Abstract

A multiple-bench slope failure occurred at Letlhakane mine on 14th July 2005. No injuries or damage to equipment was suffered and mining production was not affected.

Slope failure was preceded by the precursors of tension crack formation, crack widening and extension as well as slope monitoring targets movement. It was predicted that slope failure was imminent using the Geomos slope monitoring system, though the timing was not certain. The area to be affected by the slope failure was also known before hand as was the slope failure mode. As a result, measures were taken to avoid exposing personnel and mining equipment to the slope failure risk.

This paper discusses how the prediction of the slope failure of 14th July 2005 using the Geomos slope monitoring system resulted into avoiding potentially fatal injury, damage to mining equipment and loss of mining production.
Introduction

Letlhakane is one of three diamond mines belonging to Debswana Orapa and Letlhakane Mines. Ore is contained within two kimberlite pipes at the mine. DK1 is the larger of the two pipes, DK2 is the other one. Mining is by the open cast method and is currently taking place in DK1 pit, which has reached a depth of 290m below surface. It is planned to continue with the open cast mining system until a depth of 400m below surface. Deepening of the pit and mining of Sandstone waste rock has brought about geotechnical challenges, the most critical being slope stability. In order to manage the slope failure risk better, a Geomos slope monitoring system has been installed at the mine. The benefits of having an automated monitoring system have already been realized by the mine.

Slope stability monitoring at Letlhakane mine

Mining activities whether by open pit or underground methods bring about volumetric as well as stress and strain changes in the rock mass around a mine opening. Once deformations exceed the limits controlled by the rock strength, instability is created around the mining excavation. Falls of ground incidents in a mine are the direct consequence of rock instability.

Slope failure is both a business and safety risk to a mine. It can have devastating consequences such as loss of production, damage to equipment, injury to personnel and most serious of all, loss of life. High insurance premiums, loss of reputation and legal action are other impacts that could arise out of a serious slope failure.

The most important slope stability management tool is slope monitoring. This is the recording of the stability of the rocks making up the slopes surrounding an open pit mine.

The main reasons why slope stability monitoring is done are:

1. To verify mine design. In this case slope monitoring measurements can be used as a basis for maintaining, steepening or reducing slope angles with the resultant economic and safety benefits. Slope monitoring measurements can also be used as a basis for future mine design.
2. To give technical assurance to production and management officials on the stability status of the open pit mine.
3. To serve as a warning system as to which areas of the pit are unstable
4. To give measurements of rates of movement in the unstable zones
5. To serve as a major slope stability risk management tool. Since slope failure can have serious economic consequences on an open pit mine, slope monitoring is an essential basis for making management decisions for the safety of workers and equipment, e.g. not working below an unstable area, adopting special blasting precautions or evacuation.
At Letlhakane Mine slope monitoring is done by:

1. Visual slope monitoring by routine walkover inspections by the Geotechnical Engineer. The Engineer compares the last visit observations with the latest one and records any deleterious slope stability changes that may have occurred. The recording of any changes that occur on the open pit slope faces by production personnel during the shift is another way of visual slope monitoring. To this end, slope hazard awareness lessons are conducted twice a year for all pit workers from supervisor to operator.
2. Slope monitoring using the Geodetic Monitoring System (Geomos) survey technique.
3. A slope monitoring report is issued containing the results of the visual monitoring and the Geomos monitoring systems. The report has an action list of critical slope stability issues requiring attention with time lines and responsible individuals indicated. The report is issued to production, management and technical officials.

**The Geomos slope monitoring system at Letlhakane mine**

The term Geomos is an acronym for Geodetic Monitoring System. The system is supplied by Leica Geosystems of Switzerland through an agent in South Africa. Initially applied to the monitoring of stability of large civil engineering projects (e.g. dams, bridges, tunnels, etc), Geomos has found wide spread usage in open pit slope stability monitoring.

