Development of benchmark stoping widths for longhole narrow-vein stoping

P. Stewart*1, R. Trueman2 and G. Lyman2

In narrow vein mining it is often not possible to limit stope width to the vein width when utilising blasting for rock breakage. A probabilistic benchmarking method is used to estimate benchmark stability stoping widths and benchmark average stoping width for three commonly used narrow vein longhole blast patterns. Average stoping widths for inline, staggered and dice-5 blast patterns have been estimated at 1·3, 1·5 and 1·7 m respectively. Average stoping width can be used to assess planned and unplanned dilution. Additionally, a concept termed the benchmark stability stoping width has been defined and quantified for the three blasting patterns. Stability stoping widths for inline, staggered and dice-5 have been estimated at 1·6, 2·0 and 2·1 m respectively. Narrow vein stopes within these limits after blasting can be regarded as stable.

Keywords: Narrow vein, Dilution, Stoping, Overbreak, Benchmarking

Introduction

Improved dilution prediction in narrow-vein longhole stoping facilitates more accurate economic comparisons between longhole stoping and other narrow-vein mining methods, as well as reducing dilution uncertainty for deposits at the prefeasibility/feasibility stage.

Because dilution in narrow stoping is directly related to stope width, establishing a practical stopping width is an important parameter when attempting to predict or analyse longhole narrow-vein dilution.1 This paper defines practical stoping widths for various common narrow-vein blast patterns. The practical stopping widths determined for the Barkers mine in Western Australia can be considered benchmarks from which other narrow-vein mines can predict and analyse dilution. For these reasons, the practical stopping widths determined for Barkers have been termed ‘benchmark stopping widths’.

Premise for developing benchmark stopping widths

Over the last 20 years or so some success has been gained in quantifying geotechnical stability of open stopes using stability charts.2–5 A problem that arises when attempting to assess the geotechnical stability of narrow vein stopes is assessing the width of the stope that can actually be achieved through the medium of blasting. For example, if a mine has a vein width of 0·3 m, it is not practically possible to blast a stope to that narrow width. In order to differentiate between planned and unplanned dilution it is necessary first to determine a practical stopping width. Determining the actual stopping width that can be achieved will then enable a reasonable assessment of planned dilution during the feasibility study and enable a better estimate of stope sizes to reduce or eliminate unplanned dilution due to geotechnical instability.

Five hundred and twenty-five case studies from the narrow-vein Barkers mine1 and 146 case studies from Trout Lake and Callinan mines6 suggest depth of overbreak is not continuously related to either the stability number, nor the stope size as implied by the Clark and Pakalnis’s7 ELOS Dilution Chart .

Of the 146 Trout Lake and Callinan narrow-vein mines, 85 per cent of stope widths ranged from 4 to 12 m,6 and could be considered relatively narrow. These case studies provide further evidence of poor correlation of depth of overbreak to stability charts parameters (Stability Number, N and Hydraulic Radius, HR). Figure 1 plots the difference between actual and predicted metres of hangingwall slough. Over 50 per cent of the case studies had more than 0·5 m more slough than predicted.

The results of studies of dilution in narrow-vein mines carried out by Stewart1 are conceptualised in Fig. 2, and provide the premise for addressing operational factors such as; mining method, equipment and blast pattern. Benchmark stopping widths are the means to address these operating factors.

The implications of this study for dilution prediction in narrow-vein stopes can be summarised as follows:

(i) while stability charts are reliable for predicting whether a stope will be geotechnically stable or unstable, they are unreliable for predicting the amount of dilution

(ii) for stopes plotting in the failure/unsafe zone of a stability chart, the depth or scale of stope failure should consider failure mechanisms on a
case by case basis (e.g. kinematic analysis, stress caving of backs, unravelling of fault zone)
(iii) there is no reliable method for predicting dilution due to operating factors associated with narrow-vein longhole stoping.

