



Review of mud rush mitigation on Kimberley's old scraper drift block caves

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Synopsis

A major mud push occurred on the 870 m production level, scraper drift block cave at Dutoitspan diamond mine in November 2011, during which it is estimated that more than 4 400 m³ of mud engulfed the west cave. The production level was successfully evacuated during the mud push with no loss of life or injury to personnel, thanks largely to mine employees being well trained in and adhering to on-mine mud rush evacuation procedures. All access to the west cave was lost as a result of the mud push. Clean-up operations are currently under way to regain access to the production level, to establish the extent of damage to scraper drifts and equipment, and to evaluate what remedial works may be required to resume production. The magnitude of the Dutoitspan mud push necessitated a detailed investigation into the key contributing factors leading up to the incident, which are discussed in this paper. Mud rush mitigation measures in place on scraper drift block caving operations at Dutoitspan, Bultfontein, and Wesselton diamond mines in the Kimberley area are critically reviewed. Recommendations are furthermore made for enhanced mitigation based on mud rush risk profiles derived for different production areas in these old scraper drift block caves.

Keywords

mud push, mud rush, scraper drift, block cave, mitigation factors, risk profiles, risk management structure.

Introduction

Kimberley Underground Mines JV mines diamonds from three kimberlite pipes, namely at Dutoitspan, Bultfontein, and Wesselton mines. The Dutoitspan pipe was discovered in 1870, Bultfontein in 1871, and Wesselton in 1891; initial open-pit mining of these pipes was later followed by chambering, block caving, and sub-level caving (Cleasby *et al.*, 1975). The mines are located on the outskirts of town immediately to the south-east of Kimberley in the Northern Cape Province, South Africa. Mining currently takes place by scraper drift block caving, and at Bultfontein by rim loading on old mining levels above the current scraper drift block cave.

Mud rushes and pushes are sudden inflows of mud from drawpoints or other underground openings, and pose a serious hazard in underground mass mining of

kimberlite pipes in the Kimberley region. The rates of mud inflows are often such that escape of personnel in their path is most unlikely, and they also result in severe damage to infrastructure (Butcher *et al.*, 2005). Although the sources of mud in different mines, mud rush mechanisms, trigger mechanisms, and warning signs are generally quite well understood (Butcher *et al.*, 2000, 2005; Brown, 2007), accurate prediction of the exact time and location of a mud rush or push is not possible. As a result, best practice to combat mud rushes involves (Butcher *et al.*, 2000):

- Draw control to ensure uniform draw profiles across the cave footprint, thereby limiting isolated draw, which increases the chances of mud from the overlying waste cap being drawn down into the production level
- Limiting depletion of the allocated drawpoint reserve to 120% maximum in mud rush-prone mines
- The installation of drainage measures to reduce the potential for mud to form.
- This paper describes a mud rush mitigation strategy implemented at Kimberley Underground Mines JV following a major mud push that occurred on the 870 m production level (870 Lvl) scraper drift block cave at Dutoitspan mine in November 2011.

History of mud rushes at Dutoitspan Mine

The production footprint of the Dutoitspan 870 Lvl scraper drift block cave is shown in

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Review of mud rush mitigation on Kimberley’s old scraper drift block caves

Figure 1, with scraper drift numbers indicated for ease of reference. The block cave was historically drawn as two separate caves, with production from the East Cave (Drifts 1 to 7) far exceeding that from the West Cave (Drifts 8 to 15), see Figures 2 and 3.

Material drawn from the more mature East Cave was much finer than that drawn from the West Cave, and was thus more prone to mud formation (Du Toit, 2005), resulting in several mud rush incidents in Drift 1 as well as mud pushes in Drifts 4, 5, and 6 in the late 1990s and early

2000s. Draw from Drifts 1 and 2 were therefore increased in an effort to get water and mud to migrate to the east end of the cave. This met with limited success and draw from Drifts 1 and 2 was stopped between 2003 and 2004, and, shortly thereafter the whole East Cave was abandoned. Production thereafter continued from only the West Cave until a fatality occurred following a mud rush from Drift 9 in 2005 which resulted in the closure of Dutoitspan mine (Du Toit, 2005). The 870 Lvl scraper drift block cave was re-opened in May 2010 following acquisition of the mine by Petra Diamonds.

