Strategies for Minimising and Predicting Dilution in Narrow Vein Mines – The Narrow Vein Dilution Method

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ABSTRACT

An improved ability to predict dilution for narrow vein deposits enables more accurate economic comparisons between mechanised longhole stoping and other narrow vein mining methods, as well as reducing uncertainty surrounding dilution estimates for deposits at the prefeasibility/feasibility stage. This paper proposes narrow vein dilution prediction and minimisation strategies for both greenfield sites and operating mines, respectively. The narrow vein dilution method (NVD method) is a tool for more accurately predicting longhole narrow vein dilution. The method is based on a new concept called benchmark stoping width. Benchmark stoping width is based on probabilistic analysis of overbreak distributions from a typical longhole narrow vein mine. The premise for the NVD method is that dilution associated with longhole stoping can be predicted using the benchmark stoping width. In addition to dilution prediction, the NVD method also includes strategies for narrow vein dilution minimisation generally, including; filling, cablebolting, stress relaxation, extraction sequencing and blast overbreak.

INTRODUCTION

Dilution can be defined as the contamination of ore by non-ore material during the mining process (Wright, 1983). Dilution is associated with indirect and direct costs (Pakalnis, 1986; Elbrond, 1994; Pakalnis, Poulin and Hadjigeorgiu, 1995; Villaescusa, 1998; Bock, 1996; Bock, Jagger and Robinson, 1998; Revey, 1998; Scoble and Moss, 1994). An improved ability to predict dilution enables the economic risks associated with unplanned dilution to be reduced.

Brewis (1995) defines narrow mining to be the working of mineral deposits typically no more than two to three metres wide, with a dip exceeding 50 to 55 degrees (an angle at which broken ore can be expected to flow). Historically, conventional narrow vein mining has been associated with high operating costs and low capital costs (Brewis 1995; Paraszczak 1992; Robertson, 1990).

Over the past 20 years there has been a general trend away from conventional small-scale narrow vein mining methods towards mechanised mining methods. Longhole stoping is the dominant narrow vein mining method in both Australia and Canada. While longhole stoping has lower mining costs per tonne and higher production rates than conventional mining methods, longhole stoping has been associated with increased dilution. Therefore, mining method selection is relevant to minimising narrow vein dilution.

The economic performance of narrow vein mines is particularly sensitive to depth of overbreak or slough. Using typical narrow vein dilution costs of $25/tonne; mining direct operating costs (mucking and trucking $7/tonne) and milling ($18/tonne), and assuming 500 000 tonnes per annum ore production, Figure 1 demonstrates how the cost of 25 cm of dilution increases as vein width decreases. Based on this simplified economic model, a mine with a 25 cm average vein width incurring on average 25 cm more dilution than expected, would incur more than $6.25 million per annum in unforeseen operating costs. Furthermore, this model does not take into account opportunity costs associated with capital utilisation.

Stability charts are commonly used for stope design and dilution estimation for both large open stoping and narrow vein stoping. Figures 2, 3 and 4 show three of the most commonly used stability charts. These charts plot stability number (N or N’) against hydraulic radius (HR or S). Hydraulic radius is defined as the ratio of the area to the perimeter for the stope wall under consideration (Laubscher and Taylor, 1976). The stability number N or N’ is calculated according to Equation 1, where A, B and C are empirical factors taking into account induced stress acting parallel to the middle of the stope wall, joint orientation and gravity, respectively. Q’ is the Q classification index value (Barton, Lien and Lunde, 1974), with the stress reduction factor (SRF) and joint water reduction factor (Jw) set to one.

\[ N = Q' \times A \times B \times C \]

Fig 1 - Annual operating cost for 25 cm of dilution for typical narrow vein mine (assumes unit dilution direct operating cost = $25/tonne and 500 000 tonnes ore per annum).

Fig 2 - Modified stability chart (after Potvin, 1988).
The Mathews stability graph (Mathews et al., 1981), the modified stability chart (Potvin, 1988) and the extended Mathews stability chart (Trueman et al., 2000; Mawdesley, Trueman and Whiten, 2001) databases contain fewer than nine narrow vein stopes. For this reason, there was some concern about the applicability of these charts to narrow vein underground stopes. This paper discusses how stability charts can be applied for narrow vein stope design, while proposing a new method for dilution prediction and minimisation (the NVD method). The NVD method is based on:

- analysis of hanging wall and footwall overbreak distributions from a typical longhole narrow vein gold mine (Barkers mine, Western Australia); and
- addressing the causes of dilution as identified by analysis of over 500 narrow vein case studies, and an additional 640 relevant non-narrow vein case studies.

