Instrumentation monitoring at an underground mine to establish failure mechanisms, confirm numerical modelling and determine safe working conditions

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ABSTRACT: A number of potential failure modes were identified by observation and numerical modelling in the underground operation at Telfer Gold Mine. In order to gain a better understanding of the mechanisms of failure an instrumentation programme was designed. Monitoring methods included closure monitoring using tape, rod and sonic probe extensometers, stress monitoring, reinforcement monitoring with strain gauges, prism monitoring in the open pit and observation using a borehole camera.

The results from the monitoring instrumentation established local and regional failure mechanisms with greater certainty. The information allowed mining methods, extraction sequences and reinforcement requirements to be reliably designed, using numerical modelling as a tool.

Instrumentation was also installed to determine the ongoing stability of excavations which allowed safe working conditions to be identified throughout the mine.

The aim of each type of instrumentation method is presented along with the interpretation of the monitoring results. The practical implications of each set of results are discussed and a cost breakdown for all the instrumentation types is included.

1 INTRODUCTION

Underground mining began at Telfer Gold Mine in March 1990. The mine is located on the south western edge of the Great Sandy Desert in Western Australia, 1,000km north-east of Perth. A monitoring instrumentation programme has been carried out at the mine in order to establish mechanisms of failure, to confirm the results of numerical modelling and to allow safe working conditions to be determined. The following paper describes the monitoring methods which have been used and the relative success of each instrumentation type in achieving the goals of the programme.

2 GEOLOGY

The Telfer underground operation is situated within a series of sandstones, siltstones and quartzites of the Proterozoic Upper Yeena Group. The mine is located on the eastern limb of a dome structure. The pervasive structure is bedding which dips to the east at 35-40^0 Grade is carried within the Middle Vale Reef, which extends unbroken on strike for 1.2km except for a single north-east/south-west trending fault which displaces the lm thick orebody by 5-10m. A typical cross section through the geological sequence is shown in Figure 1.

Figure 1: Geological cross section through the underground operation at Telfer.

The siltstone units are highly variable in strength, ranging from 3MPa to 100MPa with an average around 10MPa and a stiffness of 6GPa. The sandstone units generally vary from 100MPa with a stiffness of 10-20GPa.

As well as marked variations in rock strength there are areas where fracture frequency is significantly higher. In general, there are five sets of joints throughout the underground mining area. The spacing of each joint set is variable. Plans showing variation in rock mass properties are used to predict the ground conditions in new mining areas before development of the orebody begins.

Stress measurements, using the borehole slotter, indicated the principal stresses are roughly orthogonal with the plane of the reef, with the maximum principal stress being oriented down dip.

4 MINING METHOD

The mining method employed at Telfer is a modified drift and fill method with access to the orebody via a portal, decline and crosscut system from the open pit as shown in Figure 1.

A barrier pillar has been left between the open pit and underground mine and the orebody is mined in three down dip blocks with a crown pillar being left between levels.

On-reef extraction involves development of strike drives at 5m vertical intervals followed by up dip raising between drifts which are then widened on strike to leave a series of systematic pillars. The spacing and size of pillars is determined by an assessment of local ground conditions. Timber props are used for support within the stope. Following extraction of each sublevel, the area is filled using hydraulically placed dune sand. Figure 2 illustrates the mining method. The majority of stoping is carried out using hand held rather than mechanised mining methods.

Support and reinforcement of the drifts consists of a combination of split sets and resin anchored rockbolts with mesh. Due to the shape of the drift it is difficult to achieve fully resin grouted bolts. As a result, fully grouted bolts are installed in a second pass in the areas of poorer quality rock. In areas where significant deformation of the drifts is predicted or observed, such as cross cut intersections or areas of weak, highly fractured rock, 7m long cable bolts are also installed.

5 FAILURE MECHANISMS

From geotechnical investigations and observations during the initial trial mining period, several failure mechanisms were identified.

