Time-dependent failure of open stopes at Target Mine

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Synopsis

There are numerous factors that affect open stope stability and often result in falls of ground. These falls of ground can be attributed to factors such as beam failure due to a larger than normal roof area (hydraulic radius too large), adverse ground conditions, seismicity, the stress-strain environment, absence of support, and poor drill-and-blast practices. The effect of time on the stability of open stopes is sometimes underestimated and is relatively unknown, especially on Target Mine. Actual data was collected from open stopes at Target and analysed to show the effect of time on open stope stability. The benefits of this analysis will include improved understanding of time-dependent failure, which can assist in reducing dilution and the risk of sterilization of future mining blocks.

Keywords
stope stability, open stope, time-dependent failure, dilution.

Introduction

Target Mine is situated adjacent to the town of Allanridge, some 20 km from Welkom in South Africa's Free State Province, and is the most northerly mine in the Welkom Goldfields area (Figure 1). The mine consists of a single surface shaft system with a sub-shaft (Target 1C shaft) and a decline. Ownership was attained by Harmony Gold Mining Company Limited in May 2004 (Harmony Gold Mining Company Limited, 2010).

Before discussing the selection of open stopes for the back-analyses, a brief explanation of open stoping as practiced at Target Mine will be given. The orebody is some 180 m in thickness and 270 m wide and comprises multiple reefs overlying one another. The 180 m thick reef package is termed the Eldorado Reefs, as shown in Figure 2. The Eldorado Reefs suboutcrop against the Dreyerskuil Reefs, as shown in Figure 3. The dip of the reef varies from as low as 10° in the west to 75° in the east.

Compared with most Australian and Canadian open stoping mining operations, Target Mine is unique. In most Australian and Canadian mining operations the hangingwall and footwall of the open stopes comprise waste rock, and the orebody dips relatively steeply. Due to the depth of Target Mine, some 2300 m to 2500 m below surface, a destress slot (Figure 4) is mined to create an artificial, shallow mining environment whereby the field stress is managed and kept at values of around 60 MPa. The destress slot comprises a narrow tabular stope with an average width of 1.5 m, and is mined on the Dreyerskuil Reefs.

At Target Mine the hangingwall, sidewalls, and footwall of the open stopes all comprise reef of different grades, except for the EA1, where the EB footwall is waste rock. If a stope, for example, is mined alongside an existing old stope, the western sidewall of this stope will consist of backfill. The general mining direction of open stopes is from the lowest position of the reef on the west, progressing up towards the east as shown in Figure 5.

Open stoping is the process by which massive stopes are blasted to mine selected reef packages within the orebody. These open stopes are large, varying from 10 m to 45 m in width (span), 10 m to 35 m in height, and 10 m to 100 m in length. To establish an open stope, a reef drive is developed on strike at the lowest point where the stope will be situated, as shown in Figures 5–7. This reef drive is developed to the mining limit of that specific open stope. At the end of the open stope, slot cubbies are developed cutting across the dip of the strata.

In one of the cubbies, a drop raise is developed holing into the top drive for ventilation. Once developed, the slot is drilled, as well as the blast rings for the open stope. When completed, the slot is blasted and cleaned utilizing remote loading LHD (load, haul, and dump) mechanized equipment.

