SUPPORT DESIGN USING PROBABILISTIC KEYBLOCK METHODS

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Abstract

Support design for jointed rock masses can be approached in several ways. When designing support systems for these conditions, the potential block sizes and likelihood of occurrence should be considered. This paper outlines an approach whereby probabilistic keyblock modelling using JBlock was conducted to determine potential block sizes. This was then followed by conventional deterministic Unwedge analysis using the JBlock information to determine the block size scaling factors. Cases studies at two mines are presented demonstrating this approach.

1 Introduction

Support design in jointed rock masses is often approached by the use of either "rules of thumb", rock mass classification systems such as the Q system (Barton *el at*, 1974) or RMR (Bieniawski, 1973) or conventional wedge analysis (Goodman and Shi, 1985). Often this requires that a number of key simplifying assumptions are made and the support system is designed to cater for either a mean, most likely or worst case scenario depending on the specific situation and tolerance. Probabilistic methods (Tyler *et al,* 1991; Beauchamp *et al*, 1998; Esterhuizen and Streuders, 1998) can be used to overcome issues associated with the choice of simplifying assumptions.

This paper outlines an approach whereby probabilistic keyblock analyses were used to estimate potential block sizes and frequency as part of the support design process. This approach has been used on two mines as part of recent development support design reviews.

2 Support Design Methodology

Traditionally a combination of empirical and deterministic design approaches has been used to design tunnel support at the mines discussed in this paper. Recent support design reviews (Earl, 2007; Watson, 2007) presented an opportunity to include a probabilistic approach to determining potential block sizes and frequency. An attempt was also made to account for variability during the rock mass classification process using different approaches at each mine.

The design approach adopted included the following:

- Rock mass classification
- Empirical support estimates (guideline)
- Probabilistic keyblock assessment to define block sizes and frequency
- Deterministic wedge stability assessments to determine support requirements

2.1 Rock mass classification

Both mining operations discussed in this paper make use of the Q-system (Barton *et al*, 1974) for rock mass classification. The Q value is determined from the following relationship:

$Q = (RQD / J_n) \times (J_r / J_a) \times (J_w / SRF)$

where RQD = rock quality designation (Deere, 1969)
J_n = joint set number
J_r = joint roughness
J_a = joint alteration
J_w = joint water
SRF = stress reduction factor

This can be expanded to the following definitions:

RQD / J_n represents the block size
J_r / J_a represents the minimum inter-block shear strength
J_w / SRF represents the active stress

2.2 Empirical support design

The support requirements can be assessed using empirical charts (Grimstad and Barton, 1993) which relate the rock mass class to the equivalent dimension of the excavation (D_e).

D_e = Excavation height or span / ESR

where ESR = excavation support ratio (a value of 1.6 is usually used for permanent mine openings).

A number of relationships have been developed to determine the required support pressure (P) or support resistance.

$P = (20\ J_n^{0.5}\ Q^{-0.33}) / 3\ J_r$ (for fewer than three joint sets, $J_n < 9$)

$P = (20\ Q^{-0.33}) / J_r$ (for three or more joint sets, $J_n \geq 9$)

It is also possible to estimate the maximum unsupported span (MUS) using the following relationship:

$MUS = 2 \times ESR \times Q^{0.4}$

Unfortunately much of the data used to develop these empirical relationships comes from civil engineering projects and is not always directly applicable to the mining environment. Ideally a mining mine specific database and empirical design relationships should be developed. Peck and Lee (2007) note that local site experience is an important part of the process when using the Q-system.

2.3 Probabilistic keyblock assessment

Probabilistic keyblock assessments were conducted using the JBlock software programme. JBlock was developed to evaluate the potential for gravity driven rock falls and a probabilistic approach is used to determine potential keyblock dimensions and their interaction with support (Esterhuizen, 1996; Esterhuizen and Streuders 1998). Using information such as the spacing, orientation and length of discontinuities, it is possible to simulate blocks in the walls of an excavation (Esterhuizen and Streuders, 1998). Keyblock analysis methods (Goodman and Shi, 1985) are used to evaluate whether blocks are removable and whether the chosen support will be sufficient to ensure stability.

JBlock has some limitations in that it can only consider one surface at a time and therefore blocks in corners are not considered. Random joints are not included and these can contribute to the formation of unstable blocks (Grenon and Hadjigeorgiou, 2003). For the work outlined in this paper JBlock was used to determine the likely block sizes that could be expected.