The Geomos is an automatic and continuous slope monitoring system and runs on a 24 hour basis. The system is subdivided into three parts:
1. Data collection
2. Data transmission
3. Data processing and analysis

At Letlhakane Mine, the data collection part consists of two theodolites (model Leica TCA 2003), one each located on the northern and southern rims of the DK1 pit. For safety purposes, the theodolites are housed in concrete shelters with roller blinds that can be pulled down if blasting is being done nearby. Monitoring involves automatically measuring reference points (optical prisms or targets) around the DK1 pit to determine if any deformation has occurred. The theodolites monitor a total of 109 targets that have been installed on the pit slope walls, bench floors and ramp edges.

Data collected by the theodolites is transmitted by radio from the pit edge to the Survey office where a computer fitted with Geomos processing software is located. Data comes into the computer as survey coordinates of the individual targets. Correction for temperature and atmospheric changes is made by incorporating data collected by a combined temperature/atmospheric pressure transducer. Changes that have occurred with respect to the original position of the slope monitoring targets are calculated by the software and shown in graphical format by the Geomos
Analyzer screen. The Geotechnical Engineer interprets these graphs on a daily basis and investigates any unusual movements with a pit site visit. Confirmation of slope instability is communicated by the Geotechnical Engineer to the Shift Foreman, Section Manager and the Mine Manager for appropriate safety action to be made, e.g. barricading off the area or scaling of loose rocks.

Recently an alarm system has been added to the Letlhakane mine Geomos. An Email is sent to the Geotechnical Engineer on the company intranet facility and at the same time an SMS is sent to the Geotechnical Engineer’s mobile phone when displacement tolerances are exceeded. The Geotechnical Engineer then visits the pit to confirm the instability.

Figure 1: Shelter for Geomos slope stability monitoring theodolite at Letlhakane mine.
Figure 2: Leica TCA2003 theodolite used for slope monitoring.

Figure 3: Pole mounted optical prism slope monitoring target.
Visual precursors to the 14th July 2005 slope failure
Unusual slope monitoring targets movement in the slope failure area was first noted at
the end of May 2005. This was when targets S38 and S25 moved 18mm within 1 week.
The area was inspected and no signs of physical slope instability were seen.
On 9 June 2005, cracks were observed to have occurred on the surface of the disused Cut3 Ramp on the western side of the mine on the 880m level. By the following week the cracks had extended northwesterwards and other cracks had begun to form to the northeast on the edge of the ramp bull nose. All the cracks were purely tensile in nature, i.e. there was no shear movement noted at all.

The cracks were noted to be sub-parallel to each other and trending in a strike direction of $320^\circ-140^\circ$ (NW-SE) This is the same strike direction as the major joint set J1 in both the Sandstones and the Basalt rock types. The cracks were observed to have formed only in the Sandstone rock mass. Prior to the slope failure on 14 July 2005, the strike length of the longest crack was calculated to be 183m.

![Figure 6: Plan of the D11-F13 880-890m cracked area prior to slope failure. Bold continuous red lines are the actual surveyed cracks and the broken lines are the approximated cracks. Note the parallelism of the cracks. The polygons denote the slope monitoring target positions.](image)

The sharp-cornered buttress at the North Split Shell-South Split Shell boundaries on the western side of the mine is where the cracks initially occurred and where rapid slope monitoring target movement was concentrated. The slope failure occurred in this bull-nosed area.

Initially 18mm wide, the cracks had widened to 50mm maximum a week later and to 110mm by 24 June 2005. Prior to the slope failure on 14 July 2005, the largest crack was measured to be 410mm wide.
Figure 7: Picture showing one of the cracks that had developed over the disused Cut 3 West Ramp in F11-F13 blocks as at 10 June 2005.

Figure 8: View of the largest crack on the disused 880m-890m West Ramp as at 10 July 2005.
Figure 9: Photograph of the largest crack on 13 July 2005, one day before slope failure. Note the light coloured Sandstone rock below the dark road surface capping.