**APPLICABILITY OF STABILITY CHARTS FOR NARROW VEIN MINES**

A study (Stewart, 2005) of 525 narrow vein case studies from the narrow vein Barkers mine and 146 relatively narrow (85 per cent between four to 12 m wide) case studies Trout Lake and Callinan mines (Wang et al., 2002) found that dilution for stopes plotting in the stable zone of stability charts is insensitive to $N$ or $N'$ and $HR$. And, that the relationship between narrow vein dilution and stability chart parameters $N$ or $N'$ and $HR$ is best described by a logistic relationship. Figure 5 illustrates the difference between a logistic regression model and a linear regression model for a single independent variable $X$. The S-shaped logistical distribution reflects that the dependent variable is relatively insensitive (flat section of S curve) to model parameters for a range of values before becoming highly sensitive to model parameters (steep section of S curve) over a small range of model parameters, and then reverting to being relatively insensitive again (flat section of S curve).

Stability charts have two independent variables, $N$ or $N'$ and $HR$. Therefore, if the probabilities of the stability chart were similarly plotted, the graph would be three-dimensional, with probability of stability plotted as a surface. The insensitivity of dilution to $N$ or $N'$ and $HR$ in the stable zone can be related to the flat section at the top of the S shaped curve shown in Figure 5.

As shown in Figures 6 - 9, Barkers stopes plotting in the stable zone demonstrate a poor correlation between dilution (in this
STRATEGIES FOR MINIMISING AND PREDICTING DILUTION IN NARROW VEIN MINES – THE NARROW VEIN DILUTION METHOD

FIG 5 - Comparison of linear and logistic regression models.

FIG 6 - Scatter plot showing the poor correlation between N and overbreak for 115 Barkers case studies mined before October 2000 (6040 ml to 6120 ml). These case studies all plot in the stable zone of stability charts.

FIG 7 - Scatter plot showing the poor correlation between N and overbreak for 410 Barkers case studies mined between October 2000 and February 2003 (6120 ml to 6040 ml). These case studies all plot in the stable zone of stability charts.

FIG 8 - Scatter plot showing the poor correlation between HR and overbreak for 115 Barkers case studies mined before October 2000 (6040 ml to 6120 ml). These case studies all plot in the stable zone of stability charts.

FIG 9 - Scatter plots (the second scatter plot only shows case studies with HR <10) showing the poor correlation between HR and overbreak for 410 Barkers case studies mined between October 2000 and February 2003 (6120 ml to 6040 ml). These case studies all plot in the stable zone of stability charts.
case corrected overbreak) and stability charts parameters (N or N’ and HR). Similarly, Figure 10 plots the difference between actual and predicted metres of hanging wall ELOS for Trout Lake mine and Callinan mine case studies. Equivalent linear overbreak/slough (ELOS) is one method of quantifying dilution and is estimated as shown in Figure 11. Over 50 per cent of the case studies had more than 0.5 m more dilution than predicted. These case studies provide further evidence of poor correlation of dilution (in this case ELOS) to stability charts parameters. FIG 11 - Equivalent linear overbreak/slough (after Clark and Pakalnis, 1997).

The implications of this study for narrow vein dilution prediction and minimisation can be summarised as follows:

- While stability charts can be effective for predicting whether a stope will be geotechnically stable or unstable, they are unreliable for predicting the amount of dilution in narrow stopes.
- The stability chart relationship between N and HR empirically demonstrates that geotechnical parameters N or N’ are stope size dependent. In contrast, dilution associated with drill and blast parameters such as drill pattern, drill hole deviation, explosive type and confinement do not appear to be stope size dependent.

BLAST OVERBREAK

Dilution related to blasting parameters such as blast design, drill hole deviation and quality control have been termed ‘blast overbreak’. Under this definition blast overbreak is quite literally breakage of the rock over the limits of the design.

Potvin’s (1988) study of large open stoping indicated that in most cases, blast induced dilution could not be isolated as a cause of instability. However, within the context of large open stopes, 0.5 to 1.0 m blast related overbreak would probably not be considered unstable. However, 0.5 to 1.0 m dilution would have a significant economic effect on narrow vein mines. Furthermore, it has been argued that because blast damage is rock mass quality dependent (low Q’ stopes would have higher levels of blast damage than high Q’ stopes), blast damage is indirectly taken into account by the inclusion of Q’ in existing stability charts (Mathews et al, 1981; Potvin, 1988; Mawdesley, Trueman and Whiten, 2001). This could explain why, even though blasting parameters are not included in most stability charts, they generally provide a predictive accuracy of approximately 80 per cent. That is, 80 per cent of stope case studies plot in the correct stability chart zone (Mawdesley, 2002). Statistical analysis of 115 Barkers mine case studies found that blast pattern had a statistically significant effect on overbreak (Stewart, 2005). An ‘in-line’ three blasthole pattern performed significantly better than both the ‘staggered’ and ‘dice five’ patterns. These findings further justify the need for explicit consideration of blast overbreak in the case of narrow vein mining.