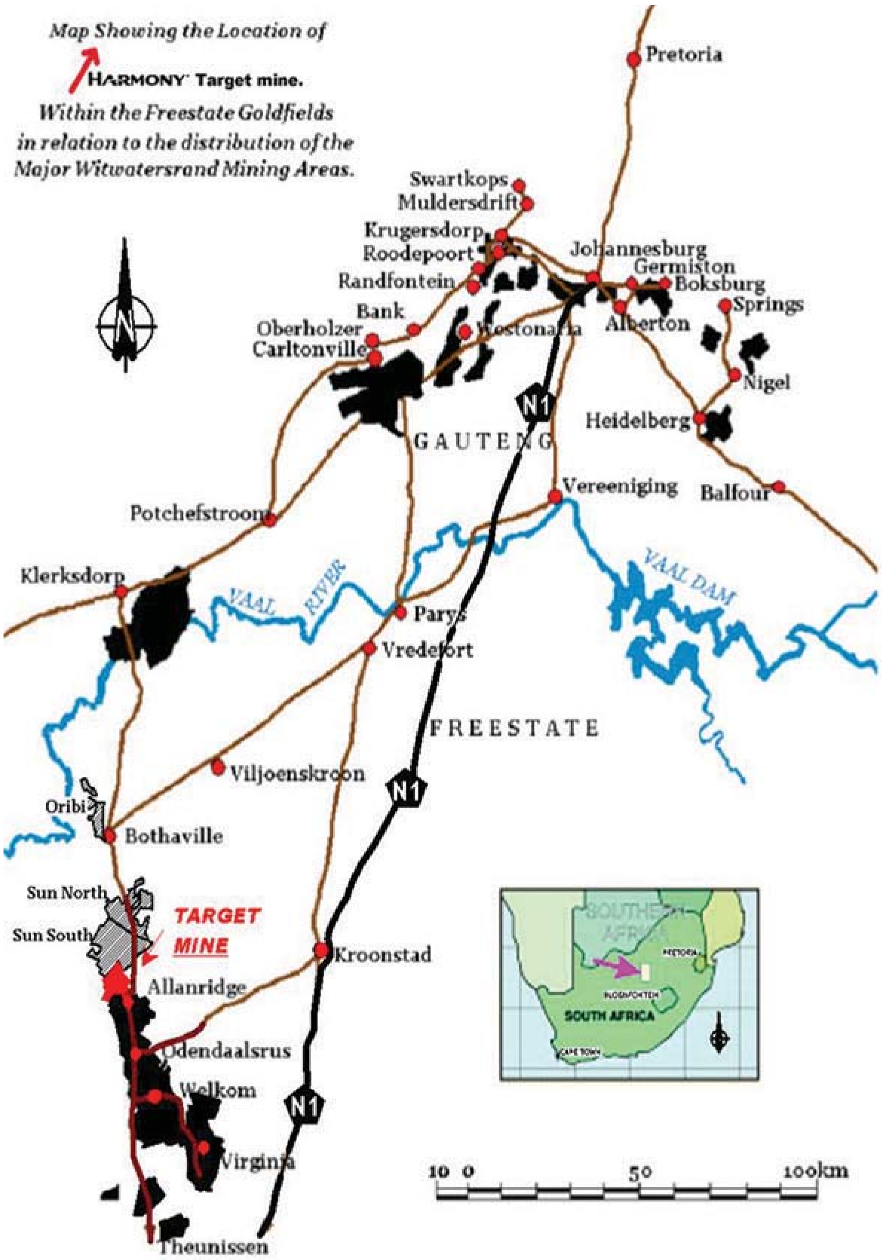


Figure 1—Location of Target Mine (Harrison, 2010

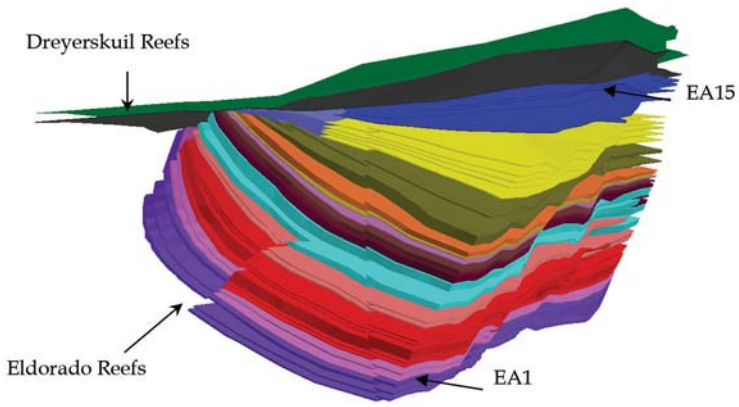


Figure 2—General isometric view looking north, showing the Eldorado Reefs suboutcropping against the Dreyerskuil Reefs (le Roux, 2015)