Development of benchmark stoping width

Benchmark stoping widths have been determined using probabilistic analysis of 115 case studies from the Barkers mine, Kundana Gold Operations. Kundana Gold Operations is located 25 km west-northwest of Coolgardie, which is approximately 595 km east of Perth in Western Australia.

Two types of benchmark stoping width have been defined:
(i) benchmark average stoping width is for predicting average dilution and provides a baseline for analysing the causes of dilution (independent of stope design outline)
(ii) benchmark stability stoping width is for geotechnical assessments of unplanned dilution.

The probabilistic approach used to determine benchmark stoping widths also facilitate consideration of the effect of blast pattern on ore loss potential.

Benchmark average stoping width

While benchmark stability stoping width can be used as the basis for analysing geotechnical stability, benchmark stability stoping width does not indicate average stoping widths. An estimate of an average stoping width enables total dilution to be predicted for stopes plotting in the stable zone of a stability graph. Furthermore, benchmark average dilution also provides a measure of dilution that is independent of biases associated with trends in setting the stope design outline. An average value is equivalent to the mean or expected value of a normal distribution. However, hangingwall and footwall overbreak is not normally distributed. Therefore, expected total dilution for each blast pattern has been evaluated using the parameters which best define the overbreak distributions for each of the three blast patterns investigated.

Benchmark stability stoping width

Minimising unplanned dilution at an operating mine requires a reasonable baseline or benchmark from which assessments and reconciliations can be conducted. Setting a reasonable benchmark is particularly important if the experience at one mine is to be related to another mine, as is the case when applying empirical methods. Benchmark stability stoping width represents the 80th percentile for stope widths. For example, if 40% of stopes at a particular narrow-vein mine had a stope width greater than the benchmark stability stoping width then this would indicate that the mine is performing below the benchmark (dilution levels in excess of benchmark).

Assumptions and limitations

The benchmark 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 outlined in this paper are assumed to be generally applicable to sites with similar operating conditions and geological formation.
The vein width ranged from approximately 200 to 400 mm for the levels contained in the Barkers 1 database. It is important to note that staggered and in-line patterns were generally used for the narrower veins widths while dice-5 was generally used for the wider veins. Because vein width was not recorded an average of 0.3 m has been applied for all three blast patterns.

Barkers mine

The following sections describe both the geotechnical conditions and the operating factors that characterise stoping practices for the 115 case studies used to determine benchmark stoping widths.

Geotechnical conditions

The average vein width in the first Barkers database was 0.3 m (0.2 to 0.4 m). The UCS of the quartz vein (ore) was 130 MPa (standard deviation of six from three tests). The UCS of the stope walls was 142 MPa.

Rockmass classification based on scanline mapping of sill drives indicates that the rockmass for the first Barkers database ranges from fair to good. It is reasonable to expect that mines with poor rockmass 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 rockmass on blast overbreak.

Mining method

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. Figure 3 provides a schematic representation of the Barkers mining method.

Barkers drilling and blasting practices

The Barkers drill and blast patterns are typical of narrow-vein longhole stoping practices. The mining sequence is schematically represented in Fig. 3.

All holes were blow loaded up-holes. Hangingwall holes were loaded with a low density ANFO product (polystyrene balls added to a product called Sanfold 50). Hangingwall holes were generally loaded with a low density ANFO (Sanfold 50). However, when blasting against fill, the first two holes were loaded with 100% ANFO. Footwall and in-line drillholes 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.

These drill and blast practices would be considered standard practice for Australian subvertical tabular narrow-vein gold mines. Therefore, the results of the benchmarking presented in this paper should be applicable to mines employing similar blasting practices. However, discontinuities in the orebody such as offsetting caused by faulting, pinching and swelling of the orebody as well as sudden changes in strike and dip of the orebody will affect the practical stoping width for a particular orebody.

Benchmark stoping widths

Minimising and predicting dilution requires a reasonable baseline or benchmark from which assessments can be made. Setting a reasonable benchmark is particularly important if the experience at one mine is to be related to another mine. Barker mine case studies have been used to determine a series of benchmark longhole narrow-vein stoping widths.