Feasibility studies require realistic estimates of dilution. Benchmarking is a useful method for estimating mining parameters where reasons for complexity no analytical or numerical solutions exist.

BENCHMARKING NARROW VEIN DILUTION

Narrow vein dilution has been benchmarked using probabilistic analysis of 115 case studies from the now closed Barkers mine, at Kundana Gold Operations (Stewart, Trueman and Lyman, 2008). These benchmarks are only applicable to geotechnically stable stopes. If a stope wall plots in the unstable zone on a stability chart then these benchmarks are not applicable. The aim of the benchmarks is to predict dilution associated with using longhole stoping for narrow vein deposits and should not be used without reference to the Barkers mine geological conditions described in this paper. For example, the Barkers case studies are unaffected by faulting or pinching and swelling of the vein. Dilution due to these factors is not taken into account by the benchmarks, and would best be estimated by wireframing a realistic ore volume similar to what might be done for reserve estimation.

Each case study represents either a stope hanging wall or stope footwall. Ideally, benchmarking includes data from a large number of sites and conditions. While several hundred additional case studies were sourced from at least three other mines, these case studies could not be included in the database either because of biases in the database or because of incomplete or unreliable records.

Kundana Gold Operations are located 25 km west-northwest of Coolgardie. Approximately 595 km east of Perth in Western Australia as shown in Figure 12. The 115 case studies analysed come from panels located between the 6120 m sill drive and the 6040 m sill drive. Site geologists recorded stope stability data including stope geometry and estimation of overbreak from the vein to the final stope walls in stope record sheets. Overbreak from vein to final stope wall was measured using a hand-held laser distance measurement device.

Barkers mine is considered an excellent benchmark mine because dilution at the mine is relatively unaffected by rock mass conditions (Figure 6 and Figure 7), and within the limits of the database dilution can be considered independent of stope span (Figure 8 and Figure 9). While stress damage had a significant effect on deeper stopes at Barkers mine (Stewart, Slade and Trueman, 2005), the shallower Barkers database used for determining benchmark stipping widths is highly unlikely to be affected by stress damage.
The average vein width in the first Barkers database was 0.3 m (0.2 m to 0.4 m). Rock mass classification based on scanline mapping of sill drives indicates that the rock mass for the first Barkers database ranges from fair to good (Brunton and Trueman, 2001). It is reasonable to expect that mines with poor rock mass conditions would experience higher levels of blast overbreak than that incurred at Barkers. Further case studies would be required to establish the effect of a poor rock mass on blast overbreak.

As illustrated in Figure 13 the Barkers mining method is a combination of the bottom-up Modified Avoca method using development waste as fill (tight filling) and longhole open stoping with small rib pillars.

The Barkers drill and blast patterns are typical of narrow vein longhole stoping practices. The benchmark narrow vein stoping widths discussed in this paper are based on the blast patterns shown in Figure 14. All holes were drilled at 64 mm diameter using an Atlas Copco H157 longhole rig, and were less than 15 m long.

All holes were blow-loaded up-holes. Hanging wall holes were generally loaded with a low density ANFO (Sanfold 50). However, when blasting against fill, the first two holes were loaded with 100 per cent ANFO. Footwall and in-line drill holes were loaded with ANFO. All holes were initiated with long delay non-electric detonators. Holes were double primed with one booster 2.5 m from the toe and one booster halfway between the collar and the first booster.

**Benchmark stoping widths**

Stewart, Trueman and Lyman (2008) developed a probability based benchmarking method to estimate benchmark stoping widths for staggered, dice five and in-line longhole drill patterns. The stability graph accuracy of 80 per cent is considered reasonable and implies that stopes are generally designed assuming a 20 per cent probability of overbreak or failure significantly exceeding design. On this basis, it was assumed that benchmark stability stoping width should include 80 per cent of case studies. The benchmark stability stoping width (BSW) is then defined as:

\[
\text{BSW}_{0.3} = \text{vein width} + (x_{hw} + x_{fw})_{50}
\]

where:

\((x_{hw} + x_{fw})_{50}\) is the total overbreak function and was determined by mathematically combining the fitted hanging wall and footwall distributions (Stewart, Trueman and Lyman, 2008)

Eighty per cent of stopes are expected to have total overbreak less than \((x_{hw} + x_{fw})_{50}\).
The ‘benchmark stability stoping width’ for each pattern defines realistic planned dilution limits. These limits provide the basis from which true unplanned dilution can be assessed. Table 1 contains the ‘benchmark stability stoping width’ for each blasting pattern.