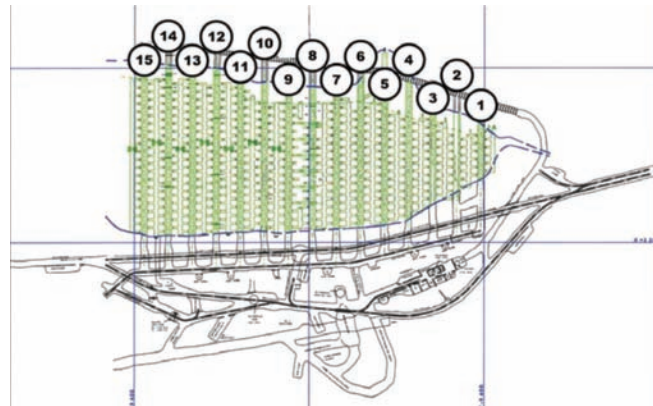


Figure 1—870 m level scraper drift block cave layout at Dutoitspan

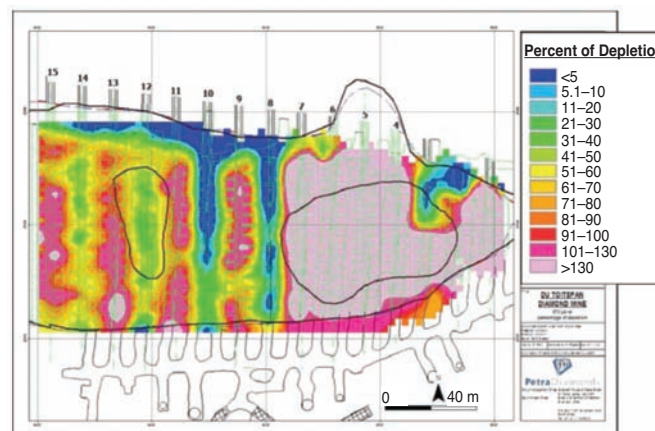


Figure 2—Percentage depletion plot, Dutoitspan

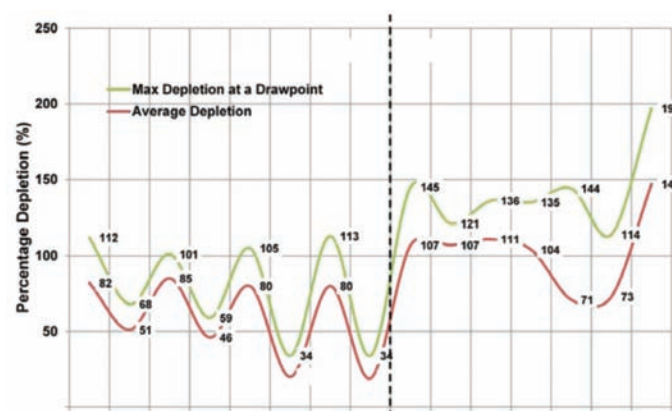


Figure 3—Drift depletion profile, Dutoitspan

Review of mud rush mitigation on Kimberley's old scraper drift block caves

Draw strategy up to November 2011

Re-opening of the 870 Lvl scraper drift block cave at Dutoitspan mine was well under way by the time the November 2011 mud push occurred. The long-term strategy focused on re-establishing the East Cave in an effort to control water and mud inflows while continuing production from the West Cave. By end of November 2011, progress with implementation of this strategy was as follows:

- Work had started to re-open and remove mud from Drift 1 and to reconstruct the drawpoints in this drift with a smaller aperture. Drift 2 was being re-equipped at the time. The aim was to reinstate draw from Drifts 1 and 2, to continue earlier efforts to get water and mud to migrate to the eastern side of the cave. However, draw from Drifts 1 and 2 had not yet started
- Drifts 3 to 6 were also being re-equipped to allow controlled draw to further enhance migration of water and mud to the east end of the cave; however, draw from these drifts had also not started
- Drift 7 had been re-opened; badly damaged drawpoints had been repaired, and limited draw implemented
- Drifts 8, 9, and 10 were still out of production as follows:
 - Drift 8 had collapsed at Drawpoints 8 and 9
 - Drift 9 had not been re-opened following the 2005 mud rush, with mud and water continuing to report to this drift
 - Drift 10 had collapsed from Drawpoint 11 all the way to the back of the cave.
- Drifts 11 to 15 had been re-opened with 6 open and 6 closed drawpoints established on rotation in each drift and with strip planning aimed at creating an even draw profile along each drift. The November 2011 mud push inundated the West Cave before the above long-term strategy could be implemented in full. Efforts since then have focused on removing the mud from 870 Lvl, to recover equipment and machinery lost during the event, and to assess the extent of damage caused to the 870 m production level.

The November 2011 mud push at Dutoitspan

The mud push at Dutoitspan occurred at about 4.30 pm on Tuesday 22 November 2011 at the start of the afternoon shift. Shift start-up was still in progress, with three employees working in Drift 13 in the West Cave, pinch-barring drawpoints as part of the mine's normal start-up procedure. Start-up work was also in progress elsewhere on the production level. The start-up work in Drift 13 began at the northern return airway (RAW) end of the cave and was proceeding towards the rim tunnel on the south side. There was water on the footwall in part of the drift where repairs were being carried out, but all the drawpoints were dry. The work crew reached Drawpoint 9, which was hanging high, and they moved on to Drawpoint 4. At that point, they noticed a hot wind coming from the cave, followed seconds later by a second, stronger wind which kicked up dust in the drift, and they started running. They triggered the mud rush alarm at the drift entrance and shouted to other personnel on the production level to evacuate. The Drift 13 crew ran past the front of Drift 15, exiting the production level via the

access ramp at the western end of the rim tunnel. While taking the corner at the top of the access ramp, they heard the mud slam into the pipework in the rim tunnel behind them, at which point the air alarm also felt silent. However, the whole of Dutoitspan 870 Lvl was successfully evacuated without any injury to personnel.

