Management of a major slope failure at Nchanga Open Pit, Chingola, Zambia

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Synopsis

On 16 July 2004, at 07:10 a collapse of about 1.8 million m^3 (about $4\frac{1}{2}$ million tons) took place on the north wall on Nchanga Open Pit.

This collapse was the result of a developing instability that was first identified when the benches in this area were exposed during September 2002. The NOP geotechnical and survey departments closely monitored the development of the failure. Control measures were implemented to reduce risk to men and equipment. These measures were continually improved and adjusted in reaction to observations and changing conditions.

The purpose of this paper is to describe in detail the monitoring results that were obtained both by traditional methods and the novel slope stability radar system (SSR). Difficulties encountered in establishing critical deformation levels and deformation rates that can be used to predict the onset of collapse are described.

Details of the monitoring and control measures, which led to the successful completion of mining in the area, are also described in this paper.

Introduction

On 16 July 2004, at about 07:10, a portion of the north wall on Nchanga Open Pit (Pit 20) collapsed. The failure zone occurred between the 21E and 23E section lines and affected the pit from the 150 m bench to the 330 m bench. Approximately 1.8 million m^3 ($4\frac{1}{2}$ million tons) of material were involved in the collapse.

This collapse was the end result of a developing instability that was identified when the benches in this area were first exposed in September 2002. Sloughing reported on the crest of the 165 m bench in conjunction with mining on the 180 m bench initially was interpreted as localized bench scale toppling associated with adversely orientated cleavage planes in the shale with grit formation. The NOP geotechnical department instituted physical inspections to closely monitor any developments and additional monitoring points were installed to allow the survey department to measure slope displacements enhance, the coverage and improve displacement measurement by the survey department in the area. With few exceptions, displacement rates in the order of 2 mm/day or less were measured—this is considered to represent a natural 'relaxation' of the rock mass that forms the north wall and gave no cause for concern.

Sloughing of the area continued as the pit was deepened and was interpreted as ongoing slope degradation commonly found at Nchanga. Typically, this is caused by a combination of weathering and erosion associated with high seasonal rainfall. Mining operations were not unduly affected by sloughing.

In July 2003, some monitoring points exhibited above average displacements and increases in movement rate. These lay in a specific area between 23E and 24E and from the 150 m bench to the 225 m bench. The increase in movement rates coincided with exposure of a small zone of upper banded sandstone in the core of a tight fold structure on the 270 m–285 m bench. Figure 1 shows a section through the slope at 24E illustrating the geological structure in the face. There was no obvious geological relationship between the elevation at which mining was taking place and the elevation at which deformation was occurring. It was surmised that displacement of vertical joint planes associated with the fold reduced confinement applied to the overlying Chingola dolomite and subsequent compression of this strata was transferred to overlying strata as settlement.

The extent of the area and nature of the movements now suggested that there existed the potential for an inter-stack scale failure rather than one of bench scale. This area then was designated as an 'area of concern' and specific rules governing mining operations in its vicinity were implemented.

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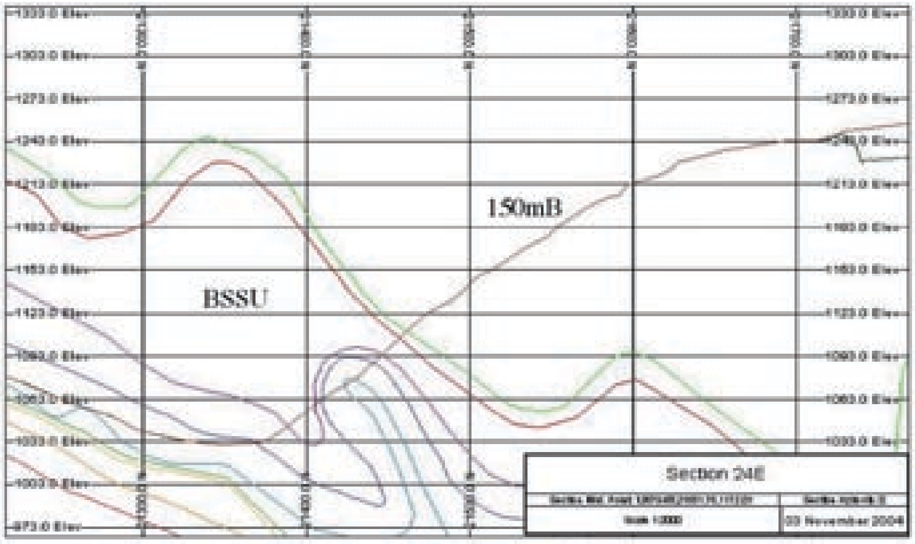