In addition, the probabilistic overbreak model was used to derive benchmark average stope widths for each of the patterns. Benchmark average stoping width, in conjunction with vein or ore width, can be used to estimate total dilution (planned and unplanned). These were calculated using by adding the average total overbreak to the average vein width of 0.3 m. Table 1 of the NVD method lists benchmark average stoping widths and provides details on how benchmark average dilution can be used to estimated dilution.

Stewart, Trueman and Lyman (2008) assumed that benchmark stoping widths are not site-specific and can be considered operating condition specific. In this case, operating condition specific refers to standard narrow vein longhole mining methods and equipment such as those used at the Barkers mine. In other words, benchmark stoping widths are primarily a function of the longhole stoping method, and not the geotechnical parameters that are responsible for unplanned dilution. Based on this assumption, the benchmark stoping widths determined for the Barkers mine are applicable to similar narrow vein longhole stoping mines. Because vein widths ranged from 0.2 m to 0.4 m the accuracy of both benchmark stope widths can be considered to be ±0.1 m. Benchmark average stoping width and benchmark stability stoping width form an important component of the NVD method.

Unfortunately, despite concerted efforts over a number of years to source data from additional narrow vein mines it has not been possible to validate these findings at another mine.

### Table 1

*Narrow vein dilution (NVD) method: prefeasibility/feasibility stage.*

<table>
<thead>
<tr>
<th>A1. Geotechnical stability</th>
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<tbody>
<tr>
<td>A1.1 Stability graph assessment</td>
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</tr>
<tr>
<td>A1.2 Stress relaxation potential assessed for tabular stope geometries; especially if principal stress is perpendicular to strike. In cases of full and tangential stress relaxation set stress factor A = 0.7.</td>
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<tr>
<td>A1.3 If geometry is irregular or complex (eg pillars or multiple lift retreat) then hydraulic radius can be estimated from radius factor R.</td>
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<table>
<thead>
<tr>
<th>A2. Fill requirements</th>
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<tbody>
<tr>
<td>A2.1 Tight filling. Treat fill as solid rock.</td>
<td></td>
</tr>
<tr>
<td>A2.2 Continuous filling with lag between stoping and fill.</td>
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<tr>
<td>HR = HRafter blasting + HR after backfilling.</td>
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<tr>
<th>A3. Cablebolting</th>
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<tbody>
<tr>
<td>A3.1 Assess if stope is supportable using modified stability chart.</td>
<td></td>
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<tr>
<td>A3.2 Stable HR can be increased by pattern cablebolting. Modified stability chart can be used to assess possible increase HR achievable with pattern cablebolting.</td>
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<tr>
<td>A3.3 Consider effect of backfilling on production cycle. Cablebolts have potential to improve productivity by decreasing delays associated with regular filling requirements.</td>
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<tr>
<td>A3.4 Cablebolts can be used for areas with localised instability potential.</td>
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### A4. Dilution prediction

