Time Dependent Failure of Open Stopes at Target Mine

There are numerous factors which affect open stope stability and often result in falls of ground. These falls of ground can be attributed to a number of 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 relatively unknown, especially on Target Mine. Actual data collected from open stopes at Target Mine and the analysis thereof is used to show the effect of time on open stope failure. The benefits of this analysis will result in improved understanding of time dependent failure which can assist in reduced dilution and the risk of sterilization of future mining blocks.

INTRODUCTION

Target Mine is situated at the town of Allanridge some 20km from Welkom as shown in Figure 1 and is the most northerly mine in the Welkom Goldfields area. The mine consists of a single surface shaft system with a sub-shaft (Target 1C shaft) and a decline. Ownership was attained in May 2004 by Harmony Gold Mining Company Limited (Harmony Annual Report, 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 180m in thickness and 270m wide and comprises multiple reefs overlying one another. The 180m thick reef package being mined is termed the Eldorado Reefs as shown in Figure 2. These Eldorado Reefs sub-outcrop 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 open stopes comprise waste rock, with the orebody dipping relatively steeply. Due to the depth of the mine, some 2300m to 2500m below surface, a de-stress slot as shown in Figure 4 is mined to create an artificial shallow mining environment whereby the field stress is managed and kept at values of around 60MPa. The de-stress slot comprises a narrow tabular stope, with an average stope width of 1.5m 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 with its EB footwall, which is waste rock. If a stope, for example, is mined along 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.
Figure 1. Location of Target Mine (Harrison, 2010).

Figure 2. Cross section view looking north showing the Eldorado reefs sub-outcropping against the Dreyerskuil reefs (Le Roux, 2015).
Open stoping is the process by which massive stopes are blasted to mine selected reef packages within the orebody. These open stopes are large in size varying from 10m to 45m in width (span), 10m to 35m in height and 10m to 100m 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 Figure 5, Figure 6 and Figure 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’s (load, haul and dump) mechanized equipment.

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

*Figure 5. Cross section view of a typical open stope design on Target Mine (Le Roux, 2015).*
Figure 6. Plan view of a typical open stope design on Target Mine (Le Roux, 2015).

a) Reef drive is developed on strike with slot cubbies and drop raise blasted.

b) Slot and blast rings are drilled.

c) Slot is blasted and cleaned with remote loading.

d) A maximum of four rings are blasted and cleaned at one time with remote loading.

Figure 7. General isometric view of a typical open stope design on Target Mine (Le Roux, 2015).
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 contribute significantly towards dilution as the rock from these falls is loaded with the blasted ore. Typically 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. One of the contributing factors to loss in profit is damage and loss of mechanized equipment due to falls of ground in open stopes as shown in Figure 8.

Figure 8. Photo of a TORO LH514 LHD in an open stope damaged by fall of ground (Le Roux, 2015).

ESTIMATING DILUTION BY APPLYING DSSI

Making use of the strain-based stability/design criterion for the Target open stopes, termed the Dilution Stress-Strain Index, the extent of failure can be determined. The relation between mean stress $\sigma_m$ and volumetric strain $\varepsilon_{vol}$ can be expressed as follows:

$$\sigma_m = q \varepsilon_{vol} \tag{1}$$

$$\varepsilon_{vol} = \frac{\sigma_m}{q} \tag{2}$$

where $q$ is the slope of the linear trend lines. The Dilution Stress-Strain Index ($DSSI$) is the relation between mean stress and volumetric strain, expressed as follows:

$$DSSI = \frac{\sigma_m}{q \varepsilon_{vol}} \tag{3}$$

For a factor of safety of 1.0, the DSSI value = 1.0 thus no failure. A DSSI value of greater than 1.0 will indicate failure conditions in tension. For a set value of mean stress, if the volumetric strain was less than the threshold, failure would occur due to relaxation. A DSSI value of less than 1.0 will indicate failure conditions in compression. Details of the method can be obtained from the original references.
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 had a significant impact whereby the planned dilution could be compared with the predicted dilution in an attempt to determine if this open stope will be profitable to mine or not. In Figure 9 the actual percentage dilution versus predicted DSSI dilution is compared, showing some good results. It is noted that some of the case studies 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 of sterilizing the adjacent open stope.

