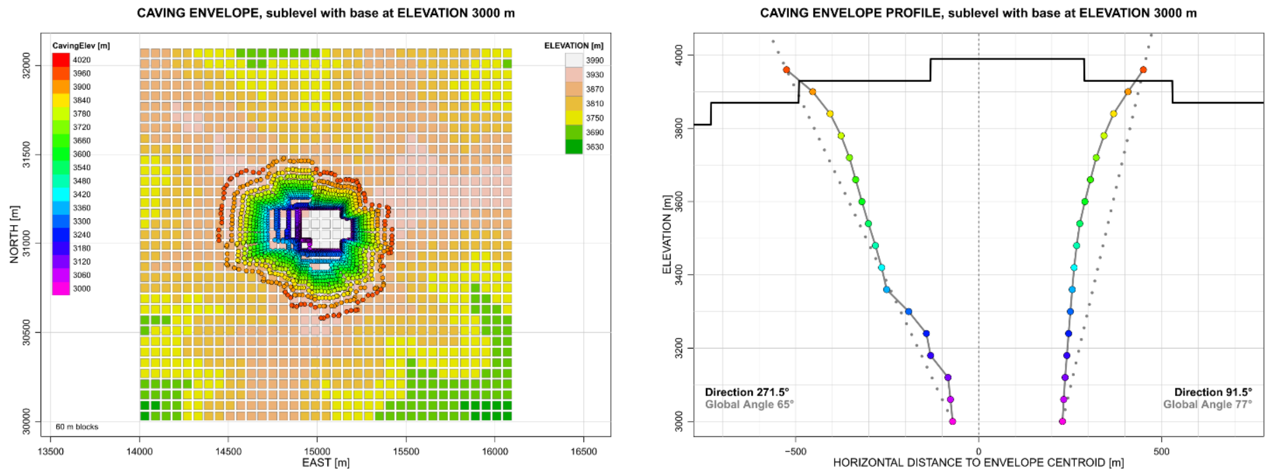


(a) (b)

Figure 10 (a) Individual caving profile in west–east direction for the level with base elevation at 3,180 m; (b) Individual caving zone for the level with base elevation at 3,180 m

The individual caving surface for each level does not represent the final caving surface area associated with the mine, since multiple 3D points associated with different individual surfaces may exist at the same elevation within the spatial domain. In the discussed example, the designed mine has 10 levels with base elevations ranging from 3,000 to 3,540 m. The superposition of the clouds of 3D points from the 10 individual caving surfaces means that at any elevation above 3,600 m, there will be 10 distinct families of points, which are not necessarily consistent with each other since they come from independent caving estimations. To determine the total caving surface of the mine and calculate the corresponding global caving angles in all directions, it is necessary to define a subsidence envelope. This process is performed for each elevation range of the block model, starting from the base of the mine. All 3D points obtained in each of the individual caving surfaces are combined into a single point cloud, and the coordinates of the point farthest from the centroid of the mine design blocks are determined at 3° azimuth intervals to ensure there are no gaps or directions without points on the final caving envelope.

Figure 11a shows the cloud of 3D points of the total caving envelope for the hypothetical mine analysed. This envelope contains 2,019 points, distributed across 120 individual profiles every 3° of azimuth, with elevations ranging from 3,000 m (mine base level) to 4,020 m (maximum elevation above the topography). The pattern of the cloud of 3D points shown in Figure 11a indicates that the subsidence envelope reflects changes in the mine's geometry between different levels. It is also observed that there is a marked asymmetry in the surface caving footprint, extending 680 m in the 28.5° direction and 1,040 m in the 124.5° direction. Figure 11b shows a west–east profile of the total subsidence envelope of the mine, highlighting the global angles (77° in the 91.5° direction and 65° in the 271.5° direction) and making evident the asymmetry present in the estimated caving envelope. This asymmetry is caused by changes in the mine's geometry between different levels, spatial differences in the geomechanical behaviour of the rock mass (MRMR), and the area's topography – variables that are represented in detail in the proposed methodology.