Benchmark stoping widths were derived from hangingwall and footwall overbreak distributions. Figures 5–7 are histograms of overbreak for hangingwall case studies. Figures 8–10 are histograms of overbreak for footwall case studies.

Fitting distributions to overbreak data

Because the overbreak distributions are not normally distributed, taking a simple numerical mean is likely to give an inaccurate estimate of expected overbreak. Therefore, expected dilution for each blast pattern has been evaluated using a distribution that best defines the
hangingwall and footwall overbreak distributions for each of the three blast patterns shown in Fig. 4.

Distributions were fitted to both hangingwall and footwall data using a maximum likelihood method. Maximum likelihood is a probabilistic analysis method that uses the probability density function to provide a method of estimating the parameters of the distribution. Because of the limited number of case studies, simple distributions with a minimal number of fitted parameters were selected. Hangingwall distributions were well represented by an exponential distribution (single parameter $\lambda$), while the footwall distributions were best
represented by a logistic distribution (two parameters \( x_0 \) and \( \lambda \)).

The exponential probability density is given by

\[
p(x) = \frac{1}{\lambda} \exp\left(\frac{-x}{\lambda}\right) \quad x > 0; \lambda > 0
\]

The exponential distribution has an average or expected value of \( \lambda \) and a standard deviation of \( \lambda \). The logistic probability density is given by

\[
(x) = \frac{1}{\lambda} \left[ \frac{\exp\left(\frac{x - x_0}{\lambda}\right)}{1 + \exp\left(\frac{x - x_0}{\lambda}\right)} \right]^{1/2} \quad -\infty < x, x_0 < \infty \; ; \; \lambda > 0
\]

\( \lambda \) provides the distance scaling value and is a uniform measure of the distribution spread. The mean or expected value of the logistic distribution is \( x_0 \). The corresponding cumulative distribution functions are

\[
P(x) = 1 - \exp\left(\frac{-x}{\lambda}\right)
\]

\[
P(x) = \frac{1}{1 + \exp\left(\frac{x - x_0}{\lambda}\right)}
\]

Table 1 contains the maximum likelihood fitted parameter values for hangingwall and footwalls for each of the three blast patterns. Stewart\(^1\) provides details of how the maximum likelihood parameter values were determined for each distribution. Comparisons between observed data and fitted distributions were good (refer to Stewart\(^1\) for actual comparisons).

Figures 11–16 compare the actual overbreak data to the fitted distributions. Fitted distributions are shown in blue while actual overbreak data is shown in red.

**Predicting dilution using benchmark average stoping width**

It is clear from the analysis conducted in the previous section that overbreak distributions for the hangingwall and footwall differ. The expected (average) value of the overbreak for the hanging wall is \( \lambda_{hw} \) and that for the footwall is \( x_0 \). Fitted values for these parameters for each blast pattern are shown in Table 1.

For stopes plotting in the stable zone of a stability graph,\(^3\) Modified Stability graph or Trueman and Mawdesley’s\(^5\) Extended Mathews Stability Graph, benchmark average stoping width can be used as the basis for predicting narrow-vein dilution. If stopes are designed in the unstable zone of a stability chart, then stoping widths will on average exceed the average stoping width.

Because the footwall and hangingwall overbreak are considered to be independent, random variables in this analysis, the average (expected) total overbreak is simply the sum of the expected hangingwall and footwall overbreak as outlined in equation (5)

\[
E[x_{hw} + x_{fw}] = \lambda_{hw} + x_0
\]

Table 2 contains the benchmark average stoping width

<table>
<thead>
<tr>
<th>Pattern</th>
<th>( \lambda_{hw}, m )</th>
<th>( \lambda_{fw}, m )</th>
<th>( x_0, m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-line</td>
<td>0.338</td>
<td>0.153</td>
<td>0.650</td>
</tr>
<tr>
<td>Staggered</td>
<td>0.456</td>
<td>0.255</td>
<td>0.778</td>
</tr>
<tr>
<td>Dice-5</td>
<td>0.380</td>
<td>0.277</td>
<td>0.979</td>
</tr>
</tbody>
</table>

