Quantifying stresses and support requirements in the undercut and production level drifts of block and panel caving mines

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Abstract

A numerical modelling strategy has been developed in order to quantify the magnitude of induced stresses at the boundaries of production level and undercut level drifts for various in situ stress environments and undercut scenarios. The results of the stress modelling were in line with qualitative experiential guidelines and a limited number of induced stress measurements documented from caving sites.

A number of stress charts were developed which quantify the maximum boundary stresses in drift roofs for varying in situ stress regimes, depths and undercut scenarios. This enabled many of the experiential guidelines to be quantified and bounded.

A limited number of case histories of support and support performance in cave mine drifts were compared to support recommendations using the NGI classification system. The stress charts were used to estimate the Stress Reduction Factor for this system. The back-analyses suggested that the NGI classification system might be able to give preliminary estimates of support requirements in caving mines with modifications relating to rock bolt length and the support of production level intersections.

1. Introduction

In block and panel caving the primary fragmentation of the bulk of the ore to be mined is achieved by natural mechanical processes without recourse to drilling and blasting. A generalised depiction of the method can be seen in Fig. 1. At a particular depth in the orebody, a production or extraction level is developed beneath a block or panel of ore. At an elevation of usually between 10 and 20 m above the production level an undercut level is developed. The pillars between the undercut drifts are removed forming a slot beneath the orebody. Once a sufficient plan area of the undercut is developed, collapses of the cave back occur and this caved material swells to fill the void. Draw bells are constructed between the production and undercut levels and the fragmented ore is removed at the production level. This induces flow in the caved material and loss of support from the back of the undercut. Once a critical undercut dimension is reached progressive collapse of the cave back occurs as the support from the cave back is removed by drawing fragmented ore. The term hydraulic radius, which is defined as plan area divided by perimeter, is often used to describe the areal extent of the undercut.

One of the critical factors controlling efficient ore extraction in caving mines is the stability of the production level excavations and to a lesser extent those of the undercut. Observation and measurement of past and current caving operations indicate that the form and timing of the undercut has a significant influence on the stability of the extraction level drifts [1–4]. This is primarily due to the high stresses that are induced in the vicinity of an advancing undercut front.

Several factors have the potential to influence the level of induced stresses experienced in the production level excavations including the timing of the undercut relative to the production level development, undercut face shape, separation distance between the undercut and production levels, cave hydraulic radius, undercut direction and in situ stress regime. The goal of this study is to quantify the effects of these factors on production and undercut level excavation stresses. Knowledge of the level of stress that is likely to occur,
combined with an estimate of the rock mass strength, will allow prediction of the level of damage. With the additional knowledge of how design variables may be manipulated to reduce induced stresses and related damage, the undercut strategy, extraction layout design, and support design may then be optimised.

2. Methods of undercutting

There are basically three different undercutting methods (refer to Fig. 2): post-undercutting, pre-undercutting and advanced undercutting. These are described in the following sub-sections, the descriptions taken from Bartlett [3].

2.1. Post-undercutting

This method is also referred to as conventional undercutting. Undercut drilling and blasting takes place after development of the underlying production level has been completed. Cones, drawbells or continuous troughs are prepared ahead of the undercut and are ready to receive the ore blasted from the undercut level.

The advantages of such a system are that no separate ore handling facility on the undercut level is required, drifts on the undercut level are required for drilling and blasting only and can be 30 m apart, and the probability of ore compacting is very small. The main disadvantages are that the rock mass between the undercut and production level is subjected to high and variable stress and support must be installed well ahead of the undercut abutment zone, which can constrain undercut advance.

2.2. Pre-undercutting

In this method the undercut is completed ahead of development on the production level as an independent operation. The method can be considered a variant of advanced undercutting. The minimum horizontal distance by which the production level development lags behind the advancing undercut is often the separation distance between the two levels. This is referred to as the 45° rule (see Fig. 2).

Advantages of the method are that the production level is developed in a de-stressed environment, the undercut level can be mined independently of the production level, support levels on the production level are generally lower, and the broken ore in the undercut level acts as rockfill reducing abutment loads on the undercut face. Disadvantages include the need for a separate ore handling facility on the undercut level, undercut drifts must be developed 15 m apart to effectively remove swell, compaction of ore can be a problem and development of drawbells must be accomplished from the extraction level into broken rock on the undercut level.

2.3. Advanced undercutting

Undercut drilling and blasting takes place above a partially developed production level. The partial extraction at the production level can be either production drifts only or production drifts and drawpoint drifts. Drawbells are always prepared behind the undercut, usually adhering to the 45° rule.

Advantages of this approach include that only a limited ore handling facility on the undercut level is required, large unsupported drawbell excavations are not subjected to high abutment stresses, and less support rehabilitation is required in areas where undercutting precedes production level development. Disadvantages include that problems on the undercut level can affect the production level and vice versa, compaction of the broken ore can occur if not extracted quickly, and development of drawbells must be accomplished from the extraction level into broken rock on the undercut level.

