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Development of an unsophisticated numerical simulation model for caving systems

E Folgoso Lozano *Montanuniversitaet Leoben, Austria*

M Nöger *Montanuniversitaet Leoben, Austria*

T Ladinig *Montanuniversitaet Leoben, Austria*

H Wagner *Montanuniversitaet Leoben, Austria*

Abstract

The main objective of this publication is the description of an unsophisticated methodology to predict caving and cave propagation for mining purposes based on numerical simulations. The aim of the methodology is to create a user-friendly tool which requires little effort to set up and analyse and which facilitates understanding of cave propagation for practical applications.

The methodology is defined as an algorithm which is performed in FLAC3D, version 7.0 (Itasca 2019). The constitutive modelling is based on model elastic behaviour, due to its simplicity and low running times. The algorithm utilises a series of routines that describe and quantify the failure process of rock during caving.

The emphasis of the methodology is on simplicity, which is reached by implementing reasonable assumptions regarding the caving situation and the rock mass behaviour. The caving propagation is driven by plastic behaviour; however, to simplify the model the caving algorithm is based on an elastic behaviour and specific functions mimicking the plastic behaviour, namely the degradation processes occurring in the rock mass during caving are accounted for by reducing the mechanical properties of the rock mass and the stress state in degraded zones in a controlled and systematic manner. Sensitivity tests are performed to analyse the weight of the mechanical parameters involved in the caving processes, as well as to optimise the reduction rate of the mechanical properties of the rock mass.

The calibration of the caving algorithm is the current stage of the development. The calibration is carried out by analysing the results obtained in the numerical models and the outcome of the semi-empirical methods available in the literature.

The unsophisticated caving predicting tool is being developed for its application on the novel raise caving mining method (Ladinig et al. 2022). The caving tool will supply understanding regarding the caving initiation and propagation for the novel raise caving method.

Keywords: *caving, numerical simulation, cave propagation, prediction, algorithm*

1 Introduction

Over the years, mass mining methods have been successfully employed on underground mining projects. Cave mining methods are described as safe, highly productive and efficient extraction methods, especially when automation is possible. These methods allow low-grade deposits to be safely and profitably exploited. The constant research and development of this field (Brown & Chitombo 2007; Brown 2007; Laubscher 2000) has been reducing the risks related to caving operations, and this trend is suspected to continue, thus the risks and hazards will be reduced further. A critical issue for all cave mining systems is the caving process itself and in particular the prediction of the nature of the caving process. Numerical simulations conducted for caving purposes require high computational effort and long running times, as well as a comprehensive list of parameters, which might not be available in many instances.

The current caving predicting tool aims to provide prognosis of caving and cave propagation based on simple assumptions. It is based on the knowledge gained over the past decades. The numerical simulations are performed in finite difference type of software, which benefit from the less complex situations based on these assumptions and simplifications. Due to its simplicity, fewer input parameters are required and the computational times are drastically reduced, compared to those reported in the literature, especially those based on discrete element models.

2 State-of-the-art

Regarding the reduction of the hazards and other issues, for instance the dilution, it is crucial to understand and measure the caveability as well as to predict the behaviour of the deposit and the host rock masses, in order to define the type of caving process that is going to develop once the mining activity starts. In the literature, researches that cope this topic can be easily found: Sainsbury (2012) and Mawdesley (2002), among others. However, some of these investigations performed complex simulations using various software, even hybrid models in which two different software are used. There are also semi-empirical methods (e.g. Laubscher 1994; Mathews et al. 1981; Mawdesley 2002) that cover the stability issues in underground openings including continuous caving.

2.1 Timeline

Stability of the rock mass has been studied for decades for different situations and extracting methods. There are available empirical methods and design guidelines for stopes. Among the numerous methodologies that handled with rock mass instability in underground excavations, Laubscher (1994) and Mathews et al. (1981) respective stability charts are widely employed in cave mining. Both of them are based on a list of study cases out of which the relation between the rock mass quality against the hydraulic radii of the excavations is displayed. Additionally, in both, there are three zones in which the stable, major failure or transition zone and caving zone of the rock mass are described. The major difference between these two methods is the rock mass quality system utilised. Mathews described N' stability number (Potvin 1988), which is based on Barton's Q' system (Barton 1988) with some additional adjustment parameters (A, B and C). Laubscher founded the stability chart on the MRMR rock mass rating which relates as well the hydraulic radii or shape factors in a similar manner as Mathews stability graph. The research on the specific area of caving and its prognosis has been developed for long time and the contributions remarked in this publication are displayed in Figure 1.