<table>
<thead>
<tr>
<th>A4.1 Total dilution for stopes plotting in the stable zone</th>
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<tbody>
<tr>
<td>Benchmark total dilution for stable stopes can be estimated as follows: Total dilution = (Benchmark average stoping width – vein width)/vein width.</td>
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<tr>
<td>The benchmark average stoping widths for common narrow vein blast patterns:</td>
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<tr>
<td>• in-line = 1.3 m,</td>
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<tr>
<td>• staggered = 1.5 m, and</td>
<td></td>
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<tr>
<td>• dice-5 = 1.7 m.</td>
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<tr>
<td>For vein widths &gt;1.2 m, an allowance of approximately 0.6 m of dilution is required to ensure the probability of ore loss is less than five per cent (from cumulative overbreak probability distributions). This estimate is based on the average dilution allowance required for a 0.7 m vein using an in-line pattern, ie 1.3 m - 0.7 m requires a 0.6 m dilution allowance to ensure ore loss probability is less than five per cent. It is reasonable to expect that a similar allowance would be required for wider veins.</td>
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<tr>
<th>A4.2 Dilution assessment for stopes plotting in the unstable or failure zone of a stability chart</th>
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<tbody>
<tr>
<td>Isoprobability contours can be used to estimate the percentage of stopes expected to exceed the benchmark stability stoping width.</td>
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<tr>
<td>eg The probability of unplanned dilution for a stope plotting on the stable-failure boundary is approximately, 20 per cent.</td>
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<tr>
<td>Benchmark stability stoping widths.</td>
<td></td>
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<tr>
<td>Vein width &lt; 0.7 m using an in-line pattern = 1.6 m</td>
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<tr>
<td>Vein width &gt;0.7 m using either staggered or dice-5 pattern = 2.1 m</td>
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<th>A4.3 Undercutting of stope walls</th>
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<tr>
<td>For stope walls with N’ or N &lt;5 empirical evidence suggests that undercutting will lead to stope wall failure (Potvin, 1988).</td>
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<tr>
<td>For stope walls with N’ or N &gt;5 the HR of undercut stope walls can be estimated by assuming that the stope height is infinite.</td>
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<tr>
<th>A4.4 Extraction sequence</th>
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<tbody>
<tr>
<td>Evaluate potential for pre-stopping stress history to cause dilution. Possible methods include: pillar stability chart, average stoping width, in conjunction with vein or</td>
<td></td>
</tr>
<tr>
<td>If stress damage potential is high then increase dilution by between 0.1 to 0.3 m.</td>
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<tr>
<td>Layered orebodies should be assessed for stress relaxation potential.</td>
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</table>

Note: see Table 3, limitations and assumptions, which contains notes as per superscript numbers.
THE NARROW VEIN DILUTION METHOD

The narrow vein dilution method (NVD method) is a tool for more accurately predicting longhole narrow vein dilution. In addition to dilution prediction, the NVD method also includes strategies for narrow vein dilution minimisation generally, including; filling, cablebolting, stress relaxation, extraction sequencing and blast overbreak. The premise for the NVD method is that dilution associated with the longhole stoping mining method can predicted using the benchmark stoping widths discussed in this paper. The NVD method remains to be validated at other sites. However, NVD method represents a potential improvement over the relatively arbitrary stope widths commonly used to predict dilution.

In much of the literature to date dealing with the subject of dilution and stope stability, the terms overbreak and stope stability are represented as being intrinsically related. However, the case studies presented in this paper suggest an alternate interpretation, and that the parameters causing narrow vein dilution can be separated into two groups:

1. geotechnical instability (stope size dependent), and
2. blast overbreak (independent of stope size).

This finding is very important because it offers a simple way to assess whether an operating mine’s dilution is likely to be related to geotechnical stability or blast overbreak. Blast overbreak can be distinguished from geotechnical causes of dilution by analysing whether dilution occurs independently of stope size.

The NVD method addresses geotechnical and blasting overbreak related stability separately. In addition, the method addresses issues associated with different types and levels of data available at two different stages in a mine’s life:

1. prefeasibility/feasibility stage, and
2. operating mine.

The NVD method is comprised of three tables. Table 1 contains the prefeasibility/feasibility NVD method. Table 2 contains the operating mine dilution minimisation method. Table 3 contains the assumptions and limitation of the NVD method.

The NVD method also incorporates improvements to the stability graph method that are particularly relevant to narrow vein mining, including; use of radius factor for complex geometry (Milne, Pakalnis and Felferer, 1996) and updated cablebolt recommendations (Diederichs and Kaiser, 1999).

### Table 2

<table>
<thead>
<tr>
<th>B1 Geotechnical stability</th>
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<tbody>
<tr>
<td><strong>B1.1</strong> Determine stable HR for geotechnical domains as per A.1 to A.3</td>
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<tr>
<td><strong>B1.2</strong> Site-specific chart (if necessary)</td>
</tr>
<tr>
<td><strong>B1.3</strong> Kinematic analysis</td>
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<tr>
<th>B2 Minimising dilution</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>B2.1</strong> Stope database</td>
</tr>
<tr>
<td><strong>B2.2</strong> Minimising geotechnical causes of dilution</td>
</tr>
<tr>
<td><strong>B2.3</strong> Minimising drill and blasting related dilution</td>
</tr>
</tbody>
</table>

Note: see Table 3, limitations and assumptions, which contains notes as per superscript numbers.
3. Tight filling means that there is no volume between the fill and the next rings/slot to be fired.