2.4 Deterministic wedge stability assessments

The stability of wedges can be analysed using the Unwedge programme (Rocscience, 2005) which applies Goodman and Shi (1985) block theory. This programme can be used to analyse wedge failure around excavations in hard rock, where discontinuities are persistent, and where stress induced failure does not occur.

The analysis is restricted to three discontinuity planes at one time and it is necessary to conducted multiple analyses on combinations of planes if more than three discontinuity planes are present. Unwedge calculates the maximum sized wedges which can form around an excavation. The user can scale the size of the wedges based on experience and field observations. This is a deterministic approach and does not consider the range of wedge sizes that could occur or the likelihood of a particular wedge size.

3 Case Studies

The approach outlined previously has been used at two Newmont Asia Pacific underground operations as part of recent development support reviews.

3.1 Callie Mine Development Support Review

Callie Mine is part of the Newmont Tanami Operations (NTO) situated 600km northwest of Alice Springs in the Northern Territory of Australia. The underground mine has been in operation since 1997. A sublevel open stoping (SLOS) mining method is used and mining operations are currently at about 900m below surface. Mineralization is hosted in a folded sequence of medium to fine grained metasediments.

The development support design was recently reviewed (Watson, 2007) to incorporate new geotechnical data from the deeper part of the mine and an improved understanding of the geotechnical conditions since the previous development support design review in 2003. Previous designs were based on worst case assumptions and did not consider the likelihood of this worst case scenario. A probabilistic keyblock approach was incorporated into the design review to get a better idea of likely block sizes and frequency.

3.1.1 Rock mass classification

Using geotechnical data from drill holes the rock mass was classified using the Q-system. The best, most-likely and worst case for each input parameter was determined based on the frequency distributions. These were then used to calculate a range of Q values as shown in Table 1 (Watson, 2007). Ground conditions range from "poor" to "good" with the most-likely falling on the "fair" to "good" boundary.

Table 1 Q input parameters summary (Watson, 2007)

Q-System parameter	Best	Most-likely	Worst
RQD	90	80	75
Jn	4	6	9
Jr	3	1.5	1
Ja	0.75	0.75	1
Jw	1	1	1
SRF	2.5	2.5	2.5
Q	36.0	10.7	3.3

3.1.2 Support estimates using Q

The Q values were used to estimate the support pressure and maximum unsupported span (Table 2). According to the support estimation chart (Grimstad and Barton, 1993) rock bolt spacings of 2.8m, 2m and 1.4m would be needed to cater for the best, most-likely and worst cases respectively. It should be noted that these estimates are considered only as a guide as site specific empirical relationships have not been defined.

Table 2 Empirical support estimates (Watson, 2007)

Parameter	Best	Most-likely	Worst
Q	36.0	10.7	3.3
P (t/m^2)	1.3	4.9	13.4
MSUS (m)	13.4	8.2	5.2

3.1.3 JBlock analysis

JBlock generates removable keyblocks and places them at random locations in a pre-defined excavation and evaluates their stability. For the Callie analyses, 10000 removable blocks were generated and statistical information of the block sizes and occurrence were obtained. Joint mapping data between the 540 and 700 levels were used as JBlock input (Table 3).

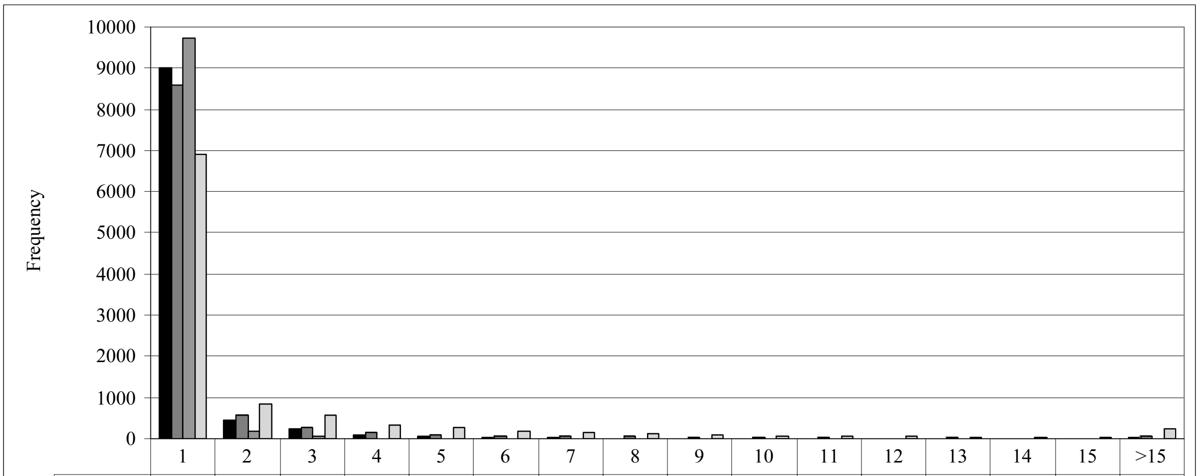
Four options were evaluated using the actual geotechnical data as a base case and varying parameters to evaluate block size sensitivity as follows:

Option 1 Callie data inputs
Option 2 Joint spacing increased for all joint sets (Mean = 2m; Min = 0.1m; Max = 5m)
Option 3 Mean and minimum length reduced for all joint sets (Mean = 2m; Min = 1m)
Option 4 Increased mean and minimum spacing for all joint sets (Mean = 2m; Min = 1m)

Table 3 Callie joint input data for JBlock analysis

Joint set	Dip	Dip Dir	Range	Spacing (m)			Length (m)		
				Mean	Min	Max	Mean	Min	Max
1	63	144	20	0.94	0.1	5	4	2	10
2	30	320	20	0.5	0.05	1	4	2	10
3	65	210	20	1.1	0.1	5	4	2	10

Figure 1 shows the distribution of block volumes for the four options modelled. It can be seen that the majority of blocks are less than 1m^3. This information provides an insight into the range of block sizes that can occur.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	>15
Option 1	8995	452	234	101	71	33	37	9	11	9	8	5	5	4	6	20
Option 2	8585	566	258	154	78	58	59	46	35	20	16	11	16	14	13	71
Option 3	9722	189	49	14	7	6	3	3	2	1	0	0	0	0	1	3
Option 4	6918	849	565	333	279	189	136	112	104	72	64	47	45	27	28	232

Figure 1 Block volume frequency for Callie Mine

For design purposes the results of the Option 1 analysis are considered the most appropriate. Table 4 is a statistical summary of the dimensions and weight of the blocks generated in Option 1.

Table 4 Statistical summary of block information

Parameter	Mean	Std Dev	Median	Cumulative %		
				80%	90%	95%
Width (m)	0.5	0.5	0.3	0.8	1.2	1.5
Length (m)	1.5	1.1	1.2	2.3	2.9	3.5
Apex Height (m)	0.5	0.7	0.3	1.0	1.5	2.0
Volume (m^3)	0.6	2.2	0.043	0.5	1.5	2.8
Mass (t)	1.8	6.2	0.1	1.4	4.3	7.8

The support requirements can be estimated using this statistical data. Using an appropriate cumulative level is generally a more conservative approach than using the mean or median dimensions. If support is designed to cater for the 95% cumulative level this implies that 95% of block occurrences are catered for in the design. The choice of a cumulative level is related to level of risk that can be tolerated. A large proportion (80%) of blocks, have a volume of less than $0.5m^3$ and a mass of less than 1.43t.

Using the block frequencies it is possible to determine the probability of occurrence for each block volume class. The blocks created in JBlock are mutually exclusive therefore it is necessary to use the total area modelled (a JBlock output) when calculating the probability of occurrence. The probability of occurrence for different block volumes for Option 1 were determined for a 100m length of a 5.5m wide tunnel and are summarised in Table 5.

From these results it can be seen that there is high probability of smaller blocks occurring and the likelihood of large blocks is relatively small. This is in line with observations at Callie where very few large blocks or wedges have been observed (Watson, 2007). This analysis focuses on the dimensions of blocks that could occur within the Callie rock mass and does not consider the stability of these blocks.

3.1.4 Unwedge analysis

An Unwedge assessment was conducted using the 95% cumulative levels from Option 1 to scale the wedge sizes. The modelling considered both horizontal (0 degrees) and decline (9 degrees or 1:6) development with a width of 5.5m. The analysis also included the identification of a worst case tunnel orientation relative to the wedge forming discontinuities (Watson, 2007).

A support system consisting of 2.4m Split Sets (3t/m) on a 1.4m by 1.5m grid was evaluated for both the horizontal and decline development and was found to have factors of safety of 5.7 and 2.3 respectively (Figure 2).