The extent of mud inundation in the West Cave is shown in Figure 4 after an estimated 4 420 m³ of mud entered 870 Lvl; also see the photos in Figure 5 (a) to (e). Mud flooded

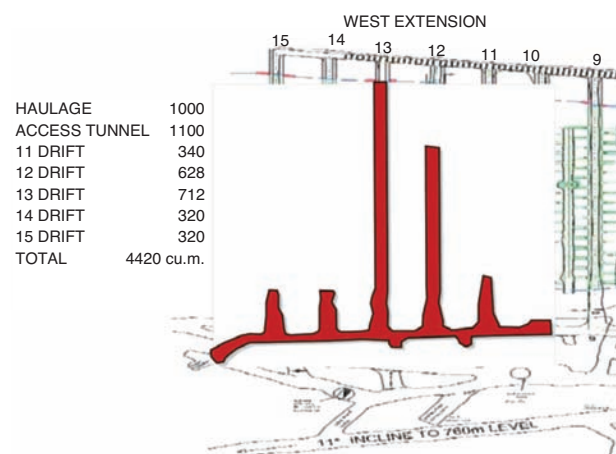


Figure 4—Extent of mud inundation, Dutoitspan 870 Lvl



(a) Mud in rim tunnel at Drift 10

(b) Haulage below Drift 10 transfer box



(c) Mud in access ramp into western end at Drift 15



(d) Mud in back of Drift 12



(e) Mud in back of Drift 13 near RAW

Figure 5—Photos of mud on 870 Lvl

Review of mud rush mitigation on Kimberley's old scraper drift block caves

the whole of Drift 13, almost all the way up to the RAW, and two-thirds of Drift 12. It pushed into the rim tunnel on the south side, flooding the whole rim tunnel from Drift 10 in the east, past Drift 15 in the west and down the access ramp via which the Drift 13 crew escaped. The winches and ground transfer boxes (i.e. 'chinamen') at the entrances to Drifts 11 to 15 were also flooded, with mud spilling through the open transfer boxes and flooding the haulage directly below. The extent to which mud pushed towards the back of Drift 12 suggests that mud entering Drift 12 through a drawpoint rather than pushing in through the front of the drift. In other words, the mud push entered the production level via both Drifts 12 and 13.

The distances the Drift 13 crew had to run up to the point when the mud reached the rim tunnel were approximately 33 m from Drawpoint 4 to reach the entrance to Drift 13 at the rim tunnel and another 40 m from Drift 13 entrance up to the rim tunnel corner west of Drift 15. A rough estimate based on assumed running speeds suggest it took maximum of 14 seconds total from the time of the second air rush up to the point when mud engulfed the rim tunnel: 8 seconds at 15 km/h to reach the rim tunnel from Drawpoint 4 and a further 6 seconds at 25 km/h to reach the rim tunnel corner when exiting 870 Lvl.

In the aftermath, all agreed that the main factor to which successful evacuation of the 870 Lvl could be attributed was that of a workforce well trained in identifying and reacting to mud rush early warning signs (air rush preceding a mud rush or push) and in following standard evacuation procedures (sound the alarm, evacuate). It was also most fortunate, given the amount of mud that entered the 870 m production level, that this was a mud push rather than a mud rush, which in all likelihood would have caught the Drift 13 crew inside the drift before the mud rush alarm could have been sounded.

It was furthermore concluded that the mud must have come from relatively high up in the caved column above 870 Lvl, for the following reasons:

- ▶ The thickness and paste-like consistency of the mud that entered the production level (i.e. a person could walk on the mud without sinking into it within an hour after the event)

- ▶ The mud push, which originally started in Drift 13, also breached into Drift 12
- ▶ The amount of mud that pushed through compared to the relatively dry conditions observed in Drift 13 just prior to the event
- ▶ The two distinct air rushes (or air blasts) that preceded the event.

Factors contributing to the Dutoitspan mud push

A full review of available draw control data and geotechnical information was carried out following the November 2011 event, to establish the factors contributing to the mud push occurring. The review focused on (a) identifying sources of water ingress and moisture conditions in the cave; (b) reviewing patterns of cave draw down in the months prior to the mud push; (c) depletion levels and waste entry; and (d) reviewing the structural condition/status of drawpoints.