3. Controls on undercut and production level behaviour

Based on experience gained in previous mining, some design guidelines have been established for undercutting that are aimed at minimising stress damage to production level excavations.

Bartlett and Croll [1] describe how changing from a post-undercut to an advanced undercut resulted in reduced support requirements and a marked reduction in rehabilitation of drifts and the support in drifts in the BA5 panel at Premier mine in South Africa. These authors also noted that as the area of the undercut increased stress levels on both the undercut and extraction levels increased. However, when continuous
caving was initiated stress levels were observed to drop. They also noted that keeping the leads and lags between adjacent drifts to less than 8 m could reduce damage to drifts.

From observations at Bell mine in Canada, Lacasse and Legast [5] noted that the speed of retreat of the undercut is an important factor and that weak zones should be the starting point of an undercut where possible. Laubscher [4] describes the technique used at Henderson mine of developing drawbells from the undercut level close to the cave front. In this way these excavations are subjected to high abutment stresses for less time. From stress measurements and observations at the Henderson mine, Brumleve and Maier [6] concluded that heavier support of drifts was necessary in poorer ground which had been exposed to abutment stresses for a longer time period.

Table 1 summarises five design guidelines proposed by Butcher [2] and the reasoning behind them. The reasons outlined in Table 1 illustrate that the ultimate goal of the experiential design guidelines is to reduce the level of or minimise exposure to high stress in the vicinity of the undercut front. If this can be achieved, then the damage to the production level will be reduced.

4. Prediction of undercut and production level stresses

A number of authors have used numerical models to study the stresses imposed upon undercut and production level drifts [7–12]. After reviewing these studies it was concluded that, although giving important results, the models did not adequately consider caved block geometry and only considered a single in situ stress regime. Conclusions derived from these studies were therefore considered site specific so that only limited general quantitative design guidelines could be developed from them.

A parametric numerical study was therefore carried out to examine the influence of the following factors on stresses in the production level of a caving orebody:

- undercut sequence,
- in situ stress regime,
Table 1
Experiential design guidelines for minimising damage to the production level in caving mines

<table>
<thead>
<tr>
<th>Guideline</th>
<th>Reasons</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Use advanced undercutting. If advanced undercutting is not possible,</td>
<td>High stresses exist below the undercut front that can cause damage to pre-existing excavations in the production level</td>
</tr>
<tr>
<td>minimise the percentage extracted for drift and drawpoint development in the production level</td>
<td>Higher extraction percentages in the production level will increase stress levels further</td>
</tr>
<tr>
<td>2. Minimise the creation of horizontal irregularities in the undercut</td>
<td>Stresses concentrate in these irregularities and increase the level of damage experienced in the production level</td>
</tr>
<tr>
<td>front</td>
<td>The longer excavations are subjected to the high stresses below the undercut front, the greater the damage will be</td>
</tr>
<tr>
<td>3. Prior to continuous caving being achieved, keep the rate of</td>
<td>Stresses decrease with distance below the undercut front</td>
</tr>
<tr>
<td>undercutting greater than the rate of damage to the extraction level</td>
<td>Stresses at the undercut front increase with the hydraulic radius necessary to achieve continuous caving</td>
</tr>
<tr>
<td>4. Place the undercut as high as practically possible above the production level</td>
<td>Stresses at the undercut front reduce once continuous caving is achieved</td>
</tr>
<tr>
<td>5. Advance the cave from the weakest ground to the strongest ground to</td>
<td></td>
</tr>
<tr>
<td>achieve continuous caving as early as possible</td>
<td></td>
</tr>
</tbody>
</table>

- separation distance between the undercut and production levels,
- hydraulic radius of cave,
- depth below ground surface.

4.1. Modelling strategy

In this study, numerical models were used to obtain predictions of elastic stresses at the boundaries of excavations in the undercut and production levels. A three-dimensional model FLAC3D [13] was used to accurately represent the shape of the cave and production level excavations.

In all cases, the rock mass and caved material were assumed to behave elastically. An elastic model was chosen to keep the analysis as simple as possible. Points on the boundaries of mining excavations undergo significant stress changes, including rotations of principal stress directions. With the type of model used it is possible to identify the potential failure zones around excavations and even how these failure zones may be modified by support and reinforcement. However, the results of non-elastic models are often sensitive to model mesh size and material properties such as the rate of strain softening and residual strength that are difficult to estimate [14,15]. Due to the wide range of rock mass behaviour that may be observed in cave mines, the effects of stress on the behaviour of undercut and production level drifts was not examined in this study through the use of elastic–plastic numerical models. Rather, an elastic-empirical approach was adopted in which empirical relations developed by Barton and Grimstad [16] were used to estimate damage levels through a comparison of elastic stresses and intact rock strength. In a recent keynote address Wagner [17] concluded that relatively simple experientially based guidelines, such as those proposed here, have tended to produce more robust predictive models in environments affected by mining induced stress.

The stress path followed can influence the strength of the rock mass surrounding an excavation. In this work the effect of the stress path was not explicitly studied with the numerical models but some account was taken of it when looking at the performance of excavations that undergo significant stress changes. This is discussed further in a later part of the paper.

