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The application of civil engineering construction practices in cave mines for improved extraction and reliability

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Abstract

The combination of a high-quality construction approach typical of that used in civil engineering construction together with the higher tolerance for deformations, water inflows and shorter design life typical of mining construction, allows for the capacity of ground support linings to be significantly increased compared to both typical civil and mining applications. This ability to push the envelope of liner ground support performance through the use of structural support liners, these being distinct from typical sprayed concrete, rock bolt and mesh liners used in most underground developments, allows for enhanced optimization of extraction and draw point reliability through adjustment of the panel layout. This paper highlights current civil engineering construction technologies that can be utilized to improve liner and draw point reliability in caving operations, including NATM type yielding liner systems and high strength composite steel and concrete liner systems, and further describes how standard civil engineering design practice should be re-imagined to support both practicality and relevance in the cave mining context where appropriate structural failure is the hallmark of good design. It is suggested that this is facilitated by the adoption of a Managed Failure Limit State as opposed to the conventional Ultimate Limit State partial safety factor design approach in common use in civil engineering design. Finally, this paper considers the potential conditions that might require each of three typical hybrid civil-mining support systems that are relevant to a recent block cave extraction level tunnel system.

1 Introduction

Mine engineering and civil engineering tunnelling are often practiced independently despite obvious similarities in the principal challenge; that being the construction of stable excavations within a predominant ground type. The differences between the approaches are partly ideological and partly rooted in materials, but fundamentally all differences appear due to the diametric approaches to risk of structural failure and obvious structural distress. Civil engineering design is intolerant of structural distress and failure and aspires to mitigate risk of failure typically over a 100+ year design life. Any structural failure or distress is likely to harm and / or alarm members of the public. Mine engineering development on the other hand seeks to minimise cost and time to develop support systems that are good enough for a single operation over a typically short 5-year timescale. Structural support failure in a mining context is often tolerable, provided it is managed, as mine access is tightly controlled with no access by the public. Consequently, the principal risk of structural failure in a mine context is to mine function and access only. Note, structural distress and failure in this paper refers to the failure of a deliberately constructed support system, rather than failure or collapse of the native rock structure. It is important to stress that sudden catastrophic structural failure is always intolerable regardless of context, as any violent forms of stress relief are likely to result in large releases of energy that will impact a much larger area underground than where the failure has occurred. This is perhaps best illustrated by the mine air-blast phenomenon that has been extensively documented elsewhere.

In block caving, this idea of tolerable progressive failure is taken to the extreme as it is the fundamental concept of block caving. In this extreme environment it is perhaps easy to dismiss traditional civil engineering techniques as being either impractical or unnecessary; however, to do so condemns the mine operator to unnecessary production inefficiencies in all but the most favourable ground conditions. This is not to say that civil engineering tunnel design practices should simply be adopted in a block cave mine context, as the inherent relative conservatism in the approach would likely lead to even greater inefficiencies and uneconomic projects. Instead, a hybrid approach is required that maximises material and support system performance up to the point of mass system failure. This requires marrying the civil engineering approaches to quality of construction and materials in order to maximise performance, to the mining approach of managed progressive failure.

After briefly outlining the typical methods and flaws of the 'Mining' and 'Civil' design approaches, this paper sets out key civil engineering techniques that are not common in a block caving context but are likely to yield significant improvements in extraction level development layout and reliability. Finally, it outlines three different support liners derived from civil engineering construction techniques that might be applied to the extraction levels of block caves to increase reliability and minimise remediation and maintenance.

2 The 'Mining' design approach

Most block cave mines have been historically constructed in strong hard rock conditions where nominal rock support linings of rock bolt, mesh and/or thin sprayed concrete are considered adequate. Ignoring hydrogeological concerns, the biggest risks tend to be from localised rock bursts or local brittle roof failures, the rock mass as a whole remaining stable. If localised collapse does occur, it can usually be remediated and more significant structural support is only required if the plastic zone continues to grow and the adjacent ground unravels, which is symptomatic of weaker rock. In these very strong rock conditions, there is little incentive to minimise local stress concentrations in the excavations, so rectangular development headings dominate, which are convenient for equipment access. Given the hard rock conditions blasting is ubiquitous and potentially the only sensible option. In short, the 'Mining' design approach has evolved from very strong hard rock conditions, but these are not necessarily representative of the mid and post caved conditions in block cave mines where extensive plastic damage to rocks is expected; yet these are the conditions that the extraction level tunnels must survive to facilitate recovery of the ore. It is further expected that the typical 'mining' design approach will become increasingly redundant as the mining industry inevitably shifts its focus to extracting ores from ever more challenging and previously uneconomic deposits.

The strength of hard rock conditions when mining has led to a complacency in concrete support, whereby sprayed concrete is routinely used in thin shells over rock bolting and mesh. The only structural requirement of the sprayed concrete in these conditions is to hold together the face of the excavation and limit local fallout of debris as the ground strains around the excavation. To this end the sprayed concrete is routinely reinforced with steel or polymer fibres that act to increase its ductility and tensile strength. Crucially they have an insignificant impact on shear strength, stiffness, and compressive strength, which are typically critical to concrete structural design. The net result of this is that the chief requirement of the sprayed concrete is that it should stick to the wall and harden; the compressive strength characteristics and even the applied thickness are often not critical to the required performance.