![Figure 9. Graph showing actual percentage dilution versus modelled percentage DSSI dilution.](image)

**OPEN STOPE FAILURE AND THE EFFECT OF TIME**

There are numerous factors which affect open stope stability and often result in falls of ground. These falls of ground can be attributed to a number of factors 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 relatively unknown, especially on Target Mine. Actual data collected from thirty-three open stopes at Target Mine and the analysis thereof was used 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 which could be beneficial, a comprehensive empirical database was established. This consisted of open stope information such as, rock mass properties, rock mass classification and cavity monitoring system (CMS) data. The following information, from thirty-three case study stopes at Target mine, was included in the database as shown in Table I:

- 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 et al, 1974)
- Modified stability number, N’ (Potvin, 1988)
- Time open stope stood before failure (fall of ground)
- Possible contributing factor to fall of ground in open stope
<table>
<thead>
<tr>
<th>Case Study</th>
<th>Q</th>
<th>HR (m)</th>
<th>Hanging wall span (m)</th>
<th>Total Actual % Dilution</th>
<th>Predicted % Dilution (DSSI)</th>
<th>Time in Months before FOG</th>
<th>Other contributing factors leading to FOG</th>
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Major dilution is defined as percentage 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 dilution of 5% and less, but this was rarely achieved. In 70% of the case study stopes, dilution was >10% and is deemed as major failure, 30% had dilution <10% and is deemed as minor failure, open stopes with underbreak were excluded from this study.

In Table I the contributing factors to the falls of ground in open stopes could be summarised as larger than normal span, holed into up-dip 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 results indicates that eventually the beam will fail. The time to failure is still an unknown factor.
Figure 10. Plot of Target Mine case studies with major and minor failure for unsupported span (m) versus Q Value (after Houghton and Stacey, 1980).

Figure 11 represents a graph after Hutchinson and Diederichs, 1996 which allows one to estimate unsupported stand up times for service excavations using unsupported spans, Q and RMR rockmass rating systems. Not all the case studies could plot on this graph as they fall outside the ranges of the graph and indicate that these stopes will all collapse immediately, which were not the case. By modifying the Q value versus unsupported span (m) in Figure 12 and plotting time in months of open stopes that remained stable before any major falls of ground occurred the following became evident:

- There were open stopes that had a stand up time of less than 1 month the shortest time to failure being fourteen days.
- A number of open stopes remained stable for a period longer than 6 months the longest being six years.
- Stand up periods can be categorised and used in the design process.

As shown in Figure 12 one of the case studies (Case Study 16) should have failed within one month according to the data, but did not do so for six years. The effect of larger than the normal mining spans, holing into up-dip open stopes, partially de-stressed, not de-stressed, blasting in close proximity, creation of brows in the open stopes and holed into NRM (narrow reef mining) should not be underestimated as a contributing factor for these falls of ground at Target Mine.
CONCLUSIONS

The objective of the study described in this paper was to develop a method which could assist in determining the stand-up time for open stopes at Target Mine. The DSSI method which is briefly described assists greatly in determining the potential dilution (depth of failure of hanging 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 that the construction of backfill bulkheads and the placing of backfill are carefully planned and sequenced. The determination of stand-up times for open stopes exposed to varying conditions such as;
larger than normal mining spans,
holing into up-dip open stopes,
partially de-stressed or stressed stopes,
blasting in close proximity,
Brow creation and
holing into narrow de-stress slots

is 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 12 will be updated. Although the graph in Figure 12 indicates stand up times for various Q values and unsupported mining spans, small falls of ground are not recorded and as such not taken into consideration. The mine does however have a strict policy that no person is allowed to enter into an open stope. Mucking of these open stopes is carried out by making use of remote loading.

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REFERENCES


Harmony Annual Report, 2010