Block caves are relatively large with undercut areas often ranging between 30,000 and 100,000 m² exploiting orebody heights of between 100 and 500 m. For this reason a dual stage approach to stress modelling was chosen. In the first stage, a large-scale model of the cave itself was used to determine induced stress levels in the vicinity of the undercut and production level drifts. The production and undercut level excavations were not included in this large-scale model but the volume of rock between the production and undercut levels was given a lower stiffness to account for the increased extraction there. The induced stresses from the large-scale model were then transferred to small-scale models of the undercut and production level drifts to obtain the maximum tangential stresses in the undercut, production and drawpoint drifts roofs. While stresses may be higher in other areas of the drifts (e.g. at drift intersections), the changes in the maximum stress in the drift roofs are considered representative and useful for illustrating the influence of the various factors on production and undercut level stresses. The changes in stress around the drawbells were not examined in this phase of the study and require use of a more sophisticated method for transferring stresses from the large-scale to the small-scale model (to account for the gradient in stress that occurs below the undercut). This method could be implemented in future numerical modelling runs.

The cases examined for post-undercut and advanced undercut sequences are outlined in Table 2. Refer to
Fig. 3 for the directions of the in situ stresses. A pre-undercut is considered to be a special case of an advanced undercut. The production level layout used in the parametric study was the same as that used at Teniente-4 South [8]. In all cases, the undercut height was constant at 4 m. In order to eliminate depth as a variable, all of the stress results were normalised to the vertical stress. Tangential stresses in the roofs of excavations were computed at various points from 45 m in advance of the cave front to 45 m underneath the cave.

The separation between the undercut and production level was 15 m floor to floor for all cases presented. A number of runs were carried out at separations ranging between 10 and 20 m. An approximately 10% difference in the magnitude of boundary stresses was noted for every 5 m difference in separation; i.e. boundary stresses at a 20 m separation would be 10% lower than those presented and would be 10% higher at 10 m.

The effect of caving height on abutment stresses was investigated by comparing the stresses at the undercut front for cave heights of 0, 75 and 150 m. At a hydraulic radius of 25 m in a hydrostatic in situ stress field ($\sigma_{h1} = \sigma_{h2}$), the maximum induced stress was very similar for cave heights of 75 and 150 m. However, the maximum induced stress in both these cases was 15% lower than what was predicted for the case where no caving has occurred (cave height of 0 m). This agrees with experiential guidelines, which suggest that cave abutment stresses will drop when the cave height increases at the onset of continuous caving.

### Table 2

<table>
<thead>
<tr>
<th>Cases examined in parametric study of production and undercut level stresses</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ stress ratio $\sigma_{h1}:\sigma_{h2}:\sigma_v$ ($\sigma_{h1}$ is parallel and $\sigma_{h2}$ is perpendicular to the direction of cave advance, see Fig. 3)</td>
</tr>
<tr>
<td>Cave geometry</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>1:1:1</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>1:2:1</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>1:1:2</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>1:3:2</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>1:2:3</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

4.2. Case study: teniente-4 south

The purpose of the case study is to validate the modelling approach through comparison of predicted elastic stresses with in situ stress measurements at the Teniente-4 South cave. The Teniente-4 production level is located at a depth of approximately 600 m below ground surface. In 1992, the Teniente-4 South sector was being mined by panel caving with LHDs at a rate of 35,000 tons per day. The rock above the undercut consists mainly of primary andesite and intrusive primary diorite with the rock mass properties shown in Table 3. The in situ stress field at Teniente-4 South,
which is influenced by the local topography and surrounding caves, is shown in Table 3.

The elastic properties used in the model are shown in Table 4.

The undercut and extraction levels at Teniente-4 South are fully developed 150–200 m ahead of the caving front (post-undercut). The undercut level is developed 18 m above the extraction level and consists of 4 x 3.6 m drifts spaced 30 m centre-to-centre. In the extraction level, production drifts of similar size lie directly beneath the undercut drifts and are intersected every 15 m by drawpoint drifts at an angle of 60°. Drawbells are excavated along the drawpoint drifts and are 15 m long, 12 m high and 12 m wide. Caving at Teniente-4 South is initiated by the creation of a flat undercut through drilling and blasting from the undercut drifts.

Numerical models of Teniente-4 South were constructed in FLAC3D using the modelling strategy outlined previously to obtain predictions of stress in the undercut and extraction levels near the cave front. In order to improve confidence in the ability of the three-dimensional elastic model to obtain reasonable predictions of stress near the cave front, stresses from the large-scale model were compared to the stresses that were measured in situ at the cave front. The predicted and measured stresses are given in Table 5. As shown, the predicted vertical stresses drop off rapidly within the first 5 m ahead of the abutment and the measured value falls within the range predicted by the model. The horizontal stresses are overpredicted and are within 20% of the measured value at a point 5 m ahead of the cave front. This suggests that the modelling approach may provide a reasonable estimate of stresses near the cave front.