4. Continuous filling (as opposed to tight fill) means there is a gap between the fill and the next rings to be fired. Milne (1996) proposes that the effective final span converges to the sum of the opening after blasting plus the opening span after backfilling. However, due to insufficient data, Milne (1996) was unable to confirm this hypothesis. However, the results of extensive hanging wall monitoring (extensometers) at the Winston Lake mine did suggest that the common practice of treating a moving backfill abutment like a rock abutment is overly optimistic (Milne 1996).


6. However, cablebolt effectiveness can be reduced by low rock mass stiffness and stress relaxation (Diederichs and Kaiser, 1999).

7. Brow stress damage would correspond to category three for pillar yield (fracturing in pillar walls) and the unstable region of the Confinement Formula Stability Graph (Lunde, 1994). The main advantage of this approach over the deviatoric stress approach is the very large database of rock mass conditions incorporated into the database means better prediction of stress damage when there is no opportunity to calibrate to underground observations.

8. Further validation required.

9. May have effect on dilution below this criterion damage limit, eg Barkers case studies.

10. It has been assumed that benchmark average stoping width is not site-specific, and can be considered operating condition specific. In this case operating condition specific refers to standard narrow vein longhole mining methods and equipment. In other words, benchmark stability stoping width is primarily a function of mining method and equipment, and not the geotechnical parameters that are responsible for unplanned dilution. Based on this assumption, the benchmark stability stoping widths determined for Barkers mine are applicable to similar narrow vein longhole stoping mines. It should be noted that rock mass classification based on scancine mapping of sill drives indicates that the rock mass for the Barkers 1 database ranges from fair to good. It is reasonable to expect that mines with poor rock mass conditions would experience higher levels of blast overbreak than that incurred at Barkers.

   For stopes plotting on the stable-failure boundary the probability of a stope width exceeding the benchmark stability stoping width is approximately 20 per cent. This estimate assumes parallel holes and standard longhole drill and blast practices.

   Standard practice:
   • Low impact explosives used on the hanging wall,
   • Blast pattern suited to the vein width,
   • 51 mm to 64 mm diameter holes <15 m long,
   • Hanging wall hole stand-off distance appropriate to the rock mass,
   • Some drill hole surveys,
   • Irregular reporting of dilution and or stope reconciliation,
   • Some blast trials, and
   • ore drive development under geological control.

   Implementation of best practices and improved quality control has the potential to achieve narrower stoping widths. In these cases the probability of a stope width exceeding the stable stoping width would be significantly less than 20 per cent.

   Each of the practices listed has been proven to be effective in dilution minimisation at least one mine:
   • Regular and systematic drill hole survey and analysis.
   • Stope survey and stope reconciliation.
   • Reporting dilution as a key performance indicator (KPI).
   • Drill and blast continuous improvement projects based on properly design randomised drill and blast trials. Design modifications based on statistically significant results obtained from stope reconciliations.
   • Blast damage modelling based on analysis of PPV.
   • Tight geological and mining control on ore-drive development to minimise undercutting.
   • Cablebolting of localised instability.
   • Smooth wall blasting, eg presplit.
   • Revaluation/calibration of feasibility study stable stope dimensions.

   Sub-standard practice:
   • No drill hole surveys,
   • Inappropriate blast pattern selected for vein width,
   • Only reporting tonnes as KPI,
   • No evaluation or reporting of dilution, and
   • No geotechnical mapping to reassess feasibility study design.
cases of stress relaxation. Vein stoping because they include separate recommendations for width and benchmark average stoping width as follows: for stopes plotting in the stable zone can be estimated from vein provided in Table 1. If stopes are designed in the ‘unstable’ zone used as the basis for predicting narrow vein dilution. Details are estimate of average stoping width for each blast pattern can be stoping