Various sources of water ingress into the Dutoitspan cave were identified as follows:

- ▶ Surface drainage trenches were not well maintained and/or blocked, especially in areas where small contractors were mining old surface dumps to the north and north-east of the Dutoitspan pit
- ▶ Poor on-mine control of surface water in the plant area, immediately south-west of the Dutoitspan pit
- ▶ Maintenance of water ring tunnels near surface, where parts of the tunnels have collapsed over the years, making maintenance in such areas impossible
- ▶ Groundwater seepage into the Dutoitspan pit from the south-western side was visible from the pit rim following the November 2011 mud push, with a pool of water having formed on top of the Dutoitspan cave in the bottom of the pit.

Despite these sources of water ingress, the October 2011 moisture condition plot for 870 Lvl in Figure 6 shows that the West Cave was relatively dry compared to the East Cave, except for water inflows at the host rock/pipe contact in the front of Drift 15.

Cave drawdown patterns in the months prior to the November 2011 mud push were reviewed by producing plots of tons drawn for the year (Figure 7a), 6 months (Figure 7b),

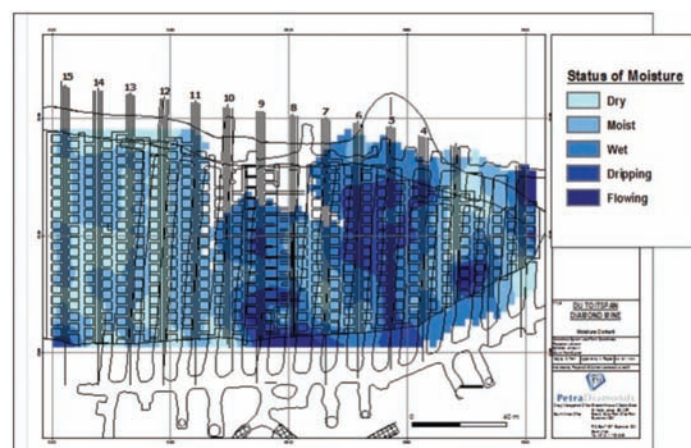
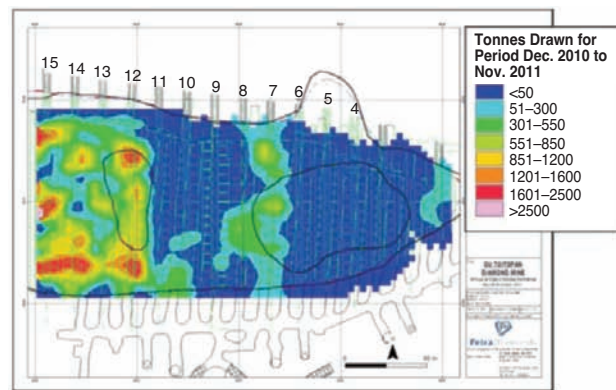


Figure 6—Moisture conditions on 870 Lvl, October 2011

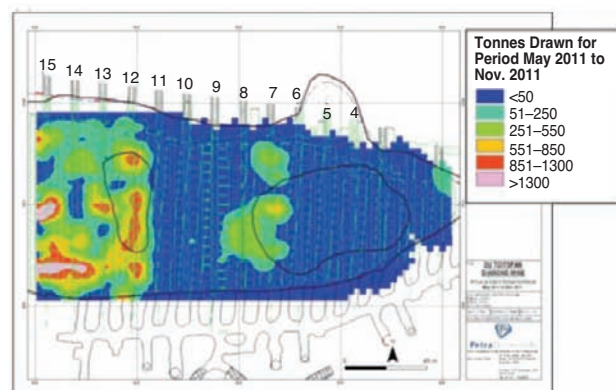
Review of mud rush mitigation on Kimberley's old scraper drift block caves

and 3 months (Figure 7c) preceding the mud push. The plots clearly show is that although cave drawdown over the year preceding the mud push was more or less evenly spread over the footprint of the West Cave, draw patterns shifted in the latter part of this period, with most of the draw between September and November 2011 coming from the front of the West Cave in Drifts 13 to 15 and the central portion of Drift 12.