Table 5 Probability of block occurrence for 100m of 5.5m wide tunnel at Callie

Block Volume (m^3)	Frequency	Percentage Probability of Occurrence
1	8995	79.73
2	452	7.71
3	234	4.07
4	101	1.78
5	71	1.25
6	33	0.58
7	37	0.65
8	9	0.16
9	11	0.19
10	9	0.16
11	8	0.14
12	5	0.09
13	5	0.09
14	4	0.07
15	6	0.11

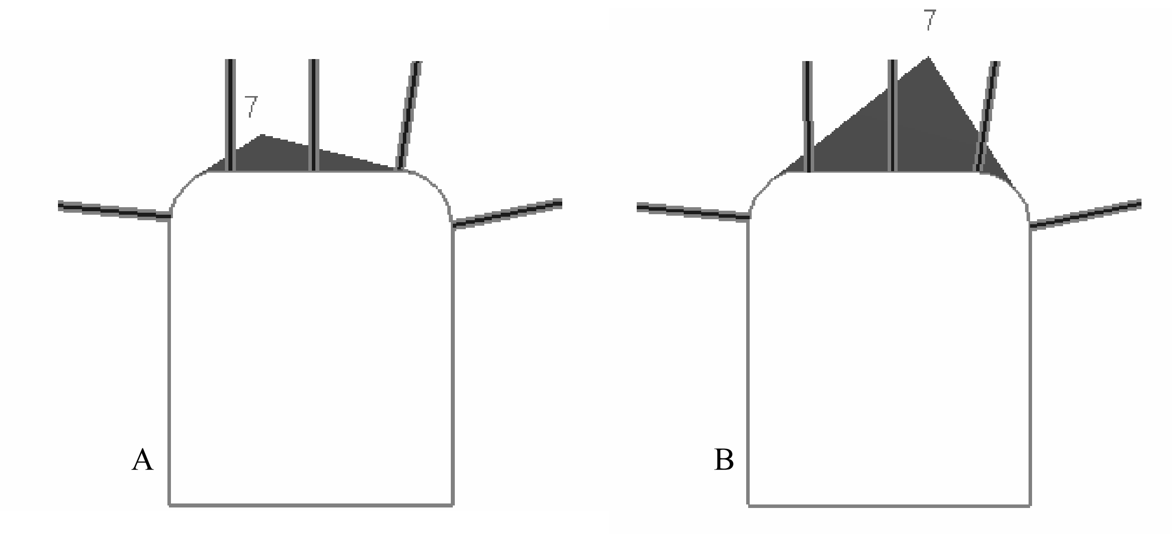


Figure 2 Unwedge profiles for worst case orientation: (A) horizontal flat development (FOS = 5.7) and (B) incline development (FOS = 2.3)

3.2 Westside Mine Development Support Review

Newmont Jundee Operations (NJO) is located 520km north of Kalgoorlie and 45km northeast of Wiluna in Western Australia. Mining commenced at Jundee in August 1995, and the first gold pour was in December 1995. Mineralization is hosted within a west-dipping sequence of basalts, with interflow sedimentary units intruded by dolerite sills.

The Jundee Westside orebody is made up of a series of lodes typically less than 1m thick and up to 500m long on strike with a dip of 40 to 50 degrees (Ascott, 2006). A central retreat uphole open stoping mining method is used. This involves retreating from the extremities of the ore drives toward a central access. Stope strike lengths are typically 30m with 5m rib pillars between panels and staggered across levels.

3.2.1 Rock mass classification

Geotechnical logging data from diamond drill core was used to classify the Westside orebody using the Q system. Each rock type was classified and the Q value distribution was determined. Generally, the different rock types had a Q value range of 0.2 to 100 with mean values in the 5 to 17 range (fair to good).

As a first pass estimate of the support requirements, the 20th percentile Q values (P_{20}) were used (the value at which 80% of data exceeds this value) and found to fall in a range between 2 and 6.6 (poor to fair). Using the Grimstad and Barton (1993) design chart (Figure 3) the bolt spacing was estimated to range between 1.4 and 1.8m (Ascott, 2005).