Figure 1—A section through the AOC indicating the geology. Note the exposure of the upper banded sandstone (BSSU) in the nose of the fold

As mining operations moved west, away from the area of concern beyond 21E, movement rates decreased. By early December 2003, however, the total displacement experienced by some points had exceeded 500 mm—an amount initially seen as representing the critical threshold above which collapse was imminent. This led to introduction of enhanced safety procedures and control measures. The wall showed few symptoms of distress such as tension cracking or severe sloughing, and it was decided that mining operations could continue. By the end of November 2003, the mining had moved back to below the area of concern.

During December 2003, movement rates were observed to peak in conjunction with blasting on the 300 m bench and then decay to a rate slightly higher than the pre-blasting rate. This pattern continued from January through to April with the period taken to re-establish an equilibrium rate, the ‘recovery’ period, continuing to increase slightly with each blasting cycle. By April 2004, blasting was having a profound effect on slope movements with rates calculated following blasts at times exceeding 150 mm/day. Total displacements on monitoring points MP4229 and MP4330 had exceeded 3000 mm. Cracking was apparent on many of the benches and faces between 150 m bench and 210 m bench. A major tension crack at the toe of the face on 150 m bench had widened to more than 2500 mm when measurements were suspended for safety reasons.

Given the obvious deterioration of the slope, more rigorous control measures were implemented and a decision was made to enhance monitoring by installing a radar-based system, the slope stability radar (SSR). The system claimed to provide continuous 24–hour coverage from a remote location and with accuracy comparable to that obtained from conventional survey. The system was deployed at NOP on 19 May 2004. Within the first couple of hours of monitoring, it became evident that deformation was taking place over a much greater portion of the slope than had been indicated by survey and visual monitoring.

A collapse involving three benches occurred on 22 May 2004 on 21E at the extreme western end of the area that had been deforming. Mining was not active on this bench at the time. From a back analysis of deformation rates immediately preceding the collapse, trigger levels of 3.5, 5.0 and 10 mm/h were derived that could be expected to give advance warning of 12, 6 and 2 hours respectively. These intervals were considered acceptable in order to successfully evacuate men and equipment from the area of concern and were adopted as ‘alert’, ‘alarm’ and ‘scram’ warning levels. These are shown on Figure 7.

The pattern of deformation continued throughout May and June, with rates generally showing an increase in association with blasting in the area of concern followed by a general decay to pre-blast levels within one or two days. Towards the end of June and in early July there was a tendency for rates to decay to a level slightly higher than those that prevailed pre-blasting.

On Monday 12 July, movement rates exceeded 20 mm/hour following an afternoon blast and continued showing no tendency to decay at levels between 20 and 30 mm/hour until Thursday 15th July. Rates then abruptly increased to levels exceeding 100 mm/hour prior to collapse on Friday 16th July.

Survey monitoring

Monitoring points installed consisted of reflective prisms located on top of steel tubes that were driven as far as possible into the ground and secured with concrete. Readings were taken from a base station on the south wall, on average 450 m from the measuring points. A distomat was used to give readings to a precision of approximately 1 mm. (The movement rate was calculated by dividing the difference between successive readings by the time interval between those readings.)

The location of monitoring points installed in the area of concern is indicated in Figure 2. Shading indicates the position of the slough at the end of November 2003, and the hatched area the extent of the July 2004 failure. Unfortunately, no monitoring points were installed in the area of concern below 225 m bench due to a combination of logistical and safety considerations.