The primary structural support of these lining systems comes from the radial rock bolting, which reinforces the plastic zone around the excavation preventing fall out and maintaining the integrity of the ground arch around the excavation. The rock bolts stop the arch from collapsing by holding in large blocks of ground, whilst the mesh and sprayed concrete bind the face of the excavation and stop small debris in-falls and the gradual unravelling of the arch through spalling. In this context, progressive failure of the sprayed concrete is tolerable as it is secondary to the primary stability of the excavation, and assuming the rock bolts are designed with sufficient ductility, progressive failure of the rock bolts may also be tolerated with additional infill bolting applied later if required. Alternatively, full remediation and re-ripping of the excavation support system could be undertaken, although this may be impractical in an active block cave given the abutment load stress changes.

In this scenario, where failure will lead to a gradual yield and increase in convergence of the excavation, traditional engineering safety factor design of the sprayed concrete and mesh is largely irrelevant as this seeks to prevent yield in the liner system from occurring by limiting internal stresses. Note, traditional engineering safety factor design is meaningful for the design of the rock bolts, which are part of the primary ground support system, although even then it is the deformation compatibility with the expected ground movements rather than the direct stresses that are of most importance.

3 The 'Civil' design approach

We might want a civil engineering design approach when designing a critical piece of mine infrastructure. We might also want to employ a civil engineering design approach when considering a robust structural support system for an excavation, such as a thick concrete and/or steel shell liner. Here the liner is expected to be subjected to significant forces and either fully or partially support the ground. This is usually only necessary in weak ground conditions, which may either be pre-existing or only manifest following the massive ground stress redistribution generated by the block caving process.

As stated previously civil engineering design does not normally tolerate structural distress. Consequently, design methods have evolved to limit stresses to tolerable limits well below the threshold when substantial failure due to applied stress is likely to occur. Historically, this was achieved using a permissible stress limit for design that essentially applied a single safety factor to the material strength characteristic that is important to the design. In most modern codes of practice this permissible stress approach has been generally superseded with a partial safety factor approach (CIRIA 1977), which allows for a composite safety factor on stress to be developed from combining independent safety factors on both the applied loading and the material strength characteristics of the structure. This allows for an independent assessment of the likelihood of the load condition occurring in combination with the likelihood of the material strength being achieved for a given circumstance or failure condition. Within the Eurocode design codes of practice this is potentially taken one step further as it incorporates a method of calculating bespoke partial safety factors based on real world test data and probabilistic distributions (CEN 2002; CEN 2004).

Whilst fully probabilistic ground characterisation and design techniques are becoming increasingly common place in geomechanics, it remains very uncommon for structural design. This is thought to be for three reasons, firstly, structural materials are usually procured and imported to well defined material specifications, so the inherent variability is substantially less than in a naturally occurring ground. Secondly, structural design is commonly concerned with achieving sufficient strength, it is rarely concerned with achieving an exact strength. Thirdly, the ubiquity and uniformity of materials used within a structural system means that variances in absolute stiffness behaviour are unlikely to change the fundamental behaviour of the structural system from that envisaged at design and where the stiffness's of differing material properties are critical to the structural failure mechanism, then relatively simple sensitivity analyses can be undertaken. This is the approach taken with the design of composite steel and concrete deep mine shaft linings, where structural failure of the shaft is clearly intolerable, and the stiffness of the concrete varies over time relative to the steel.

To achieve a framework for creating a hybrid design approach suitable for use in the design of failure tolerable linings, we first have to examine what the conventional safety factors mean in this context.

3.1 Partial load factors

Partial load factors differ depending on if a single load action is being considered in isolation or a combination of actions. Clearly the likelihood of maximum load occurring concurrently from all possible load conditions is lower than it is occurring in just one. The load factors themselves are similarly lower for more well-defined loads with greater certainty, than less well-defined ones, although there is normally no appreciation of a credible maximum. This is of particular relevance in a mining context in relation to water loading, where if water pressures are factored up by 1.35 as is common practice for a static structural load, it can often be equivalent to a surface flood of over 100 m depth, which is clearly not usually credible.

The other aspect of load factors in codes of practice is that there is usually a recognition that extreme loading conditions that are not within normal operating conditions, should not be significantly factored up. Typically, only 1.05 is used for accidental load cases, on the basis that they are often transient dynamic loads, and it will be sufficient to survive the loading once, rather than resist it repeatedly.

3.2 Partial material factors

Partial material factors take into account the variability in the material supplied, particularly strength, and additionally the variability in the installation quality of the material which often also impacts its strength. For example, modern steel production is highly controlled, and bolted connections are highly reliable, so the steel strength is not particularly impacted; consequently, a material safety factor of 1.15 on specified strength is commonly used. Masonry on the other hand has more variability in the strength at manufacture, and substantial variation at point of construction from the reliance on the quality of workmanship, so material factors on masonry of over 3 are not uncommon. Structural concrete lies in between, but typically nearer to steelwork with a material safety factor of 1.5 (BSI 2002; BSI 2004).

These partial material factors themselves are typically applied to the characteristic material strength, which is usually representative of the 5th percentile strength. This being the strength of the material exceeded by 95% of all samples tested. Consequently, with all else being equal, at 100% characteristic strength utilisation you would expect to see failure in approximately 5% of fully loaded and stressed areas. Note, in the majority of structures maximally stressed areas are very localised and only form a small part of the whole structure.

