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Cave mining — 16 years after Laubscher's 1994 paper 'Cave mining – state of the art'

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Abstract

This paper supplements a keynote address prepared for the 2010 Second International Symposium on Block and Sublevel Caving. The author gauges the cave mining industry's position (practice and theory) since the publication of what he considers a seminal paper on 'Cave mining – state of the art' (Laubscher, 1994), hence '16 years after'. For clarity, this paper is not meant to be a critique or an endorsement of the cave mining design rules as presented by Laubscher's (1994) paper, as well as an endorsement of a selection of emerging and noteworthy cave mining design and optimisation approaches. The latter methodologies are expected to gain significance as cave mining enters into a new phase of large-scale operations at greater depths which the author and others describe as super caves. In this next era of cave mining, improved knowledge and incorporation of the governing physics and fundamentals of the associated caving process or phenomena will become even more important for cave design and performance prediction and, therefore, reliability.

The paper starts by providing a snap-shot of contemporary caving designs (and practices), highlighting achievements made by the cave mining industry since the introduction of mechanised caving in primary ores. It concludes by listing the developments made in the last 16 years as well the current and future challenges. The author concludes that contemporary designs and the number of design rules in Laubscher (1994), while still remaining in use, may be reaching their limit when applied to large-scale operations or super caves and they need to be supplemented by a number of the emerging techniques. The attributes which make super caves unique are presented. The opportunity is to continually improve and to test these emerging methods.

Finally, it should be noted that the paper is written from the author's perspective as a mining research engineer and more recently (1997 to current) as the technical director of two international industry collaborative projects; the International Caving Study (ICS) and the Mass Mining Technology (MMT) projects. These projects focus on improving the understanding of the underpinning fundamentals associated with the caving of strong rock masses or primary rock (i.e. rock mass characterisation, caving mechanics including seismicity, preconditioning, gravity and disturbed flow, primary and secondary fragmentation and confined blasting), mainly at moderate depths and stress environments. The original intent of the ICS was to critique, improve and/or supplement a number of the design rules as presented in the Laubscher (1994) seminal paper, given the move towards caving of strong rocks or primary rocks. The MMT then put more emphasis on the study of caving fundamentals.

1 Introduction

In 1994 (effectively 16 years prior to this paper) Dr D.H. Laubscher published a paper 'Cave Mining – the state of the art' arguably focusing on block caving methods (block, panel and their variants). Seven years later the same paper was reproduced by Laubscher (2001). Equivalent papers on practices, or state-of-the-art, in sublevel caving are discussed elsewhere, for example Bull and Page (2000), Kvapil (2004), Hustrulid and Kvapil (2008) and Power and Just (2008). Arguably, the paper by Laubscher (1994) became the most widely used reference for cave mining design based on mechanised block and panel caving methods. There was nevertheless some debate as to when such design rules and/or guidelines could be reliably applied during the overall cave mining design process, i.e. feasibility, design or operational stages. There is, however, the school of thought that the design rules in Laubscher (1994) are strictly speaking better suited for use at prefeasibility stages where the accuracy of the predictions is still relatively low (A. Guest, 2004, written comm.), i.e. +/- 30%. Regardless, Dr A. Guest also acknowledges that they can still be used during all stages of caving mining design but only as guidelines and preferably supplemented by either expert input or appropriate peer review.

Laubscher's (1994, 2001) papers coincided with the period when caving methods were increasingly being applied to strong rock masses often referred to as primary rocks as opposed to secondary rocks based on Codelco Chile's mining nomenclature. In the case of Codelco's El Teniente mine and according to Brzovic and Villaescusa (2007), primary rocks are:

> *"… competent, brittle behaving and massive rocks (copper ores) with almost no open discontinuities. However, when closely mapped, they exhibit a high frequency network of small scale veins (stockwork veins) coupled with widely spaced faults".*

They continue to argue that:

> *"… the predominantly vein network structures do not strictly match the discontinuity definition provided by ISRM (1978) because these veins have low permeability and also an intermediate to high tensile strength".*

The fracture characteristics described by Brzovic and Villaescusa (2007) have been shown to govern the response and behaviour of the El Teniente primary rocks (caving and primary fragmentation processes) and this is relevant to some of the arguments presented in this paper. On the other hand, secondary rocks are rock masses that cave and fragment readily due to the high frequency of open discontinuities and the associated high fracture frequency per meter (FF/m) ratings. The majority of modern and mechanised caving operations are mines predominantly in primary rock formations.

Given the limited experience globally in caving mining particularly of strong rock masses during the 1980s and 1990s, the papers by Laubscher (1994, 2001) provided a much needed and timely reference and platform for design. The paper lists parameters to be considered before the implementation of cave mining including the use of his mining rock mass rating (MRMR) for cave prediction and undercut dimensions to achieve continuous caving. It was nevertheless argued that the bulk of the experiences from which the reported cave design rules evolved were in weak to moderately strong rock masses (MRMR of less than 50), and at moderate depths. This is illustrated in Laubscher's 1994 stability diagram for the various worldwide caving mines. The relevance of the corresponding rules to strong rock masses became subject of a number of the International Caving Study PhD sponsored research, e.g. Mawdesley (2002); Harries (2001); Eadie (2002); Wattimena (2003).