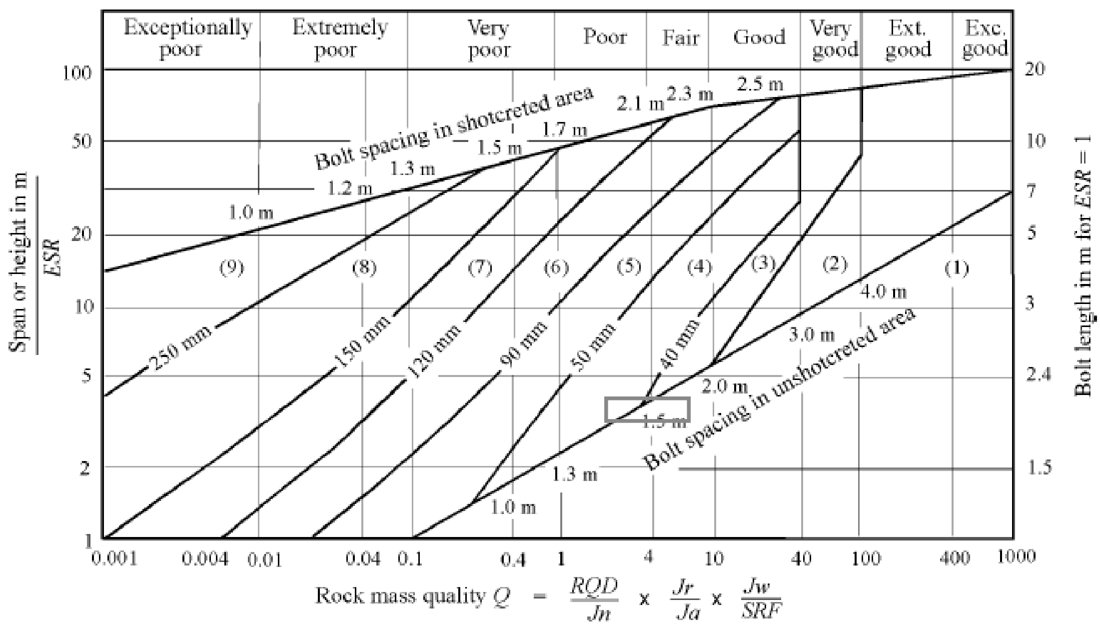


Figure 3 Support design chart (after Grimstad and Barton, 1993) showing Westside Q values.

3.2.2 JBlock analysis

Using discontinuity set data from Westside (Ascott, 2005) probabilistic keyblock analyses were conducted to determine potential block sizes (Table 6). Three cases were modelled, the first using the raw data as recorded, the second was with modified spacing and the third with modified spacing and length of discontinuities. The spacing and length were increased to allow the generation and evaluation of larger blocks (Earl, 2007). In each case 10000 removable blocks were generated and the block volume distributions are shown in Figure 4.

Table 6 Westside joint input data for JBlock analysis

Joint set	Dip	Dip Dir	Range	Spacing (m)			Length (m)		
				Mean	Min	Max	Mean	Min	Max
1	77	215	10	0.9	0.2	3	2.2	1.5	3
2	50	266	10	0.8	0.2	2	3.5	1.5	10
3	60	22	10	1	0.3	10	3.8	1.5	15
4	62	78	20	0.1	0.1	10	3.4	1.5	10
5	89	155	10	1	1	10	3	1.5	8
6	63	117	10	0.3	0.3	10	2.9	1.5	7