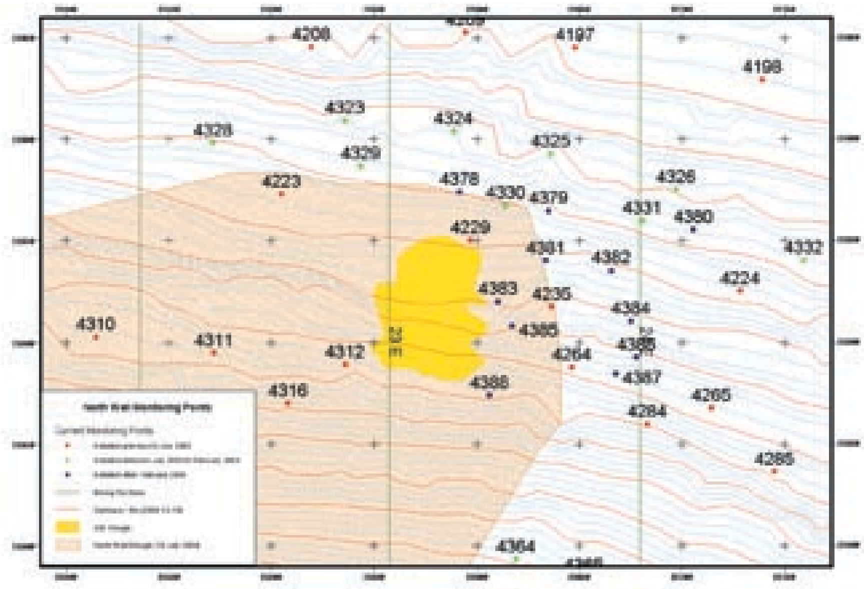

Figure 2—Monitoring points installed on the north wall: up to MP4316—prior to July 2003; MP4323 to MP4332—between July 2003 and February 2004; MP4380 to MP4388—after February 2004

Figure 3 indicates the total displacement measured for a selection of monitoring points for the period from December 2003 to July 2004. Three groupings of points are evident:

- MP4330 and MP4229 lie in the area of collapse and have undergone approximately 6500 mm and 7500 mm of movement, respectively, over the period. MP 4229 appears to approach its asymptote in the period following 7th July
- MP4235 and MP4331 both exhibit over 2500 mm of displacement. Whereas MP4235 lies on the margin of the collapsed zone and could be expected to move considerably, MP4331 lies some 60 m from the margin and could be expected to exhibit movements of the same order as MP4325, which was installed at the same time. That it has not done so could be indicative of some local anomaly not associated with the main collapse
- MP4325 and MP4284 lie outside the area of collapse and have remained relatively unaffected. MP4325 has undergone approximately 400 mm of movement, as would be expected with a background rate of 2 mm/day over the period. MP4284 has undergone approximately 1000 mm of deformation. This is far more than would be expected from the background rate and it is probable that this point has been subjected to a local anomaly.

From examination of the selection of points shown in Figure 3, it is clear that no unequivocal information regarding either the extent of the area of potential collapse or its likely time of collapse can be gleaned. The degree of uncertainty involved in making those predictions and in developing criteria by which to allow men and equipment to work safely is high, and criteria must therefore err on the conservative side.

Figure 4 illustrates deformation data that been converted into movement rates for the period December 2003 to May 2004. The response of deformation rate to blasting is clearly visible, particularly in April and early May when a series of blasts within the area of concern appear to have changed the longer-term pattern of rate increase and decay. Prior to April, following a blast, rates would increase and then decay to pre-blast levels. From the May blast, movement rates have taken much longer to decay and monitoring points lying within the collapse area, MP4229 and MP4330, have decayed to rates much higher than those pre blast. This is perhaps indicative of a change in strength characteristic of the slope from one of primarily peak shear strength to that approaching residual shear strength.

Management controls

Once the potential for failure occurring on a stack scale was recognized, a number of management controls was introduced in the form of an operating procedure to provide for safety of men and equipment. These included:

- Mining operations were restricted to daylight hours only as it was considered essential that survey readings and physical observations were essential
- Face shovels were replaced by rubber tyred front end loading equipment to facilitate rapid evacuation. Access was limited to one truck at any one time. No parking of vehicles was permitted. When bench space permitted, a ‘no-go’ area was cordoned off immediately below the face for a distance of 35 m. This was the maximum distance that it was anticipated that falling rock would impinge onto the bench. Often it was necessary to locate slow moving drills on benches below the area of concern but personnel were regularly briefed on evacuation rules and maintained contact with the control station via radio
- Continuous survey monitoring of the Area of Concern was instigated from a south wall station (Level 1) on about the 135 mB on 24E. The surveyor was required to start the daily survey with a conventional, detailed