2 Contemporary practice

Caving methods have become the underground bulk mining methods of choice and expected to continue in the foreseeable future. Since Laubscher's 1994 paper, much has been accomplished by industry in terms of caving strong rock masses (Moss et al., 2004; Araneda and Sougarret, 2007). Caving of strong rock masses has become accepted practice even though there are still some challenges to be resolved. Some of these challenges associated with the caving of strong rock masses even at moderate depths are discussed later.

Contemporary practise is best summarised, but not exclusively, through the following key generic design and operational parameters:

- mining block heights
- production rates
- undercutting strategies
- extraction level layouts
- mining rates
- infrastructure and material handling systems.

Specific details on contemporary practice can be found in the MassMin Conference series: 1992, 2000, 2004 and 2008, and in the 2007 proceedings of the First International Symposium on Block and Sub-level Caving

— Cave Mining. In addition to the contributions to caving knowledge through the ICS research, contemporary design and practices are also summarised in Brown (2003) and later in Brown (2007).

Based on limited data available to the author the following section summarises the broad aspects and some achievements of contemporary caving designs.

2.1 Mining block heights

Brown (2003, 2007) defines block height as the height of the block to be caved from the extraction level to the surface, the base of a pre-existing open pit, a level or a mined-out area above.

Based on a benchmarking study conducted for the ICS and published in the MassMin 2004 proceedings, Flores et al. (2004) produced the following relative frequency diagram on current block heights.

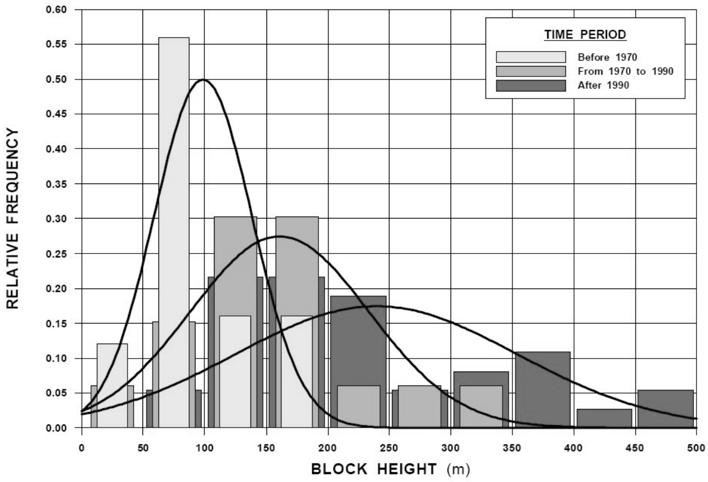


Figure 1 Range of block caving block heights (after Flores et al., 2004)

The current industry average (or benchmark) is in the range of approximately 240–250 m, with 500–550 m as the current target.

2.2 Production rates

While acknowledging that a number of interrelated factors can influence final achievable production rates or targets (e.g. infrastructure, mining systems, caving rates and layouts) the current production rates from a single production sector or unit are in the range 10,000–40,000 tonnes per day (tpd). With the current best in the range of 77,000–96,000 tpd recorded at the Freeport's deep ore zone (DOZ) (Ross, 2009, written comm.). Chadwick (2010) later reports that after several expansions, the DOZ had reached a sustained production rate of some 80,000 tpd of copper.

2.3 Undercutting strategies

The contemporary undercutting options are:

1. Post-undercutting.
2. Pre-undercutting.
3. Advance-undercutting.

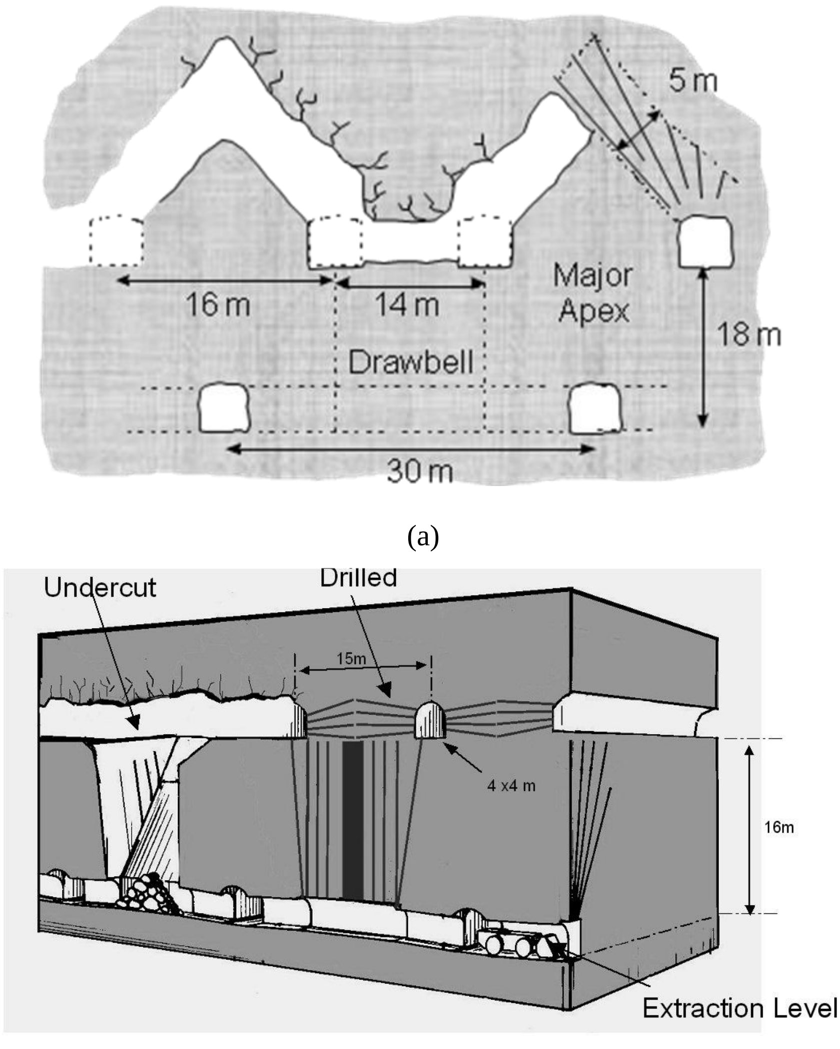
These are also defined in Brown (2003, 2007) as:

- *Post- or conventional undercut* – an undercutting strategy in which the undercut is mined after the development of the underlying extraction level, including the drawpoints, has been completed.
- *Pre-undercut* – an undercutting strategy in which the undercut is mined before the development of the underlying extraction level and the drawpoints.

- *Advance- or advanced undercut* – an undercutting strategy in which the undercut mining face is advanced slightly ahead of a partially developed extraction level on which drawpoints have not been excavated.

The most commonly used options in recent operations are the pre- and advanced-undercuts predominantly where the stress environment or induced stresses are relatively high (Rojas et al., 2000, 2001). The underlying design philosophy is to protect the extraction or production level from the mining induced or abutment stresses that are often associated with post-undercutting development. However, operationally and logistically there is often preference towards applying post-undercutting which technically is better suited to lower stress environments. The undercutting method selection criteria are described by Laubscher (1994) and later by Butcher (1999, 2000).

In terms of geometry (height), the narrow incline, also referred to as crinkle-cut, is increasingly becoming the preferred option with narrow and flat geometry the second choice. However, the disadvantage of the latter is the assurance of complete breakage of the undercut area. Figure 2 are sketch diagrams of these undercut geometries showing approximate values, or dimensions, often considered during design.



(a)

(b)

Figure 2 Illustration of (a) incline (crinkle cut) and (b) narrow flat undercut layouts

2.4 Extraction level layout

The commonly used extraction level layouts are the so-called El Teniente (straight through), the Henderson (Z shaped), or Herringbone. The choice between the layouts is often governed by ease of development, size of the mining footprint and in some cases, pillar stability. The basic drawpoint spacing configurations have ranged from 12 × 24 m, 15 × 30 m and more recently 17 × 31 m (Callahan et al., 2008).

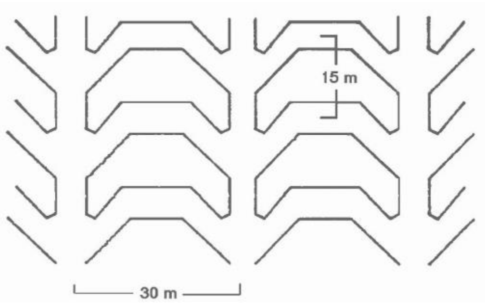


Figure 3 Example of a typical Herringbone layout

2.5 Mining rates

The key mining rates during block cave construction are those associated with tunnelling (development), undercutting, drawbell establishment and draw rates. These effectively determine the cave establishment time which is currently rated to be too long and therefore presents an opportunity for improvement. Some of the reported rates include the following.

2.5.1 Tunnelling rates

There has been recent focus in increasing both single heading and multiple heading developments rates. This follows recognition that one of the bottlenecks in mechanised block caving construction time was poor tunnel development rates. The current average rate being quoted in industry is 300 m/month for a single heading development. Such a rate has become possible with the advent of dedicated long-round rigs by two major mining equipment manufacturers, Sandvik and Atlas Copco. However, for comparison such rates are still very low when compared to the rates achieved in civil engineering tunnel construction which can be double today's mining's best (Moss, 2009, written comm.).

2.5.2 Undercutting rates

The industry benchmark for mechanised block and panel caves based on data from the ICS was 2,100 m^2 per month (Flores et al., 2004). This was later surpassed by Northparkes Lift 2 which was able to achieve 6,000 m^2 per month during the last stages of undercutting (Silveira, 2004). More recent achievements, based on unpublished figures, include Ridgeway Deeps (RWD). The RWD's undercut achieved 5,500 m^2 per month during July 2009 and 5,700 m^2 per month in August 2009 (Duffield, 2009, written comm.). While these high rates of undercutting may be beneficial in terms of rapid cave establishment, their impact on the surrounding rock mass such as triggering seismic events needs to be studied.

2.5.3 Drawbell establishment

Current and preferred industry practice is to blast drawbells in a single blast or single shot using electronic delay detonators that reduce the time needed to construct a drawpoint. This was demonstrated during the construction of the Freeport DOZ and Northparkes Lift 2 block caves, resulting in unprecedented high rates of drawbell establishment or openings per month (Silveira, 2004).