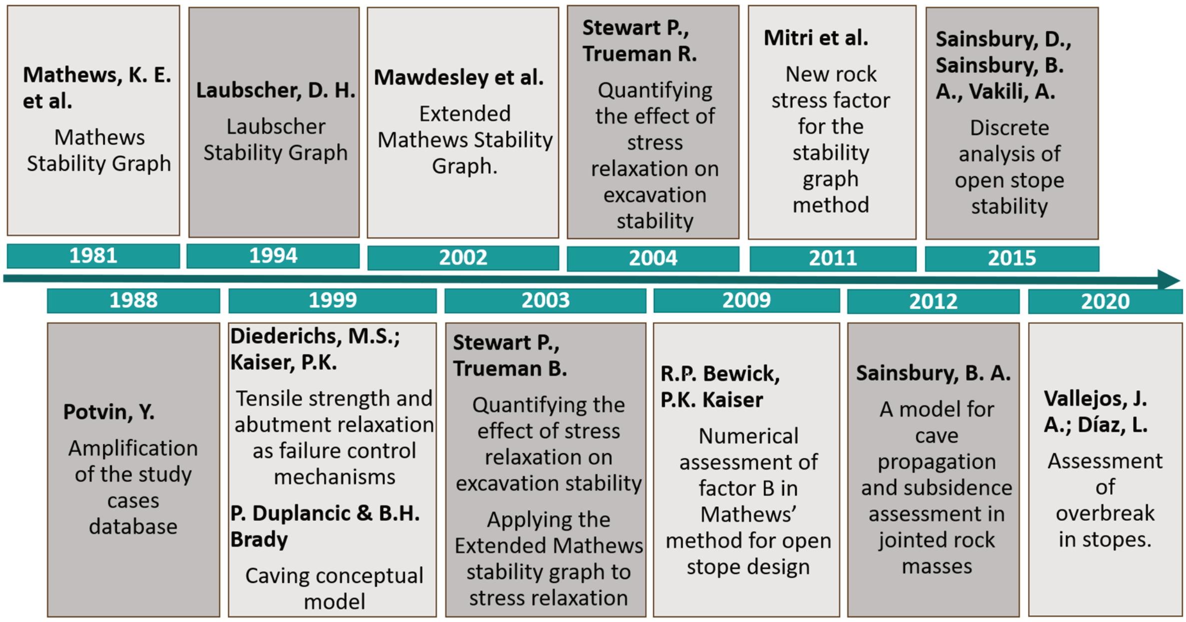

Figure 1 Timeline of the publications and advances discussed

2.2 Semi-empirical methods

Mathews stability graph (Mathews et al. 1981) is employed in underground mining, especially in Canadian mines, for the open stope stability assessment, mainly for determination of the maximum spans for the openings in the early stages of the mine design. Later on, Potvin (1988) made a review on the method by adding new study cases and proposed new adjustment factor to the N stability number (rock mass classification system employed at the Mathews stability graph). Nickson (1992) additionally introduced more cases to tackle cable bolt support in hard rock underground excavations. Diederichs & Kaiser (1999) determined that the factor A required and adjustment for those cases under low confinement situations, in Voussoir beam type of roof, which includes tensile stress environments. The factor A was modified to cope with low confinement stress situations. This methodology was not developed specifically for caving mining methods; however, Mawdesley (2002) introduced an extended version which copes with caving initiation to be implemented in caving mining methods.

Laubscher (1994) published the widely known stability graph and is extensively used for assessing the cave propagation. The graph is based on a collection of real caving cases out of which three states were defined. The first area corresponds to the 'No caving' situation, also named 'Stable'. There is a transitional area, called 'Transition' where the failure of the rock mass is claimed to increase as it reaches the caving line. The final area, is 'Caving', in which the open stope has reached a dimension that is supposed sufficient to develop blocky fragments that will detach and caving propagation occurs on its own. In order to use the stability graph, it is required to calculate some factors regarding the shape of the opening (hydraulic radius) and the rock mass properties (MRMR). This stability graph resembles the Mathews stability graph (Mathews et al. 1981), however, the rock mass classification system employed, N' stability number, is distinctive.

Mitri et al. (2011) determined that, based on their experiences, a relaxed stress environment in the surroundings of an excavation may lead to instability, especially in narrow stopes. Low confinement stress state at both the hangingwall and the footwall might trigger overbreaks and therefore, higher rates of dilution. Their proposal defined a new rock stress factor A for the N' stability number, for the central area of the opening face, based on the maximum stress factor (MSF), which is the relation between the maximum major principal stress and the UCS of the rock. Based on the results of a simulation ran in FLAC3D, which compared to the A factor after Potvin, it could be concluded that the factor proposed by Mitri et al. (2011) provides a better fitted with the field observations. It was also concluded, that the curves defined after Potvin (1988) to determine the stability of the excavation should not be modified based on this new A factor.

Opposite to the formulas and methodologies explained, Stewart & Trueman (2003a) discussed the factor A and the recommendations provided in the Mathews Extended stability graph (Mawdesley 2002). However, after Stewart & Trueman (2003a) it was determined that A factor equal to 0.7 provides better results in both full relaxation and tangential relaxation. The results were compared to other methodologies, such as the one after Diederichs & Kaiser (1999). In the Extended Mathews Stability Graph (Mawdesley 2002) was established that A factor must be set accordingly with the methodology proposed after Mathews, in which the A factor is the ratio between the UCS value and the induced stress on the excavation.

Bewick & Kaiser (2009) proposed a variation of the B factor of the Mathews N' stability number, after numerical simulations in a finite element software, based on a plain strain behaviour. The following formula defines the calculation procedure for the proposed B factor. In the specific case of the hangingwall situation, it was concluded that the angles between the joints and the hangingwall face from 0 (joints parallel to the hangingwall face) to 45 degrees do not match with the ones proposed after Potvin. However, from 45 up to 90 degrees, the new proposal fit the method. Therefore, the conclusion was that the low confinement drives the B-curve shape for 45 degrees and over. Orientations from 40 to 60 degrees (from the excavation face) were defined as potentially more dilution-causing. On the opposite side, low angles might suggest different triggering factors, such as blasting or stress, as Potvin (1988) claimed. Bewick & Kaiser (2009) identified the joint rock mass strength as the main factor for controlling the B factor curve for a given hangingwall.

Vallejos & Díaz (2020) presented a numerical modelling concept for hangingwall overbreak in which the traditional semi-empirical tools and the reviews supplied by several authors were discussed. One of the targets of the study addresses the stope stability regarding the low stress state. There are some criteria which involve low values of principal stresses: sig3 ≤ 0.2 MPa, sig3 = 0 or sig3 = tensile strength of the rock mass. In this publication the conclusions after Stewart & Trueman (2003a; 2003b) are discussed, which suggest that the excavation relaxation should be studied in the 3D space, since the intermediate principal stress must be considered.

2.3 Numerical methods

Besides the enhancement of the accuracy of semi-empirical methods, there are reported numerical methods which aim to reproduce caving and its mechanisms. Most of these methods rely on finite element software (FEM) or on the opposite side, discrete element modelling software (DEM), the latter being more computational demanding and time consuming.

Sainsbury et al. (2015) published a numerical methodology, based on 3D discrete element simulations in order to solve potential inaccuracies due to the employment of semi-empirical methods, especially for particular geology set-ups. The methodology was developed for narrow vein mining for increasing the accuracy of the design results. It was suggested to employ it from the early to the late stages of the development of the stope. The main issue of this methodology is the amount of rock mass data required as input parameters, which prohibits its use during early design stages. Additionally, this type of simulations is high computational demanding and requires long running times to produce results.