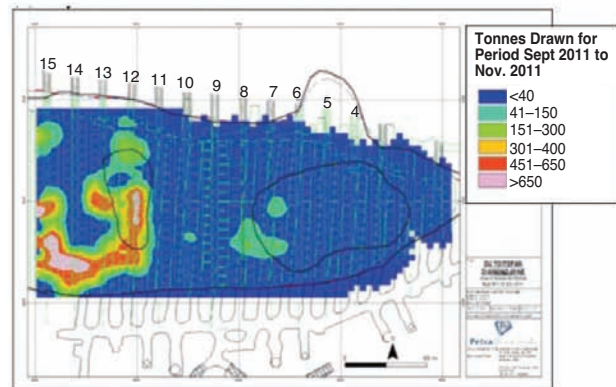
Figures 2 and 3 show that the East Cave generally was 130% depleted in terms of the allocated reserve included in the life of mine plan for 870 Lvl. The West Cave, on the other hand, showed a different draw pattern, with Drifts 9, 11, 13, and 15 at between 80% and 100% depletion, while Drifts 8, 10, 12, and 14 were at much lower depletion levels. The reason for this drawdown pattern in the West Cave dates back to the way the cave was developed, with the uneven-



(a) December 2010 to November 2011



(b) May to November 2011



(c) September to November 2011

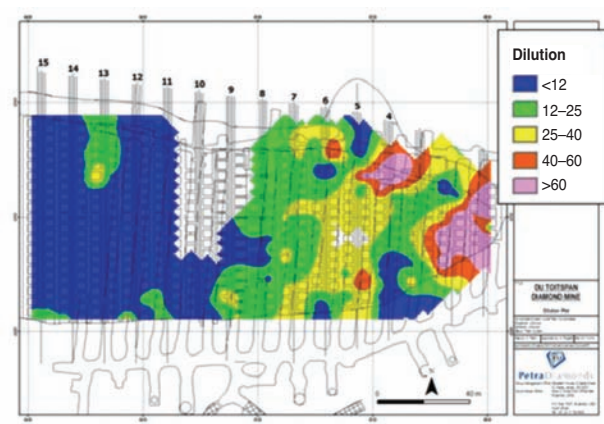
Figure 7 – Tons drawn from 870 Lvl

numbered drifts being constructed ahead of the undercut while the even-numbered drifts were constructed later, in the de-stressed zone below the undercut. Figure 8(a) shows that some waste was reporting to drawpoints in the back of Drift 13 during March 2011, whereas by November 2011, waste started reporting across various parts of the West Cave footprint as shown in Figure 8(b).

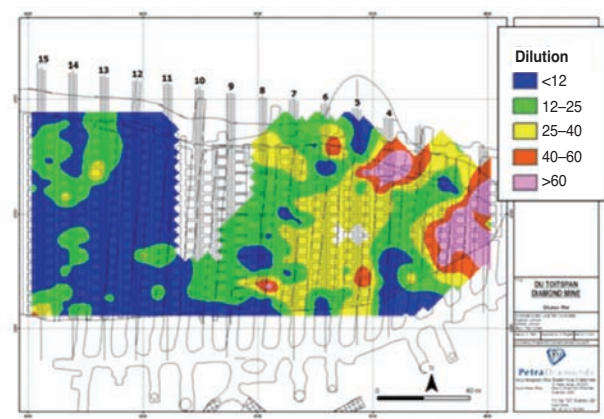
The structural condition of drawpoints in the West Cave in November 2011 is schematically presented in Figure 9. This plot shows why draw shifted towards the front of the cave in the latter half of 2011, with badly damaged drawpoints (A-class drawpoints) in Drifts 11, 14, and 15 making it impossible to draw the central and back portions of these drifts. This resulted in severe isolated draw from the front of the cave and from Drifts 12 and 13, which were still in reasonably good condition compared to the other drifts in the West Cave.

To summarize the findings of the above review:

- Various sources of water ingress into the Dutoitspan cave were present in the months leading up to November 2011
- The pool of water that formed on top of the cave suggests that the column of caved ground above 870 Lvl was approaching a saturated condition