2.5.4 Draw rates

Differential draw rates are assumed in most feasibility studies. The general practice is to assume low rates of 100 mm/day during the early stages of caving, even as low as 75 mm/day. As the cave matures, caving rates in the range of 200–400 mm/day are assumed. Fragmentation is often a major factor in determining actual draw rates. Finer material allows for higher rates of draw.

2.6 Cave performance prediction

Laubscher (1994) suggested a family of empirical relationships, charts, diagrams and reference tables to help with the design process and to predict cave performance. This was primarily based on good geotechnical information or the corresponding MRMR knowledge of isolated drawzone geometry (IDZ) and expected fragmentation size.

As part of the ICS, critical reviews of some of the conventional design rules were undertaken and subsequently reported initially by Mawdesley (2002) and later by Trueman and Mawdesley (2003). The reviews showed:

- inconsistencies in the use of the Laubscher (1994) caving chart and in particular adjustments from RMR to MRMR
- limited case histories with MRMR values greater than 50 and thus reducing confidence in caveability prediction of high MRMR rock types.

This resulted in some modification to the method (Jakubec and Laubscher, 2000) and the development of an alternate empirical method, the Mathews Stability chart (Mawdesley, 2002; Trueman and Mawdesley, 2003).

In addition to the above limitations associated with cave initiation predictions using the 1994 Laubscher design rules, the areas that appear to create the most difficulties for designers include:

- appropriate characterisation of primary rock masses (Brzovic and Villaescusa, 2007)
- fragmentation predictions, particularly where stress caving, i.e. general comminution or attrition, are the dominant mechanisms
- gravity flow, e.g. interaction and interacting draw (Guest, 2007) and, therefore, drawpoint spacing and draw strategy design.

Regardless of these limitations, mining of strong rock masses using contemporary practice has largely been successful as evidenced by the case studies reported, for example in the MassMin 2004 and 2008 conference proceedings.

3 Emerging cave design methodologies

A number of methods are being developed to provide viable alternative design and optimisation methodologies. These are expected to gain more significance as cave mining operations increase in size and depth as they all attempt to incorporate the governing physics associated with the different caving processes. From the author's perspective good practice is to use both approaches (conventional and emerging which are largely numerical) even though there is the tendency to simply adapt designs or practices viewed as successful in equivalent mining and/or geotechnical environments. The following sections are a snapshot of the emerging developments, some of which are being used to supplement Laubscher's (1994) design methodology rather that replacements.

3.1 Cave performance predictions

Significant attempts to model and predict cave performance using numerical simulations, emulators or models have since been made. Broadly speaking, these approaches attempt to model, or at least incorporate the underlying or governing physics of the caving processes. Some of these are discussed.

3.1.1 Rock mass characterisation and response

The basis of the design rules and methodology in the Laubscher's (1994) paper is the Laubscher rock mass classification system which provides the rock mass rating (RMR) and the rock mass strength needed for design. An emerging approach to characterise and predict the behaviour of a rock mass is the synthetic rock mass (SRM). This is a numerical methodology designed to help predict the large-scale response of the rock mass to caving based on its strength, discontinuity characteristics and discrete fracture network (DFN) techniques.

3.1.2 DFN modelling and applications

A key building block of a SRM is the DFN of the cave volume being assessed for caving. This is integral part of rock mass characterisation and modelling.

Rogers (2009, written comm.) states:

> *Central to much of the advancements in rock mass characterisation and modelling has been the increasing use of discrete fracture network (DFN) techniques. DFN models seek to describe the heterogeneous nature of fractured rock masses by explicitly representing key elements of the fracture system as discrete objects in space with appropriately defined geometries and properties. By building geologically realistic models that combine the larger observed deterministic structures with smaller stochastically inferred fractures, DFN models capture both the geometry and connectivity of the fracture network as well as the geometry of the associated intact rock blocks. Figure 4 is an illustration of a small scale DFN model.*
> *There have been two main avenues of application of DFN modelling to caving science:*
>
> - *applications to fragmentation assessment; and*
> - *applications to synthetic rock mass modelling and the better derivation of rock mass properties.*
>
> *To improve our ability to predict the ultimate draw point fragmentation distribution, we need to know where the rock mass is starting from and this is a key area that DFN models have added value. Their ability to synthesise a wide range of fracture related geotechnical data together in a verifiable discrete model allows a stepped increase in our ability to define the in situ fragmentation distribution. Integration of these models with fracture mechanics codes allows the evolution of fragmentation during caving to be understood and therefore the prediction of primary and secondary fragmentation.*

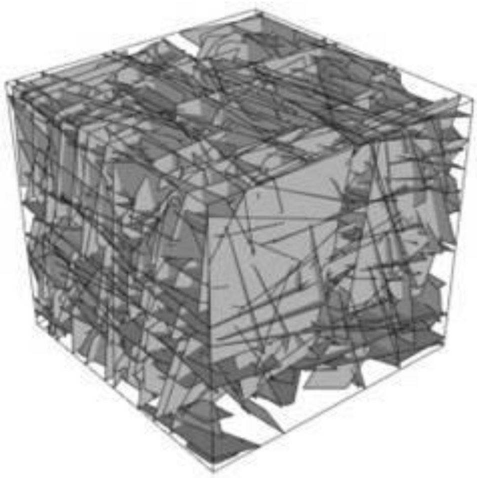


Figure 4 Example of a small scale DFN model (courtesy of Rogers, 2009, written comm.)