3.3 Limit states

Civil and structural engineering design normally consider two limit state conditions, termed SLS, the Serviceability Limit State, and ULS, the Ultimate Limit State. A limit state effectively being an imposed limit on the predicted response of a structure. The Serviceability Limit State represents the normal operating condition and is typically used to predict deformations and cracking as it is concerned with comfort, operation, appearance and durability. As it is used for prediction partial safety factors on loads and materials are not applied, as in all cases it is the Ultimate Limit State that is used to check for safe operation and guard against failure.

The Ultimate Limit State is the safety check on the design and is not predictive. It incorporates both material and load partial safety factors, and it is usually the governing criteria for a structural design and determines the required structural element sizes and material strength characteristics.

3.4 Problems designing for managed failure with civil engineering techniques

In a mining context we are often interested in when failure of the whole liner system will occur, that is collapse of the lining system and/or excavation. It is hopefully apparent that this will not be the case when the Ultimate Limit State condition is exceeded, or even unlikely to be the case when an overall safety factor of 1 is reached, as the material factor itself is applied to a characteristic material strength where 95% samples tested would survive. Whether collapse of a liner system will occur or not will depend on each individual system and collapse mechanism. Many points of failure might result in local spalling or yielding but not total collapse. Total collapse in a mining scenario would only be captured with an advanced progressive second order analysis where points of failure in the system are systematically identified and the whole system altered accounting for the failed or yielded part of the liner. Whilst these explicit modelling scenarios are routinely considered in rock mechanics, they remain uncommon in civil and structural design which is focussed on preventing any failure rather than predicting what happens systematically after failure.

4 Managed Failure Limit State design approach for strong support mine linings

For a structural ground support liner in a block cave, here being a primary shell support structure rather than simply rock bolts, we need to consider an alternative design approach whereby a basic structural engineering design method is reconsidered using modified partial safety factors in order to better estimate performance at failure. In this sense a further design case for the Managed Failure Limit State is proposed.

For a structural shell, it is suggested that the managed failure state design should consider a 50% probability that the material is overstressed at any given location; this requires the use of the mean, rather than characteristic material strength with no material load factor. Assuming a typical 40 MPa concrete in a mining context this might mean applying 8 MPa to the characteristic strength to convert it from the 5th to the 50th percentile value, and later validating this from the on-site material conformance testing carried out during construction. As this represents 20% of the characteristic strength at 40 MPa a suitable corresponding material factor to represent the compressive failure state would be 0.8, as illustrated in Table 1.

Table 1 Comparison of typical limit state safety factors for 40 MPa concrete structural design

Safety factor	Serviceability Limit State	Ultimate Limit State	Managed Failure Limit State
Load factor	1.0	1.35	1.0
Material Factor	1.5	1.5	0.8
Combined factor	1.5	2.03	0.8

For concrete this is potentially a trivial process, however, as steel components are not manufactured on site and the steel industry is geared up for providing guaranteed strength, the actual strength of steel supplied might vary substantially. Without very careful specification, procurement and conformance testing of the actual grade and strength, the actual properties of the steel supplied will not be known, although its guaranteed minimum strength and grade will be. This is only problematic when second order failure mechanisms are needed to be considered in complex structures containing multiple materials, such as when steel ring beams are encased in concrete, or when the strength of the material directly effects its stiffness and thereby the support system's interaction with the ground.

5 Mechanical excavation

It is beyond the scope of this paper to exhaustively consider possible excavation techniques; however, a brief discussion of the potential benefits of mechanical excavation in block cave mine development is included here. Whilst mechanical excavation is commonly used in civil tunnelling projects the authors consider that it may not be an obvious option for mine development. Drilling and blasting on the other hand is ubiquitous for hard rock mining roadway development and thereby the default excavation technique for block cave roadways. Specialist tunnel excavation machines with combined excavation and mucking functionality potentially offer several benefits over drill and blast excavation as briefly listed in the table below:

Table 2 Outline comparison of mechanical and drill & blast excavation techniques for roadway development in moderate to soft rock

Aspect	Drill & blast excavation	Mechanical excavation
Shape control	Poor	Good
Overbreak	High	Low
Pillar damage	High	Low
Cycle time	Moderate	Continuous
Set up time	Fast	Fast
Adaptability	Very high	Moderate

The key aspects related to the use of civil techniques to improve draw-point recovery and reliability as discussed here are shape control and overbreak. If structural shell liners are to be provided to provide enhanced ground support the importance of initial excavation shape control is hard to overstate. The shape of the liner will directly determine the forces developed within the liner and thereby its functionality and performance. Whilst it is possible to rehabilitate out of shape excavations to install the correct geometry of support liner, this will inevitably require further overbreak, re-work and a preparatory regularising concrete layer. This is not ideal for two reasons: Firstly, this is potentially a substantial amount of additional work, and secondly, it is not necessarily the case that the original rock strength will be realised through the application of bolts and concrete. Consequently, overbreak should always be minimised by prioritising excavation shape control and method.