(a) Waste entry (%) during March 2011, Dutoitspan 870 Lvl



(b) Waste entry (%) during November 2011, Dutoitspan 870 Lvl

Figure 8—Waste dilution in months preceding the November 2011 mud push

Review of mud rush mitigation on Kimberley's old scraper drift block caves

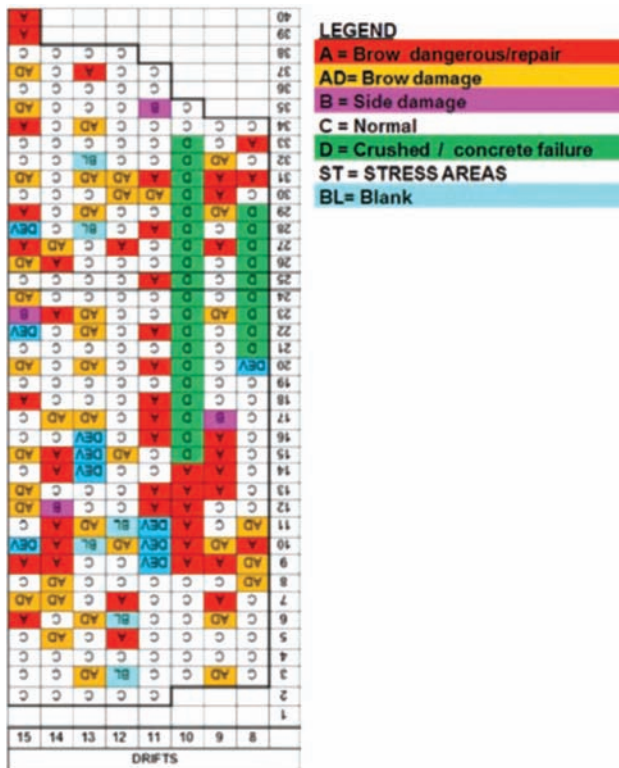


Figure 9—Structural condition of West Cave drawpoints by November 2011

- More waste started reporting to drawpoints across the West Cave footprint as available drawpoint reserves were being depleted
- The condition of many drawpoints in parts of the West Cave, furthermore, had deteriorated to such an extent by the time of the mud push that ore had to be drawn from specific areas in order to maintain production. As a result, the front of the cave as well as Drifts 12 and 13 were overdrawn relative to the rest of the West Cave.

The presence of significant amounts of water in the caved muck, the level of depletion of the West Cave, and severe isolated draw in parts of the West Cave, combined, are therefore considered the main causes of the November 2011 mud push.

Mud rush risk management strategy

As a result of the findings of the above review, a mud rush risk management strategy was developed at the request of mine management to assess the mud rush potential at individual drawpoints in a scraper drift block cave. Mud rush risk scoring systems in use at three other Petra Diamonds mines, namely at Cullinan, Finsch, and Star, as well as at Mt Lyell Mine (Copper Mines of Tasmania) and at Freeport (Rio Tinto) were reviewed. Reference was also made to SIMRAC work on mud rushes (Butcher *et al.*, 2000) and to audit protocols in use in Australia to assess the risk of inrushes and subsidence (WMC, 2003).

The risk scoring process adopted for scraper drift block caves at Kimberley Underground Mines JV evaluates all the key contributing factors to mud rush risk at drawpoints as set

out in Tables I to IX. The scores assigned to the different contributing factors listed in these tables were derived empirically using engineering judgment combined with a reverse-engineering approach to give 'very high' risk scores at drawpoints and/or in those parts of the 870 Lvl production footprint where mud rushes or pushes have occurred over the last 5 to 10 years - up to and including the November 2011 mud push.

How does the risk scoring system work? Individual risk scores from Tables I to IX are added to derive a total risk score for every drawpoint on the production level. Moving average risk scores are then determined for each drawpoint to assess the increased (or reduced) risk level at a drawpoint due to changes over time in:

- Surface water management
- Mine dewatering
- Moisture conditions in the caved mass
- Percentage waste reporting to the drawpoint
- Drawpoint depletion
- Draw control
- The structural condition of the drawpoint

Table I

Mud rush risk rating, surface water ingress into caved mass

Description	Risk score
No surface water ingress	0
Surface of muck pile/caved mass visibly damp/wet	5
Surface run-off onto muck pile/into caved mass	10
Water pooling on top of muck pile/caved mass after rainfall	20
Water still pooling on top of muck pile/caved mass for more than 6 weeks	30
Water still pooling on top of muck pile/caved mass for more than 3 months	40

Table II

Mud rush risk rating, underground water ingress into caved mass

Description	Risk score
No groundwater seepage on/from old upper mining levels	0
Groundwater flowing into cave on old upper mining levels	10
Groundwater flowing from cave on old upper mining levels	10

Table III

Mud rush risk rating, drawpoint moisture conditions

Drawpoint moisture condition	Risk score
Dry	0
Moist	10
Wet	20
Dripping	20
Flowing	5

Review of mud rush mitigation on Kimberley's old scraper drift block caves

Table IV

Mud rush risk rating, drawpoint waste percentage

Percentage waste reporting to drawpoint	Risk score
0	0
0–10%	1
10–40%	2
40–60%	3
60–80%	4
80–90%	4
90–100%	5

Table V

Mud rush risk rating, drawpoint depletion

Percentage drawpoint depletion	Risk score
0–60%	0
60–80%	1
80–90%	2
90–100%	3
100–120%	4
> 120%	5

Table VI

Mud rush risk rating, scoops drawn

Scoops drawn, ratio ^a	Risk score
0	0
1	5
1.5	10
2	15
2.5	20

a Ratio of (No. of scoops for a drawpoint) vs. (Average no. of scoops for active drawpoints in a scraper drift). 3-month moving average

Table VII

Mud rush risk rating, drawpoint status

Structural condition of drawpoint	Risk score
C - Production drawpoint	0
B - Side damage	2
A - Badly damaged	10
AD - Brow/side damaged	7
D - Totally damaged	5
BL - Blank drawpoint	4
Stress damage at drawpoint or in drift	3
Undeveloped into caved ground	4