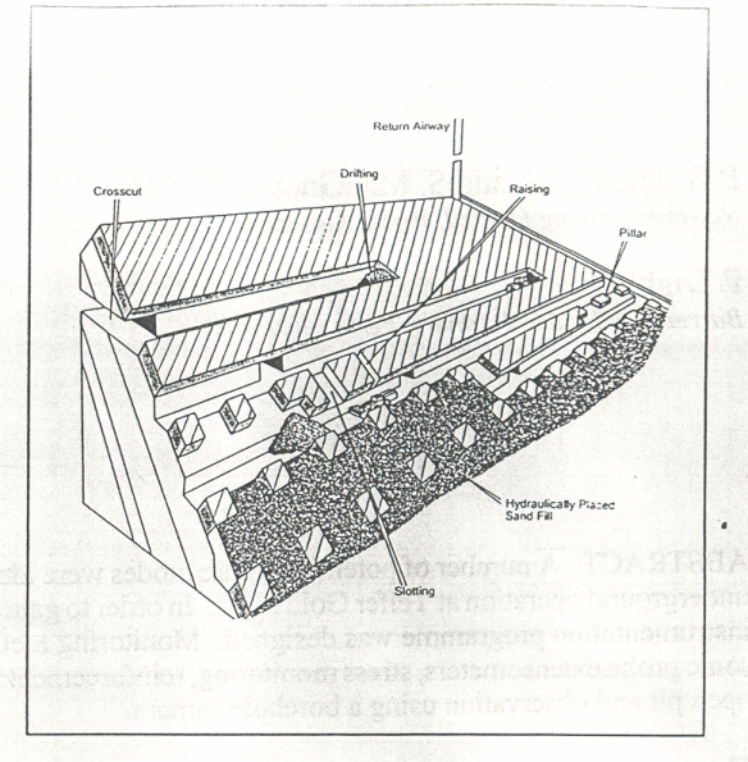

Figure 2: Schematic diagram showing underground mining method.

As the stoped area increased in size, wider variations in ground conditions were intersected and regional rather than local failure mechanisms were encountered.

The failure mechanisms which were identified were as follows:

a) Regional Mechanisms

i) Shear Movement on Bedding

Numerical modelling indicated shear on weak bedding. planes was possible in the hangingwall sequence due to mining of both the underground and the open pit, as shown in Figure 3a.

ii) Subsidence

Numerical modelling indicated that vertical displacements or subsidence above the underground would be up to 50mm directly above the stope and up to 30mm at the toe of the overlying highwall which could possibly lead to open pit instability as shown in Figure 3b.

iii) Stress

As mining spans increased and the crown pillar between stoping blocks decreased in size, the mining abutments were likely to become relatively highly stressed. Weak intact rock combined with relatively high stresses were expected to cause potential stability problems in the crown pillar and possibly the barrier pillar.