(a) (b)

Figure 11 (a) Total caving envelope for the synthetic mine; (b) Caving envelope profile in west–east direction

Once the total caving envelope of the mine has been estimated, it must be compared with the initial zoning of impacts to determine if the assumed angles for the continuous and discontinuous subsidence zones are valid or if they need to be adjusted and a new analysis must be performed. Figure 12 shows a west–east section of the initial zoning of impacts, in which the blocks located within the obtained caving envelope are highlighted in green. In total, there are 1,200 blocks inside the envelope, of which 1,193 were initially zoned as discontinuous subsidence or crater, 4 blocks were zoned as continuous subsidence and 3 blocks were zoned as unaffected. The very high percentage of blocks within the discontinuous subsidence or crater zones, and the comparison of Figure 12 with the theoretical deformation zones shown in Figure 1, suggest that it is not necessary to modify the angles initially assumed for the zoning of affected areas.

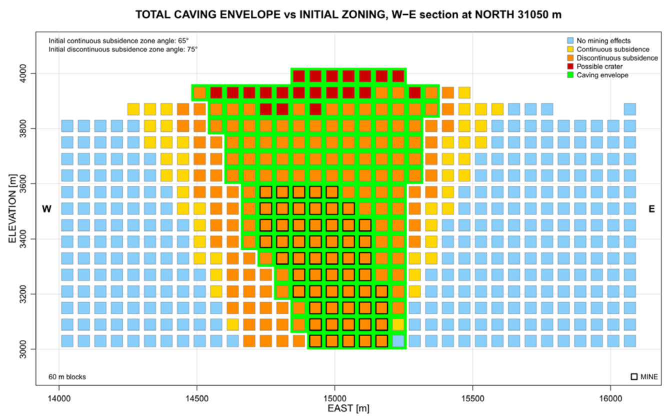
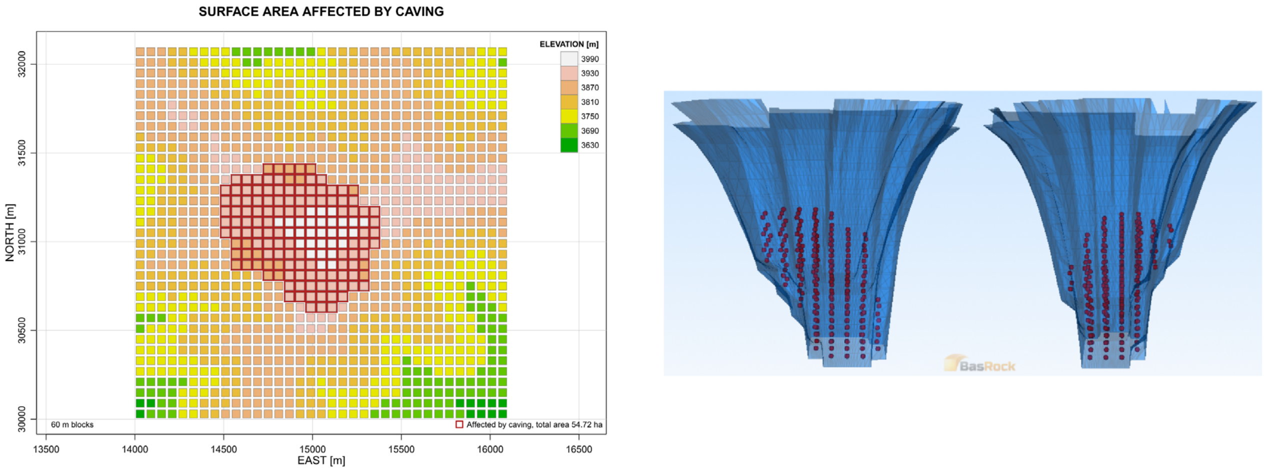


Figure 12 Caved zone represented in a west–east section of the synthetic block model

The identification of the blocks contained within the caving envelope allows the surface area affected by caving to be determined, as illustrated in Figure 13a. This type of information is important for siting of surface infrastructure and assessment of environmental impacts during the project's scope and pre-feasibility phases.