4.3. Production level stresses—post-undercut sequence

Small-scale models of an LHD extraction level were used to obtain estimates of the maximum induced stress around the production drifts for a separation between the undercut and production levels of 15 m. Stresses from large-scale models were used to specify initial conditions in the small-scale models. The predicted maximum tangential stresses normalised to in situ vertical stress in tunnel roofs for each in situ stress regime are plotted in Fig. 4 as a function of distance from the cave boundary for varying hydraulic radii.

Fig. 4 indicates that stresses in the production level production drifts generally increase with hydraulic radius, which is in accord with the experiential guidelines. In general, the maximum tangential stress in the roofs of production drifts increase by about 20% with a doubling of hydraulic radius to achieve continuous caving. Exceptions were for $\sigma_2$, $\sigma_{h1}$: $\sigma_{h2}$ = 1:2:3 and 1:1:2 ($\sigma_{h1}$ parallel and $\sigma_{h2}$ perpendicular to the direction of cave advance) where stresses in the production drift roof were high but largely unaffected by the size of the cave. In all the in situ stress regimes modelled except those noted above, there is a significant fall in induced stress from the peak as the cave passed over the drifts. In the majority of in situ stress cases, significant stress changes are apparent; i.e. induced stress levels rise quite significantly as the cave approaches that section of the drift and falls sharply as the cave passes over the top.

4.4. Production level stresses—advanced undercut sequence

An advanced undercut sequence was examined for the in situ stress cases outlined in Table 2. Advanced undercutting was examined by making two changes to the large-scale post-undercut model:

1. The undercut is extended out from the cave front a specified distance. The broken rock in the undercut is assumed to have the same properties as the caved material.
2. The stiffness of the extraction level ahead of the cave front is increased to represent partial development.

<table>
<thead>
<tr>
<th>Stress</th>
<th>Measured (MPa)</th>
<th>Predicted (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near undercut front</td>
<td>54</td>
<td>63</td>
</tr>
<tr>
<td>At undercut front</td>
<td>38</td>
<td>51</td>
</tr>
<tr>
<td>Five metres ahead of undercut front</td>
<td>28</td>
<td>44</td>
</tr>
</tbody>
</table>

Table 3

<table>
<thead>
<tr>
<th>Stress Magnitude (MPa)</th>
<th>Dip (deg)</th>
<th>Dip direction (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_1$</td>
<td>36</td>
<td>3</td>
</tr>
<tr>
<td>$\sigma_2$</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>$\sigma_3$</td>
<td>14</td>
<td>61</td>
</tr>
</tbody>
</table>

Table 4

<table>
<thead>
<tr>
<th>Young’s modulus (GPa)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock mass</td>
<td>30</td>
</tr>
<tr>
<td>Caved rock</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Table 5

In situ stress field at Teniente-4 South [8]

<table>
<thead>
<tr>
<th>Stress Magnitude (MPa)</th>
<th>Dip (deg)</th>
<th>Dip direction (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_1$</td>
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<td>28</td>
</tr>
<tr>
<td>$\sigma_3$</td>
<td>14</td>
<td>61</td>
</tr>
</tbody>
</table>
For this study, partial development ahead of the cave front consists of production drifts only or production and drawpoint drifts.

The small-scale model with only the production drifts or production drifts and drawpoint drifts excavated was used to examine stresses in a partially developed production level below the advanced undercut. Results of these model runs are shown in Figs. 5–7.

Again, in general, the induced stresses at the boundaries of excavations increase with hydraulic radius. For most in situ stress regimes and cave orientations again a doubling of the hydraulic radius leads to about a 20% increase in induced stress. Exceptions can occur in the roof of drifts where the principal stress is horizontal and parallel to the direction of the drift. Induced stresses in production drifts are similar whether drawpoint drifts are excavated in advance of mining or not. In most in situ stress regimes, with the exception of some where the major principal stress is horizontal and perpendicular to the drift direction, significant stress changes occur. In the main, induced stress levels are significantly lower with the cave front 15 m in advance of the section of drift being investigated. This gives some credence to the so-called 45° rule. Induced stress levels continue to fall under most stress conditions, albeit at a reduced rate, as the distance between the cave front and drift section increases. However, the extent of the stress changes decreases significantly for excavations that are not in advance of the cave front.

Fig. 4. Predicted normalised tangential stresses in production drift roofs for a post-undercut.
4.5. Undercut level stresses

A small scale model assuming 4 m wide and high drifts was constructed for the undercut level and stresses obtained from large-scale models at this level imposed upon the model for the in situ stress regimes noted previously. Maximum induced tangential stresses in the back of drifts are shown in Fig. 8.

In general, the magnitude of the induced stresses increase with increasing hydraulic radius to continuous caving. A doubling of the hydraulic radius leads to an approximately 30% increase in induced stress close to the cave front. Induced stresses are generally higher the closer the drift section is to the cave front falling rapidly over the first 15 m away from the front. Drift sections therefore experience a gradual increase in induced stress as the cave front approaches. The magnitudes of the maximum induced stresses are of course higher at the undercut level than at the extraction level.