There are investigations about the caving processes and the caving propagation, for instance, using strain softening ubiquitous joint modelling (Sainsbury 2012). In this, by applying softening processes in the material as well as the drawing sequences, the model was able to measure the caving propagation and the mobilisation of the bulk material, for those most relevant underground mass mining methods: block, sublevel and panel caving. Since the models were large-scale ones, and the constitutive model so elaborated and complex, once again the running times must have been rather long. Therefore, the accuracy and predictability may be improved, indeed certainty about input parameters is critical for result accuracy. However, the running times required prohibit its systematic and regularly employment during operations. Additionally, this methodology employed synthetic rock mass model (SRM) to define the rock mass, in order to resolve the inaccuracy of the empirical methods to consider the scale factor and assess the rock mass properties: geotechnical strength index (GSI) and rock mass rating (RMR) among others. Although the technique is valid, the computational constrains as well as long computing times seem to be still an issue to be sorted out.

Itasca developed their own 3D numerical simulation for caving purposes, which included propagation and subsidence due to the caving (Hebert & Sharrock 2018). CAVESIM was defined as a cellular-automata, which operates based on CaveHoek constitutive model, implemented in FLAC3D. This methodology and software to predict caving and the consequences of the caving processes, as described in caving conceptual model (Duplancic & Brady 1999) in a highly sophisticated manner.

Generally, those complex simulations are single study cases difficult to extrapolate to other orebodies or situations. Defining such an intricated model requires large amounts of data and parameters, that may not be available or that are not measured on a regular basis, especially in greater depths where data collection is often quite limited at a design stage. Provided the model is created and all the parameters are known, the complexity of the model itself would lead to long simulation times, measured in weeks or even months. The understanding of the outcome of those sophisticated simulations imply also study time, for instance, to point out the determining input factor that cause one or the other effect on the model. All in all, a minimal change required in such an intricate model would shatter all the previous work.

3 Unsophisticated simulation method

The unsophisticated simulation method is be based on a three-dimensional continuum numerical model in FLAC3D software (Itasca Consulting Group, Inc. 2019). The constitutive modelling is at this stage based on the linear elastic model. Such a linear elastic model has been utilised in simulations regarding dilution prediction in stoping operations; compare Vallejos & Díaz (2020). These dilution mechanisms in stoping and caving have in common that rock mass detaches from stope walls. Hence, foregoing study on stoping operations indicates that linear elastic models may be suitable for modelling of unravelling processes. The code of the unsophisticated caving predicting tool is based on a series of routines that evaluate the behaviour of the rock mass under failure, Hoek–Brown failure criterion (Hoek & Brown 2019) and potentially others in further stages, such as the displacement criteria, in order to determine the caving process during the mining sequence of operations.

One of the main objectives of the methodology is simplicity, which is achieved by implementing assumptions regarding the caving situation and the rock mass in general. The behaviour of a volume of rock mass is remarkably difficult to describe due to the many features involved at the time. A realistic rock mass becomes highly difficult to be reproduced in numerical models and requires large amounts of time to get results. Therefore, in order to reduce the complexity of the rock mass and decrease along the running times, the rock mass is described in a simplistic manner. As a direct result of the rock mass simplification, the input data required for the simulations is also reduced. Similarly, the caving processes are simplified, by means of using well-known failure mechanisms, which determine the softening of the rock mass undergoing caving.

The unsophisticated simulation method aims is the description of the caving process resembling what happens in reality in a simplified manner. Therefore, the outcome becomes easier to assess and understand, including the study of the key parameters involved during the caving processes and the softening of the rock mass. Caving is described as in Duplancic's caving conceptual model Duplancic & Brady (1999). Additionally, the methodology relies on Hoek & Brown (1980, 2019) to identify damage on the rock mass. It was developed for the design of excavations in rock mass, due to the incorporation of the rock mass classification system GSI. It is reported as a well-known and widely applied criterion. As it has been already mentioned, this is the criterion employed in the proposed methodology to define if an area of the model is failed under the given stress state and rock and rock mass properties.

3.1 Duplancic's model

The numerical model allows the user to show how the propagation of the caving occurs, regarding the different areas involved in the process. Those areas were defined by Duplanic & Brady (1999), which include the caved material, the bulk material released from the rock mass, the airgap between the caved material and the cave back as well as the loosening and seismic zones where the fracturing spreads upwards into the rock mass; compare Figure 2. The developed methodology aims on representing these different zones appropriately.

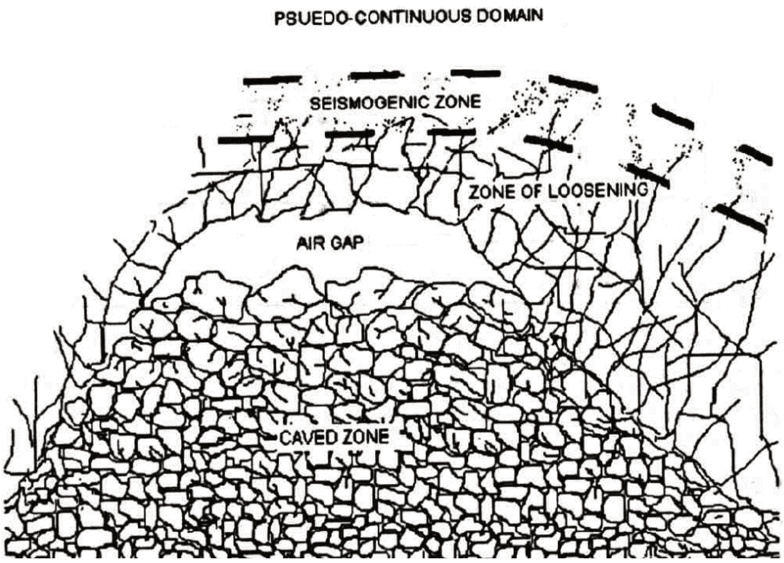

Figure 2 Duplancic and Brady's caving conceptual model (Duplancic & Brady 1999)

Duplancic and Brady's caving model describes the following zones in their conceptual model:

1. The elastic region is defined as the host rock, which shows an elastic deformation and its properties are mainly the undisturbed ones.
2. The seismogenic zone represents the seismically active region, mainly due to the rearrangement of the stresses in this area due to the excavation of the undercut. The rearranging stresses may trigger the joints placed in this zone and make them slip. Additionally, new fractures may open.
3. The yielded zone or loosening zone represents the area with discontinuous deformation. The rock mass contain within this zone no longer provides support to the rock mass right above and the rock mass is under a low stress environment. There are large displacements and the fracturing is visible.
4. An airgap is formed between the mobilised or caved material and the loosening zone, which actually represents the cave back.
5. The mobilised zone represents the rock blocks that have fallen down from the loosening zone. The detachment occurs mainly due to the lack of confinement and the loss of cohesion of the rock mass during the loosening process.