Table VIII

Mud rush risk rating, condition of caved ground reporting to drawpoint

Ground conditions at drawpoints	Risk score
Fine ground	5
A few lumps with lots of fine ground	3
A lot of lumps with a small amount of fine ground	0
A big lump in mouth of drawpoint	5
Compacted	10
Mud	40

Table IX

Mud rush risk rating, hang-ups

Extent of hang-up within the caved mass	Risk score
No hang-up	0
Hang-up within reach	2
Hang-up out of reach, but can be seen	5
Top of hang-up cannot be seen	10

Table X

Mud rush risk matrix

Risk colour code	Risk rating	Risk tolerance	Global risk mitigation ¹	Immediate mitigation actions ²
0 – 30	Low		None	Cave production continues as normal, ongoing cave monitoring to identify any mud rush hazards as well as any changes in conditions
30 – 45	Moderate	Acceptable	The identified hazard shall be managed throughout the project	Cave production continues as normal, review draw control strategy, increased cave monitoring to identify any changes in mud rush hazard levels, review dewatering strategy for affected areas
45 – 60	High	Unwanted	Specific risk mitigation measures shall be implemented as long as the costs of the measures are not disproportionate to the risk reduction obtained. (ALARP principle: As Low As Reasonably Practicable)	Access to hazard impact areas restricted, reduced draw from affected drawpoints / production area, management intervention to ensure appropriate mitigating measures are implemented to prevent escalation of hazard levels
RED AREA > 60	Very high	Unacceptable	The risk shall be reduced to at least 'unwanted' regardless of the cost of risk mitigation	Immediate evacuation of RED AREA, urgent management intervention to ensure implementation of the necessary mitigation measures

¹ Over and above normal good practice in terms of draw control and mine dewatering.

² All hazards identified and risk mitigation measures decided on, to be noted in the minutes of on-mine draw control meetings on an ongoing basis.

Review of mud rush mitigation on Kimberley's old scraper drift block caves

- The condition of caved ground reporting to the drawpoint
- Whether or not hang-ups have formed above that drawpoint within the caved mass.

Mud rush risk plots are then generated, and presented and discussed at the mine's monthly draw control meetings, as follows:

- A colour-coded plot of moving average risk scores over the last three months, to study short- to medium-term trends in draw control and mud rush risk
- A colour-coded plot of moving average risk scores over the last twelve months, to study longer term trends in draw control and mud rush risk.

The colour coding used on these mud rush risk plots and the average risk scores shown for individual drawpoints, as well as for different drifts and parts of the production level, are evaluated in terms of the mud rush risk matrix presented in Table X, with risk tolerance levels, global risk mitigation, and immediate mitigation actions to be implemented as outlined.

The ranges in risk rating indicated in Table X, namely:

- 0–30, low risk
- 30–45, moderate risk
- 45–60, high risk, and
- > 60 very high risk

were reverse-engineered (or 'calibrated') to give a relatively good correlation with mud push and mud rush incidents that have occurred at Dutoitspan mine over the last 5 to 10 years. Figure 10 shows the 3-month moving average plot as an example of a typical result obtained).

Figure 10 shows very high mud rush risk potential in the front part of the West Cave as well as in Drifts 12 and 13 where the November 2011 mud push occurred, in Drift 9 where the 2005 mud rush occurred, and in Drifts 1, 4, and 5 as well as in the back of Drift 6 in the East Cave where mud rushes and pushes have occurred in the past. It furthermore indicates a very high mud rush risk potential in the central portion of Drift 7, which is where a small mud push developed in early February 2012, about 3 months after the November 2011 mud push in the West Cave. A smaller mud

push, which occurred mid-February 2012 in Drift 8, however, was not 'predicted'.

Implementation

Mud rush risk scores and results obtained from this reverse-engineering 'calibration' exercise were considered to adequately reflect actual risk profiles in the Dutoitspan 870 Lvl scraper drift block cave by mine management, and a decision was made to implement the system in operating scraper drift block caves at the neighbouring Bultfontein and Wesselton mines.

As an example, Figure 11 gives the 3-month moving average mud rush risk scores for Bultfontein 845 Lvl for November 2012. The plot indicated a high risk score at Drawpoint 21 in Drift 5. A review of the draw control data showed that this was a badly damaged drawpoint (or A-class drawpoint) from which more than 300 scoops of material was drawn during November 2012, which equated to a relatively high rate of draw compared with draw from many other drawpoints in the cave. A draw control decision was therefore made to repair Drawpoint 21 and to limit draw from this area to reduce the risk score for this drawpoint to a more acceptable level.

Conclusions

An integrated mud rush risk management strategy was developed and implemented in operating scraper drift block caves at Kimberley Underground Mines JV following a large mud push that occurred on the 870 m production level at Dutoitspan mine in November 2011. The risk scoring system adopted was first calibrated to give a good correlation with historical data from 870 Lvl at Dutoitspan mine.