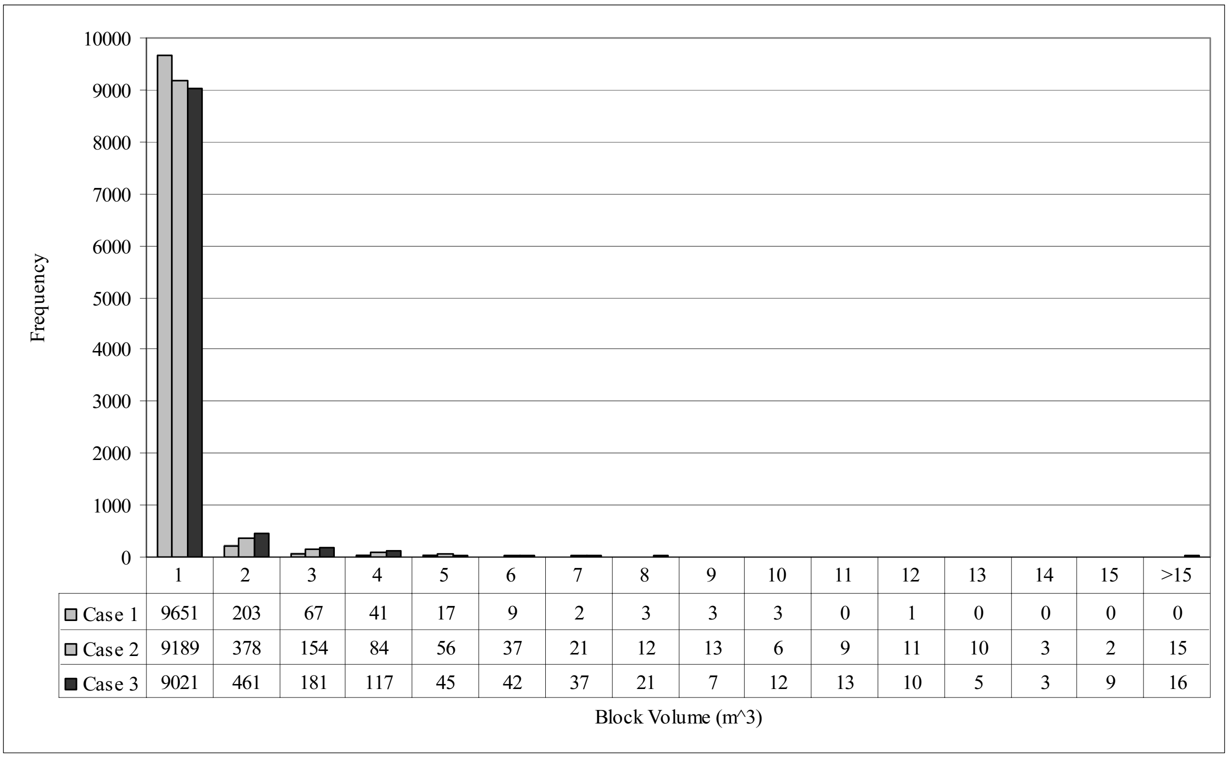


Figure 4 Block volume frequency for Westside

The 80, 90 and 95 cumulative percentage values were determined for a range of dimensions for each case (Table 7). Historical rockfall data from NJO suggests that blocks or wedges that fail from the roofs of excavations tend to be typically around 1m^3 or less. Therefore the results of the first JBlock analysis (Case 1) appear to be reasonably consistent with these observations, with 95% of all blocks created using JBlock having a volume of less than $1m^3$ (Earl, 2007).

Table 7 Cumulative percentage levels for block dimensions

Dimension	Cumulative percentage	Case 1- as mapped	Case 2 - modified spacing	Case 3- modified spacing & length
Length (m)	80%	1.31	1.71	1.92
	90%	1.81	2.25	2.32
	95%	2.26	2.88	3.20
Width (m)	80%	0.52	0.70	0.71
	90%	0.72	1.10	1.12
	95%	0.92	1.35	1.28
Height (m)	80%	0.72	1.21	1.36
	90%	1.08	1.82	2.04
	95%	1.56	3.00	3.06
Volume (m^3)	80%	0.11	0.3	0.42
	90%	0.33	0.9	0.98
	95%	0.77	1.8	2.10
Mass (t)	80%	0.31	0.86	1.20
	90%	0.94	2.57	2.80
	95%	2.19	5.13	5.90
Face Area (m^2)	80%	0.48	0.71	1.00
	90%	0.88	1.42	1.60
	95%	1.36	2.12	2.40

Using the approach outlined previously the probability of occurrence for different block volumes for a 100m length of a 5.5m wide tunnel was determined for each of the cases modelled (Table 8). It can be seen that there is a high likelihood of blocks of $1m^3$ or less occurring whilst the probability of occurrence decreases with increasing block size.

To determine the probability of block failure either though failure of the rock bolts or in between the rock bolts units it is necessary to include the probability of block instability. The probability of failure would be the product of the probabilities of block occurrence and block instability and thus would be lower than the probability of block occurrence.

Smaller blocks can fail in between the rock bolts but will generally be contained by the surface support. Large blocks are supported by the support system of rock bolts and surface support.