The reader is referred to papers by Elmo and Stead (2009) and Elmo et al. (2010) for additional description and application of DFN approaches by the same authors.

Similarly, Mas Ivars et al. (2007) argue that:

> *DFN defines the characteristics of the fracture pattern that influence the mechanical behaviour of rock and the cave models. Fracture density, persistence distribution and fracture-to-fracture correlations are potentially critical characteristics of DFNs that deserve assessment.*

3.1.3 SRM modelling and multi-scale numerical modelling

SRM modelling is a numerical representation of a rock mass which takes into account the intact rock mass strength properties and the DFN forming the rock mass. Cundall et al. (2008) describes the evolution of the SRM as:

> *The Synthetic Rock Mass (SRM) methodology was developed (or extended) within the MMT project to quantify rock mass behaviour at the scale of 10–100m, which is impossible to assess directly in the laboratory or field, when failure is important. The approach synthesizes rock-mass response by combining intact rock mechanisms (deformation and brittle fracture) with mechanisms involving discontinuities, at a scale relevant to the problem being considered.*
>
> *The SRM approach represents a jointed rock mass as an assembly of joint-set elements embedded in a matrix that allows new fractures to initiate and grow dynamically, according to the imposed stress and strain level. The approach, pioneered by Pierce, Mas Ivars and colleagues (Pierce et al., 2007 and Mas Ivars et al., 2008), uses a combination of the Bonded Particle Model for the rock matrix (Potyondy and Cundall, 2004) and the newly developed Smooth Joint Model for pre-existing fractures. The Bonded Particle Model is based on the discrete-element code PFC3D. In this model, the rock is represented as an assembly of spherical particles bonded together at their contacts. The bonds can break, depending on the stress level, thus representing fractures that originate and grow naturally within the assembly.*

Cundall et al. (2008) illustrates the SRM concept according to Figure 4.

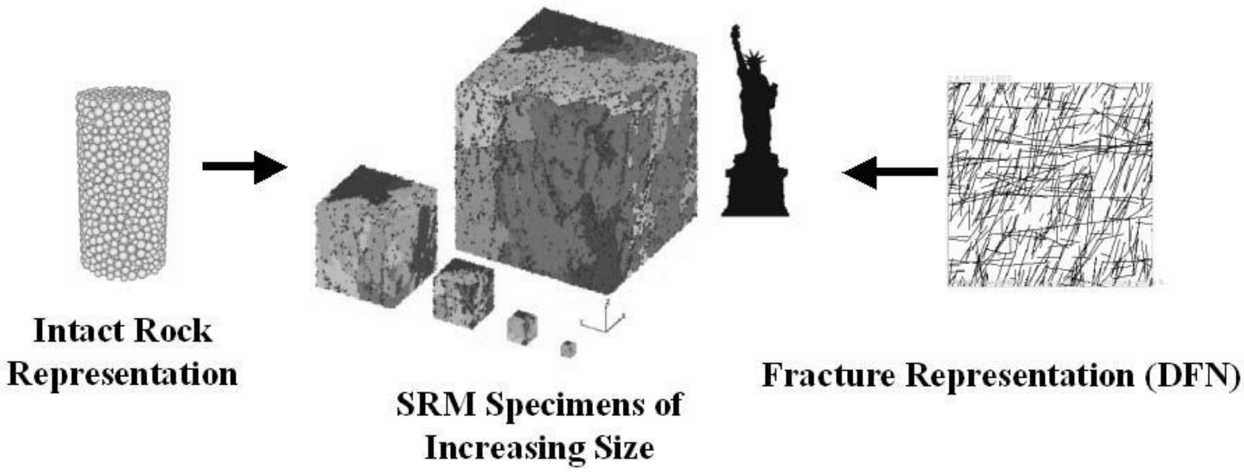


Figure 5 SRM concepts, after Cundall (2008)

Broadly speaking the SRM approach aims for the numerical prediction of the mechanical response of a rock mass (its stress–strain relationship) on differing length scales and the incorporation of this response (via calibrated nonlinear constitutive relationships) into continuum models to predict the deformability and mechanical behaviour at relatively larger scales (Weatherley, 2010, written comm.).

Although the concept was originally developed within the framework of the discrete element method, recently the approach has been adapted to multi-scale, continuum-discontinuum finite element (FE) models (Beck, 2008; Beck et al., 2009; Pine et al., 2006; Elmo et al., 2008, 2010; Vyazmensky et al., 2009a, 2009b; Elmo and Stead, 2009). Regardless of the particular numerical methodology employed, the primary focus remains to synthesise rock mass response by taking into account intact rock properties and discontinuities at the scale of interest.

Some of the applications rendered tractable for numerical simulation by the SRM approach for caving mining include:

- caveability and cave propagation prediction
- primary and secondary fragmentation prediction

- identification of seismicity zones within and surrounding the mine
- the simulation of drive deformation and performance
- block cave stability at depth
- subsidence modelling and prediction.