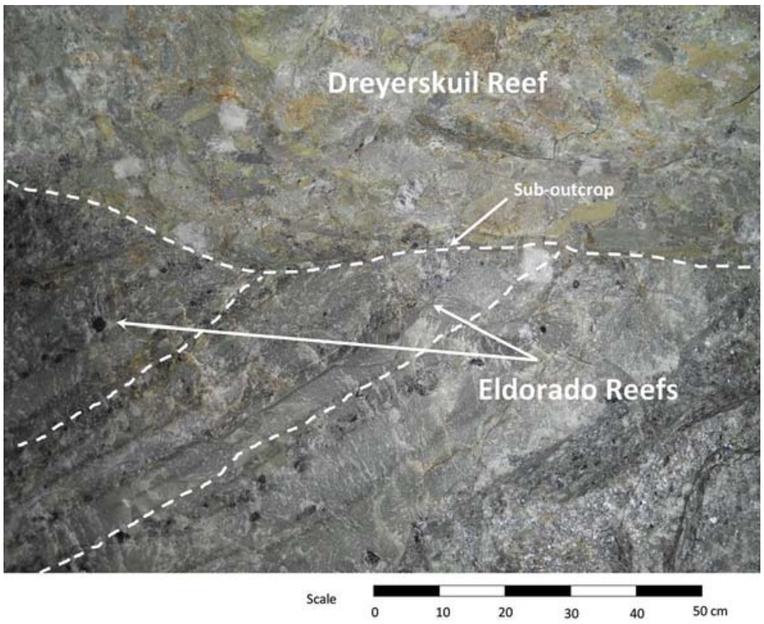


Figure 3—Photograph showing the Eldorado Reefs suboutcropping against the Dreyerskuil Reefs (le Roux, 2015)

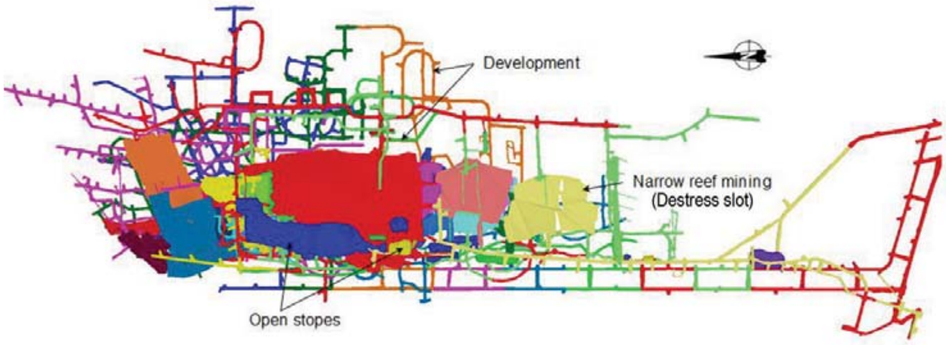


Figure 4—Plan view of Target mining block (le Roux, 2015)

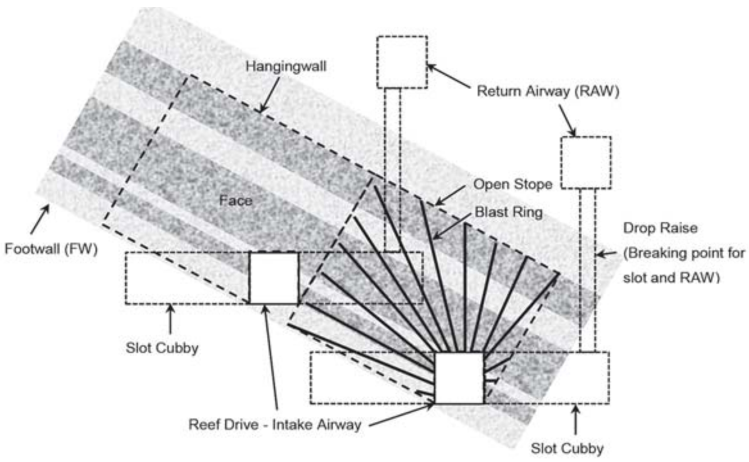


Figure 5—Cross-sectional view of a typical open stope design on Target Mine (le Roux, 2015)

The open stope is then created by blasting a maximum of four rings at a time, on retreat, and is cleaned utilizing remote-loading LHDs. No personnel are allowed to enter these open stopes at any time, as no support is installed.