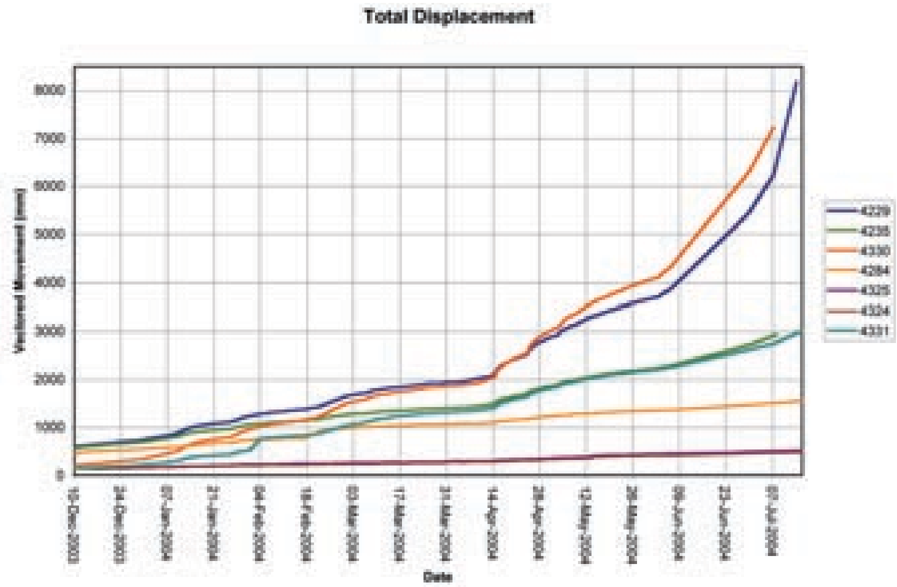

Figure 3—Total displacement of selected monitoring points from 10 December 2003 to 7 July 2004

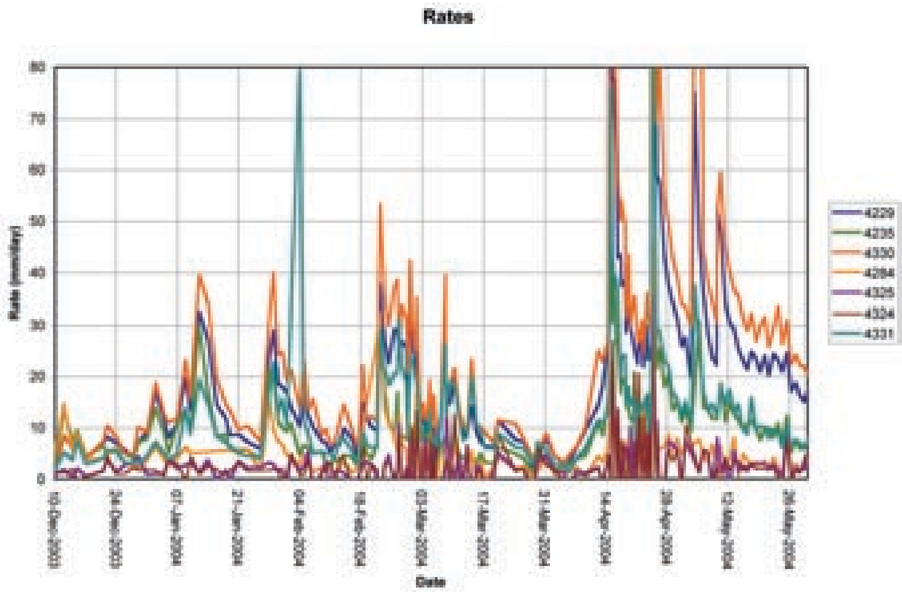

Figure 4—Movement rates: 10 December 2003 to 19 May 2004

survey giving three-dimensional co-ordinates of all points. Thereafter he took distance measurements only at regular intervals (starting off at 30 minutes) to each monitoring point. Additional monitoring points were installed when access to the face was possible. Many were lost, however, as a result of sloughing and normal mining attrition

A geotechnical observer was posted with the surveyor on Level 1. He maintained radio communication with the control tower and the geotechnical office and was tasked primarily with identifying visible movements and alerting operational personnel. The geotechnical observer also plotted the distance measurement on a graph. Should certain trigger levels be exceeded, his duty was to inform the senior geotechnical engineer

Following any rainstorm of sufficient intensity to cause temporary cessation of production operations, approval to resume operations would be given by the senior geotechnical engineer (SGE) or the group geotechnical engineer following examination of the face and survey monitoring records

Movement rate trigger levels that would initiate appropriate actions should they be exceeded were listed in detail in the procedure (KCM-MP-60). These were regularly revised upwards and reached a level of 60 mm/day following a review with SRK in April 2004.