The proposed model reproduces the main parts of the conceptual caving model. However, seismogenic and loosening parts are defined as a single zone, the damaged region, in which the properties of the initial rock mass are reduced. The reduction of the properties occurs in a cycle-wise manner. The description of the cycle is illustrated in Figure 3.

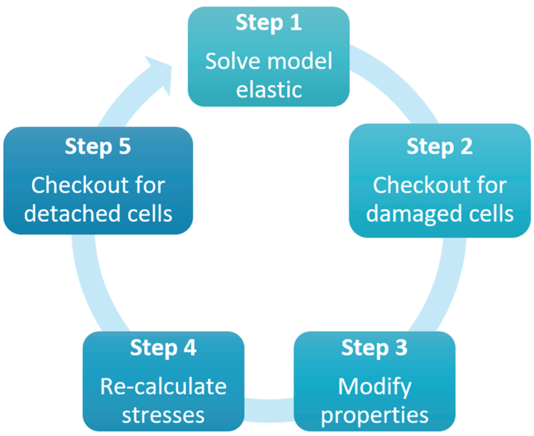

Figure 3 Scheme of the unsophisticated simulation method for the proposed methodology

Therefore, the model describes the hanging wall and the footwall, which delimit the orebody. Since the parts involving the ore and the nearby hangingwall and footwall are the most important ones, in terms of describing the behaviour of the caving process and propagation, they are defined in a finer grid to enhance the accuracy of the results. The rock mass and the undercut are defined and the rock and rock mass properties are introduced as the required input. The undercut is extracted and from this point onwards, the caving cycle is initiated, which contains five steps.

Step 1: Solving to the equilibrium. The model is solved in elastic behaviour, as it has been proved satisfactory for caving purposes.

Step 2: Checking out damaged areas. The model is assessed under the Hoek–Brown criterion (2019). If the zone has failed under the criterion, it will be considered 'damaged' and in the following steps it will undergo some modifications.

Step 3: Modification of properties. Any area considered 'damaged' is weaken by reducing its rock mass rating, GSI. Consequently, the rock mass mechanical properties such as the elasticity modulus and the rock mass are recalculated based on the reduced GSI value after the relation of Hoek & Diederichs (2006) and Hoek & Brown (2019). Figure 4 provides an illustrative example for the modification of the rock mass strength in step 3.

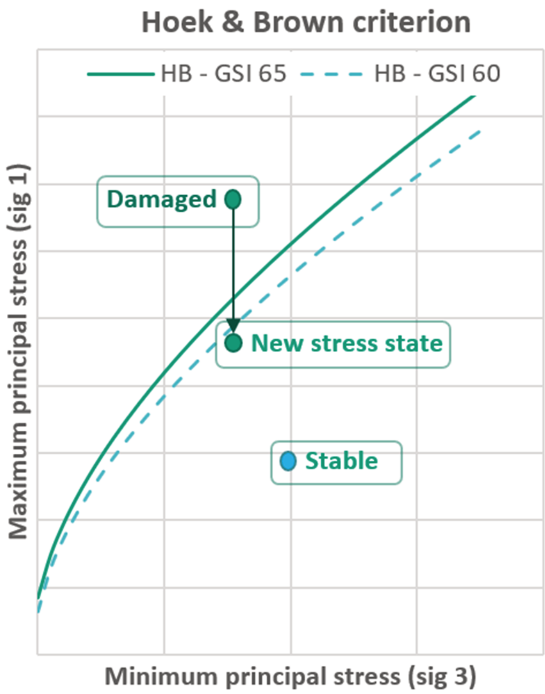

Figure 4 Hoek–Brown criterion. Simple example for the description of the stress re-calculation of the unsophisticated simulation method in steps 3 and 4

Step 4: New stress state. Based on the reduction of the properties and the failure under the stress criterion, the stress state of the damaged zone is reduced accordingly. The new GSI value along with the reduced properties build-up a new Hoek & Brown (2019) envelop which defines the new stress state for the damaged zone. Provided the maximum principal stress (sig 1) exceeds the initial envelop, the new maximum principal stress is placed on the new Hoek–Brown envelop, with the same minimum principal stress (sig 3); see Figure 4.

Step 5: Detachment process. Due to the rearrangement of the stresses around the excavation, there might be a reduction of confinement that allow certain zones to fall. The stresses to be assessed are the tangential stresses. Additionally, there are geometrical constrains that shall be fulfilled in order for a zone to detach from the host rock mass. Basically, the geometrical constrains refer to the presence of a free face that allows the damaged zone in the low confinement environment to fall freely.

Steps 3 and 4 determine the softening process of the rock mass based on the description of the Duplancic's conceptual model (Duplanic & Brady 1999). Step 5 defines the detachment from the loosening zone towards the caved zone described in the conceptual model. After Step 5 the cycle is complete. However, the cycle must be run several times in order to develop the softening of the material. Initially, the first simulations were run 50 times to observe and evaluate the damage occurred in the host rock. Therefore, the continuous caving propagation can be assessed. Additionally, every section of the undercut can be studied independently, to determine whether and when the caving starts provided a certain hydraulic radius.

4 Calibration and sensitivity tests

The objective of the calibration of the caving algorithm is assessing its validity to represent caving environments and the propagation of the caving process through the rock mass. In addition, the calibration and the sensitivity tests conducted provide knowledge to understand properly the behaviour of the whole model and verify its applicability. For this reason, the first simulation models consider flat horizontal undercuts, and after the validation of those, more complex layouts are to be assessed, including inclined openings and more complex geology set-ups. Regarding the geology units, the first models to be evaluated and calibrated, employ only one type of material. Using a single material allows a more straightforward understanding due to the reduction of unknowns on the system, such as the interactions that may occur between two different geological units. However, this simple model improves the understanding of the system and the development of the unsophisticated simulation method, regarding the establishment of the relations among the different parameters a setting a solid ground for further development.