4.6. Summary from parametric study

The results from the parametric study are generally in accord with the qualitative experiential guidelines given in Table 1. This gives additional confidence in the modelling strategy adopted. Additionally a number of these experiential guidelines have been quantified and bounded.
For production level drifts:

- As expected the magnitude of induced boundary stresses in drifts is sensitive to the in situ stresses and their orientation.
- If the hydraulic radius to achieve continuous caving doubles, maximum induced stresses in extraction level drifts increase by approximately 20% in most in situ stress environments. Exceptions to this occur in drift roofs where the major principal stress is approximately horizontal and perpendicular to the direction of drift advance.
- When the vertical separation between the undercut and production levels is in the range of 10–20 m, an increase or decrease in the separation distance of 5 m leads to an approximate difference in induced stresses at drift boundaries of 10%; i.e. an increase in separation of 5 m leads to a 10% decrease and a 5 m decrease leads to a 10% increase.
- When continuous caving is achieved for a hydraulic radius of 25 m in a hydrostatic in situ stress field, the maximum induced stress reduces by 15% and the vertical induced stress reduces by 30% at the undercut level. At the production level drifts, the maximum induced stress reduces by 2% and the vertical induced stress reduces by 14%.
- Significant induced stress changes occur for many in situ stress states; i.e. stresses increase as sections of

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**Fig. 6.** Predicted normalised tangential stresses in production drift roofs for an advanced undercut with drawpoint drifts.
drifts are approached by the advancing cave and decrease as the cave passes over. Exceptions to that are in drift roofs where the maximum in situ principal stress is approximately horizontal and perpendicular to the cave advance.

- In the main for an advanced undercut induced stress levels are significantly lower with the cave front 15 m in advance of the section of drift being investigated. This gives some credence to the so-called 45° rule. Exceptions are again in drift roofs where the maximum in situ principal stress is approximately horizontal and perpendicular to the drift advance. Induced stress levels generally continue to fall, albeit at a reduced rate, more than 15 m from the cave front.

- For an advanced undercut, any excavations in advance of the cave front are subjected to induced stresses similar to those in a post-undercut. Only the excavations formed behind the cave front significantly benefit from an advanced undercut.

For undercut level drifts:

- In general the magnitudes of the induced stresses increase with hydraulic radius up to continuous caving being achieved.

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![Graphs showing tangential stresses in drawpoint drift roofs for advanced undercut with drawpoint drifts](image)
Induced stresses are generally higher the closer the drift section is to the cave front, falling rapidly over the first 15 m away from the front. Exceptions are in drift roofs where the maximum principal stress is horizontal and perpendicular to the drift advance.

The magnitudes of the maximum induced stresses are of course higher at the undercut level than at the extraction level.

5. Estimating damage and support

The stress charts shown in Figs. 4–8 will enable the stress effects of different undercutting strategies to be quantified for different in situ stress regimes. These in themselves are therefore a useful extension of the experiential guidelines. It should also be possible to infer rock mass damage and support requirements utilising this information.

In the updated NGI classification system [16] the maximum tangential stresses ($\sigma_\theta$) at the boundary of a drift, normalised to the intact uniaxial compressive strength ($\sigma_c$), are used to infer the effects of stress through the stress reduction factor (SRF). Table 6 outlines the effects of stress for varying tangential stresses at the boundaries of drifts.

A preliminary estimate of the effect of stress upon extraction and undercut level drifts should now be
possible by estimating maximum tangential stresses from Figs. 4–8, normalising those to the intact rock uniaxial compressive strength and then referring to Table 6. Given that the maximum tangential stresses are calculated as a function of distance from the cave front, it should also be possible to estimate stress effects at varying distances from the cave front.

With scanline mapping or core logging data for an individual site the SRF can then be used with this data to estimate the tunnelling index, \( Q \) [16]. A database of over 1000 case histories has been collected and an empirical chart has been developed to estimate support categories based upon the size and use of the tunnel and the estimated \( Q \) value.

The bulk of the case histories in the NGI classification database are civil engineering tunnels in which the induced stresses are due to the excavation of the tunnel only. In the case of the drifts in a caving mine, the induced stresses are due to both the excavation of the drift and the redistribution of the stress field around the cave. Additionally, drifts at the production level in advance of the cave front are subjected to increasing compressive stresses as the cave advances towards them, followed by a decrease in stress levels as the cave passes over. Any influence that stress changes may have is not accounted for in the empirical database developed for the NGI classification system.

The procedure of computing maximum tangential stresses at the boundaries of excavations and using these together with rock mass quality indices and support performance records is well developed. The same procedure as used in the NGI classification system could therefore be used to assess support requirements for caving mines in variable geotechnical environments. What is lacking in caving is a significant database of well-documented support and support performance case histories to enable support categories to be developed.

A number of case histories specific to caving mines have been collected as will be discussed in the next section of this paper but are insufficient to develop an empirical relationship. Comparisons between the support requirements predicted by the NGI classification system and those installed at the caving case study sites were made and these are outlined in a later part of the paper. In this way, some indication can be given as to whether or not the current estimates of support based on the tunnelling quality index \( Q \) can be used in caving in the absence of a case history database specific to this mining method.