Introduction of slope stability radar monitoring

The 'slope stability radar system' (SSR) is a technology adapted for the mining industry by GroundProbe, Pty from Brisbane, Australia to monitor slope movement from a remote location with a high degree of precision. The system is capable of continuously scanning a face on a 24-hour basis, without the need for reflective prisms, and calculating average movement in several hundred zones (pixels) over the face.

Between 120 m bench and 300 m bench from 22E to 24E approximately 3600 pixels were computed per scan. The SSR unit was located on the south wall of NOP at an elevation equivalent to the 225 m bench and an average distance of 450 m from the area of concern on the north wall. The precision of measurement within a pixel was to sub-millimetre. The system is not influenced by darkness, rain or dust and is fully self-contained for ease of deployment. A high-resolution digital camera was set to record images regularly to complement radar information. The system was deployed on NOP on 19 May 2004. Within the first two hours of monitoring it became evident that deformation was occurring over a substantial part of the slope from 150 m bench to 315 m bench and from 21E to 24E, a much larger area than had been detected by survey and visual monitoring.

Scan duration was approximately 14 minutes and results were sent to a computer in the control centre via a radio link. Time-displacement plots and movement rates were plotted from the results. Trigger levels were determined and applied to particular higher risk areas and set to raise an alarm automatically should they be exceeded. An example of a screen display is shown in Figure 5. From this figure it is possible to distinguish an area of increased deformation from a background, relatively static area and also to distinguish two zones of much higher deformation within the overall deforming area.

A combined displacement and movement rate graph is shown in Figure 6.

Deployment of the SSR had a number of operational benefits for NOP:

- 24 hours, 7 days a week continuous monitoring coverage gave real time warning of rock fall and collapse, thereby reducing risks to men and equipment operating in the current area of concern or other designated high rock fall risk areas. This meant that restrictions on working hours necessitated by survey monitoring and visual observation could be relaxed
- Accurate detection of movement over the complete area of concern (+21 000 m^2) with the capability to detect zones of instability that are not covered by the current prism monitoring system and may not be evident from visual observation. This meant that equipment withdrawn from localized areas of instability could often be deployed elsewhere in the area of concern
- Improved productivity through extending operating hours beyond daylight and reducing down time by eliminating subjectivity in allowing re-entry following a withdrawal period. This gain in operating time was significant and was a major factor in ensuring that ore recovery was maximized
- Improved understanding of the overall behaviour of the slope, in particular its time-related performance and response to blasting. It is expected that this will lead to an improved design of the Pit 20 Cut 2 slopes with the potential for improved and early ore recovery.