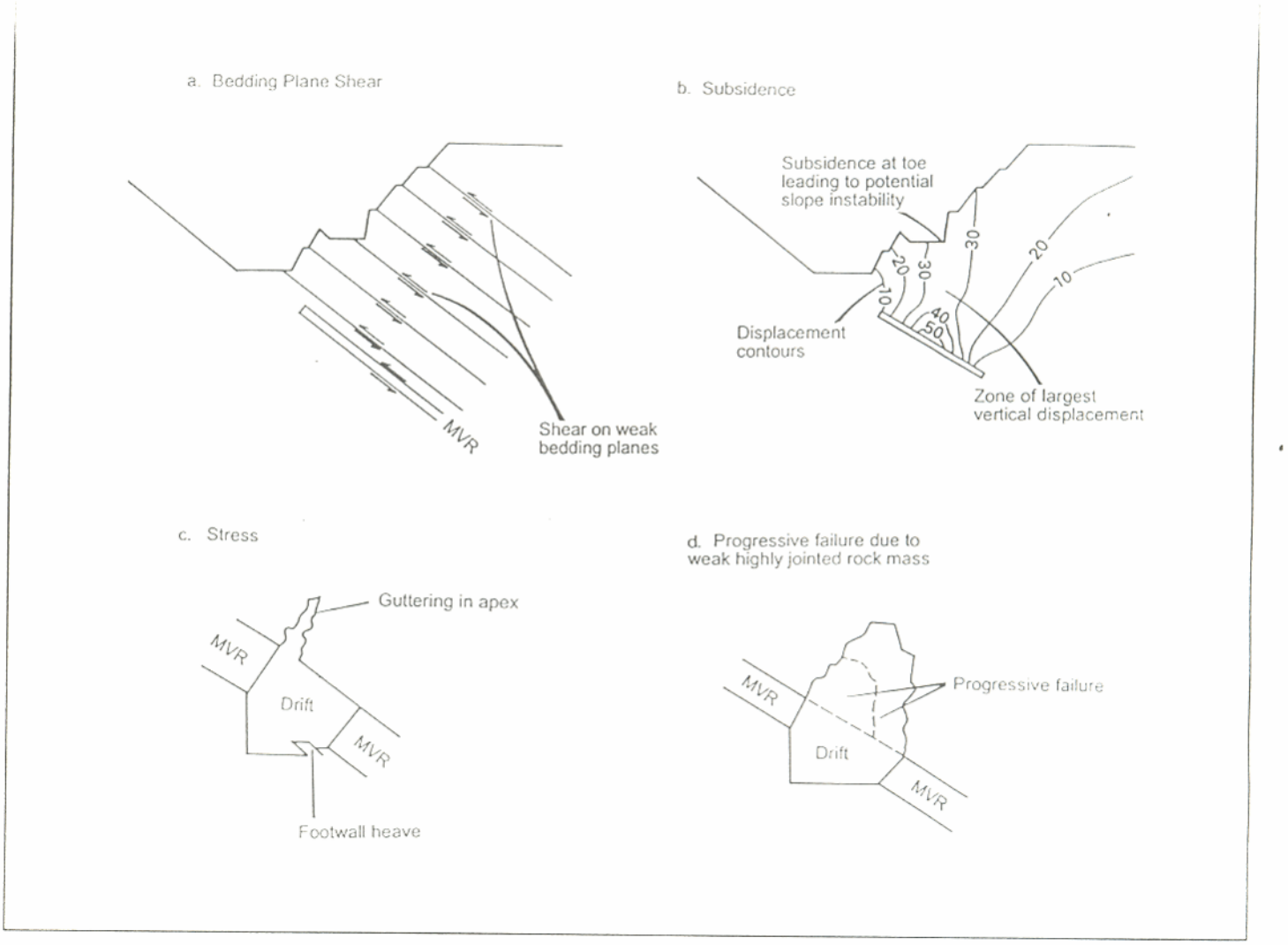

Figure 3: Failure mechanisms at the Telfer underground operation.

b) Local Mechanisms

i) Structural

The highly jointed nature of the rock mass created the potential for block failures to occur by falling and sliding.

ii) Stress

"Guttering" or crushing of rock in the apex of the drift and footwall heave have taken place which is indicative of the local effects of stress. Figure 3c shows the area where deterioration due to stress has occurred around drifts.

iii) Weak Intact Rock

Locally, weak intact rock has caused problems with deterioration in drifts at small mining spans. When combined with highly structured ground, progressive failure or "beehiving" has been seen to occur several metres into the hangingwall as shown in Figure 3d.

iv) Squeezing and Swelling Ground

Changes in moisture content have caused deformation around drifts due to swelling.

This has been exaggerated by the marked difference in the stiffness of the siltstone and sandstone units causing squeezing.

6 MONITORING METHODS, RESULTS AND INTERPRETATION

Due to the diverse failure mechanisms which were predicted by modelling and indicated from visual observation, a wide ranging monitoring programme was initiated. The aim of the monitoring was to highlight characteristic stress and displacement patterns which would be symptoms of the postulated failure mechanisms. In addition, by monitoring rates of movement and variations in the patterns of movement over time, it was hoped to produce characteristic ground response curves for displacement. The response curves could then be used to predict failure which would allow safe working conditions to be maintained.

The following, sections describe the different types of instrumentation which were used in the monitoring