### 6. Case histories

A number of case histories were collected from the Andina, El Teniente, Northparkes and Palabora caving mines. Although limited in number, the case histories come from a wide range of geotechnical environments and the full range of undercut methods.

Use is made of the stress charts (Figs. 4–8) to estimate the maximum tangential stresses in the roofs of drifts at the case study sites. These tangential stresses are then normalised to the intact strength of the host rock at that site and a Stress Reduction Factor determined by referring to Table 6. \( Q \) values are then determined for the various drifts and support requirements estimated using the NGI support guidelines. A comparison is then made between the estimated support and the support that is installed, taking into account the performance of the support at the sites.

#### 6.1. Andina Panels II and III

These panels are both extracted by a post or conventional undercut. Panel II is located entirely in a relatively weak rock mass, which has the local term secondary rock. The separation between the undercut and extraction level is 15 m. The in situ stress regime is \( \sigma_v: \sigma_h1: \sigma_h2 = 9:18:13 \text{ MPa} \) and the average \( Q \) of the rock mass is 0.4. \( Q' \) is the index, \( Q \) assuming that the joint water and stress reduction factors are both equal to 1. This allows the rock mass to be rated independently of the effect of stress [18]. Continuous caving is reported to have occurred at a hydraulic radius of 26 m. The average uniaxial compressive strength of the intact host rock is estimated at 108 MPa.

Panel III is a mixture of secondary (weak) and primary (moderately strong to strong) rock mass. Initial continuous caving was achieved in the weaker rock mass (\( Q' \) average of 0.4) at a hydraulic radius of 11.7 m. The in situ stress regime in Panel III is

### Table 6

<table>
<thead>
<tr>
<th>( \sigma / \sigma_c )</th>
<th>Stress level and effect</th>
<th>SRF</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.01</td>
<td>Low stress, near surface, open joints</td>
<td>1.0</td>
</tr>
<tr>
<td>0.01–0.3</td>
<td>Medium stress, favourable stress conditions</td>
<td>0.5–2</td>
</tr>
<tr>
<td>0.3–0.4</td>
<td>High stress, very tight structure. Usually favourable to stability, maybe unfavourable to wall stability</td>
<td>1</td>
</tr>
<tr>
<td>0.5–0.65</td>
<td>Moderate slacking after &gt; 1 h in massive rock</td>
<td>5–50</td>
</tr>
<tr>
<td>0.65–1.0</td>
<td>Slacking and rockburst after minutes in massive rock</td>
<td>50–200</td>
</tr>
<tr>
<td>&gt;1.0</td>
<td>Heavy rockburst (strain-burst) and immediate dynamic deformations in massive rock</td>
<td>200–400</td>
</tr>
</tbody>
</table>
\[ \sigma_v: \sigma_{h1} : \sigma_{h2} = 17:22:13 \text{ MPa}. \] The average uniaxial compressive strength of the intact host rock is estimated at 108 MPa.

Drift support is the same in both panels. In the undercut levels the drifts are generally unsupported with spot bolting but wooden props are often erected in the immediate vicinity of the cave front. Drifts are 3.6 m high and wide. In the extraction level 2.4 m long and 22 mm diameter fully grouted rebar are placed in the back of production drifts on a 1 m spacing, with 2.5 m \( \times \) 16 mm cable bolts in the walls on 0.5 m (vertical) \( \times \) 1 m (horizontal) spacing. Mesh with 100 mm of shotcrete is also placed. Additionally, 8 m long cables in the back are placed at intersections on 2 m spacing. Generally drift conditions are good in both the undercut and extraction levels and the support where placed is adequate for the conditions at all sections of the drifts relative to the cave front.

In Panel II the NGI classification system predicts spot bolting only up to immediately adjacent to the cave front in the undercut level. In production drives 1.7 m long rock bolts spaced at 1.5 m with 50 mm of fibre reinforced shotcrete are recommended. At intersections on the production level 1.8 m long rock bolts at 1.3 m spacing and 100 mm of fibre reinforced shotcrete are considered appropriate.

In the weak secondary rock in Panel III spot bolting is predicted using the NGI system as the support for the undercut level drifts 15 m back from the cave front. Immediately adjacent to the cave front, 1 m long bolts with 1.3 m spacing are the predicted support requirements. In production drives 1.7 m long rock bolts spaced at 1.5 m with 50 mm of fibre reinforced shotcrete are recommended. At intersections on the production level 1.8 m long rock bolts at 1.3 m spacing and 100 mm of fibre reinforced shotcrete are the predicted support.

6.2. El Teniente Esmeralda panel

The Esmeralda panel is currently being extracted as a pre-undercut. The rock mass has a \( Q' \) of 5.3 up to continuous caving being achieved at a hydraulic radius of 27 m. The in situ stress regime is \( \sigma_v: \sigma_{h1} : \sigma_{h2} = 26:34:34 \text{ MPa}. \) The separation between the undercut and production level is 18 m. The average uniaxial compressive strength of the intact rock is estimated to be 100 MPa.