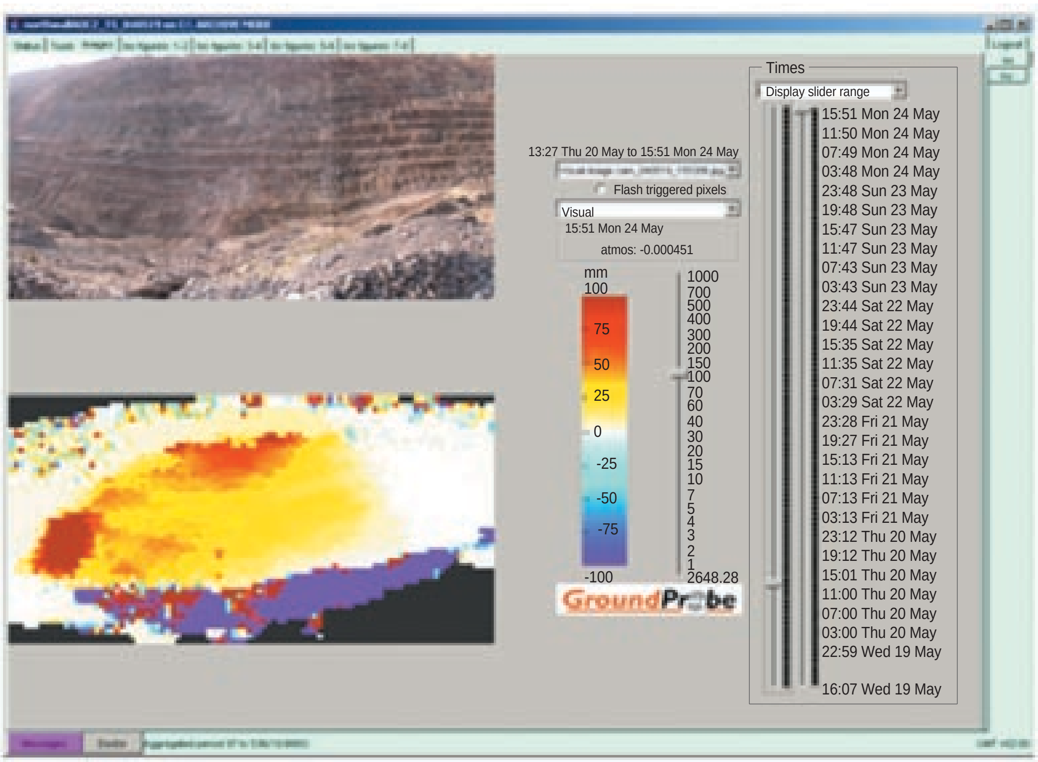

Figure 5—Initial radar survey results showing information that is relayed from the deployed unit to the central site. On screen, warmer (more dense) colours to the bottom right and upper central portions of the figure indicate greatest movements within the monitoring duration

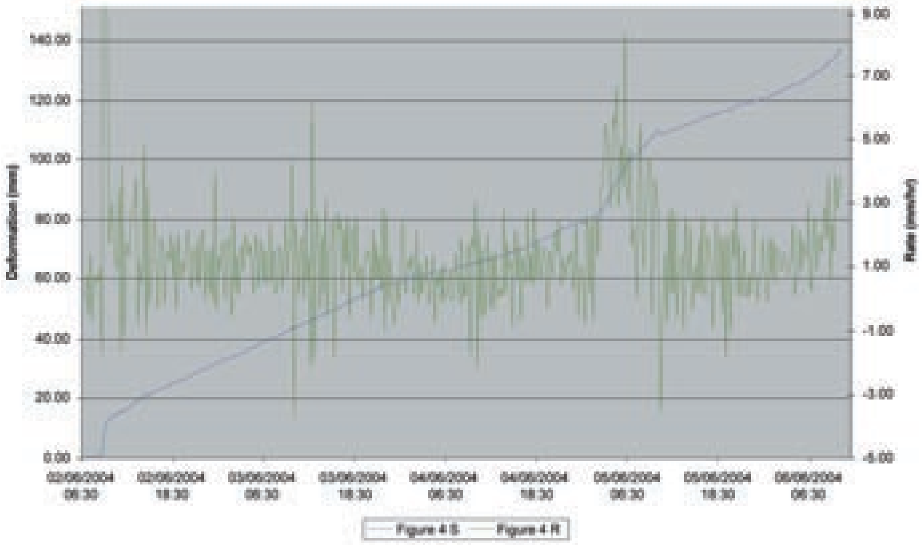

Figure 6—Typical deformation and instantaneous movement rate plots derived from SSR data for a particular window. Note the variation in rate that often occurs between successive scans. A later variation to the software eased interpretation by smoothing the rate graph