Financial implication of dilution and falls of ground

Thirty-three open stopes were used for the back-analysis of fall-of-ground statistics. Dilution due to falls of ground in open stoping can have an impact on profitability. These falls of ground

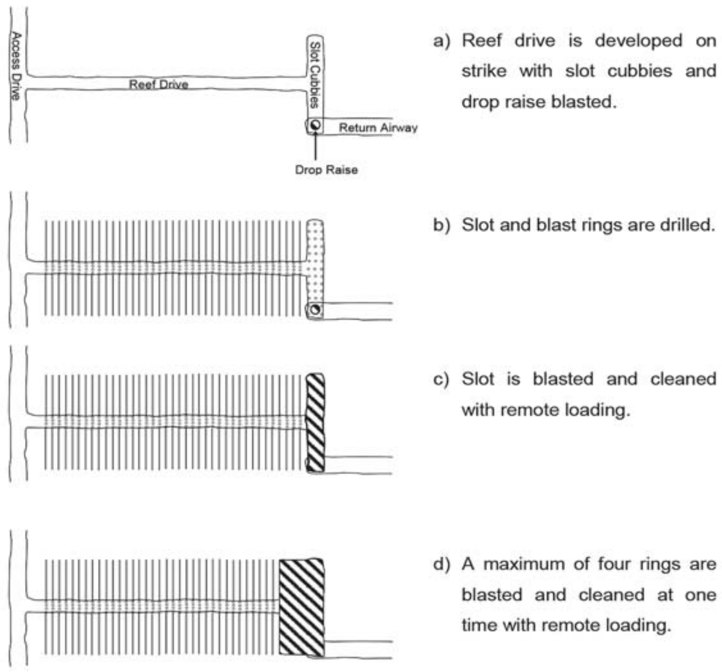


Figure 6—Plan view of a typical open stope design on Target Mine (le Roux, 2015)

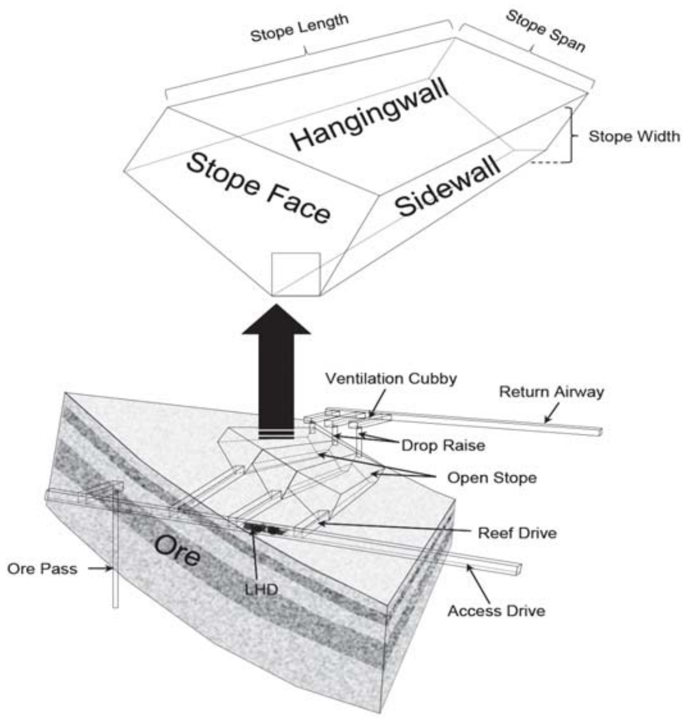


Figure 7—General isometric view of a typical open stope design on Target Mine (le Roux, 2015)

contribute significantly towards dilution as the rock from the falls is loaded with the blasted ore. This would be country rock in the case of typical open stopes, but at Target Mine the dilution may consist of unpay ore, backfill, waste rock, or a combination of these materials. One of the contributing factors to loss in profit is damage to and loss of mechanized equipment due to falls of ground, as shown in Figure 8.