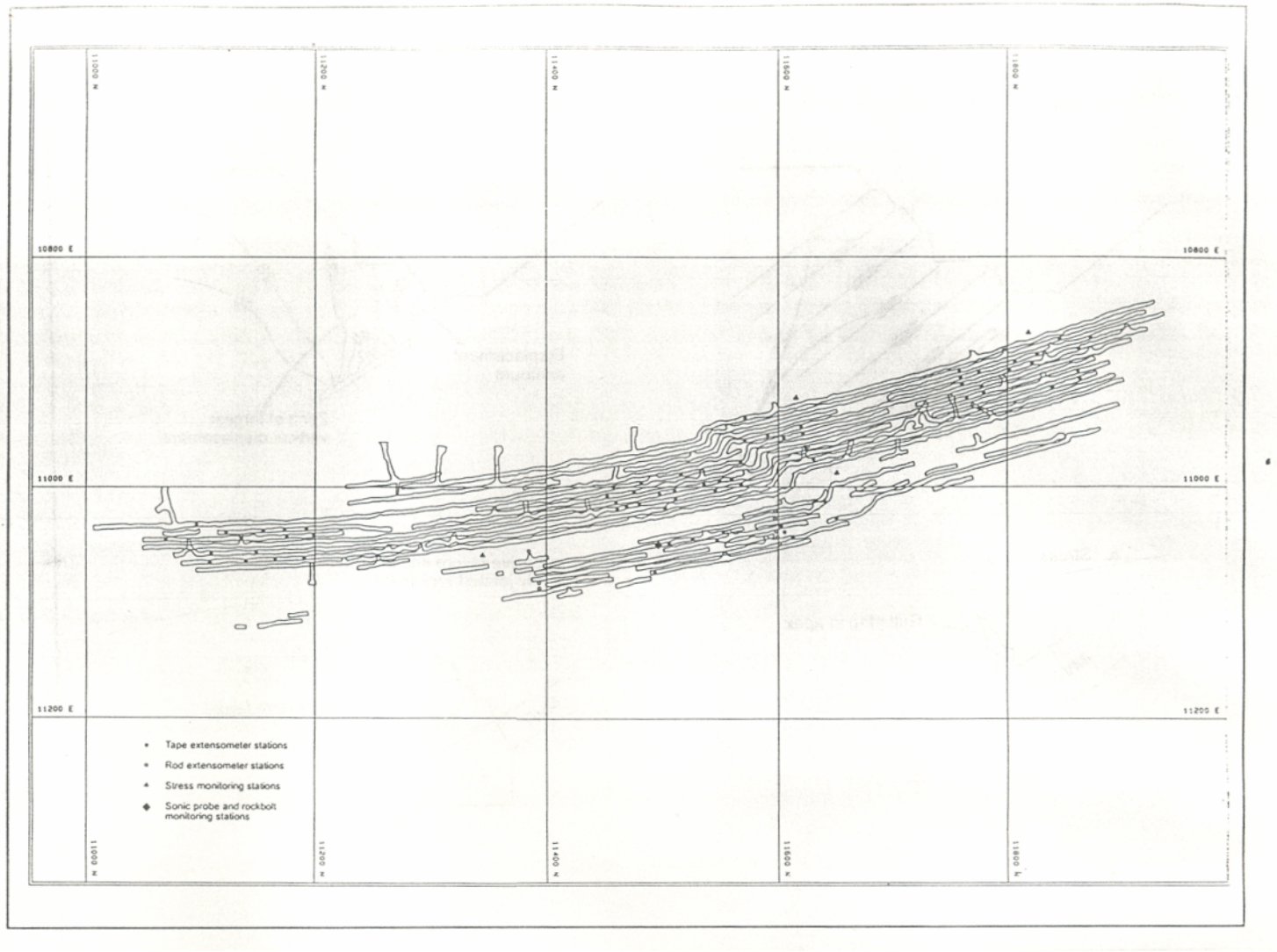

Figure 4: Plan of Telfer underground operation showing location of monitoring stations

programme, the reasons why each type was used, the results and interpretation of the monitoring data, the practical implications to mining and the cost effectiveness of each monitoring method (in Australian Dollars). The sections are subdivided into methods employed for identifying regional and local failure mechanisms. Figure 4 shows the locations of the various monitoring stations throughout the mine.

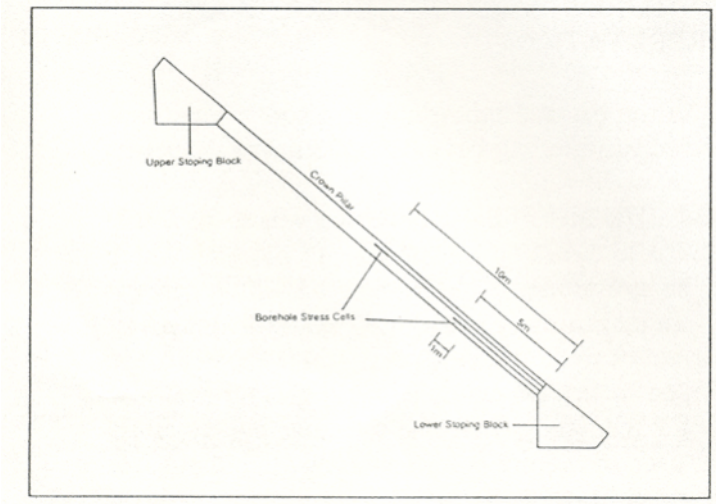

Figure 5: Stress monitoring configuration.

6.1 Monitoring of Regional Failure Mechanisms

6.1.1 Stress Monitoring

a) Aims

Stress monitoring measures changes in stress over time. The absolute magnitude of stress is not measured but the mining induced stress is recorded.

On a regional scale, the stress build up in the barrier pillar and crown pillars is important in controlling the ground conditions in the excavations immediately down dip.

Monitoring was carried out in both the barrier and crown pillars as shown in Figure 5. The aim was to have monitoring in the middle of the pillar and midway between the centre and edge of the pillar. Along strike the aim was to have instruments installed in different ground conditions. The geometry of the pillars meant that only the stress measurement perpendicular to the orebody had to be monitored to determine the relative change in stress.

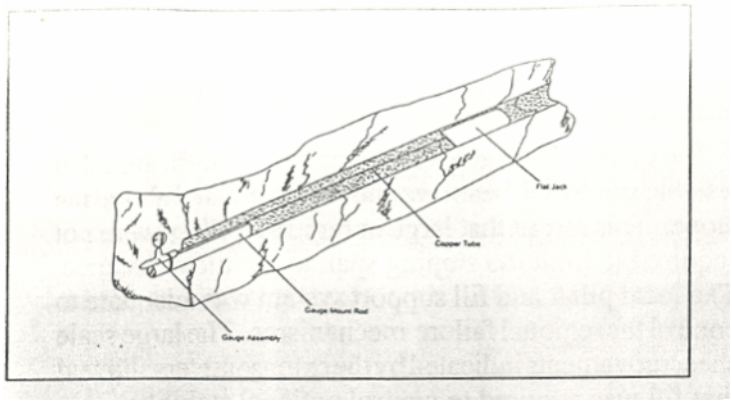

Figure 6: Borehole stress cell (schematic).

b) Type

A borehole stress cell was used for monitoring. It consists of a 1m long flat jack connected via a copper tube to a stress gauge, as shown in Figure 6.