Figure 10: Photograph of the largest crack area soon after slope failure on 14 July 2005. The ground to the right hand side of what used to be the crack has collapsed. Compare with Figure 9 on how the area looked like before slope failure.
Slope monitoring targets behaviour

The area where cracks had developed initially had seven active targets monitoring the area. Four more targets were added by 5 July 2005.

Figure 11 is a graph showing the horizontal displacement of the slope monitoring targets in the cracked area until the day of the slope failure. From the graph the following deductions were made about the behaviour of the slope monitoring targets:

- The slope monitoring targets showing the greatest displacement were S34, S25 and S38.
- Significant ground movement began around the end of May 2005/beginning of June 2005. This probably indicates the formation of the first tension cracks. By then cumulative horizontal displacement of 35mm had already been recorded.
- A considerable steepening of the graphs was observed from 12-13 June 2005. This period coincides with the formation of new cracks towards the north-eastern edge of the bull nose area. When this happened, it was noted that the first cracks to have formed, on the south western side of the cracked area, stopped reactivating. From this point until slope failure, the crack approximately midway between the first crack and the bull nose edge showed the highest movement. Visually, this crack also showed the fastest widening action. Subsequently, Target S34 close to the bull nose corner became the fastest moving target until slope failure occurred.
- Between 12-19 June 2005 the graphs of S34, S25 and S38 targets showed an almost constant slope indicating constant ground movement velocity, the highest being 12mm/day for S34. The largest crack continued to widen.
- An unexpected phenomenon occurred on 19 June-7 July 2005. There was a reduction in the slope of the targets graphs indicating a slow down in ground movement within the cracked area. Rock mass velocity as measured by the three targets reduced to 8mm/day. The graphs do not become horizontal, though. This means that although ground movement had reduced, it was still occurring and therefore the area was still unstable. The largest crack continued to extend in width. It is not known why this slow down in ground movement occurred.
- From 7 July ground movement accelerated until slope failure on 14 July 2005. Slope failure occurred by the toppling failure mechanism with the largest crack forming the slope failure limit.
- On 14 July 2005, highly accelerated movement of S34 and S38 targets was noted at 10:30 hours, slope failure occurred at 11:56 hours.
- Highest ground movement velocity measured on S34 was 242mm/day prior to slope failure, compared to 20mm/day the day before. Cumulative displacement for S34 before failure was 742mm. Vertical movement on the day of the failure was very small.
- It was not possible to make a long term prediction regarding the day the slope failure was going to occur from the graphs. It is apparent that the period of rapid continuous acceleration suggests impending slope failure.
Figure 11: Geomos graph showing cumulative movement of targets in the cracked area from 12 March 2005 until slope failure on 14 July 2005.

Figure 12: Geomos slope monitoring system graph showing S34 and S38 targets displacement on 14 July 2005 until the slope failure occurrence. Note the steep concave upward shape of the graphs before failure. The targets show no significant vertical movement.
Analysis of the slope monitoring targets in the cracked area as of 23 June 2005 showed that the largest displacements were occurring within the bull nose area (Figure 13). This is a sharp buttress on the western side of the mine forming the North-South Split Shell mining sequence boundaries. It was established that three of these targets (S34, S25 and S38) had moved more than 170mm by then. S34 showed the highest displacement of 225mm.

3-d calculation of the targets movement shows that the targets were moving in a north-easterly direction at an angle of 039°-043°, perpendicular to the cracks direction, and a negligible dip direction 6°-10° downwards. Physical observation of crack width extension is proof of this calculated ground movement. No vertical or shear movement has been observed on the cracks. Slope failure occurred in the direction predicted by the targets movement.