Estimation of dilution using the DSSI

The extent of failure for the Target open stopes can be determined using the strain-based stability/design criterion, termed the dilution stress-strain index (DSSI) (le Roux, 2015). The relationship between mean stress σ_m and volumetric strain e_{vol} can be expressed as follows:

Figure 8—A TORO LH514 LHD in an open stope, damaged by a fall of ground (le Roux, 2015)

$$\sigma_m = q\varepsilon_{vol} \quad [1]$$

$$\varepsilon_{vol} = \frac{\sigma_m}{q} \quad [2]$$

where q is the slope of the linear trend lines. The DSSI is the relationship between mean stress and volumetric strain, expressed as follows:

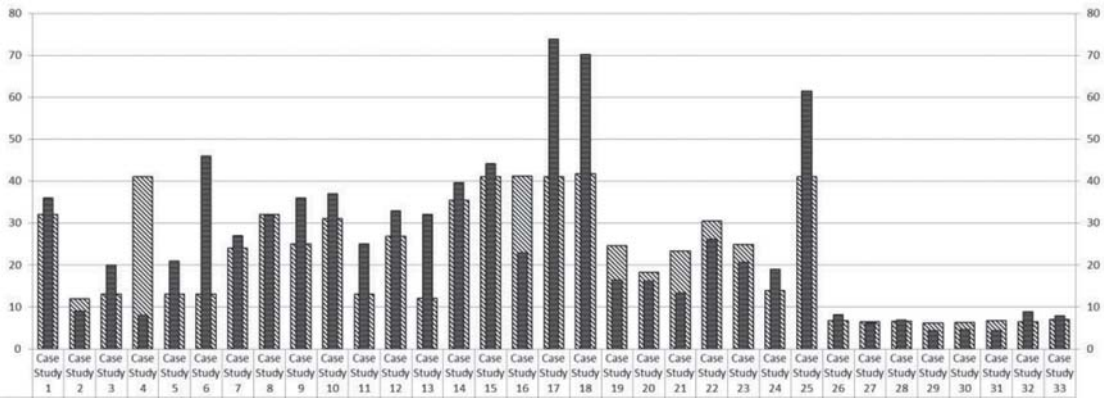
$$DSSI = \frac{\sigma_m}{q\varepsilon_{vol}} \quad [3]$$

For a factor of safety of 1.0, the DSSI is equal to 1.0, thus no failure occurs. A DSSI greater than 1.0 will indicate failure conditions in tension. For a set value of mean stress, if the volumetric strain is less than the threshold, failure would occur due to relaxation. A DSSI of less than 1.0 will indicate failure conditions in compression. This method considers all three principal stresses and strains, which is appropriate for the three-dimensional environment of the open stopes at Target Mine (le Roux, 2015).

Applying the DSSI criterion at Target Mine enabled the planned dilution to be compared with the predicted dilution in an attempt to determine whether a particular open stope would be profitable to mine or not. In Figure 9 the actual percentage dilution is compared to predicted dilution, showing some good correlations. It is noted that in some of the case studies the actual dilution exceeded the predicted dilution. This can be attributed to excessive standing times during and subsequent to stoping, delays in placing backfill, adjacent mining activities (blasting), and seismicity. These falls of ground have the potential to sterilize the adjacent open stope.

Open stope failure and the effect of time

There are numerous factors that affect open stope stability and often result in falls of ground, such as beam failure due to a larger than normal roof span, adverse ground conditions, seismicity, the stress-strain environment, absence of support, and poor drill-and-blast practices. The effect of time on the stability of open stopes is sometimes underestimated and is relatively unknown, especially on Target Mine. Actual data collected from 33 open stopes at Target Mine was analysed to show the effect of time on open stope failure. To investigate and document the behaviour of open stopes and to evaluate alternative open stope design methods that could be beneficial, a comprehensive empirical database was established. This consisted of information such as rock mass properties, rock mass classification values, and cavity monitoring system (CMS) data. The following information from the 33 case study stopes at Target Mine was included in the database, as shown in Table I:



	Case Study 1	Case Study 2	Case Study 3	Case Study 4	Case Study 5	Case Study 6	Case Study 7	Case Study 8	Case Study 9	Case Study 10	Case Study 11	Case Study 12	Case Study 13	Case Study 14	Case Study 15	Case Study 16	Case Study 17
DSSI % Dilution	32	12	13	41	13	13	24	32	25	31	13	27	12	35	41	41	41
Total % Dilution	36	9	20	8	21	46	27	32	36	37	25	33	32	40	44	23	74