11 Comparison of observed data with fitted exponential density for in-line blasting pattern for hangingwall overbreak
12 Comparison of observed data with fitted exponential density for staggered blasting pattern for hangingwall overbreak
13 Comparison of observed data with fitted exponential density for ‘dice-5’ blasting pattern for hangingwall overbreak
14 Comparison of observed data with fitted logistic density for ‘in-line’ blasting pattern for footwall overbreak
for each blasting pattern. These were calculated by adding the average total overbreak to the average vein width of 0-30 m.

**Benchmark stability stoping width**

Stability graphs have an accuracy of ~80%. This implies that stopes are generally designed assuming a 20% probability of overbreak or failure significantly exceeding design. On this basis, it has been assumed that a practical narrow-vein benchmark stability stoping width should include 80% of case studies. The practical stoping width has therefore been based on an overbreak distance $x_{80}$, the stope width that will not be exceeded in 80% of blasts. The benchmark stability stoping width is then defined as

$$\text{BSW}_{80} = \text{vein width} + (x_{fw} + x_{hw})_{80}$$

with all distances measured in meters.

Eighty percent of stopes are expected to have total overbreak less than $(x_{fw} + x_{hw})_{80}$.

The fitted hangingwall and footwall distributions were mathematically combined to determine a total overbreak function. Figs. 17–19 show the total overbreak function for in-line, staggered and dice-5 blast patterns respectively.

Table 3 contains the $(x_{fw} + x_{hw})_{80}$ values obtained from the cumulative total overbreak functions for each blast pattern and benchmark stability stoping widths for the blast patterns analysed. Benchmark stability stoping width is one example of how the narrow-vein cumulative total overbreak functions can be applied. It is important to note that applicability of these functions is not limited to these examples.

**Assumptions and limitations**

The applicability of benchmark stoping widths is qualified by a comprehensive set of assumptions and limitations.
limitations. For example, deposits with 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.

Benchmark stoping widths are applicable for vein widths up to 1.2 m. For vein widths greater than 1.2 m, the cumulative probability functions indicate that a 0.6 m total dilution allowance is required to ensure the probability of ore loss is less than 5%. Total dilution allowance refers to sum of hangingwall and footwall overbreak.

It has been assumed that benchmark stoping widths are operating condition specific and not site-specific. For this reason, the benchmark stoping widths determined in this chapter are generally applicable to sites with similar operating conditions and geological formation.

The vein width ranged from approximately 200 to 400 mm for the sublevels contained in the database presented in this paper. It is important to note that staggered and in-line patterns were generally used for the narrower veins widths, while dice-5 was generally used for the wider veins. Because vein width was not recorded, an average of 0.3 m has been applied for all three blast patterns. Based on the vein widths ranging from 0.2 to 0.4 m, the benchmark stoping widths have an accuracy of approximately ±0.1 m. In the case of in-line patterns the benchmark widths have the potential to slightly overestimate the stoping width by up to 0.1 m, while in the case of the staggered and dice-5 there is the potential to slightly underestimate by up to 0.1 m.

### Application of benchmark stoping widths to Barkers database

Ideally, an independent data set would have been used to validate the benchmark stoping widths. In the absence of a validation set of data to check the general validity of the benchmark stoping widths, the validity of the methodology has been checked using the original data set to check the modelling methodology. As defined in Equation 6 the benchmark stability stoping width is given by the quantity \( (x_{hw} + x_{fw})_{0.3} \), which is the 80% point on the distribution function. It follows that the percentage of stopes with widths greater than the benchmark stability stoping width should be ~20%.

Table 4 contains the actual estimated stoping widths within the database assuming a 0.3 m vein width. At this point is worth noting that vein widths actually ranged from 0.2 to 0.4 m. Because vein widths range from 0.2 to 0.4 m, the stope widths shown in Table 4 have an accuracy of ±0.1 m.