From the cloud of 3D points that defines the total caving envelope (Figure 11a), it is possible to generate a 3D wireframe compatible with most mining modelling software programs. Figure 13b shows the resulting wireframe and the centres of all the mine blocks, in two views from the south and west of the domain. This figure was generated using the GEM4D software (Basson 2026).

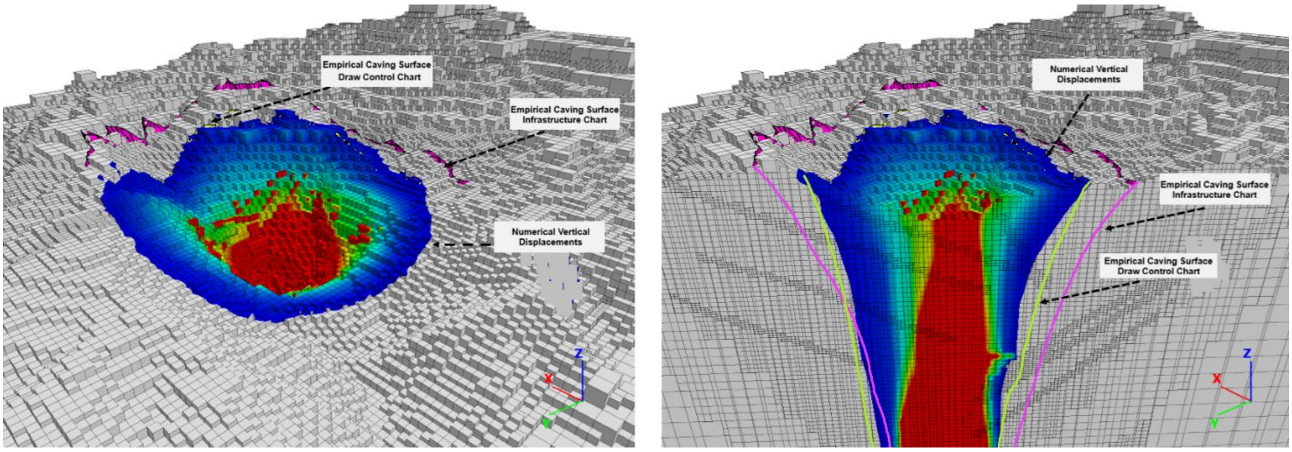


(a) (b)

Figure 13 (a) Area affected by caving; (b) 3D views from the south and the west of the total caving envelope and mine blocks

The methodology proposed in this study is automated using a script written in the R programming language (R Core Team 2024). The input data consist of the block model of the study area, which includes geological, structural, geotechnical and mining information as discussed in previous sections. The execution parameters include the initial angles for the continuous and discontinuous subsidence zones, the swelling and dilution factors, the density of each of the geotechnical units, and the maximum values and application conditions for each of the adjustments to the RMR_{90}. The final results include graphs of each variable and phase of the application of the methodology (such as those shown in Figures 3 through 13), wireframes of the caving surfaces for each level of the mine, and the original block model augmented with the information generated during the process (preliminary zoning of impacts, adjustments to the RMR_{90}, MRMR, and identification of the blocks contained within the subsidence zone). The automation of the methodology allows one to perform fast and efficient sensitivity analyses and evaluations of different design conditions, and to update the estimations and results as new information is acquired or existing information is refined (e.g. if a new structural model of the deposit is generated).