	Case Study 18	Case Study 19	Case Study 20	Case Study 21	Case Study 22	Case Study 23	Case Study 24	Case Study 25	Case Study 26	Case Study 27	Case Study 28	Case Study 29	Case Study 30	Case Study 31	Case Study 32	Case Study 33
DSSI % Dilution	42	25	18	23	30	25	14	41	7	6	7	6	6	7	6	7
Total % Dilution	70	16	16	13	26	21	19	62	8	6	7	4	5	4	9	8

Figure 9 – Actual percentage dilution *versus* modelled percentage DSSI dilution

Table I

Case study data

Case study no.	Q	HR (m)	Hangingwall span (m)	Total actual % dilution	Predicted % dilution (DSSI)	Time (months) before FOG	Other contributing factors leading to FOG
1	0.03	12	47	36	32	0.5	Larger than normal span
2	0.47	6.9	19	9	12	1.0	None
3	0.12	6.9	17	20	13	3.0	Holed into up-dip open stope
4	0.14	7.5	19	8	41	1.0	Partially de-stressed
5	1.48	7.7	23	21	13	6.0	Holed into up-dip open stope
6	1.48	7.3	27	46	13	1.0	Not de-stressed
7	0.47	7.8	20	27	24	3.0	Blasting in close proximity
8	1.48	12	47	32	32	0.5	Larger than normal span
9	1.48	9.1	37	36	25	1.0	Not de-stressed
10	0.03	7.1	30	37	31	2.0	Partially de-stressed
11	0.03	6.9	20	25	13	1.0	Not de-stressed
12	0.03	6.8	18	33	27	3.0	Not de-stressed
13	0.03	9.1	31	32	12	1.0	Holed into NRM
14	0.03	8.1	20	40	35	3.0	Not de-stressed
15	9.23	16.9	45	44	41	1.0	Larger than normal span
16	0.92	13.0	34	23	41	72.0	Larger than normal span
17	16.08	18.7	45	74	41	1.0	Larger than normal span
18	1.85	14.7	36	70	42	1.0	Larger than normal span
19	0.47	5.5	9	16	25	6.0	Broken hangingwall beam (large brow)
20	0.92	11.4	25	16	18	2.0	Larger than normal span
21	0.47	7.0	18	13	23	3.0	Holed into NRM
22	2.74	11.5	30	26	30	1.0	Not de-stressed and larger than normal span
23	4.74	8.6	32	21	25	1.0	Not de-stressed
24	0.92	11.4	25	19	14	2.0	Larger than normal span
25	0.14	7.8	17	62	41	2.0	Holed into NRM
26	0.92	5.8	14	8	7	6.0	None
27	7.20	6.5	17	6	6	7.0	None
28	1.74	7.7	22	7	7	8.0	None
29	9.23	8.1	20	4	6	12.0	None
30	7.60	8.0	21	5	6	8.0	None
31	1.90	6.5	15	4	7	8.0	None
32	2.96	5.9	17	9	6	4.0	None
33	0.30	6.1	20	8	7	3.0	None

➤ Predicted stope dilution from DSSI
➤ Actual dilution from CMS survey data
➤ Stope geometry (beam span and hydraulic radius)
➤ Rock mass classification value, Q System (Barton, Lien, and Lunde, 1974)
➤ Time that open stope stood before failure (fall of ground)
➤ Possible contributing factor(s) to fall of ground in open stope.

To determine the Q-value, the Joint Water Reduction Factor (Jw), was taken as unity for all the open stopes on Target Mine. These stopes were either dry or had a minor inflow of water. The Stress Reduction Factor (SRF) was taken as between 0.5 and 2 for open stopes in high stress conditions and unity where medium stress or favourable stress conditions were found.

Major dilution is defined as dilution greater than 10% (local definition). Minor dilution is where the measured dilution is equal to or less than 10%, and underbreak is where the measured dilution is negative (<0%). At Target Mine, all open stopes are designed for a dilution of 5% and less, but this was rarely achieved. In 70% of the case study stopes, dilution was >10% and deemed as major failure; 30% had dilution <10% and were deemed as minor failure; open stopes with underbreak were excluded from this study.