Table 8 Probability of block occurrence for 100m of 5.5m wide tunnel at Westside

Block Volume (m^3)	Frequency			Percentage Probability of Occurrence		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
1	9651	9189	9021	98.84	86.28	87.19
2	203	378	461	8.94	7.84	9.97
3	67	154	181	3.05	3.27	4.04
4	41	84	117	1.87	1.80	2.63
5	17	56	45	0.78	1.20	1.02
6	9	37	42	0.41	0.80	0.95
7	2	21	37	0.09	0.45	0.84
8	3	12	21	0.14	0.26	0.48
9	3	13	7	0.14	0.28	0.16
10	3	6	12	0.14	0.13	0.27
11	0	9	13	0.00	0.19	0.30
12	1	11	10	0.05	0.24	0.23
13	0	10	5	0.00	0.22	0.11
14	0	3	3	0.00	0.06	0.07
15	0	2	9	0.00	0.04	0.20
>15	0	15	16	0.00	0.32	0.36

3.2.3 Unwedge analysis

A number of wedge stability analyses were conducted using Unwedge. The 95% cumulative values for the block dimensions determined using JBlock (Case 3) were used as to scale the wedges (Earl, 2007). Two approaches were used, firstly the potential wedges were scaled by length, width and height combined, and secondly by volume (and mass).

For case 3 the 95% cumulative levels for length, width and height were 3.2m, 1.3m and 3.1m respectively. These three dimensions are all mutually exclusive and may not be at these values simultaneously; however a block with these dimensions is essentially the worst-case for a 95% cumulative level (Earl, 2007). Factors of safety in excess of 1.3 (as used in Ascott, 2005) were obtained for all tunnel orientations.

The 95% cumulative level for block volume was 2.1m^3 for Case 3, which would be equivalent to a mass of approximately 6t. The factor of safety in this case never dropped below 2 and in general was much higher. The support system evaluated consisted of 2.4m long friction anchors spaced at 1.3m by 1.5m (Earl, 2007).

4 Discussion

Both operations used a number design tools when designing tunnel support. In both cases, the point of departure was the classification of the rock mass using the Q system (Barton *et al*, 1974) and empirical estimates of the support requirements. The support estimates were used as a guide as the Q database is based predominantly on civil engineering case studies (Peck and Lee, 2007).

Different approaches were used at the two operations to account for variability in the rock mass. Callie attempted to identify a most-likely case whilst Jundee adopted a more conservative approach and used the 20th percentile value (the value at which 80% of data exceeds this value). Both approaches are useful in demonstrating the rock mass variability and the support requirements.

The need to consider block shapes and sizes when designing a support system for jointed rock masses has been documented by several authors (Windsor and Thompson, 1992; Windsor, 1999). Block shape determines the removability whilst the block size determines the support capacity needed. Both of these considerations are satisfied using JBlock, as the blocks generated are all removable although not all blocks are unstable, and block sizes are also determined.

JBlock information on block dimensions was useful in determining the scaling factors to be used in the Unwedge analyses. Using this approach it was possible to have an appreciation of possible removable block sizes that could be formed. It was still necessary to make an engineering judgement on whether the mean or maximum dimensions should be used. Cumulative distribution curves and the frequency of block occurrences were used to assist in making this decision. A 95% cumulative level was used as this is commonly used in support design in South African mines (Daehnke *et al*, 1998). The authors consider this a more reasonable design approach to simply using a mean or worst case value.

The probabilistic keyblock approach can be negatively influenced by the using of input parameters with a low confidence and it is important to take care when collecting data. Sensitivity analyses should be conducted to understand the impact variations in the discontinuity parameters can have on the block size distribution and descriptive statistics.

The work outlined in this paper considers the variability in block sizes and likelihood of particular sizes occurring as part of the design process. Beauchamp *et al* (1998) outline an approach whereby Unwedge was used to identify critical wedges. These wedges were then analysed using Monte Carlo simulation and varying bolt strength, joint cohesion and friction angle.

5 Conclusions

Rock mass classification and empirical support estimates were used as an initial guideline on both mines. The sizes of removable blocks should be considered when designing support for jointed rock masses. Furthermore it is necessary to consider the likelihood of different block sizes occurring when making simplifying assumptions such as the mean or worst case block size.

This was demonstrated through two case studies in which JBlock was used to conduct probabilistic keyblock analysis as part of the design process. Limitations of the currently available tools resulted in a hybrid approach whereby both JBlock and Unwedge were used.

The design approach described in this paper is considered superior to only using empirical support estimates or deterministic wedge analysis based on a mean worst case estimate of block size. There are limitations to this approach and sound engineering judgement is still required.

The fact that both block size distribution and frequency are considered is a step towards a risk based design approach. A combination of the approaches described by Beauchamp *et al* (1998) and in this paper would be an improvement and could form part of a risk based design methodology.

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