The significance of minimising overbreak generally when constructing panel drives may not be obvious, however, it directly impacts the extent of intact rock within the mine pillars; small increases in overbreak effectively reduce significant proportions of pillar area. For example, 300 mm average overbreak on 40 m × 20 m pillar equates to almost 5% of pillar area and a corresponding 5% increase in stress. Localised pillar damage has an equally large effect, so effectively 1 m of combined pillar damage and overbreak on roadways bounding a 40 m × 20 m pillar accounts to 16% loss of pillar area. As pillar spacings are often determined by draw cone interaction as well as pillar stability it is challenging to increase pillar size to compensate. Consequently, the use of mechanical excavation techniques for roadways should seriously be considered when the long-term panel pillar stability is a concern, as may be the case in block cave mines.

The other potential benefit of mechanical excavation in block caving relates to the continuous excavation and lining process that can be achieved. Block cave mines have extensive and continuous roadways at both extraction and undercut levels, so potentially mechanical excavation could yield significant development programme efficiencies over drill and blast depending on the preferred development and cave sequence.

6 Supply chains

Before considering the implementation of any civil engineering techniques briefly outlined in the following sections within a mining environment, careful evaluation of existing and potential supply chains must be made, as these will directly impact the feasibility of applying a civil engineering technique in a mine context.

Civil engineering contractors are well used to taking on and pricing significant risk within a competitive tender environment. Their contracts are typically set up so that only close adherence to the design and material specifications will result in full payment. Contracts themselves may apportion some, none or equal risk between the Client and the Contractor. In short, the Contractor is strongly incentivised to deliver all aspects of the design and normally bears the risk of not achieving this, this encompasses material procurement, delivery, transport, installation and construction. This contractual arrangement is a major factor in achieving the very high-quality construction practice and supervision sometimes required by critical civil engineering infrastructure projects.

Supply chains in complex mine are very different, often with a few embedded Contractors who supply men and materials only. All construction risks lie with the operating mine, and the mine production rightly takes precedent over construction. In this scenario the Contractor is both unwilling and probably unable to take on construction and programme risks, and so the mine operator is fully responsible for the construction; although as they rightly prioritise Production they do not necessarily fully understand the importance or implications of the construction process and decisions. Mines are usually remote, transport and logistics to the mine site are complex, transport and logistics through the mine site underground are even more complex; however, many of these challenges are also often addressed by civil engineering tunnelling contractors in busy urban sites, so the real difference in the supply chains is down to an inherited enthusiasm to prioritise ore extraction above all else. Construction processes are inherently too complex and challenging to undertake in a haphazard fashion and still expect any sort of cost or programme efficiency. In parallel with this, staff recruitment and retention at mine sites is often challenging and socio-economic factors place significant restrictions on importing skills; this leads to further challenges in the adoption and implementation of new and unfamiliar techniques. It is inherently difficult to implement new high-quality civil engineering practices in this context, and success should not reasonably be expected without significant and continual discipline, focus and prioritisation of the novel practices at the mine site by the mine operator.

Whilst the challenges of construction in mines are great, the resourcefulness of miners should not be lightly dismissed, and a dedicated and motivated team of miners will be fully capable of owning and implementing any appropriate novel civil engineering construction technique given adequate time, resources and technical support to help adapt it to the unique constraints and mine environment.

7 Thick structural sprayed concrete

It is now commonplace in civil tunnelling to construct thick structural liners in excess of 300 mm at a 40 MPa design concrete strength. This is achieved with the use of modern spraying equipment, experienced nozzlemen and supervisors and strict Quality Assurance and Quality Control practices. This can only be achieved with consistent concrete batched and delivered to site. This innovation has freed civil tunnellers to construct full thickness structural shells behind the excavation face, providing substantial and quasi-immediate support in soft ground conditions, whilst following the complex curvature profiles of the excavated ground. Whilst the use of sprayed concrete is common in mining generally, it is usually only thinly applied and not used as primary structural ground support. The use of sprayed concrete has developed from the common implementation of NATM construction methods in Europe, whereby the initial primary support was provided by sprayed concrete, so it was a natural extension to look to thicken this into the permanent liner support also.

The use of thick sprayed concrete for structural support has two distinct advantages within a mine environment. Firstly, it can be used to provide near instant support to the excavation advance, allowing continual, progressive and adaptive excavation support in partially stable ground conditions to be achieved. Secondly, structural sprayed concrete shells can be formed that mirror the excavation geometry at tunnel intersections; these maintain the ground arch by preventing fall out and in so doing minimise overbreak and lining materials. Whilst this is common in civil engineering caverns, the complexity of minimised junction geometry in a typical block cave production panel with a non-orthogonal layout makes this a highly desirable structural form.

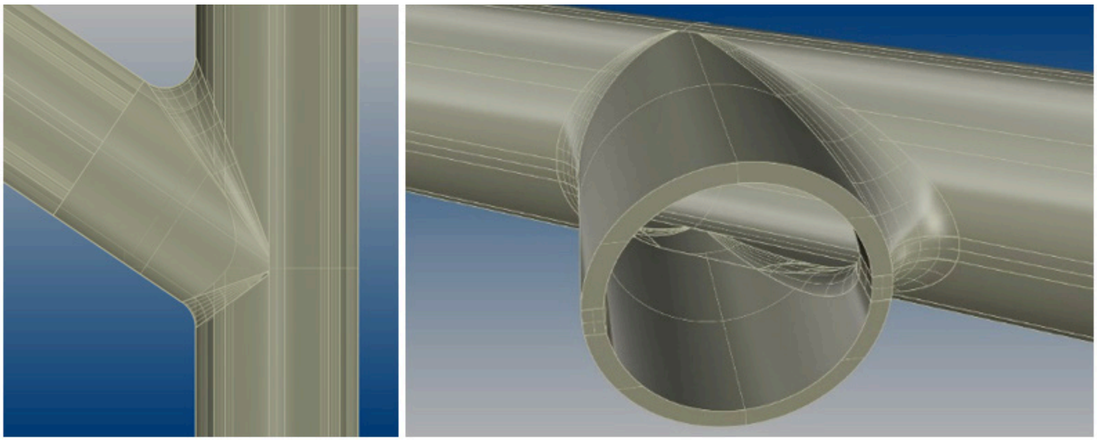

Figure 1 **Model showing the complex local curvature resulting at tunnel intersections with a non-orthogonal 'El-Teniente' style panel layout to access draw-points in block cave. Plan view left. Perspective detail right**