Implementation of the system in operating scraper drift block caves at the neighbouring Bultfontein and Wesselton mines has allowed earlier identification of drawpoints and production areas within the cave footprint with a high mud rush risk potential. This has resulted in improved scheduling of remedial work and strip planning. Integrating all the draw

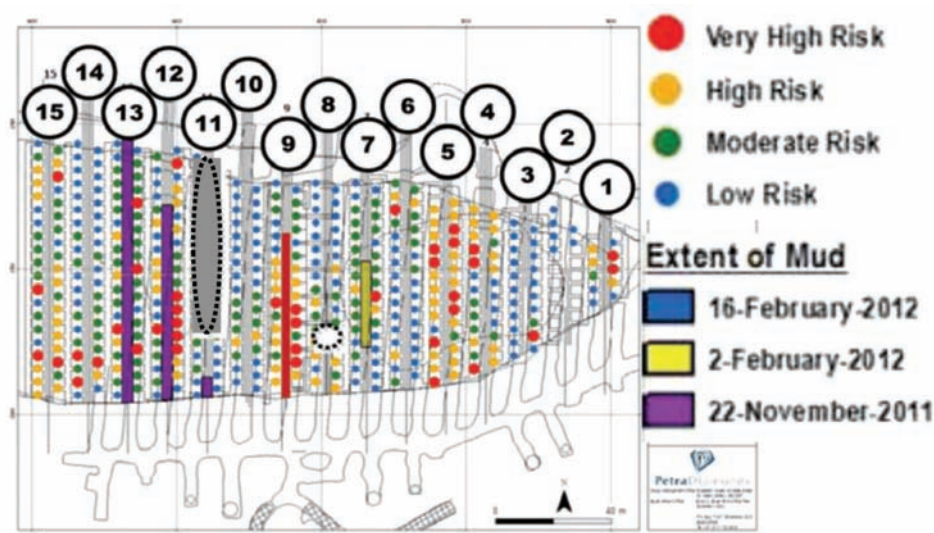


Figure 10—Mud rush risk plot for Dutoitspan 870 Lvl

Review of mud rush mitigation on Kimberley's old scraper drift block caves

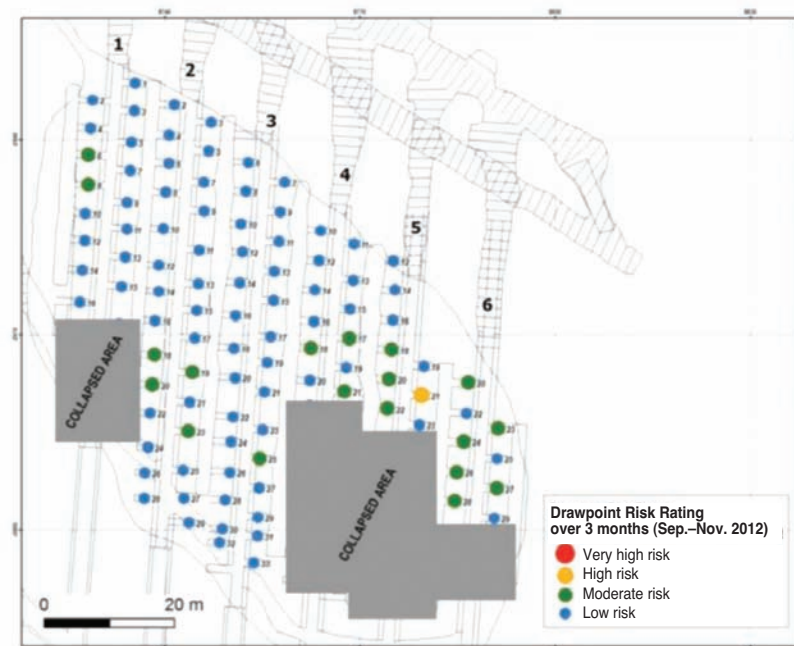


Figure 11 – November 2012 mud rush risk plot for Bultfontein 845 Lvl

control data into a single risk score for each individual drawpoint allows for easy visual presentation of data, as a result of which discussions at draw control meetings are more focused to address high-risk areas.

Dewatering drilling during 2012 furthermore intersected a major groundwater strike immediately north-west of the Dutoitspan pit, with pumping from the borehole yielding more than 8 000 litres per hour on a sustained basis. Water flowing into the pit from this area has since dried up and the pool of water on top of the caved muck pile in the bottom of the pit has disappeared. A lot of work has also been successfully completed in lining and repair of surface stormwater drains to improve surface water management in the area, thereby reducing water ingress into the Dutoitspan cave.

Finally, work continues to remove the mud from 870 Lvl, to recover equipment and machinery lost during the event, and to assess the extent of damage caused to the 870 m production level.

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risk management strategy now employed on these scraper drift block caves in Kimberley.

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