It is important to note that the methodology proposed in this study – the details of which are discussed using a synthetic dataset – has been applied to the evaluation of an actual sublevel caving project in Colombia, northwestern South America. Figure 14 shows a comparison between the empirical caving surfaces estimated using the proposed methodology and the results of numerical modelling of vertical displacements, in isometric view (Figure 14a) and in profile view (Figure 14b). Both empirical charts (infrastructure and draw control) were used to estimate the empirical caving surfaces shown in Figure 14. There is a very good agreement between the zone with meaningful numerical displacements and the draw control surface (green curve in Figure 14) estimated with the proposed methodology, both in shape and in extension. The more conservative caving surface (magenta curve in Figure 14) was used to analyse the location of critical infrastructure and to determine the affected area for environmental impact assessments of the project.



(a) (b)

Figure 14 Comparison between the empirical caving surface obtained with the proposed methodology and the results of numerical modelling for a real mine in Colombia. (a) Intersection of the surfaces with the topography; (b) Surfaces geometry on a vertical section

5 Conclusion

This study presents a methodological proposal to extend and automate the use of Laubscher's empirical method for estimating caving profiles and caving surfaces associated with underground mining operations. Using this methodology, it is possible to account for the effects of spatial variations in the geomechanical properties of the rock mass, the changes in the geometry of the excavation, and topography on the development of caving surfaces. The estimation of caving angles, caving profiles and caving envelopes using the proposed methodology constitutes a significant improvement over the traditional application of Laubscher's empirical method, which is generally performed only on a few vertical sections and assumes simplified conditions for the strength of the rock mass and the geometry of the excavation.

The application of the proposed methodology requires geological, structural, geotechnical and mining information spatially distributed throughout the analysis domain. The most efficient way to represent and process this information is through a block model, which must contain RMR_{90} values, predominant geotechnical units, blocks crossed by faults and blocks associated with the planned mining operation – variables that are generally well-known in pre-feasibility studies. This study uses a synthetic dataset generated for a hypothetical sublevel caving mine in a copper-gold porphyry deposit to discuss the general principles of the methodology and the results obtained when applying it. The proposed methodology can be used in the early stages of a mining project, when there is less information available, by generating a block model with some reasonable values for the required variables, considering that the block model is used mainly to identify the zones affected by the mining process, and to determine the caving angles in multiple vertical profiles.

The first phase of the methodology involves careful definition of the RMR_{90} adjustment factors required to calculate the MRMR, based on an initial zoning of affected areas. The preliminary identification of continuous and discontinuous subsidence zones, as well as the possible crater, allows precise definition of the location and magnitude of adjustments for weathering, water, joint orientation, blasting and mining-induced stresses associated with the planned mine, in accordance with the principles of the MRMR method and applying them with objective mining and engineering criteria.

Once the MRMR value is known for all the blocks in the domain, the caving angles are estimated for each level of the mine, using 360 individual profiles at 1° azimuth intervals. This is done by applying Laubscher's empirical charts to each block intersected along the entire caving profile, from the edge of the mine to the ground surface. Mine design blocks along the profile are accounted for by assuming a caving angle of 0° on them. The 3D points associated with each profile constitute the individual caving surfaces, and their superposition allows for the determination of the final caving envelope associated with the mine, in 120 profiles every 3° of azimuth.

The results obtained using the proposed methodology allow detailed and accurate initial assessment of the caving surfaces associated with an underground mine, which can be of great importance during the pre-feasibility phases of a project, particularly for the siting of critical infrastructure, as well as for determining the extent of areas affected by subsidence and for evaluating the environmental impacts generated by mining operations. The automatisation of the methodology allows one to perform fast sensitivity analyses and to efficiently evaluate different design scenarios, as well as to update the estimations and results as new information is acquired or existing information is refined.

The proposed methodology does not explicitly consider the effect of major structures and faults on the estimated total caving envelope; however, this effect is indirectly included because additional adjustments are made to the RMR_{90} in model blocks crossed by faults, resulting in lower MRMR values and lower caving angles according to Laubscher's empirical method. Further analysis can be made by manually cutting or extending the obtained caving surface when it crosses a major fault zone. The methodology also does not account for the effect of the planned mining sequence, since the analyses are performed for each individual level; however, a generalisation that includes this effect is feasible if the sequence is included in the input data.