Analysis of the slope monitoring targets movement using design sections showed that the mode of slope failure likely to result from the cracked area was going to be toppling failure. Testimony to this hypothesis was that the top most target S34 was moving faster than the lower targets (S38, S25) when a section was plotted. Slope failure occurred largely by the toppling mode.
Pro active measures taken

On 23 June 2005, the mine invited SRK Consulting to assist in the evaluation of the cracked area. Together with the mine Geotechnical staff, a detailed analysis was made of the slope monitoring data, hydrogeological data, and geology as well as of design sections and bench plans of the area.

At the time the fastest slope monitoring target was moving at a velocity of 23mm/day. The maximum horizontal strain was calculated to be 0.32% (225mm horizontal deformation at S34 target over a vertical height of 70m). Based on the two parameters, it was concluded that the rock mass in the cracked area had already failed. Ground collapse was therefore a matter of time although the exact timing could not be predicted. The most likely slope failure mechanism was determined to be toppling failure, although deep-seated step path slope failure mode was assessed to be a possibility, too.

The slope bottom directly below the cracked area was busy at that time with the mining activities of drilling, charging, blasting and loading. If a slope failure were to occur, the failed ground would land at toe of the slope. The probability of injury to personnel, including multiple fatalities from slope failure in the area was therefore high. Mining equipment working in the area was likely to be damaged from the impending slope failure. It was shown that part of the slope failure would affect the Cut 3 West Ramp at the bottom of the pit. By then a temporary Cut 3 East Ramp had been established to access the Cut 3 ore at the pit bottom.

The delays that come with accident investigations especially where a fatality is involved were going to cause mine production losses. This is because such investigations go far beyond the mine boundaries bringing in Government Mine Inspectors, top Debswana management, shareholders (Botswana Government and De Beers management officials), police and representatives of the surrounding communities. A large part of the mine or even the entire mine would have remained closed during such a high level investigation. Within the short to medium term mining volumes attributable to the lost mine equipment from the imminent slope failure were going to result in production shortfalls.

The mine’s technical officials would suffer reputation loss if no action was taken to prevent injury to personnel especially in the event of fatalities. Eventually, the loss of credibility would result into reduced worker morale culminating into production losses.
In summary, the immediate impacts of the predicted slope failure were:
- Injury to personnel including the possibility of multiple fatalities
- Damage to mining equipment
- Loss of mining production
- Loss of reputation

With these serious slope failure consequences in mind, a decision was made by the Geotechnical Section on 23 June 2005 in conjunction with SRK Consulting to leave a 65m wide buffer zone from the toe of the slope below the cracked area on the 808m level. It was established that the fall of ground would affect an area up to 50m from the toe of the slope; a further 15m was added after considering a factor of safety of 1.3.

This area was to be left unmined with the North split shell Cut 4 mining sequence and was only to be mined later with the Cut 4 South split shell mining sequence. The 65m safety zone was marked with drums and a rock safety berm was installed and no one was allowed to work beyond the rock berm. When the slope failure occurred, the failure rubble therefore fell into an area where no-one was working.

Limited access was allowed on top of the ramp where the cracks had formed to Water Services Section personnel. The ramp was not used for accessing production areas but was used as an access road to the third stage sump dewatering pump station. Water Services personnel were allowed to service the pump station area only during day light hours. They were also working on installing water pipes so that the pump station could be transferred to an area of the ramp before the cracked area. This way they were not going to pass through the cracked part to access the pump station.

The Water Services personnel were evacuated from the ramp through the two-way PCR radio system as soon as the Geomos slope monitoring system showed increased acceleration in S34 and S38 target movement. Slope failure occurred 1 1/2 hours after evacuation.

Slope failure description

The slope failure occurred on the western side of Letlhakane mine on 14th July 2005 at 11:56 hours. The slope failure covered a strike length of 183m, and five benches (70m vertical height). Total rock volume displaced by the failure was 233,000m³ or 524,000 tonnes. The slope failure can therefore be described as a large multiple bench type of failure. Slope failure mode was observed to be toppling failure; the top material collapsed before the bottom part. Minor sloughing failure was also noted, especially on the lower part of the slope. No sliding was seen during the slope failure and no floor heave was recorded.