The cell is installed in a borehole which is then grouted. The flat jack is then prestressed in order to fail the grout around the instrument which allows deformations in the surrounding rock to be measured as a change in stress.

Installation rods and a portable hydraulic pump are needed to install and prestress the cell.

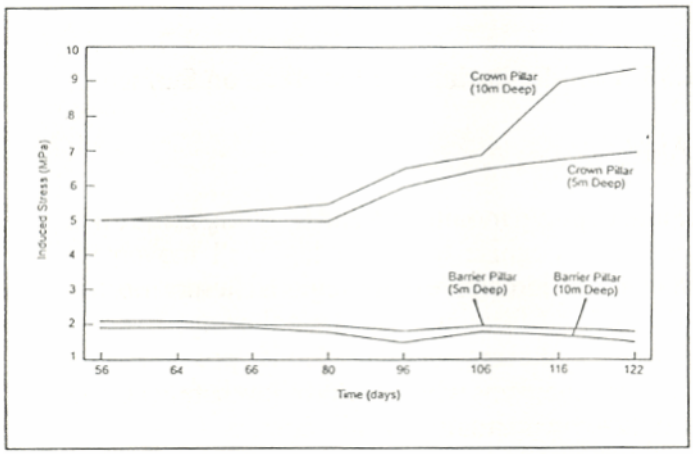

Figure 7: Stress monitoring results for the crown and barrier pillars.

c) Results and Interpretation

The results for the barrier pillar show there has been no increase in stress as mining has advanced up dip. In fact there has been a net decrease or destressing of the pillar. Stresses in the crown pillar have shown a significant increase as mining has advanced.

d) Practical Implications

The results show the barrier pillar is not highly stressed. This indicates the pillar can be mined without influencing the stability of the overlying pit. Excavations in the underground operation are unlikely to show significant deterioration due to stress as mining of the pillar progresses.

In contrast, the crown pillar is highly stressed and becomes more so as it reduces in size. The practical implication is development of drifts in the crown pillar has to be delayed as long as possible to minimise deformations around the excavation. Closure monitoring of excavations in the pillar is essential to identify areas of significant deterioration and determine safe ground conditions.

e) Cost

The cost of a borehole stress cell is around $420. Additional costs include hire of the installation tools and drilling and grouting, which will be site specific. It is estimated that the total cost of installation at Telfer was $600 per instrument and $6,000 for the whole programme. This is more than repaid by the fact that early extraction of the barrier pillar is possible, based on the interpretation of the stress monitoring results.

6.1.2 Rod Extensometer Monitoring

a) Aims

Rod extensometers were used in two applications at Telfer. The first involved monitoring at the toe of the open pit highwall in order to determine if significant displacements were occurring above the barrier pillar.

The second application was to identify where displacements occurred in the hangingwall of the ore drifts and if the displacements extended into the sandstone.

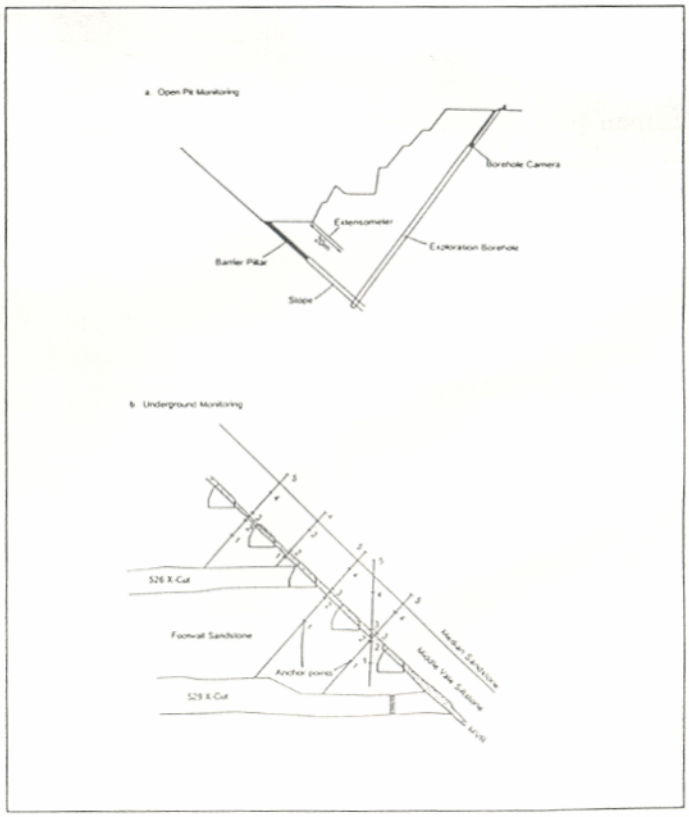

Figure 8: Rod extensometer layout for monitoring regional displacements.

b) Type

Figure 8 shows the two rod extensometer configurations. 20m, four point rod extensometers with remote readout were installed in the open pit.