8 Yielding liners

Yielding liner systems were originally developed for NATM tunnelling to allow for large convergence of the primary liner to take place before the final liner is installed. This allows for most of the plastic deformation from the ground to occur, and the excavation to stabilise, minimising the loads acting on the final liner and thereby support costs. NATM tunnelling as a technique looks to maximise the support from the rock in weak ground conditions by allowing the ground to deform (Palmstrom 1993). This is achieved by inhibiting rock deterioration at the face by providing immediate 'light' support to the excavation and the subsequent monitoring of the supported excavation to confirm when deformations have stabilised to enable the installation of the permanent support. It is inherently linked to sequential excavation and support with an advance that is continuously varied depending on the prevailing ground conditions.

Yielding liners are normally formed from thick sprayed concrete liners that incorporate specialist engineered yield elements at discrete locations on the perimeter (Steiner 2019). Yield elements, sometimes termed Lining Stress Controllers (LSCs) are produced by several manufacturers and are engineered with bespoke stress strain characteristics to match the prevailing ground deformation characteristics. Typically, these elements exhibit a short linear elastic phase, followed by a long plastic plateau to provide the yield capacity, which is usually equivalent to 30-50% strain. Tunnel lining LSCs are variously fabricated from buckling steel rings and tubes and high-tech concretes incorporating special aggregates.

For block cave mines, the large deformation characteristics of the yielding liner systems allow the maximum support from the rock arch to be realised up to the point of global pillar failure by maintaining the integrity of the extraction tunnel surfaces. Potentially up to 5% convergence could be accommodated before a concrete liner becomes fully stressed and starts to break up, in comparison to standard sprayed concrete liners where 0.5% percent will likely exhibit substantial damage. It is crucial to realise that yielding liners only act as continuous shells from an axial compression perspective, and inherently have very limited shear and moment capacity at the yielding element locations; it is analogous to a chain. Consequently, the principal stress directions must be closely considered throughout the intended life of the liner to make sure that large horizontal components do not cause instability. In block caving, the stability of yielding liner systems may be increased through cable bolting the solid liner panels into the adjacent rock mass. Cable bolting, if used, is required to provide a ductile shear mechanism between the back of the liner segment and the ground so that slip can occur, without which the liner will not be free to contract and yield without damage.

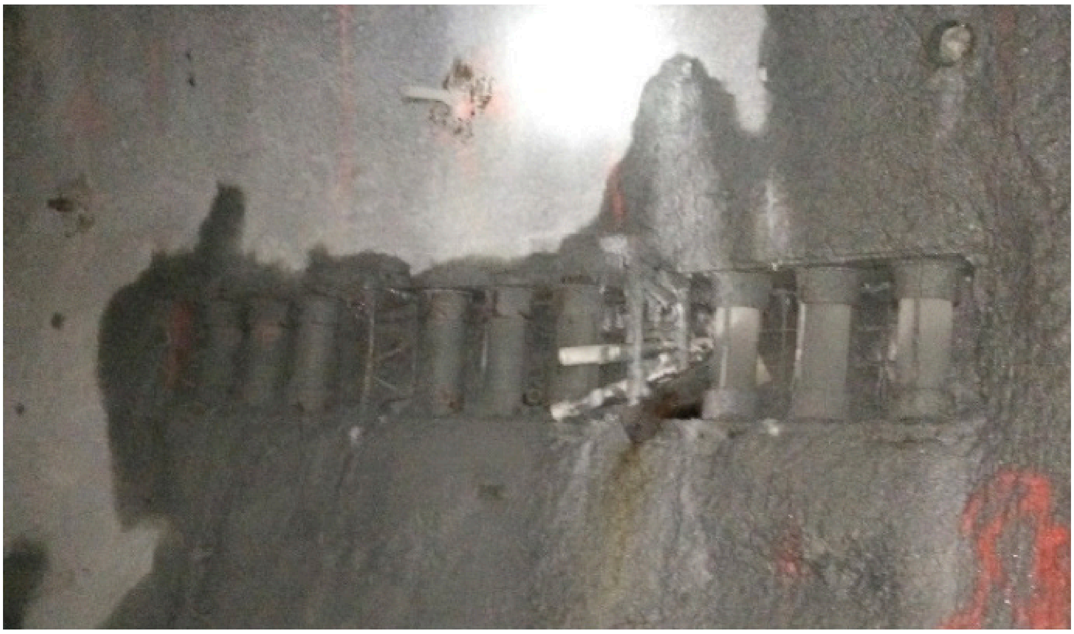

Figure 2 Lining stress controllers installed within a thick structural sprayed concrete liner for a mine production tunnel