The calibration is carried out by comparing the results to the already mentioned Mathews Extended stability graph (Mawdesley 2002). The Mathews Extended stability graph targets the caving progression on the rock mass given a hydraulic radius the so-called shape factor ‘S’. In this case, the graph requires the calculation of the ‘N number’, which is based on Barton’s Q’, data regarding the stress situation, the orientation of the joint sets of the rock mass fabric and the action of the gravity on the face (factors A, B and C). Shape factor ‘S’, which is also known as hydraulic radius (HR), refers to the dimensions of the surface likely to cave, in this case, the roof of the undercut. HR is the ratio area of the roof divided the perimeter of the roof. There is a ‘Stable’ zone where the stopes were stable or showed little deterioration over time. The ‘failure or major failure’ zone contains the cases in which the deterioration of the stope shape was greater than in the stable zone, but there was no self-propagating caving. Finally, the ‘Caving’ zone contains the cases in which the stopes were unstable and continuous caving occurred; see Figure 5.

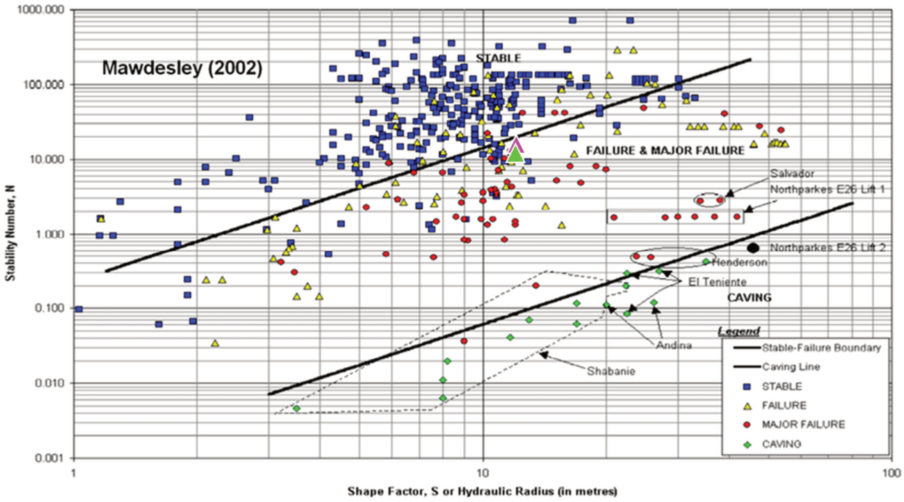

Figure 5 Mathews Extended stability (Mawdesley 2002). Pink triangle: location of the deep excavation case. Green triangle: location of the shallow excavation case

The sensitivity tests are performed for the analysis of the parameters involved in the caving tool’s softening process. This includes all the mechanical properties of the rock mass and the rock mass classification system employed, the GSI. As it was described in the previous section, the GSI is reduced as the damage propagates in the rock mass over the cycles of the caving predicting tool. The GSI is reduced by a reducing factor, so-called GSI reduction factor. The GSI reduction factor refers to the number of GSI units that are reduced every time the rock mass is softened. It is required to understand the weight of the GSI reduction factor and establish the most adequate rate of GSI decrease. Thus, sensitivity tests are conducted for this purpose. The grid size of the model is also a key point to consider during the sensitivity tests. It has been mentioned that the finer the grid, the more accurate the results obtained. However, as the grid gets finer, the higher the computational demand and the longer the running times. Therefore, one target of the sensitivity tests is the assessment of the most appropriate grid size, finding a balance between accuracy and solution time.

At the current stage, the aim is to gain knowledge and understanding of the model in order to verify the unsophisticated simulation method, prior to practical application for mine layout development. Therefore, simplified models with regular excavations are performed, which are square, flat and horizontal. Ultimately, the initial batch of simulations are to be calibrated by means of the Mathews Extended stability graph (Mawdesley 2002).

The ultimate target of introduced the unsophisticated caving predicting tool is its practical application on underground mass mining layouts to assess their behaviour regarding caving and the caving propagation as well as for decision making on their layouts. For instance, the caving predicting tool is to be applied on the raise caving method development.

4.1 Validation studies

Two sets of simulations have been performed, based on different stress states, i.e. deep and shallow location of the excavation. Both these models share the rock and rock mass properties as well as the same geometry. The data of the simulations is displayed in Table 1.

Table 1 Rock and rock mass input parameters for the simulations conducted

Density (kg/m^3)	Poisson ratio	Young's modulus (GPa)	GSI (initial value)	UCS (MPa)	m_i
2,700	0.25	50	75	150	18

Barton's Q' was obtained based on the relation of the GSI to the RMR, GSI = RMR – 5 for RMR >=23 (Hoek et al. 2006), and later, the RMR was transformed into Q' based on Bieniawski (1976). A, B and C adjustment factors (Table 2) were calculated employing the original methods after Mathews et al. (1981), which are the ones employed as well in the Mawdesley's Extended Stability Graph (Mawdesley 2002).

Table 2 Parameters for the Extended Mathews Stability Graph (Mawdesley 2002)

Type	Q'	A	B	C	N'	HR
Shallow	31.33	0.7	0.5	1	10.96	12.5 (50 m × 50 m)
Deep	31.33	1	0.5	1	15.66	12.5 (50 m × 50 m)

The caved rock mass, which would be located in the cave, is not modelled. The reason for this is to avoid modelling of the draw sequence. As material from the sides cannot cave, this simplification does not have a significant influence on the outcome. The location of both cases is displayed on the Extended Mathews Stability Graph (Figure 5).

4.1.1 Validation study 1: deep excavation – highly stressed environment

The model representing the deep location of the excavation was modelled with a vertical stress of 25 MPa and horizontal ones (in both horizontal directions) of 35 MPa. The aim of these initial batch of simulations is the definition of the dependencies between the cell sizes and the GSI reduction factor over 50 cycles of the caving algorithm. The rock mass quality of the model can be reduced down to a GSI of 25. The detachment of a cell occurs when the confinement stress falls below 0.5 MPa in compression and the cell has a free surface below it. Since the cells are horizontally oriented cubes, the free surface is set to the bottom face. The undercut has a size of 50 m × 50 m, which gives a shape factor of 12.5.