Acknowledgement

The authors would like to thank Dr Jarek Jakubec and Dr Ivo Karzulovic for support and insights offered during several technical meetings and conversations. Their extensive experience in caving mining was instrumental during the conceptual development of this methodology. They would also like to thank their colleagues for their contributions during this study, as well as AngloGold Ashanti in Australia and Colombia and at CIG2 Ingenieros in Colombia for the opportunity and encouragement to present this work.

Use of artificial intelligence disclosure statement

In the preparation of this work, the authors used DeepL Translator v26.2.1 to improve the language and clarity of the manuscript by translating some sections from Spanish to English. The authors have reviewed the content and edited it where required and take full responsibility for said content.

References

Basson, F 2026, *GEM4D*, computer software, https://www.basrock.net

Brown, ET 2002, *Block Caving Geomechanics*, Julius Kruttschnitt Mineral Research Centre, Indooroopilly.

Contreras, C, Elmo, D, Jakubec, J & Thomas, A 2022, 'Reviewing Laubscher's empirical method to estimate subsidence limits', in Y Potvin (ed.), *Caving 2022: Proceedings of the Fifth International Conference on Block and Sublevel Caving*, Australian Centre for Geomechanics, Perth, pp. 805–818, https://doi.org/10.36487/ACG_repo/2205_55

Ding, H, Chen, S, Chang, S, Li, G & Zhou, L 2020, 'Prediction of surface subsidence extension due to underground caving: a case study of Hemushan iron mine in China', *Mathematical Problems in Engineering*, vol. 2020, https://doi.org/10.1155/2020/5086049

Egaña, M & Ortiz, JM 2013, 'Assessment of RMR and its uncertainty by using geostatistical simulation in a mining project', *Journal of GeoEngineering*, vol. 8, no. 3, pp. 83–90.

Eivazy, H, Esmaieli, K & Jean, R 2017, 'Modelling geomechanical heterogeneity of rock masses using direct and indirect geostatistical conditional simulation methods', *Rock Mechanics and Rock Engineering*, vol. 50, pp. 3175–3195, https://doi.org/10.1007/s00603-017-1293-0

Jakubec, J & Laubscher, DH 2000, 'The MRMR rock mass classification system in mining practice', *MassMin 2000*, The Australasian Institute of Mining and Metallurgy, Melbourne.

Karzulovic, A, Caviedes, P & Pardo, C 1999, 'Subsidencia por efecto del caving mina El Teniente' (Subsidence due to the effect of caving at the El Teniente mine), *Proceedings of SIMIN 1999*, pp. 9–14.

Laubscher, DH 1990, 'A geomechanics classification system for the rating of rock mass in mine design', *Journal of the South African Institute of Mining and Metallurgy*, vol. 90, no. 10, pp. 257–273.

Laubscher, DH 2000, 'Block caving manual', *International Caving Study*, Julius Kruttschnitt Mineral Research Centre and Itasca Consulting Group, Inc.

Laubscher, DH & Jakubec, J 2001, 'The MRMR rock mass classification for jointed rock masses', in WA Hustrulid & RL Bullock (eds), *Underground Mining Methods*, Society for Mining, Metallurgy and Exploration, Littleton, pp. 475–481.

R Core Team 2024, *R: A Language and Environment for Statistical Computing*, computer software, R Foundation for Statistical Computing, Vienna, https://www.R-project.org/

Sillitoe, RH 2010, 'Porphyry copper systems', *Economic Geology*, vol. 105, no. 1, pp. 3–41, https://doi.org/10.2113/gsecongeo.105.1.3

Woo, KS, Eberhardt, E, Elmo, D & Stead, D 2013, 'Empirical investigation and characterization of surface subsidence related to block cave mining', *International Journal of Rock Mechanics and Mining Sciences*, vol. 61, pp. 31–42, https://doi.org/10.1016/j.ijrmms.2013.01.015