In a confidential report to the author and the MMT2 project sponsors and specifically in reference the approach by Pierce et al. (2007) being developed for the MMT, Hoek and Martin (2010, written comm.) state that the SRM approach shows best promise as an alternative method for modelling discontinuous rock masses but it needs to be validated.

3.1.4 Seismicity and the caving process

As part of SRM development, Reyes-Montes et al. (2007) and via the MMT caving mechanics research, novel seismology and microseismic analysis techniques have been developed. These developments provide means of tracking the rate of caving, the fracturing modes and geometry, and potentially the height of the yield zone as well as the position of the cave back. Improved knowledge of seismicity during caving is becoming even more important given the caving of strong rock masses.

3.1.5 Block cave stability versus depths

Of the examples listed earlier where the SRM techniques can be applied (Section 3.1.3), block cave stability at increasing depths will gain significance in future caving operations particularly with relatively weak rock masses. For example, the stability of extraction levels and undercuts has always been an engineering constraint on block cave design. Historically, the management of stress and cave loads via draw strategy and extraction sequences have been core components of cave management. In recent times, maturing mines are reaching greater depths and new mines are being planned in weaker rocks but at much greater depths. Anecdotally, stability issues are becoming even more important for these operations and the rules of thumb from shallower mines are showing signs that they have reached their limits of applicability.

There is now the opportunity to use the emerging technologies to study and improve stability assessment from a mine scale down to a support element scale. The improved resolution of some of the approaches should allow mines to consider new layouts and unconventional strategies that push cave mining to even greater depths. Figure 6 is an example from a DFN based FE model (Beck, 2010, written comm.) for assessing extraction level stability. The purpose of this model was to evaluate drive deformation and the capacities of steel arches and steel sets for drawpoint support in areas of the extraction level with potential for pillar instability.

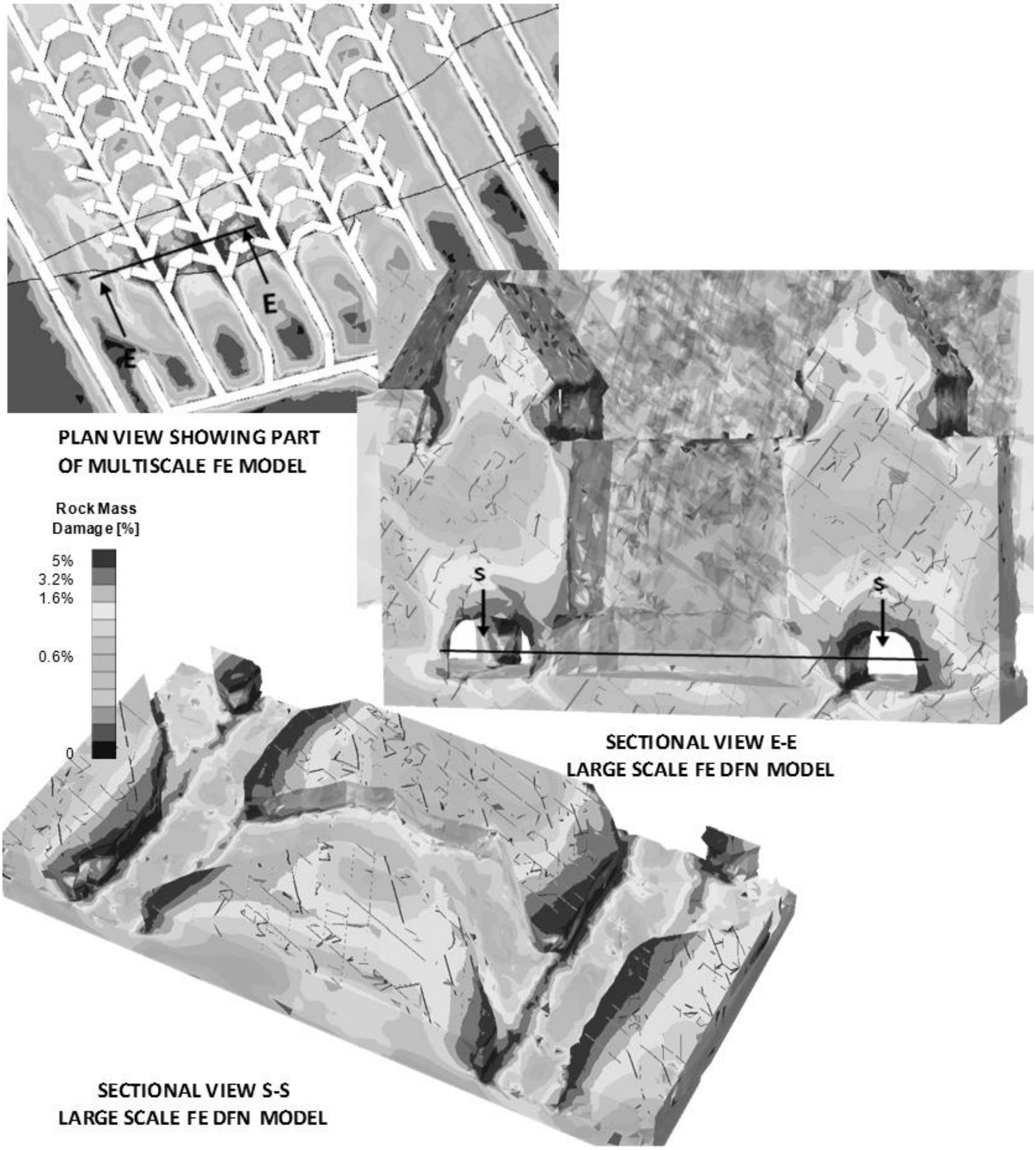


Figure 6 A complex DFN based FE model (Beck, 2010, written comm.) for assessing extraction level stability

It should be noted that the emerging tools in the arena of multi-scale modelling of mines, from the basis of physics and the characterisation of key geometrical structures governing rock mass response, promise to become powerful addenda to current design and operation of cave mines.