Four and five point rod extensometers were installed in the underground, varying in length from 9 to 22m depending on the orebody/cross cut geometry. Anchor points were fixed in the immediate footwall, the immediate hangingwall, a mid point in the hangingwall siltstone unit and in the sandstone unit.

Surveying of the extensometer head was necessary to ensure the crosscut was stable. Remote readout of the extensometers was not possible due to the relatively high humidity experienced underground. Manual readings were taken using a vernier.

c) Results and Interpretation

The open pit monitoring indicated that no movement was taking place in the area of the barrier pillar. This confirmed results from the stress monitoring, and indicated no significant deterioration was taking place in the pillar.

The rod extensometer results in the cross cuts showed that displacements in the hangingwall of the stope extended into the sandstone. This indicated that a stable sandstone beam was not being created above the stope. Movements in the footwall were generally low but significant shear movement across the orebody and within the hangingwall were indicated in specific areas.

Figure 9 shows typical results from the underground extensometer monitoring.

d) Practical implications

The open pit extensometer monitoring results con-firmed significant deterioration of the barrier pillar was not taking place.

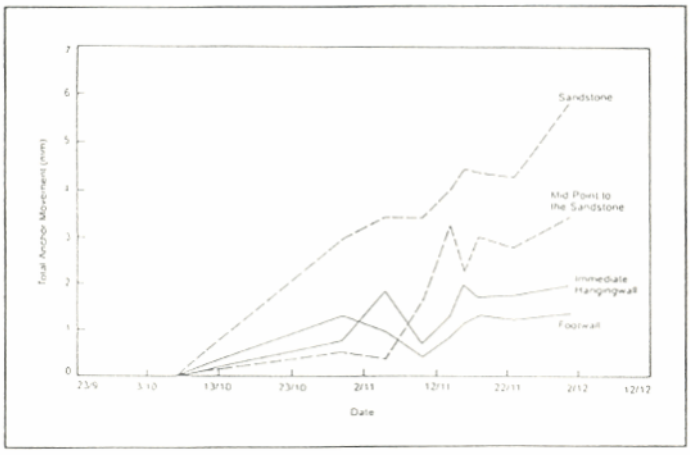

Figure 9: Typical rod extensometer results from the underground cross cuts.

This indicated early extraction of the pillar would be possible without causing slope stability problems in the pit. The results were in agreement with findings from stress monitoring.

The rod extensometers in the cross cuts indicated that a stable sandstone beam was not being created above the stope. This meant that large or regional pillars were not required to limit the stoping span to a critical distance. The local pillar and fill support system was adequate to control the regional failure mechanisms. The large scale shear movements indicated by the extensometers showed that fill was required to control regional stability.

e) Cost

The cost of the rod extensometers is dependent on their length, but on average one instrument was around $100. Drilling costs varied significantly between open pit and underground.

It is estimated that the total cost for a typical installation in the open pit was around $1,000 and in the underground was $1,200. The total cost for the programme was around $12,500. The potential for the early extraction of the barrier pillar and no requirement for regional pillars, more than justified the expenditure.

6.1.3 Prism Monitoring and Levelling on Surface

a) Aims

The aim of prism monitoring and levelling in the open pit were to recognise trends in highwall movement which would be indicative of the regional failure mecha-nisms postulated from numerical monitoring. In addi-tion, prism monitoring aimed to identify possible open pit failure mechanisms which would allow safe access to the portals to be maintained at all times.

b) Type

An automatic prism monitoring system was originally installed, but the system proved unreliable and not of sufficient accuracy to predict trends in movement. Survey prisms with holders and target plates were monitored from a survey station on the footwall side of the pit. Levelling was carried out using survey control behind the highwall, and involved picking up the elevation of traverse lines of grouted steel pegs using a survey staff.

c) Results and Interpretation

Detailed interpretation of the monitoring results to determine open pit failure has been described elsewhere and is not discussed in this paper, except to say that prism monitoring results clearly indicated the onset of an open pit failure and allowed prediction of its size and location.

Prisms installed in the pit bottom showed no significcant movement. Prisms higher in the slope showed movement was taking place along 500m of the highwall above the northern half of the underground operation. Due to open pit failure masking purely underground induced movement, no definitive answer on the regional undergroundfailure mechanism could be deduced. However the zone of movement and the patterns of movement between the open pit and underground were consistent with the results of numerical modelling.