The contributing factors to the falls of ground in open stopes (Table I) can be summarized as larger than normal span, holed into updip open stope, partially de-stressed, not de-stressed, blasting in close proximity, and holed into NRM (narrow reef mining).

Figure 10 is an adaption of the Q-value 'no support curve' after Houghton and Stacey (1980), used mainly to determine the stability of unsupported spans for long-term service excavations. While not really suitable for open stopes, plotting the Target Mine

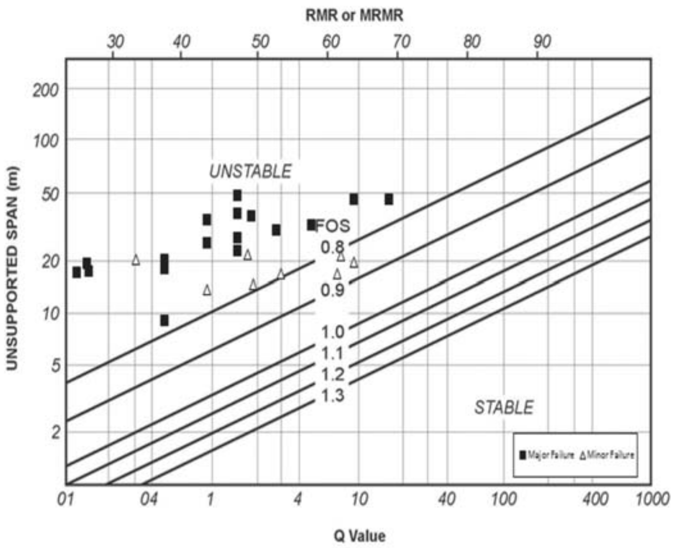


Figure 10—Plot of unsupported span (m) versus Q-value for Target Mine case studies with major and minor failure (after Houghton and Stacey, 1980)

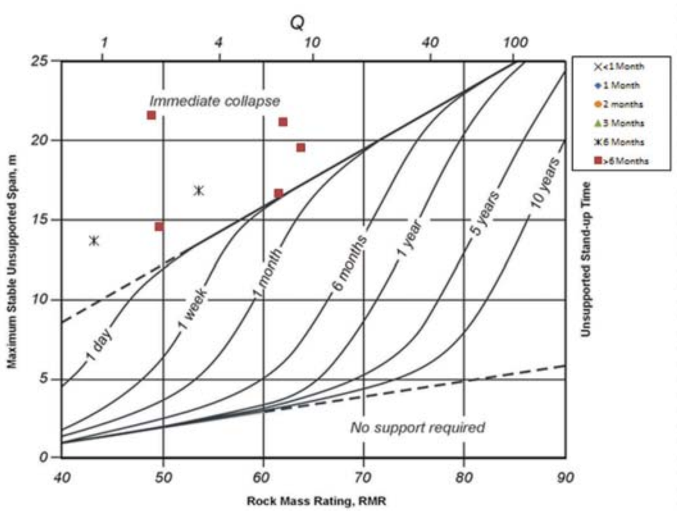


Figure 11—Unsupported span (m) versus Q-value (after Hutchinson and Diederichs, 1996)

results in this way indicates that eventually the beam will fail due to the multiple reefs overlying one another. The time to failure is still an unknown factor.

The graph in Figure 11 (after Hutchinson and Diederichs, 1996) allows one to estimate unsupported standup times for service excavations using unsupported spans, and the Q and RMR values. Figure 12 is an adaption of the Q-value 'no support curve' (after Hutchinson and Diederichs, 1996), used mainly to determine if entry into an open stope is permitted. Not all the case studies could plot on these graphs as some fall outside the ranges of the graphs, indicating that these stopes will collapse immediately (as shown in Figure 11), which was not the actual case. By modifying the Q-value *versus* unsupported span (m) chart in Figure 13 and plotting time (in months) for which open stopes remained stable before any major falls of ground occurred, the following became evident.

- Some open stopes had a standup time of less than 1 month, the shortest time to failure being 14 days.
- A number of open stopes remained stable for longer than 6 months, the longest being six years.
- Standup periods can be categorized and used in the design process.