Beck (2010, written comm.) describes the potential benefits one may expect:

> *In case studies using multi-scale models, the opportunities became apparent very quickly. Some of the most important geotechnical risks for caving mines were shown to be significantly, and in some cases simply dependent on mine scale extraction sequencing and geometry. For example, some particular undercut collapses were found to be almost solely caused by the extraction sequencing*

or the mine design, all else being equal, and could be replicated with high similitude models using a sensible range of input parameters that could easily have been derived before any mining took place. Cases of cave stalling, plug collapse and infrastructure failures at some mines were also found to be a consequence mainly of the geometry of the mine and the excavation sequencing".

3.1.6 Flow simulation (gravity flow)

In spite of its significance in layout design and draw control strategies and therefore ore recoveries, gravity flow (or flow of caved materials) remains the most contentious of the caving fundamentals (Guest, 2007). However, plausible advances including the improved understanding of gravity flow have still been made through physical modelling, and corresponding flow simulations or emulators.

Power (2004a, 2004b), Halim (2006) and Castro (2007) undertook a large-scale physical model programme as part of the MMT research using granular materials from a local quarry, and claimed to represent the largest physical model used to emulate the flow of coarse fragmented ore into block caves. Data from this work was later used for the initial calibration of one of the emerging flow emulators called REBOP. Some of these flow simulators are discussed next.

3.1.6.1 REBOP

The rapid emulator based on PFC3D (REBOP) is a numerical modelling tool that provides rapid analysis of the movement and extraction of fragmented rock under draw in mine operations that use block or panel caving. A complete description of the REBOP flow model can be found in Pierce (2009). It was designed to be easy to use and does not require the user to be an expert in the mechanics of flow. However, some background information on selected key mechanisms is provided to assist the user in interpreting simulation results.

The primary output from a draw analysis using this package includes time or tonnage-based histories of extracted ore grades (and other rock properties), plots of material distribution above the drawpoints and 3D visualisation of the fundamental volumes associated with each drawpoint: isolated movement zones (IMZs) and isolated extraction zones (IEZs). An equivalent flow emulator for sublevel caving application is still under development also via the MMT research.

3.1.6.2 CA

Power (2009, written comm.) describes a cellular automata (CA) model for caving applications that can accurately forecast recovery over a 20 year period, or the next week or month according to the needs of the operation. It includes the effects of drill and blast, asymmetric flow associated with caving propagation (when predefined), and different particle movement. In addition to this, alternative models exist which use mathematical relationships generated by the CA models to carry out basic free flow life of mine (LOM) forecasts in 5–10 minutes rather than hours. Other emerging equivalent CA approaches are described by Castro (2007) and Sharrock et al. (2004).

3.1.6.3 PCBC

PCBC is viewed by some as an optimisation model to optimise block geometry rather than a flow model, even though there are built in flow rules. Regardless, it has arguably become one of the most widely used and tested methods for cave planning and scheduling tools. It is a program developed by Gemcom Software International (Diering, 2000, 2004a, 2004b).

Diering points out that:

> *It is a tool for use by planning engineers for use in feasibility studies as well as in operating mines. It allows a numerical model to be set up which subsequently allows the draw columns above draw points to be simulated. By doing this, we are able to compute mineable reserves for a variety of scenarios as well as produce production schedules giving tons, grade and other economic information. Features of PCBC include:*
>
> - *Sophisticated empirical mixing models allowing for vertical and horizontal mixing as well as the mixing which results from toppling or sliding of material close to surface.*

- *Definition of mineable reserves using best height of draw technique which allows for easy delineation of practical footprints as well as sensitivity studies of price and mining cost variations.*
- *Generation of numerous production schedules to study the interaction of the key scheduling parameters, such as total production rates, rate of commissioning of new draw points, draw point maturity curves (or production rate curves per draw point) and cave draw down scenarios.*

The origins of the method are nevertheless intimately linked with the work by Laubscher (1994).

In terms of flow and flow simulation, the last 10–16 years in granular flow research have shown that in mining, effective applied research delivers real operation benefits, in planning improvement, operational revenue, extension of asset life and maximising of orebody potential. Castro (2007) as part of his PhD thesis review provides a good review of the capabilities of a number of published flow simulators.

3.1.7 Other significant developments

In addition to the emerging cave design methodologies described previously, significant developments in key areas associated with caving geomechanics have also been made including:

- preconditioning
- block cave secondary fragmentation
- stress measurements.