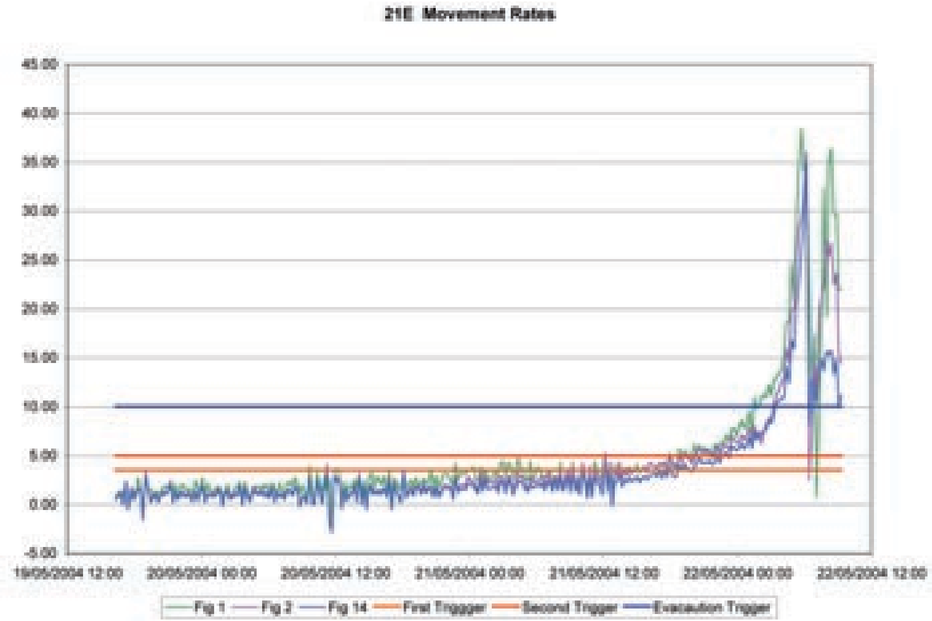

Figure 7—Back analysis of 21E. failure Figures 1, 2 and 14 refer to different windows placed retrospectively on the area. Trigger rates derived from the analysis are indicated by horizontal lines

Establishment of criteria

On Saturday, 22 May 2004, a collapse occurred at 21E in an area indicated as experiencing high rates of deformation by the SSR. Unfortunately the displacements in this area were not routinely scrutinized by observers since this was outside the active mining area. The collapse occurred shortly after implementation of the SSR and personnel were still in the process of understanding the results and putting monitoring procedures in place. No advance warning of this failure was thus issued. No injury to personnel or damage to equipment occurred due to the collapse.

A back analysis was carried out on data obtained from an analysis window that was located retrospectively to cover the area of collapse. The displacement rates are indicated in Figure 7. The following conclusions were drawn from the back analysis:

- The increase in movement rates can clearly be seen in Figure 7. The change in rate of movement is a definite indicator of imminent collapse
- There is no indication of the total amount of deformation that had taken place prior to collapse. Each time an SSR scan commences the displacement

automatically starts from zero and there is no indication of previous displacements. Any predictive criteria based on deformation therefore is inappropriate
At approximately 12 hours prior to collapse an instantaneous rate of 3.5 mm/hour was exceeded
At approximately 6 hours prior to failure an instantaneous rate of 5 mm/hour was exceeded
At approximately 2 hours before failure an instantaneous rate of 10 mm/hour was exceeded.

As these time intervals were considered acceptable in order to successfully evacuate men and equipment from the area of concern, they were adopted as ‘alert’, ‘alarm’ and ‘scram’ warning levels with associated management responses as indicated in Table I.

The eventual collapse

A constant displacement rate averaging 2–3 mm/hour was observed until 9 July, when it started to increase. The reason for this change is unclear. By Sunday 11 July the rates had increased to between 5 and 10 mm/h. On Monday 12 July the rates suddenly increased to 20 mm/h following blasting during the afternoon and continued at between 20–30 mm/h until early in the morning of Thursday 15 July (about 02:00). This continuing increase had not been observed previously and was considered indicative of a change in condition within the slope. Rates continued to accelerate throughout Thursday and a decision was made at 20h00 to withdraw men and equipment from mining operations lying between 20E and 21E and relocate them further west. At 06h30 on Friday 16 July, rates had increased to 70 mm/h, all operations within the pit were suspended and remaining men and equipment withdrawn, although they were working over 200 m west of the area of concern. Final collapse of the slope commenced at about 06h50 with sloughing and collapse of benches on 150–165 m levels. The main collapse followed at 07h10 when an estimated 4.5 million tons of rock moved and completely inundated the 330 m bench from 21E to 23E. The change in movement rates in the days and hours leading up to collapse can be seen clearly in Figure 8. The maximum movement rate immediately prior to failure exceeded 100 mm/h.