The results of levelling were inconclusive due to the accuracy of the method used. It is proposed to use an automatic levelling system in the future to improve accuracy.

d) Practical Implications

Prism monitoring allowed constant safe access to the underground operation to be maintained at all times and therefore ensured continuity of production. If it had not been possible to recognise definite trends in movement, safe access to the underground could not have been guaranteed and it may have been necessary to temporarily close the underground operation.

e) Cost

The total cost of the survey monitoring for both the prisms and the levelling, including establishment of control and survey stations was around $7,000. This cost is insignificant when compared to the potential shut down of the underground operation.

6.1.4 Borehole Camera

a) Aims

The aim of using the borehole camera was to identify physical features, such as shear on bedding planes, which would be indicative of the regional failure mechanisms postulated from numerical modelling. Greater certainty in the failure mechanism would allow future numerical modelling to be used as a predictive tool.

b) Type

A black and white borehole video camera was used which was lowered down 90mm diameter exploration holes to a maximum depth of 120m as shown in Figure 8a. Viewing was via a television screen and recording was carried out on a standard video cassette recorder.

c) Results and Interpretation

The observations made with the video camera clearly showed shear movement on bedding planes of up to 25mm. This indicated that the regional failure mechanism which had been predicted from numerical modelling was consistent with physical observation.

d) Practical Implicatons

Considerable faith could be placed in the numerical modelling as a design tool and further expense on modelling could be justified. Additional modelling was used to indicate that the regional shearing mechanism removed the need for a large regional pillar, thereby avoiding temporary sterilisation of ore reserves.

e) Cost

The cost of hiring the borehole camera was $400 per day.
The camera was required on site for a total of two days plus two days travelling to and from site. The cost ofthis form of data collection allowed numerical modelling to be more focused and hence saved money on unnecessary computer time.

6.2 Monitoring of Local Failure Mechanisms

6.2.1 Closure Monitoring

a) Aims

Closure monitoring was used to identify the rate of hangingwall movement into the drifts. The aims of the instrumentation were to recognise the effects of the various stages of the mining cycle on drift stability, to identify the zone of influence mining has on the surrounding area and to determine trends in movement which could indicate the onset of collapse of the drift.

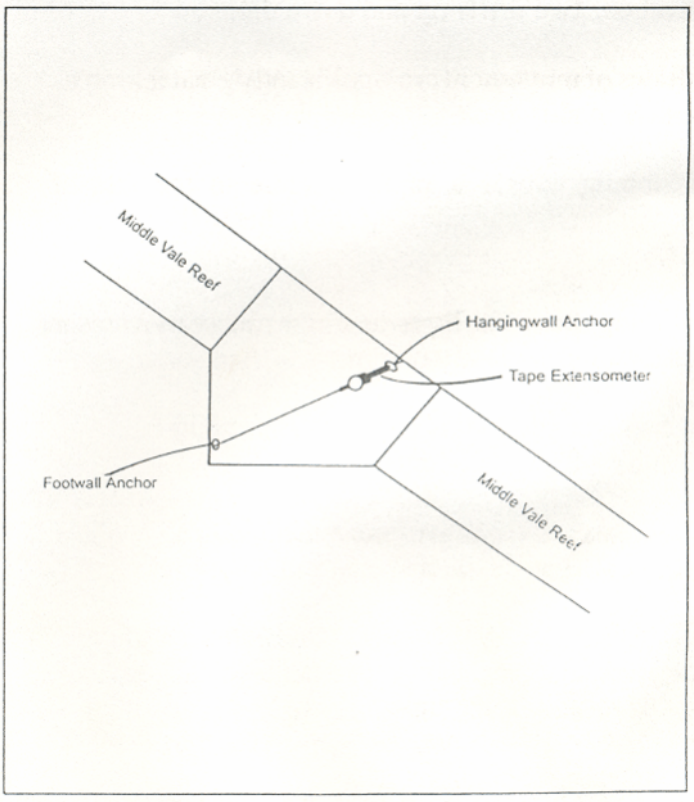

Figure 10: Layout of closure monitoring stations.

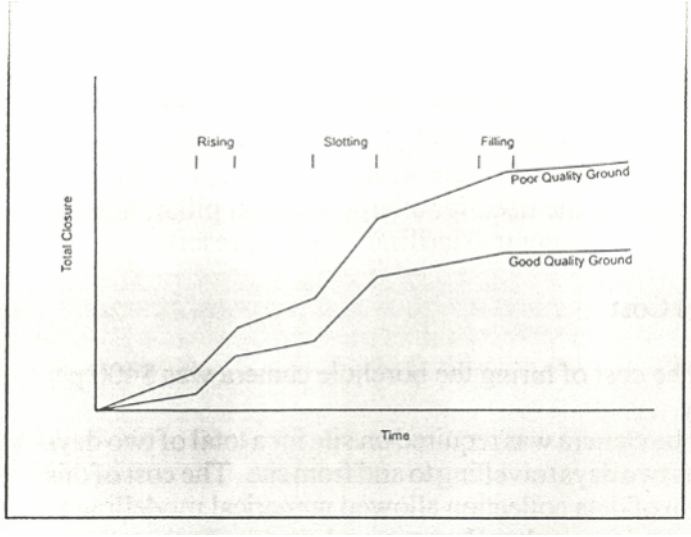

Figure 11: Composite graph of movement from closure monitoring.