Figure 6 shows the outcome of the different simulations based on this model. The results displayed show a crosscut of the model at the centre of the excavation in which the maximum principal stresses are shown. The plots belong to the situations after cycle number 10, 30 and 50. On the left side of the figure, the coarse grid (2.5 m sided cells) with the different GSI reduction factors are shown. The GSI reduction factors refer to GSI units reduced from the rock mass quality, every time the rock mass is softened are shown (for this specific case 1, 2 and 5 GSI units are considered). It can be noticed that the three simulations display generally the same outcome, independently of the reduction factor employed. Although the outcome of the GSI reduction factor 5 provided larger detachment volume and a higher cave backs, the difference between the simulations is not large. The slight differences between the three simulations is directly related to the rapidness of the relaxation based on the softening of the rock mass, namely the GSI reduction factor.

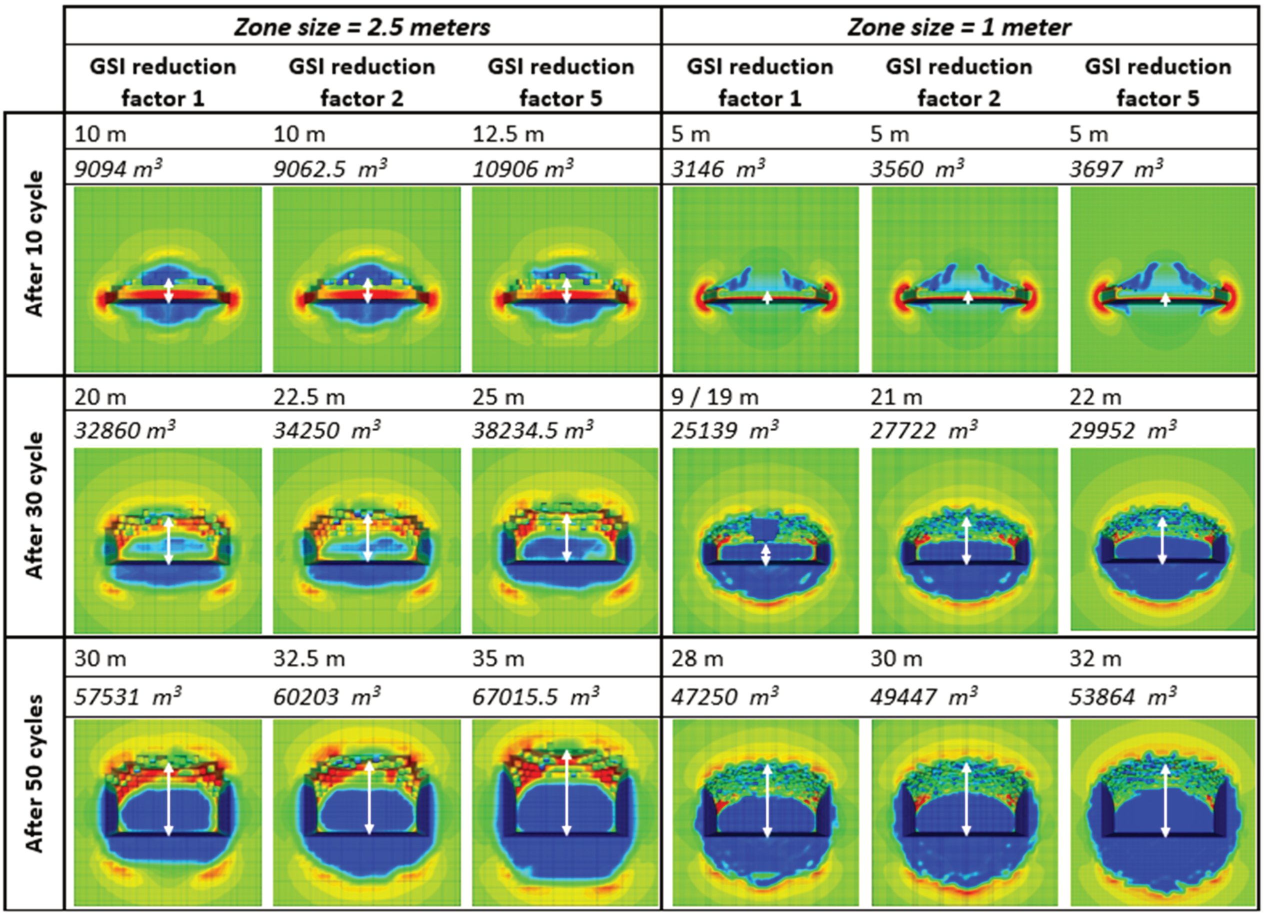

Figure 6 Results of the first batch of simulations for the comparison between the different GSI reduction factors (1, 2, 5) and the two different cell sizes (coarser and finer grid). The figures show a vertical cut through the model, where the backside of the cut is included too, in which the maximum principal stress is displayed (sig 1). Results after 10, 30 and 50 cycles of the caving algorithm. Initial GSI of the model is 75. The plots display the height of the cave back in metres and the volume detached in cubic metres

On the right side, the figure displays the results for the same reduction factors with a finer grid (1 m sided cells). The first issue to be noticed is that after 10 cycles, the distribution of the stress does not look similar to the previous set of models, which is related to the reduced cell dimensions. However, as the simulations progressed, the final stages looked as the ones obtained for the coarser grid. The height of the cave back was within the same range. Due to the reduced cell size, the accuracy of the outcome (e.g. the stresses on the cells) becomes more accurate. Therefore, fewer cells are detached in the finer-gridded simulations. Nevertheless, they seem to be comparable and the parameters involved, the cell size and the GSI reduction factor, do not seem to have a large impact on the outcome, after the caving algorithm was run for 50 cycles.

4.1.2 Validation study 2: shallow excavation – low stress environment

The second batch of simulations refer to a low stress environment that resembles a shallower location, about 500 m of depth, in the same rock mass medium. In this case, the stress state is based on the gravitational stress distribution of the overburden. The stress state at 500 m is 13.5 MPa (at the level of the excavation). Another major difference with the previous set of simulations is the definition of the minimum value of confinement that allows the free fall of the cells. For this batch of simulations, a cell freely falls (detaches from the host rock mass) when the confinement environment is low enough that the own weight of the cell overcomes the friction forces resulting from the tangential forces and a friction angle of 30° at the sides of the cell. The limit tangential stress is about 0.24 MPa in compression.