Conclusions

The high level of slope monitoring practised by NOP, together with the management responses devised, enabled all of the economical ore to be extracted from the 300 to 330 m benches between 21E and 23E. No injuries to men or damage

Table I

Trigger levels and management response determined from back analysis of the 21E failure

Trigger Level	Response
3.5 mm/hour	ALERT: Increase frequency of rate calculations to every 30 minutes
5.0 mm/hour	ALARM: Increase frequency of rate calculations to every 15 minutes Inform control tower of alarm status. Inform geotechnical engineer on duty.
10 mm/hour	SCRAM: Immediate evacuation from area of concern

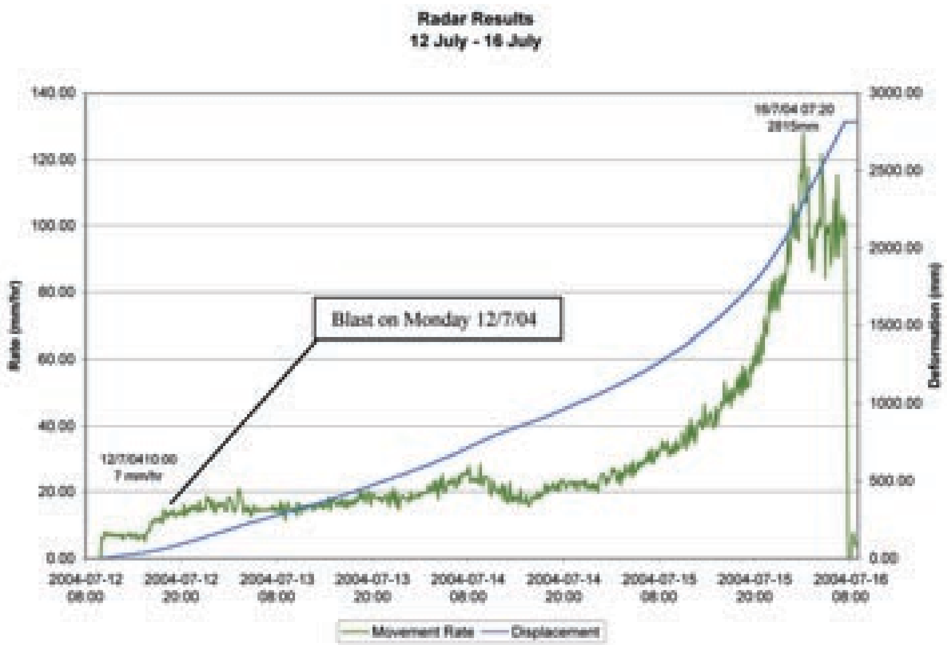

Figure 8—Movement rates and displacement in the four days prior to collapse

to equipment were recorded during the monitoring period. It is generally accepted that these outcomes would not have been achieved without using the high-level surveillance capabilities of SSR. The value of ore recovered far exceeded the cost of monitoring using SSR.

A number of other technical and managerial conclusions can also be drawn from the monitoring exercise:

The magnitude of the eventual collapse was not recognized until initial SSR results had become available. Face parallel cleavage planes lying within the shale with grit sequence had been identified during face mapping and also observed in other areas of the pit but, historically, had not given rise to similar collapses. The significance of the geologically complex fold zone in the lower part of the face has not yet been fully assessed.

Criteria for the prediction of collapse were developed on an ongoing basis during the period of monitoring. Initial criteria were, of necessity, very conservative, and it is unlikely that complete ore extraction could have been achieved had NOP continued to apply them rigorously. It appears that, for the NOP situation, criteria based on displacement rates are appropriate for ongoing monitoring with cognisance being taken of acceleration, particularly towards final collapse. Total displacement data was available for very few points and therefore criteria based on total displacement are difficult to implement in practice.

The advantage of a system such as SSR cannot be understated, particularly where alternative monitoring points were unavailable. The volume of data obtained does in itself create a problem with interpretation, and intense scrutiny is necessary to identify key monitoring windows that will accurately reflect overall slope behaviour.

As more information became available and greater understanding of slope dynamics was gained, the overall perception of risk changed significantly. This was evidenced by ongoing development and refinement of operating procedures throughout the monitoring procedure. High levels of data analysis and communication of emerging situations to management and workforce are essential elements of a successful strategy.

The analysis and criteria developed must be seen as site specific and only applicable to geotechnical domains similar to those existing at NOP.

Data obtained from continuous monitoring of the slope have created the potential to back analyse its performance using detailed numerical modelling and to calibrate its response to mining and blasting. The potential further exists to utilize this information in future slope designs.

Acknowledgements

The co-operation and enthusiasm of NOP management in developing and implementing the strategies and criteria that emerged during the monitoring period are gratefully acknowledged as is their permission to publish this paper.

Particular recognition must be given to the staff of the survey and geotechnical departments for their time, effort, courage and commitment in installing monitoring points, taking survey readings and physically inspecting difficult and sometimes dangerous areas.

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