Ground collapse was observed to be in the north-easterly direction. The largest crack within the cracked area formed the ultimate slope failure limit. The area to the north-east of the largest crack collapsed whereas the area to the south-west remained intact. The slope failure left a vertical surface two benches high below the crest of the failed
material. The actual depth of the failure surface was not known since it was covered by failure rubble.

Most of the failed material ended up on the 808m bench floor. The failure rubble was thrown as far as 45m from the toe of the slope on the 808m elevation. Some failure material was caught on the Cut3 West Ramp while a few boulders reached the Cut3 pit bottom. Fragmentation was mostly medium with average boulder size of approximately 1mx1mx1m dimensions. A few large slabs were observed at the top of the failed material. The failure took place in the Sandstone rock type only.

Figure 14: Letlhakane mine DK1 pit plan showing location of slope failure of 14 July 2005.

Figure 15: Plan showing the slope failure of 14 July 2005 and the failure rubble extent. The solid line was the 65m distance from the toe of the slope on the 808m level bench where no human activity was allowed. The displacement vectors indicate total movement and the direction of slope failure.
Figure 16: Photograph showing the slope failure of 14 July 2005 at Letlhakane Mine.

Figure 17: Section at S34 and S38 slope monitoring targets showing the relationship between slope target movement, slope failure area and slope failure rubble.
Date of slope failure | 14 July 2005
---|---
Slope failure mode | Toppling mostly, minor sloughing
Rock type | Sandstone (Ntane & Mosolotsane)
Failure Volume | 233,000m$^3$
Failure Tonnage | 524,000 tonnes
No of benches affected | 5
Failure area vertical height | 70m
Failure area strike length | 183m
Direction of slope failure | North-east
Maximum horizontal strain at failure | 1.06%

*Table 2: Slope failure parameters*

**Conclusion**

Approximately 233,000m$^3$ of ground collapsed during the slope failure that occurred in the Sandstones on the western side of Lethlakane mine DK1 pit on 14 July 2005. The failure mode was toppling although some sloughing occurred as well. The failure was preceded by tension crack development.

Slope failure occurred in the direction predicted by the slope monitoring targets movement recorded by the Geomos, i.e. north-easterly. The decision that the cracked area was unstable and that slope failure was imminent was based upon information from the Geomos. Using the Geomos system information, the mode of slope failure was predicted. The medium term decision to sterilize a 65m wide zone at the toe of the cracked area insured that no injuries, damage to mining equipment and loss of mining production occurred during the slope failure. Otherwise a slope failure of that scale could have resulted in multiple fatalities had no action been taken to change the mining plan.

Up to 742mm of ground movement was measured prior to slope failure. This gives a horizontal strain of 1.06% over the 70m vertical height over which the slope failure occurred. Ground movement immediately prior to the slope failure moved at least 242mm/day. There was a significant increase in ground movement prior to the slope failure.

The Geomos slope monitoring system was successfully used in the management of the slope failure that occurred at Lethlakane Mine on 14 July 2005 by assisting in proactive decision making that avoided personnel injury, damage to equipment and loss of production. Just a single fatality would have added the loss of reputation consequence to the mine’s technical staff. The Geomos slope monitoring system is therefore an effective slope stability management system. Every medium to large scale open pit mine should have an automatic slope monitoring system in place as part of the slope failure risk management process.
Future slope monitoring

It is planned to improve the slope failure risk management process further at Letlhakane mine by installing a slope monitoring system in 2006 that will scan the entire slope face rather than monitor only at points as is the case with the Geomos system. Preparations are underway to purchase the Slope Stability Radar (SSR) slope monitoring system from GroundProbe of Australia. The SSR will augment the Geomos and visual inspections by the Geotechnical Engineer and will therefore form part of an integrated slope monitoring system at Letlhakane mine.

Figure 18: GroundProbe’s Slope Stability Radar slope monitoring system.

References