9 Composite steel-concrete

No practical liner is capable of fully supporting a fully progressed cave, so understanding the philosophy of a hard-lining approach in block cave conditions is a prerequisite to design. If the lined excavation is significantly softer than the surrounding rock, then the majority of the load will be carried in the rock and the liner will only act to locally support the excavated face and prevent unravelling or spalling; the primary load path remaining through the mine pillars. Conversely, if the lined excavation is significantly stronger than the surrounding rock, then the liner will become the primary load path and also the mine pillar. In a deep block cave mine, the relative stiffness of a strong liner to the adjacent rock is likely to vary as the surrounding rock degrades and the apex support structures are eroded, consequently, the liner will always attract substantially more load as the cave progresses compared to the likely nominal initial support load that is required to provide support to the excavation. Ultimately, if a liner was sufficiently strong to survive the full caving process with cave propagation fully to the surface, then this liner would be attracting more than the full geostatic pressure at depth from surface, as the column of broken rock that it directly supports will experience additional drag down forces from the surrounding broken rock material that is not supported at depth.

Therefore, the goal of a hard liner is not to fully support the cave, but rather to provide maximum support to the apices above the intersections in order to delay the collapse of the major apex as long as possible and maximise ore recovery. As such the support system differs from a normal design with a specific design strength, instead being an aspirational design criterion where the strength required is the maximum that is practically achievable over and above a minimum that will facilitate a worst-case economic return. Whilst highly unusual in civil design practice, this aspirational design is considered to be fully in keeping with the balance of probabilities inherent in block caving.

A very strong liner in a block cave context might contain 10% steel embedded as H-section hoops within a concrete section in excess of 300mm thick. This support system has some similarities with high strength composite deep shaft liners and perhaps also traditional tubbing deep shaft solutions, however, neither of these precedents is readily adapted to the complex curvatures found at roadway and draw-point intersections. The geometry of the roadway intersections is imposed by the block cave sequence and layout and cannot be easily rationalised without extensive pillar loss. Consequently, a liner system that can be adapted to the complex curvature is required, that is also comparatively straightforward to construct. This may be achieved through the use of the highly repetitive planar steel frames embedded within a reinforced concrete shell, thereby minimising complex full-strength steel connections and unique parts. In addition to comparative ease of construction and high strength, the liner system must also exhibit uniform yield behaviour in order to maximise access time as the full cave loads develop, and this is aided by the simple and highly repetitive structure.

10 Comparison of structural shell support types

To provide further clarity on when a yielding liner might be of value over a high-strength liner or simply conventional sprayed concrete support, a series of finite element models were developed using ANSYS to examine the relative potential excavation support pressures and strains that could be generated. The potential excavation support pressures developed from these models are only of value when viewed comparatively to each other as there is only a uniform pressure load applied to the extrados of the liners and not a representative ground model. Similarly, the corresponding strain and deformation results are only illustrative of an idealised behaviour response rather than actual in-ground behaviour.

All models are 1 m wide with a 2.1 m external arc length and a 2 m radius, this geometry being indicative of a section of roadway. A plastic steel material model was implemented in combination with a multi-linear isotropic hardening concrete model. This enables cracking and crushing of the concrete to be modelled, so that the applied external pressure post-initial failure (visual distress) but prior to collapse can be estimated. A nominal 35 MPa concrete characteristic compressive stress has been used in this analysis with a corresponding 3.2 MPa maximum tensile stress.

The typical yielding liner model is 250 mm thick concrete reinforced with a light structural steel reinforcing mesh. The yielding liner elements are not explicitly modelled, and instead linear spring supports are used to allow 125 mm of circumferential compression (50% strain of a 250 mm thick LSC element) at 1 MPa pressure. This liner has intrinsically higher deformation capacity, although this is achieved through a corresponding nominal support pressure until the strain limit of the yield elements is reached. After the capacity of the yield elements is used up the concrete shell starts to act as a solid concrete liner. Failure ultimately occurs through crushing at the outside of the crown and at the inside of the supports, the section loss leading rapidly to instability and collapse. Note there is no net tension developed in the concrete, so the light reinforcement included is largely redundant with negligible impact on support strength.

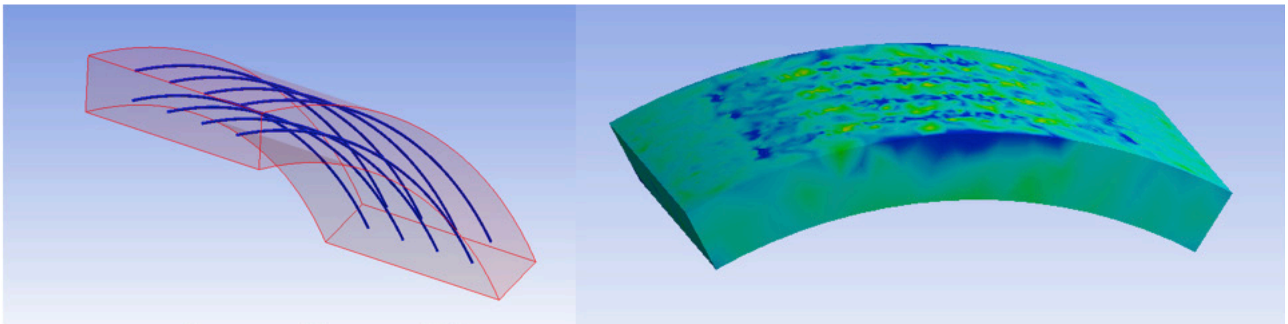

Figure 3 The yielding concrete liner as modelled in ANSYS. The blue areas of concrete (above the steel reinforcing bars) fail in crushing immediately prior to collapse