| 11. | Like benchmark average stoping width, it has been assumed that benchmark stability stoping width is not site-specific and is a function of mining method and equipment. An in-line pattern can be used for vein widths less than 0.7 m. If an in-line pattern is used for a vein width of 0.7 m then the probability of ore loss is approximately five per cent. However, depending on geological and rock mass conditions an in-line pattern can result in bridging. |
| 12. | Inside the stable zone the probability of unplanned dilution decreases from 20 per cent the further a stope plots inside the stable zone and conversely, inside the failure zone the probability of unplanned dilution increases from 20 per cent the further below the stable-failure boundary. The extended Mathews isoprobability contours (Mawdesley et al, 2000) can be used to estimate the probability of unplanned dilution at a particular position on the extended Mathews stability graph. While the probability of failure is affected by distance from the stability graph stable-failure boundary, the amount of unplanned dilution in narrow vein stopes does not appear to be related to position on the stability graph. |
| 13. | This recommendation is based on the assumption that an undercut stope wall cannot obtain support from arching to the abutments and therefore, assuming the stope height is infinite is a good approximation of the effect of removing lower abutment support. This recommendation is based on engineering assessment of the destabilising effect of undercutting and has not been validated with case studies. However, in the absence of alternatives this approach seems to be reasonable, and is likely to be more realistic than assuming that undercutting has no effect at all. Comment: in one of your chapters undercut footwalls were related to non-undercut hanging walls. |
| 14. | Stress damage related unplanned dilution ranged from 0.1 m to 0.3 m and is based on data from one mine (Barkers mine) and therefore requires further validation. However, the upper limit of 0.3 m could be a function of mineability of ore drives. Barkers mine ore drives had high levels of support including shotcrete and cablebolting. Based on these levels of support it is reasonable to infer that mineability was moderately difficult. If stress related conditions in the ore drives were more difficult than Barkers, then stress damage related dilution could exceed 0.5 m. However, more case studies are required from other mines to validate this proposition. |
| 15. | Ideally, a narrow vein stope dilution database should record the following information; • stope dimensions, • undercutting, • failure mechanism, • drill and blasting patterns including explosive types and initiation sequence, and • support of stope walls. |
| 16. | Drill hole inaccuracy is a significant cause of dilution (Aplin, 1997; Revey, 1998). |
| 17. | Randomised trials mean that changes to drill and blast parameters are undertaken randomly without consideration for any other parameters. The data collated from randomised drill and blast trials is less likely to be affected by systematic bias. This is the basis of experimental design. |
| 18. | It seems that because the relationship between blast damage and overbreak is rock mass dependent there is no generic model for predicting overbreak using blast damage modelling. However, individual mines could compare overbreak stability to damage modelling and use this information in blast design. The value of blast damage modelling is in the ability to compare the blast damage potential of alternative blast designs. Peak particle velocity (PPV) is a good predictor of blast damage (Singh, 1998; Villaescusa et al, 2003). Blast damage contributes to dilution (Henning et al, 1997). Blast damage modelling involves monitoring blast vibration to determine site-specific constants k and α. Once k and α have been determined PPV can be estimated as follows: 

\[
PPV = K (a)^α
\]

where:

- \(a\) is defined as the Holmberg-Persson term
- k and \(α\) are the rock mass and explosive specific attenuation constants (Holmberg and Persson, 1980)

Once the PPV limit for blast damage has been determined it is possible to design blast that do not exceed the PPV limit. However, scatter in delay timings and inconsistencies in rock mass attenuation properties can significantly affect the reliability of actual PPV versus design PPV. |
| 19. | Pageau et al (1992) found that by implementing smooth wall blasting, including a presplit, they were able to reduce dilution at the Richmont mines, Francouer mine Quebec from ten to 15 per cent to five per cent. Multiple lift retreat stoping and the leaving of rib pillars often results in complex geometry. The cablebolting recommendations of Diederichs and Kaiser (1999) are particularly relevant to narrow vein stoping because they include separate recommendations for cases of stress relaxation. Predicting dilution for narrow vein longhole stoping For stopes plotting in the ‘stable’ zone of a stability chart, an estimate of average stoping width for each blast pattern can be used as the basis for predicting narrow vein dilution. Details are provided in Table 1. If stopes are designed in the ‘unstable’ zone of a stability chart, then stoping widths will on average exceed the average stoping width for a particular blast pattern. Dilution for stopes plotting in the stable zone can be estimated from vein width and benchmark average stoping width as follows: 

\[
Total \ \text{dilution} = \frac{\text{Expected stope width} - \text{vein width}}{\text{Vein width}} \ (3)
\]

Deposits with more complex geometry and structural influences are likely to incur more unplanned dilution than a simple tabular vein with gradual changes in strike and dip. The Barkers average stoping width is a benchmark from which planned dilution in more complex geological formations can be estimated. Minimising dilution The NVD method has the potential to improve the process of selecting the optimum narrow vein mining method, while also listing ways to minimise dilution in the case where a higher dilution method is more economic overall. The dilution prediction method for mines at the feasibility study stage (Table 1) can be used to assess the appropriateness of the mining method and determine the likely filling and/or cablebolting requirements if narrow vein longhole stoping is the preferred mining method. The dilution prediction methods are limited to mechanised narrow vein longhole stoping. However, elements of the NVD method will be applicable to narrow vein mining not using longhole stoping. |
In the case of an operating mine the NVD method proposes a back analysis of existing stope data that enables a mine to first identify whether dilution is most likely caused by geotechnical factors or alternatively is blast overbreak related. Table 2 contains details of this approach. Once it has been established whether the primary cause of dilution is geotechnical or blasting overbreak related, a number of strategies are suggested to minimise dilution.