According to the definition of benchmark stability stoping width presented in this paper, a stopping widths equal or greater than 1.6 m wide would be classed as failures when using an in-line pattern, 2.03 m when using a staggered and 2.15 m when using dice-5.

The stoping width was calculated as the sum of the hangingwall overbreak from the vein, the footwall overbreak from the vein and an assumed 0.3 m average vein width. The number of case studies falling inside the benchmark stability stoping widths for in-line, staggered and dice patterns were 87, 83 and 80% respectively. Given the limited number of case studies in each group these values agree reasonably well with the 80% probability assigned to the benchmark stability stoping width. These results indicate that the distribution fitting and probabilistic modelling methods used are reasonable.

### Predicting dilution for narrow-vein longhole stoping

Narrow-vein longhole stoping dilution can be predicted using benchmark stoping widths. Depending on whether a stope plots in the stable zone or the failure (unstable) zone of a stability chart, either one of the following two methods can be applied to predict dilution for narrow-vein longhole stoping.

<table>
<thead>
<tr>
<th>Dice-5 stope widths, m</th>
<th>Staggered stope widths, m</th>
<th>In-line stope widths, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>1.1</td>
<td>1.3</td>
</tr>
<tr>
<td>2.4</td>
<td>1.05</td>
<td>1.0</td>
</tr>
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<td>1.35</td>
<td>2.0</td>
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<td>1.0</td>
<td>0.7</td>
<td>1.6</td>
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<tr>
<td>1.4</td>
<td>2.45</td>
<td>2.8</td>
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<td>1.45</td>
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</tr>
<tr>
<td>1.6</td>
<td>2.2</td>
<td>2.8</td>
</tr>
<tr>
<td>0.7</td>
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<td>2.95</td>
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<tr>
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<td>2.0</td>
<td>2.95</td>
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<td>1.9</td>
<td>1.3</td>
<td>3.0</td>
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<tr>
<td>0.7</td>
<td>1.7</td>
<td>3.0</td>
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<tr>
<td>1.6</td>
<td>2.4</td>
<td>3.0</td>
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<tr>
<td>0.9</td>
<td>2.0</td>
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<tr>
<td>1.6</td>
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<td>0.8</td>
<td>2.55</td>
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<td>0.9</td>
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<td>3.0</td>
</tr>
<tr>
<td>0.8</td>
<td>2.55</td>
<td>3.0</td>
</tr>
</tbody>
</table>

### Table 3 Total overbreak \((x_{hw} + x_{fw})_{0.3}\) and benchmark stability stoping width

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Total overbreak, m ((x_{hw} + x_{fw})_{0.3})</th>
<th>Benchmark stability stoping width, m (0.3) m vein</th>
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</thead>
<tbody>
<tr>
<td>In-line</td>
<td>1.30</td>
<td>1.60</td>
</tr>
<tr>
<td>Staggered</td>
<td>1.73</td>
<td>2.02</td>
</tr>
<tr>
<td>Dice-5</td>
<td>1.85</td>
<td>2.15</td>
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</table>
Stewart et al. Development of benchmark stoping widths

Stopes plotting in stable zone

For stopes plotting in the stable zone, an estimate of average stoping width for each blast pattern can be used as the basis for predicting narrow-vein dilution. If stopes are designed in the unstable zone of a stability chart, then stoping widths will on average exceed the expected stoping 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:

\[
\text{Total dilution} = \frac{\text{expected stope width} - \text{vein width}}{\text{vein width}}
\]

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 adjusted.

Stopes plotting in unstable or failure zone

For stopes plotting in the unstable zone of a stability chart, it can be expected that unplanned dilution due to geotechnical factors will be higher. As demonstrated by the Extended Mathews isoprobability contours (Mawdesley et al. 2001), the probability of instability increases the further below the stable-failure boundary the case study plots. Therefore, the percentage of stopes exceeding the benchmark stability stoping width is likely to exceed 20%.