The high strength steel-concrete rigid liner is modelled at 350 mm thick concrete with an embedded single curved 350 mm deep steel H-Section in 250 MPa yield strength steel (Note, higher strength steels could easily be used to further increase performance if required). Additionally, it contains large 20 mm diameter steel reinforcing bars as distribution steel. To represent shell continuity fixed end supports are used which generate bending forces. The behaviour of this model in the ground will be very dependent on ground conditions and the configuration of concrete bar reinforcement. Potentially, this liner can be made to act fully compositely so that the concrete and steel yield at the same time. Whilst this configuration reduces maximum support pressure it is considerably easier to construct as there is no reliance on full composite action being achieved between the concrete and the steel which would require large amounts of shear reinforcement. Note, in a block cave scenario the load is expected to increase with the rock deformation rather than reduce as with conventional tunnel design scenarios, so there is no value to be had from the extra ductility of the steel yielding after the concrete.

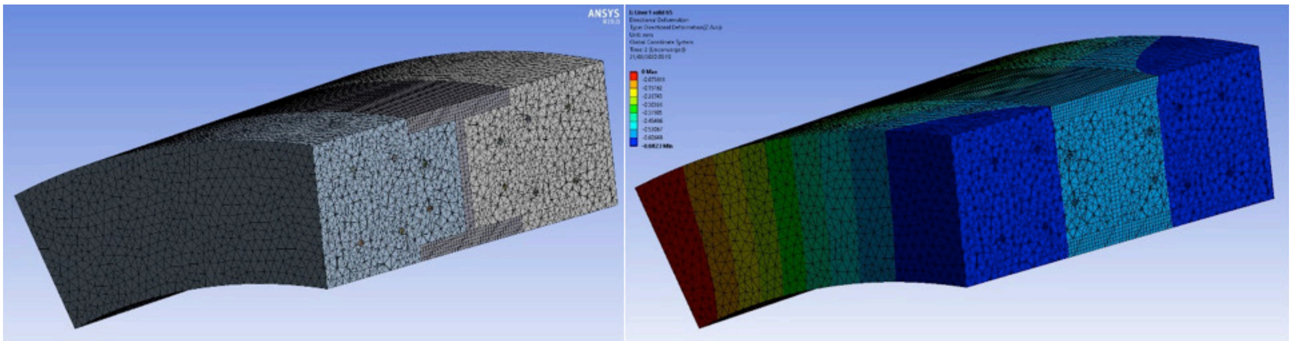

Figure 4 The high strength steel-concrete liner as modelled in ANSYS. Note the steel by being stiffer than the concrete attracts more load and deforms more than the concrete and consequently yields first. Note the image shows a half section to illustrate the variation in deformation across the section

The sprayed concrete model consists of a simple 150 mm thick concrete, with rigid fixed end supports. The fixity of the end supports indicate that this shell is structurally on the limit of compression behaviour with a small amount of net tension developed. As this is fundamentally a plain concrete shell, the inherent deformation capacity is limited by the 0.5% concrete strain limit, and the strength by the shell thickness. Given the arbitrary choice of loading, tensile forces are minor and insufficient to justify explicit reinforcement, although it is recommended that fibre reinforcement be routinely added to concrete that is expected to eventually break up above a roadway. This adds ductility to the concrete and limits spalling.

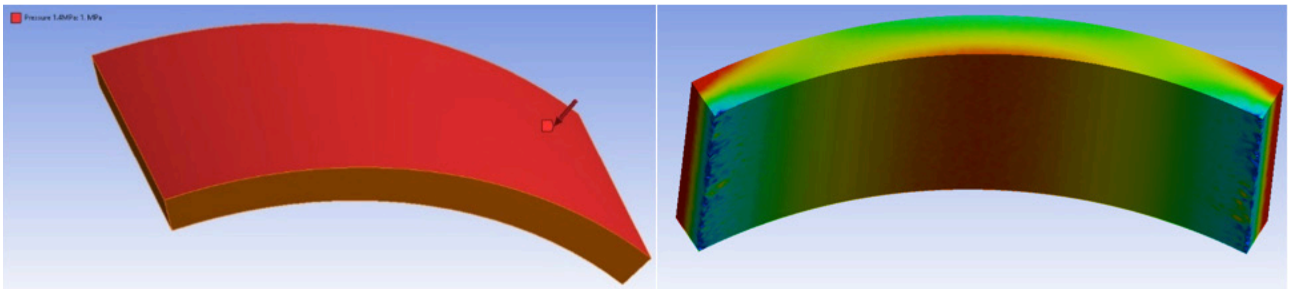

Figure 5 The 150mm sprayed concrete liner as modelled in ANSYS. Note that significant beam behaviour is evident in the shell at this thickness, with compressive crushing failure occurring local to the supports; this is in direct contrast to the yielding liner behaviour illustrated in Figure 5 above

The typical results from the analyses are summarised in table 2 below. The support working pressure for the yielding liner is based on the assumed 1 MPa crushing strength of the circumferential yield elements, whilst for the rigid liners it is considered to be the pressure that corresponds with the peak concrete compressive strength being at or below the characteristic concrete strength of 35 MPa. This being the 5th percentile strength, so 95% of the concrete should be stronger than this and effectively no damage should be seen. The undamaged maximum support pressure looks at a corresponding support pressure when the mean compressive strength of the concrete is reached; this is the most likely stress above which damage will start to occur. The beam action seen in the 150 mm thick model explains why comparatively this performs less well than the thicker liners relative to the liner cross sectional areas.