Undercut level drifts are 4 m wide and 3.6 m high. These drifts are reinforced with 2.3 m long resin anchored bolts with a 1.0 m spacing and mesh. Generally the support is adequate, damage being confined to local areas where the rock mass is more fractured.

The so-called 45° rule is practiced, where production level drifts are developed at least 18 m behind the cave front. The drifts are 4 m wide and 3.8 m high. Reinforcement and support in these drifts consists of 2.3 m long grouted bolts spaced at 1 m. Seventy-five millimetre of mesh reinforced shotcrete is also placed. At intersections 8 m long cement grouted cables are installed on a spacing of 1.5–2 m. Cables are also wrapped around ribs. In general the support is performing well and experimentation with a reduced level of support is being considered.

Support predictions in the undercut level using the NGI classification system and the stress charts outlined in Fig. 5 is rock bolts at a spacing of 1.1 m with 75 mm of fibre reinforced shotcrete assuming the maximum tangential stress close to the cave front. The length of rock bolts is 2.3 m based on the size of the excavation only and 1.2 m if an ESR of 3 is assumed.

In the production level drifts rock bolts spaced at 1.7 m with 45 mm of fibre reinforced shotcrete is the predicted support. At intersections rock bolt spacing is 1.4 m with 75 mm of fibre reinforced shotcrete. A rock bolt length of 2.3 m is recommended based upon the absolute dimensions of the drifts and 1.8 m long if an ESR of 1 is used.

6.3. Northparkes Lift 1

The Northparkes Lift 1 block cave was an advanced undercut, with the production level drifts only being developed ahead of the advancing undercut. The in situ stress regime is \( \sigma_v: \sigma_{h1} : \sigma_{h2} = 12:23:15 \text{ MPa}. \) The average \( Q' \) of the rock mass in the vicinity of the drifts is 8.7. The undercut was extended to a hydraulic radius of 44 m but continuous caving was not achieved and the cave was induced until reaching a weaker rock mass. A double undercut is extracted, each undercut being approximately 20 m in height. The lower undercut is developed between a fully developed upper undercut and production level. The stress charts do not take such a scenario into account and so the support and support performance in the lower undercut is not considered in this study. The average uniaxial compressive strength of the intact host rock has is estimated at 110 MPa.

In the upper undercut, drifts are 4.2 m wide by 4.5 m high. Installed support consists of 2.1 m long split sets on a spacing of 1.25 m (8 bolts per ring). In general the support performed adequately.

At the production level, drifts are 4.2 m wide by 4.2 m high. Support consists of 2.4 m long resin grouted rock bolts on a \( 1 \times 1 \) m square pattern and 50 mm of fibre reinforced shotcrete. At intersections 6 m long fully grouted cablebolts are installed on a spacing of 2 m. Expamet straps are installed at bullnoses. The support is performing well and it is considered that it might have been possible to install a reduced level of support.

Support predictions using the NGI classification system (assuming the maximum tangential stress immediately adjacent to the cave front) for the top
undercut drifts are 1 m long bolts (assuming an ESR of 3) spaced at 1.6 m with 45 mm of fibre reinforced shotcrete or a bolt spacing of 1.2 m with no shotcrete. Rock bolt lengths of 2.5 m are predicted assuming the absolute dimensions of the excavations.

For the production level drifts spot bolting is recommended, with 1.6 m long bolts spaced at 1.6 m and 50 mm fibre reinforced shotcrete in drawpoint drifts. At intersections between production level and drawpoint drifts the predicted support are 1.8 m long rock bolts spaced at 1.3 m with 90 mm of fibre reinforced shotcrete. Rock bolt lengths of 2.4 m are recommended based upon the size of the excavation only.

6.4. Palabora

The Palabora block cave is being extracted using an advanced undercut. At the time of writing this paper the hydraulic radius of the undercut was 16 m. The average $Q'$ of the main host rock is estimated to be 23. In situ stress measurements indicate a hydrostatic state of stress of 38 MPa. The average uniaxial compressive strength of the intact host rock is estimated at 140 MPa.

Undercut level drifts are 4 m wide by 4 m high. Support consists of 2.4 m long resin grouted rebar on a spacing of 1.25 m. Additionally weld mesh is installed with 1.0 m long split sets to hold the mesh. Fibre reinforced shotcrete nominally 50 mm thick is used where ground conditions are considered to warrant it. Some spalling of sidewalls is evident remote from the cave front even after bolts are placed but before mesh or shotcrete are installed. The shotcrete and mesh prevent further problems and the full support appears to be working well close to the cave front at this hydraulic radius.

At the production level, drifts are 4.5 m wide by 4.2 m high. Rock bolt support is the same as for the undercut level with 2.4 m long resin grouted rebar on a spacing of 1.25 to 1.0 m above the floor of the drift. Additionally 50 mm of fibre reinforced shotcrete is placed. At intersections 8 m long cement grouted cables are installed at approximately 2 m centres. Trussing and mesh are also placed at bullnoses and camel backs at intersections. The full support appears to be working well at the current undercut dimensions.