As discussed earlier there is significant evidence suggesting the volume of dilution or ELOS is not continuously related to the stability number and hydraulic radius. This means that two stope case studies could plot in the same position on the stability graph and yet incur different volumes of unplanned dilution. Therefore, it is suggested that considering failure mechanisms on a case by case basis best assesses unplanned dilution for stopes plotting in the failure zone. For example, a small block size rock mass with full relaxation could be expected to unravel less dramatically over time. However, if large pervasive structures are likely to dominate stability then large failures could result in large volumes of dilution.

Ore loss potential

While the staggered and dice-5 patterns can be adjusted to accommodate veins of increasing width, the in-line pattern is drilled into the centre of the vein. There is potential for loss of ore if the in-line pattern is used in a vein of substantial width.

By analysing the overbreak distributions for different blast patterns, it is possible to evaluate ore loss potential as well as dilution. Although an in-line pattern may have a smaller practical stoping width than staggered and dice-5 patterns, in some cases the vein width may be such that adopting an in-line pattern could result in ore loss. Depending on the grade, ore loss can have a worse economic implication than dilution. By analysing the overbreak distribution with respect to vein width it is possible to examine the effect of blast pattern on both the probability of dilution and probability of ore loss.

For example, the cumulative distribution curve for in-line blasting in Fig. 19 indicates that total overbreak is less than 0.66 m 20% of the time. Taking account of 0.3 m nominal vein width, this result indicates that when vein width exceeds 0.96 m, there will be a 20% chance of underbreak with an in-line pattern. The curve can be used to estimate ore loss probability as a function of vein width. Using Fig. 19 there is a 10% probability of ore loss if the vein width exceeds 0.8 m and there is a 5% probability of ore loss if the vein width exceeds 0.7 m. These curves should be interpreted within the context of the inaccuracy of benchmark stoping widths associated with vein widths ranging from 0.2 to 0.4 m, which is ±0.1 m and also recalling that because in-line patterns were thought to correspond to smaller vein widths the benchmark stoping width for in-line patterns could be up to 0.1 m narrower than estimated, while conversely the staggered and dice-5 patterns could be up to 0.1 wider than estimated.

Conclusions

The benchmark stability stoping width will enable a site’s dilution to be benchmarked while also facilitating improved empirical analysis of narrow-vein stope case studies. The in-line blast pattern benchmark stability stoping width was 1.6 m. In the case of the staggered blast pattern the overbreak distribution analysis indicated a benchmark stoping width of 2.0 m. The dice-5 pattern benchmark stability stoping width was 2.1 m.

Benchmark average stoping width is effectively an average stoping width from which expected average dilution can be estimated. The expected stoping width estimated from probabilistic modelling of overbreak for in-line, staggered and dice-5 patterns are 1.3, 1.5 and 1.7 m respectively. The expected or average stoping widths can be used to predict dilution in narrow-vein longhole stopes.

Because vein width ranges from 0.2 to 0.4 m, the benchmark stoping width and benchmark average stoping widths have an accuracy of approximately ±0.1 m. In the case of in-line patterns widths are potentially overestimated by up to 0.1 m, while in the case of the staggered and dice-5 there is the potential to slightly underestimate by up to 0.1 m.

Application of the benchmark stoping widths to the Barkers 1 case studies suggests the modelling methodology is valid. However, the validity of the benchmark stoping widths at mines with similar operating conditions to Barkers remains to be validated. Given that benchmark stoping widths are largely a function of operating conditions such as equipment and blast pattern, it has been proposed that benchmark stoping widths can be considered operating condition specific and not site-specific. This is true to the extent that Barkers mine can be considered to have employed standard practice in terms of quality control practices, equipment suitability and operator experience and skill. On this basis it is reasonable to apply both benchmark stability stoping width and benchmark average stoping widths to similar narrow-vein operations where stopes plot on or above the stable-failure boundary of a stability graph. Irregular geology will have an impact on expected dilution and adjustments to expected dilution should be made accordingly.
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References