It should also be noted that the large steel section embedded in the steel-concrete rigid liner acts to concentrate stress prematurely in the concrete, so the concrete yields before the steel resulting in some minor local damage before the steel is fully utilised. The fully composite liner has a peak strength approximately three times higher than the undamaged liner strength. As stated previously, this end of life plasticity has no real value in a block cave scenario, so this liner should be re-engineered to ensure that the steel and concrete yield at about the same time, maximising support pressure.

Table 3 Comparative deformation and maximum support pressures for three structural lining support systems

	250 mm thick yielding concrete liner	350 mm thick high-strength steel-concrete rigid liner	150 mm thick sprayed concrete rigid liner
Relative cross sectional area	167%	233%	100%
Undamaged support working pressure (MPa) (maximum concrete stress below characteristic strength, 35 MPa)	0.14 (12%)	3.3 (367%)	0.9 (100%)
Undamaged maximum support pressure (MPa) (maximum concrete stress below mean strength value, 43 MPa)	3.38 (322%)	4.0 (380%)	1.05 (100%)
Undamaged maximum radial deformation (mm)	56	0.7	1.1
Peak support pressure (MPa) (last solution before collapse)	4.15 (319%)	9.0 (692%)	1.3 (100%)
Peak support radial deformation (mm)	70	1.7	1.5

11 Liner recommendations

Three distinct structural support systems have been illustrated and whilst the choice of which system is most suitable for implementation is impacted by many site specific economic and logistic factors, from a geological perspective the choice is much simpler.

If the ground is competent and self-standing on excavation with a limited degree of plastic deformation expected throughout caving and the rock mass remaining stable, then a sprayed concrete and rock bolt liner will be adequate. This is by far the most economical of the three liner systems outlined. The rock bolts act to anchor the liner to the rock mass, and sufficient reinforcement in the form of fibres, bars or mesh should be included to manage spalling and breakup as the cave progresses. This is a nominal concrete liner that is not expected to provide structural support to the excavation, whose main support will be provided by the rock bolts.

If the ground is competent and self-standing on excavation and significant plastic deformations of the rock mass are expected, then the yielding liner should be considered. This can safely accommodate relatively large convergence whilst preventing fragmentation of the excavation surface, and potentially provides a moderate level of structural support pressure to the excavation once the cave is well developed. However, as this liner is discontinuous with a series of stiff panels in between soft yield points, it may not function as intended if a large change in the principal stress direction of the ground occurs as may typically be seen from undercutting, abutment loading, abutment stress shadowing and finally cave load development. The full horizontal and vertical load cycle acting on the liner needs to be carefully assessed before implementation, and it is likely best used in post-undercut extraction level development, when vertical loading is expected to only increase.

If the ground is stable on excavation but of poor quality such that stability cannot be guaranteed during the undercutting phase with rock and cable bolting, and significant changes in principal stress direction are anticipated then the high-strength steel-concrete composite structural liner may be the preferred approach. This expensive liner can provide the maximum practical support to an excavation face in all directions. The final strength of this liner will be substantially affected by quality of materials and construction, and if there is a clear requirement for this liner then these should be prioritised. As the full design strength requires full composite action to be achieved between both the steel and the concrete parts to ensure that the strength of both materials act in unison rather than independently, it is easily conceivable that only half the design strength of the liner will be realised through poor construction quality and material procurement.

12 Summary and conclusions

Whilst civil tunnelling practice and mining practice have been practiced separately for many years, in challenging ground conditions a hybrid approach as outlined in this paper might be most appropriate. From a design standpoint this should consider actual failure and collapse scenarios by looking explicitly at the Managed Failure Limit State in preference to conventional structural ultimate limit states.

In ground that has limited stability on excavation then civil NATM techniques might be beneficial. These would include the use of mechanical excavation, incremental advance and sequential lining, and active ground monitoring to confirm ground reaction response and plastic deformation. In ground with a slow plastic response yielding liner solutions should be considered.

In ground that is stable on excavation but expected to undergo a significant increase in vertical pressure and corresponding large plastic deformations, as might be expected from block cave progression, then a yielding liner solution might be considered. This should have substantially better survivability than a conventional rock bolt and sprayed concrete liner, requiring less rehabilitation and maintenance as the block cave progresses.

In ground that is stable on excavation but expected to go through substantial principal stress changes from cave initiation and development, and ultimately become unstable as the plastic zone and cave process progresses, then a high-strength steel-concrete liner is likely to provide the most reliability and ore recovery from the extraction level. The performance of this liner will be greatly impacted by material and construction quality, and in light of the substantial cost, special care should be given to its material procurement and construction to maximise its performance.

In all cases where the stability of the apices between the drawbells is in question, then the substantial advantages of mechanical excavation should be considered to maximise the intact rock available at the extraction level.

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