Additionally, the rock mass degradation degree was limited by introducing minimum GSI values below which the material could soften. Three minimum GSI values were input: 30, 40 and 50. In other words, the rock mass could degrade until reaching these minimum GSI values, which were set to 30, 40 and 50 GSI. The target of this batch of simulations was again establishing relations between the different parameters involved in the caving algorithm and gain knowledge about the behaviour of the rock mass provided a limiting softening degree (based on the minimum GSI values 30, 40 and 50). Limiting the softening of the rock mass provided valuable information about the behaviour of the rock mass under the caving algorithm. By setting the appropriate GSI minimum value, it would be possible to calibrate and characterise better the rock mass behaviour during the caving processes. The GSI reduction factors employed for this series of simulations were 1 and 5 GSI units and the cell size was set to 2.5 (coarser grid) (Figure 7). The selection of these parameters was defined after the outcome of the previous simulations.

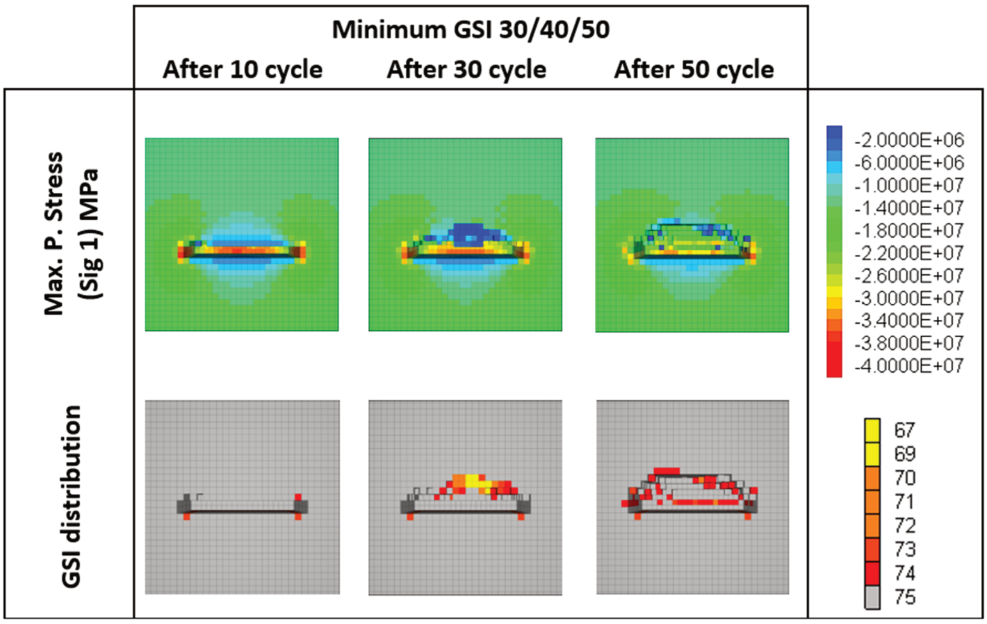

Figure 7 Results of the shallow location of the excavation, representing low stress situation. The figures show a vertical cut through the model, where the backside of the cut is included too. Results after setting a minimum GSI value for the rock mass softening procedure (30, 40 and 50) with a GSI reduction factor of 1. Cell side 2.5 m (coarse grid)

The following set of simulations employed the same parameters as the previously explained; however, the GSI reduction factor was set to 5 units. The outcome of this batch of simulations is illustrated in Figure 8. In this case the outcome of the simulations, depending on the different minimum GSI thresholds, is not substantially different, but it can be noticed that the model whose minimum GSI was set to 30, shows slightly large cave back, for both the maximum height at the centre of the excavation roof and in volume detached from the rock mass. Compared with the results shown in Figure 7, it can be claimed that the GSI reduction factor does not seem to have a significant impact, since the final cave back has about the same height and volume detached as in the case of the reduction factor of 1.

The outcome of the simulations in which the GSI reduction factor was set to 1 GSI unit, the results was the same: independent of the minimum GSI value input, the stress distribution and the shape of the cave back is the same. The reasoning behind this behaviour is the material had no chance to soften until the thresholds (GSI minimum value) employed. Once the rock mass reached a value around 67 GSI, the material was relaxed enough to detach, so the material was not able to soften beyond that value. Figure 7 shows the cross sections of the model at the centre of the excavation, displaying the maximum principal stress (sig 1) and the GSI values around the excavation.

Comparing the results obtained for these cases and the Extended Mathews Stability Graph, it can be concluded that the outcome may lay on the range of failure or major failure, which lays between the stable and caving zones. The volume of material detached from during the performance of the simulations is significant, however, provided that the excavation is 2,500 m^2 and it is excavated at once, the detachment of such a volume could be expected.

The current set provides a better fitting than the previous deep excavation, regarding the stability graph, since the results show a major failure under the given rock mass parameters, stress environment and simulations configuration (relate Figure 5 with the results discussion). The main reasons for a better fitting regarding the stability graph, might be the low stress environment for this particular set of simulations, according to the depth where the excavation is supposed to be. Additionally, the more restrictive criteria for the detachment (lower confinement level has to be reached in order the rock to detach from the host rock) prohibits continuous caving as in the case of the deep excavation.