In the undercut level drifts the estimated support categories close to the cave front using the NGI system are rock bolts with a spacing of 1.3 m and 70 mm of fibre reinforced shotcrete. At intersections rock bolt spacing is estimated to be 1.2 m with the addition of 90 mm of fibre reinforced shotcrete. Away from the influence of the cave front moderate slabbing is expected but only spot bolting is recommended. A rock bolt length of 2.3 m is recommended based upon the size of the excavation only but these are 1.2 m long if an ESR of 3 is assumed. The support categories predicted from the classification system are similar to those installed and which appear to be working well. An exception is rock bolt length, which is predicted to be much shorter than actually installed unless the absolute dimensions of the drift is used without recourse to the ESR, in which case the rock bolt length recommended and that installed are similar.

In the production level drifts recommended support are 1.7 m long rock bolts with a spacing of 1.5 m and 50 mm of fibre reinforced shotcrete. At intersections 1.8 m long rock bolts (assuming an ESR of 1.6) with a spacing of 1.3 m and 90 mm of fibre reinforced shotcrete are recommended. If the absolute dimensions of the drifts are assumed (an ESR of 1) the recommended rock bolt length is 2.4 m. The density of support recommended by the NGI system is similar to that installed with the exception of the fact that cable bolts are placed in intersections. Recommended and installed rock bolt lengths are similar only if the absolute dimensions of the drifts only are taken into consideration.

6.5. Summary of case histories

The back-analysis of a limited database gives an indication that, with certain modifications, it should be possible to use the stress charts developed as part of this study in combination with the support recommendations of the NGI classification system to predict support requirements in caving mine drifts. Additional case histories are required to confirm this preliminary finding.

In undercut level drifts support predictions using the NGI classification system and stress charts to estimate boundary tangential stresses are similar to those used in practice, with the exception of the lengths of rock bolts installed. Rock bolt lengths recommended by the NGI system are generally substantially less than those installed in caving mine drifts. However, if the bolt length is based solely on the absolute dimensions of the drifts (i.e. an ESR of 1 is assumed) then recommended and installed rock bolt lengths are very close. It would appear therefore that a preliminary assessment of undercut level drift support requirements might be possible in undercut drifts if an ESR of 1 is used to estimate rock bolt length only.

Support requirements recommended by the NGI classification system for production level drifts appear to be generally similar to those installed in practice, with the exception of rock bolt length and the type of support used at intersections. Rock bolt lengths predicted are slightly less than those installed in practice if an ESR of 1.6 is assumed. However, if an ESR of 1 is assumed for rock bolt length only they are similar. Also, in most caving operations cement grouted cable bolts, generally 8 m long and spaced between 1.5 and 2 m apart, are installed in intersections at the production level.
It may be that with respect to rock bolt length the support being installed in caving mine drifts is overly conservative. To confirm whether or not this is the case would require some caving mines to trial reduced length rock bolts and the performance of the support evaluated with respect to the longer bolts being installed in practice.

The maximum induced tangential stress experienced by the drifts are used to determine support requirements. In practice stresses increase as the caving front comes closer to sections of drifts. In production level drifts stress levels then generally fall as the caving front moves over the top and away from the sections of interest. Where the support installed in drifts is adequate to withstand the maximum induced stresses, the changing stresses do not appear to have an adverse impact upon drift performance.

7. Conclusions

A numerical modelling strategy has been developed in order to quantify the magnitudes of the induced stresses at the boundaries of production level and undercut level drifts for various geotechnical environments and extraction layouts and sequencing. A case study where induced stresses had been measured was back-analysed and model results were similar to those measured. The results obtained from stress modelling were also compared against a number of experiential qualitative guidelines and they were generally in line with them. These gave confidence in the modelling strategy adopted. The stress modelling enabled a number of the qualitative experiential guidelines to be quantified and bounded, which is a useful extension to current understanding and which should aid the design process. Stress charts are presented which quantify the maximum boundary stresses in drift roofs for varying in situ stress regimes. These boundary stresses are normalised to the vertical stress to account for variations in orebody depth.

A limited number of case histories of support and support performance in cave mine drifts were compared to support recommendations using the NGI classification system. The stress charts were used to estimate the stress reduction factor for this system. Differences between predicted and installed support related to rock bolt length and the support of intersections at the production level. Nevertheless, the back-analyses did suggest that the NGI classification might give an acceptable preliminary estimate of support requirements in cave mines with modifications. These modifications relate to estimates of rock bolt length based upon the absolute dimensions of the drifts and the installation of fully grouted cable bolts (nominal 8 m long at spacings of 1.5–2 m) at production level intersections.

It may be that with respect to rock bolt length the support being installed in caving mine drifts is overly conservative. Trials with shorter rock bolts would be needed to confirm if this is the case. The changing stresses experienced by caving mine drifts as a result of the changing proximity of the caving front did not appear to adversely affect the performance of documented case histories. The fact that the drifts appeared to be supported adequately for the maximum induced stress may be the reason for this. Back-analyses of more case histories are required to confirm all the findings with respect to support prediction documented in this paper.

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