As shown in Figure 13, one of the case study stopes (no. 16) should have failed within one month according to the data, but remained stable for six years. For case studies 1 and 8 the open stope spans were larger than the norm, resulting into a standup time of less than one month. For the case studies with a standup time of one month, the scatter in the data can be attributed to high stress conditions as a result of these stopes not being de-stressed, larger than the norm mining spans, and holing into narrow reef mining above the stope, as shown in Table I. The effect of larger than the normal mining spans, holing into updip open stopes, partial or no de-stressing, blasting in close proximity, creation of brows in open stopes, and holing into NRM should not be underestimated as contributing factors for these falls of ground at Target Mine. Mining only open stopes in de-stressed ground conditions, improved blasting practices, avoiding holing into narrow reef mining, and eliminating the creation of brows in the open stopes will all contribute to extending the standup time for these stopes.

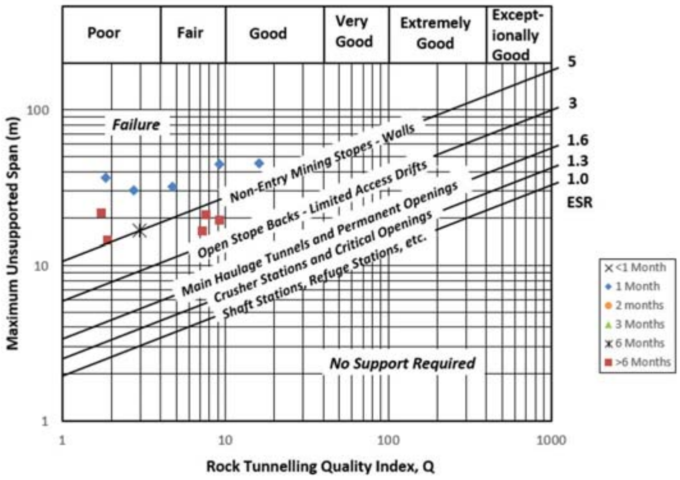


Figure 12—Unsupported span (m) *versus* Q-value (after Hutchinson and Diederichs, 1996)

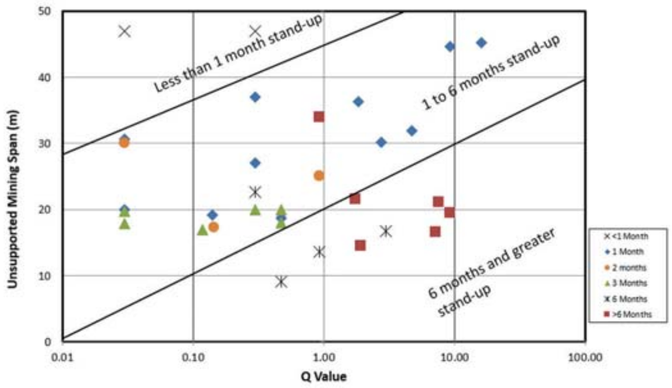


Figure 13—Modified standup time graph for unsupported span (m) *versus* Q-value for Target Mine open stope conditions

Conclusions

The objective of the study described in this paper was to develop a method that could assist in determining the standup time for open stopes at Target Mine. The DSSI method assists greatly in determining the potential dilution (depth of failure of hangingwall and sidewall in open stopes) for a given stope design. The stope design can then be modified should the required dilution factors not be achievable.

At Target, a number of open stopes can be extracted at a given time. This often requires the construction of backfill bulkheads and the placing of backfill to be carefully planned and sequenced. The standup times were determined for open stopes exposed to varying conditions, such as:

- Larger than normal mining spans
- Holing into updip open stopes
- Partially de-stressed or stressed stopes
- Blasting in close proximity to stopes
- Brow creation
- Holing into narrow de-stress slots.

All of the above are of vital importance to the proper planning and sequencing of open stopes. As more open stopes are mined at Target Mine, the empirical graph in Figure 13 will be updated. Although the graph in Figure 13 indicates standup times for various Q-values and unsupported mining spans, small falls of ground are not recorded and as such are not taken into consideration. The mine does, however, have a strict policy that no person is allowed to enter an open stope. Mucking of these open stopes is carried out by remote loading.

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