Assumptions and limitations

It is important to note that the applicability of benchmark stoping widths is qualified by a comprehensive set of assumptions and limitations. These assumptions and limitations are listed in Table 3. For example; deposits with shallow dip, more complex geometry and structural influences are likely to incur more dilution than steeply dipping simple tabular veins with gradual changes in strike and dip.

Benchmark stoping widths are applicable for narrow vein longhole stoping with standard drill and blast practices. Best practice or substandard practice would result in lower and higher levels of dilution, respectively. The NVD method clearly defines what is meant by ‘standard practice’, ‘best practice’ and ‘substandard practice’.

Benchmark stoping widths are applicable for vein widths up to 1.2 m. The benchmark stability stoping widths determined for various vein widths are only applicable to narrow vein longhole open stoping. It has been assumed that benchmark stoping widths are operating condition-specific and not site-specific. For this reason, the benchmark stoping widths are generally applicable to sites with similar operating conditions and geological formation.

The vein widths used to determine the benchmark stoping widths ranged from approximately 0.2 m to 0.4 m. Because vein width was not recorded an average of 0.3 m has been applied for all three blast patterns and this means that benchmark stoping widths have are associated with a ±0.1 m error. It is important to note that staggered and in-line patterns were generally used for the narrower veins widths while dice-five was generally used for the wider veins. These differences would result in minor biases with an estimated ±0.1 m error.

The validity of the benchmark stoping widths at mines with similar operating conditions to Barkers remains to be validated. It is envisaged that improved dilution prediction will lead to a highly valuable narrow vein database. Numerous other operations provided data for this project, including Mount Isa Lead mine, Kanowna Belle and several of the Kambalda nickel mines. However, for various reasons relating to dependencies between variables, this data could not be used for this project. Despite the data not being used, the authors would like to express their appreciation for the support and collaboration offered by personnel at these operations.

CONCLUSIONS

Barkers, Callinan and Trout Lake mine case studies suggest that overbreak is not continuously related to N and HR, and that the relationship between HR and overbreak, and N and stability is best described by a logistical relationship. Based on this result it was concluded that the caused overbreak is unlikely to be related to geotechnical parameters if a stope plots well inside the stable zone. And therefore, in this scenario reducing stope size would not reduce dilution. This interpretation implies that the causes of narrow vein dilution can be separated into two unrelated causes:

1. geotechnical instability (stope size dependent), and
2. blast overbreak (unrelated to stope size).

Benchmark stoping widths can be used to define realistic planned dilution limits. These limits provide the basis from which true unplanned dilution can be assessed. Benchmark average stoping width, in conjunction with vein or ore width, can be used to estimate total dilution. Benchmark stoping widths are primarily a function of the longhole stoping method (operating-condition specific). On this basis, the benchmark stoping widths determined for Barkers mine are applicable to narrow vein longhole stoping with similar operating conditions and remain to be validated at another mine. It is recognised that complex geology (eg cross-cutting structures) will require adjustment to both the benchmark stability stoping width and the benchmark average stoping width.

The NVD method is a tool for predicting narrow vein dilution based on the benchmark average stoping widths. In addition to dilution prediction, the NVD method also includes recommendations and strategies for narrow vein dilution minimisation generally, including: filling, cablebolting, stress relaxation and managing stress damage and blast overbreak. It is envisaged that improved dilution prediction will lead to more accurate comparisons of the expected cost of dilution in longhole stopes compared to other mining methods while recognising that optimal mining method selection will, in some instances, accept a higher level of dilution if it results in a higher overall NPV for an operation. While the NVD method remains to be validated at other sites, the method represents a potential improvement over the relatively arbitrary stop widths commonly used to predict dilution.

ACKNOWLEDGEMENTS

The work presented in this paper would not have been possible without the financial support of the AMIRA BART II sponsors initially and finally the ongoing support of the Julius Kruttschnitt Mineral Research Centre.

The close collaboration of site personnel from the Barkers mine at Kundana Mining Operations made it possible to collate a highly valuable narrow vein database. Numerous other operations provided data for this project, including Mount Isa Lead mine, Kanowna Belle and several of the Kambalda nickel mines. However, for various reasons relating to dependencies between variables, this data could not be used for this project. Despite the data not being used, the authors would like to express their appreciation for the support and collaboration offered by personnel at these operations.

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