3.1.7.1 Preconditioning

The introduction of preconditioning by hydraulic fracturing (HF) for caving application deserves special mention. Its application in cave mining was demonstrated initially via the ICS project. van As et al. (2004) suggested that hydraulic fracturing could be used to precondition ore for caving which would ultimately reduce the risks associated with caving hard rock orebodies. The technique has since been demonstrated to be an extremely cost-effective means of cave inducement, managing seismicity, caving rates and reducing in situ and primary fragmentation (Chacón et al., 2004; Araneda et al., 2007).

However, in spite of some evidence of the effectiveness of preconditioning, some of the questions still to be addressed or fully quantified include:

- When to use preconditioning and what technology (hydrofracturing or blasting or combination)?
- How do existing structures and stresses aid or interfere with preconditioning depending on method selection (particularly hydrofracturing)?
- How much preconditioning is required?

The author is of the opinion that preconditioning will become an important component of future caving and hence the continued importance of addressing these issues.

3.1.7.2 Fragmentation

Next to gravity flow, fragmentation continues to be one of the least understood of the caving fundamentals. Given the increasing caving heights also under higher stress regimes, the ability to predict fines generation and their migration through the caved columns are becoming just as important. Pierce et al. (2010, written comm.) have developed a credible hybrid framework for secondary fragmentation modelling. The hypothesis used is that secondary fragmentation in block and panel caving can occur via three main modes of breakage:

- impact breakage within the air gap at the top of the cave
- compression breakage within stagnant zones of the cave (broken rock)
- shear driven breakage within movement zones.

The shear breakage model is now incorporated into the REBOP simulation package so that secondary fragmentation analyses may be conducted automatically as part of draw simulation studies. However, this still needs to be improved. Beck (2010, written comm.) also proposes an approach for prediction fragmentation using the SRM methodology. Regardless the block cave fragmentation software (Esterhuizen, 1994, 1999) remains the industry most used software for prediction primary fragmentation. This is in spite of some of the noted limitations associated with that methodology (Eadie, 2002).

3.1.7.3 Stress measurements

The knowledge of the stress environment is just as important in cave mining. This was also reinforced in Laubscher (1994). In caving this is important in terms of prediction of cave initiation and propagation, choice of undercutting strategies including general rock mass response and therefore support or rock reinforcement. There is still much debate as the most appropriate method(s) to use, however, a plausible approach based on acoustic emission analysis techniques has since been introduced in cave mining and well described by Villaescusa et al. (2000) and Lavrov (2003). In spite of the debate associated with its application, remote measurements of the stress environment will even become crucial as cave mining is introduced at even greater depths.

4 Conclusions

Even though a number of limitations have been reported, Laubscher's (1994) paper which was later reproduced (Laubscher, 2001) is still considered seminal by a number of researchers, mining consultants as well as caving practitioners. It continues to be used as a reference guide to current caving scenarios (16 years later). Since that paper was published (and not necessarily a direct consequence of the paper):

- A lot has been achieved by the cave mining industry in terms of cave mining design as well as practice. Effectively there is a generic template or contemporary practice for cave mining in primary rocks at moderate depths.
- A number of the modern caving operations including Codelco El Teniente panel caves, Palabora, Northparkes block caves, DOZ, Henderson, RWD all represent contemporary practice and their respective designs fall within the contemporary design template. However, new innovations are still required to improve caving efficiencies.
- Advances have been made in predictive technology based on numerical simulators, emulators and models which include the DFN, the SRM scheme, flow models or emulators and preconditioning. This is in addition to methods for in situ stress measurements based on the AE analyses techniques.
- The topics of stress measurement and preconditioning will equally gain increasing importance to future caving where the need to better control or manage the caving process is greater.
- The general knowledge and understanding of caving methods has significantly improved and has gone beyond a few individuals or companies being the sole custodians of caving knowledge and expertise.

However, as an industry, there are still some major challenges which may collectively threaten the viability of cave mining. For example:

- not being able to achieve continuous caving resulting in cave stalling or slow caving rates
- differential cave propagations due to the presence of different geological lithology
- seismicity caused by unfavourable undercutting practices
- early dilution or waste ingress and accelerated fines migration containing waste
- structural collapses and instabilities due to mining of large panel widths
- extraction level instabilities due to poor undercutting practices — the presence of remnant pillars or compaction of caved materials a consequence of poor draw practices.

The reasons for such difficulties are debatable and have included poor operational practices and controls, rather than technical or geotechnical risk related factors.

4.1 The future

The caving industry is now moving towards the next generation of caving geometries and scenarios (super caves) where current practice and knowledge may be reaching its limits. The rules in Laubscher (1994), which have a strong empirical and experiential basis, now need to be supplemented by methods which consider more of the governing physics of the caving processes. Laubscher himself highlighted and acknowledged areas where improvements needed to be made for example:

- the quality of geotechnical and geological data used
- understanding of the caving stress environments
- our ability to predict fragmentation (primary and secondary) in strong rocks
- improve knowledge in drawpoint/draw zone spacing and the interactive theory of draw. This was also echoed by Guest (2007).

These issues will become even more crucial as industry moves towards the next generation of large-scale caving operations. The emerging methodologies need to be acknowledged by the industry at large, continuously improved and, more importantly, tested and validated.

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