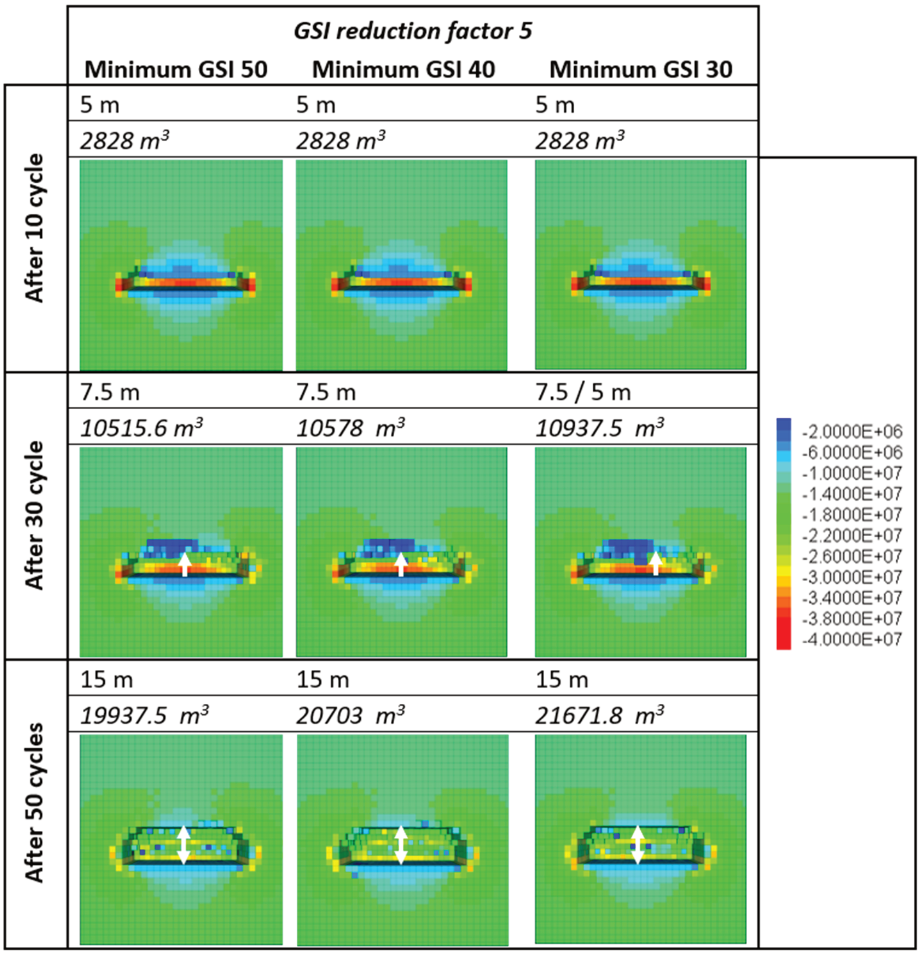

Figure 8 Results of the shallow location of the excavation, representing low stress situation. The figures show a vertical cut through the model, where the backside of the cut is included too. Results after setting a minimum GSI value for the rock mass softening procedure (30, 40 and 50) with a GSI reduction factor of 5. Cell side 2.5 m (coarse grid)

5 Following steps of the caving tool development

The next steps are going to focus on the development and improvement of the unsophisticated simulation method. Further calibration and knowledge must be gained by finding more interrelations between the stress state and the rock mass quality to relate to the semi-empirical charts. The It is required to continue modelling and finding new relations between the input parameters for other regions of the Extended Mathews Stability Graph. Lower rock mass qualities are to be assessed in order to calibrate the methodology.

Provided a satisfactory calibration, the next model geometries are going to be more complex, including different rock types, for instance. Additionally, it is planned that the extraction of the excavation is going to be sequenced, and the effect of the step-wise extraction is going to be studied regarding its effect on the caving processes and the softening of the rock mass. Furthermore, inclined excavations are to be modelled, as different excavation orientations may show different issues and behaviours.

Supplementary to the sequencing and geometrical configurations, the dimensions as well as other parameters of the rock mass will be modified in several simulations. The following sensitivity tests will assist to study and understand the influence of those parameters in the overall caving situation in these more complex models. After the simulation of those models and by modifying a list of parameters, a broad selection of situations is covered, e.g. longwall, block and sublevel caving methods. By modifying the geomechanical properties and the dimensions, many different situations and rock masses' types can be reproduced and more adjustments will be done and knowledge gained, which are required to sort out a more generalised solution.

Summarising, the methodology will be calibrated for a wide list of mining caving methods and a large range of rock mass conditions. Since a large amount of geometries are to be performed in the numerical simulations, the caving predicting methodology under development will be proven for an extended list of mining methods. The caving predicting tool is being developed for its implementation in the raise caving (Ladinig et al. 2021) method. The caving tool forecast will provide valuable knowledge about the cave initiation and caving propagation throughout the rock mass for the novel raise caving (Ladinig et al. 2022) mining method.

6 Conclusion

The developing caving prognosis tool aims to predict the caving and its propagation through the rock mass, provided a simplification of the rock mass. The outcome of the unsophisticated predicting caving tool will provide knowledge about the stability of underground openings which are subjected to caving processes during mining operations, such as raise caving mining extraction method. Therefore, the amount of input data required is reduced significantly. Additionally, due to the simplification of the simulation model, reduced number of input parameters and the employment of model elastic behaviour, the running times are greatly reduced, especially compared with the more sophisticated software and algorithms developed in DEM.

The major advantages of the unsophisticated caving predicting tool are its ease of use and understanding along with its low running times. The complexity of the caving processes is reduced by the application of simplifications, mainly related to the implementation of elastic behaviour and the rock mass softening based on the well-known Hoek & Brown (2019) failure criterion. Therefore, the input parameters required are highly reduced, reducing along the uncertainty that a long list of input parameters would cause. Related to the simplification of the methodology, the running times are lowered, since the application of the model elastic is rather fast compared with more sophisticated ones. Thus, its ease of use and speed turn the unsophisticated caving tool into a low demanding methodology for caving prognosis.

Initial simulations were conducted successfully. Overall, the behaviour of the model, the shape of the cave back and cave propagation provide realistic results at least on a qualitative basis. The target of the initial simulations was the assessment and definition of the relations between the key factors involved in the model and the algorithm. Namely, the relation of the results and the cells sizes, the reduction factor of the GSI (which defines the rapidness of rock mass degradation during the cycles of the simulation). After the first batches of simulations, it can be concluded that the cell sizes studied do not interfere with the outcome. The coarse grid (2.5 m sided cubes) and the fine grid (1 m sided cubes) provide similar outcomes after running the caving algorithm for 50 cycles. Therefore, the coarse grid was utilised for the second batch of simulations due to the fact that provides lower running times. The outcome of the second batch of simulations revealed that limiting the softening of the rock mass (setting a minimum GSI value that can be reached) has a minimal impact on the outcome.

Provided that the N' stability numbers of both deep and shallow situation are close to one another, laying into the 'failure or major failure' zone, the results of both sets of simulations seem singular, with significant difference. The major difference among this two, the deep and shallow excavations, is the stress state. The deeper excavation presents higher stresses which might not reflected in the database used for Extended Mathews Stability Graph (Mawdesley 2002). Additionally, the unconfined environment under which the rockfalls freely is less restrictive than in the shallow excavation. Therefore, the shallow excavation which presents lower stress state, and the detachment criteria included in this set of simulations, lead to lower detached volume from the host rock and shorter cave backs, compared with the deep excavation.

Further investigation is required for improvement of the methodology as well as for following calibration.

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