b) Type

A tape extensometer was used to measure the distance between anchors installed in the hangingwall and foot-wall of the drift, as shown in Figure 10. The tape extensometer measures to an accuracy of 0.1mm with repeatable results to 0.2-0.3mm.

c) Results and Interpretation

Figure 11 shows results of closure monitoring at various stages of extraction and during specific mining operations. The main conclusions from the instrument-tation were:

i)Mining in one drift can cause deformations in excavations two drifts up and down dip.

ii)Rates of movement are significantly greater in areas of poorer quality rock.

iii)Stoping causes a rapid increase in the rate of movement in the surrounding drifts due to the increase in span.

iv)Filling dramatically reduces the rate of movement in the drift immediately up dip.

v)Characteristic trends in movement can be determined for specific areas.

vi)Increases in the rate of movement indicative of the onset of collapse of the drift can be recognised.

vii)The introduction of water to a drift (from filling and drilling) causes significant deformations in that drift and the drifts up and down dip.

d) Practical Implications

The main implication to the operation was that the closure monitoring system could be used as a cheap, rapid, repeatable method of determining safe working conditions throughout the mine. The effectiveness of the backfill system was emphasised and the benefit of the early placement of fill highlighted. The importance of water in controlling deformations was indicated which increased the emphasis of supervision in controlling water.

e) Cost

The cost of the tape extensometer was $2,550. At the time of preparation of this paper over seventy closure monitoring stations had been installed at a cost of less than $500, including replacement of damaged pegs. The use of the monitoring method for safety purposes justified the expenditure.

6.2.2 Sonic Probe Extensometer

a) Aims

Closure monitoring indicated large deformations were taking place around the drifts as a result of one or all of the local failure mechanisms. However the magnitude, location, type and timing of specific mechanisms of deformation was not known. Accurate, sensitive monitoring methods were considered necessary in order to determine these unknowns.

A sonic probe extensometer was therefore installed to identify where movement was taking place in the hangingwall, when the movement occurred and how much movement was taking place at specific horizons.

b) Type

The sonic probe extensometers were 20 point, 7m long instruments. Two extensometers were installed at a site in the configuration shown in Figure 12.

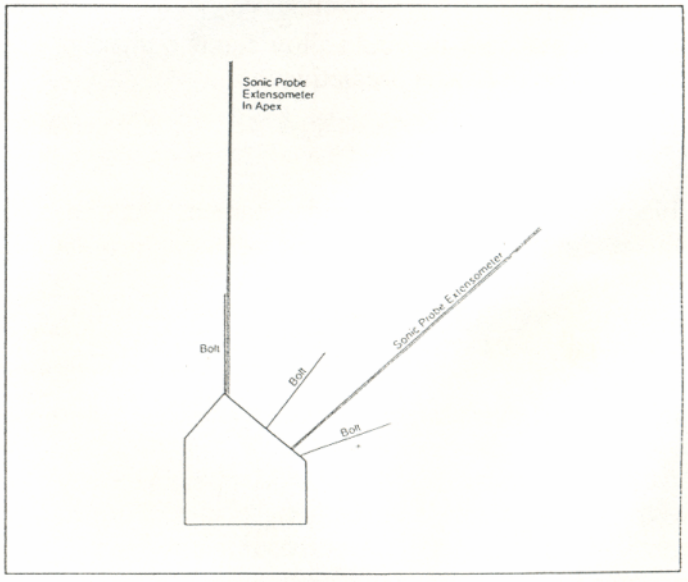

Figure 12: Location of sonic probe extensometer and instrumented rockbolt.

The monitoring points were anchored in the hole on a 30-40cm spacing in order to accurately identify the horizons in which movement was taking place. The instrumentation was installed as close as practically possible behind the face of the advancing drift.

c) Results and Interpretation

The results of the monitoring are shown in Figure 13. Displacements up to a distance of 1m into the backs occurred almost immediately after development. Over six week period and with 50m face advance, up to 2mm deformation was recorded in the first metre of the hangingwall. Over time, the zone in which deformation was taking place extended to 1.3m and then 1.6m into the hangingwall, showing progressive failure was taking place. The rate of deformation decreased slightly over time, but significant rates of movement were still taking place at the end of the monitoring period.

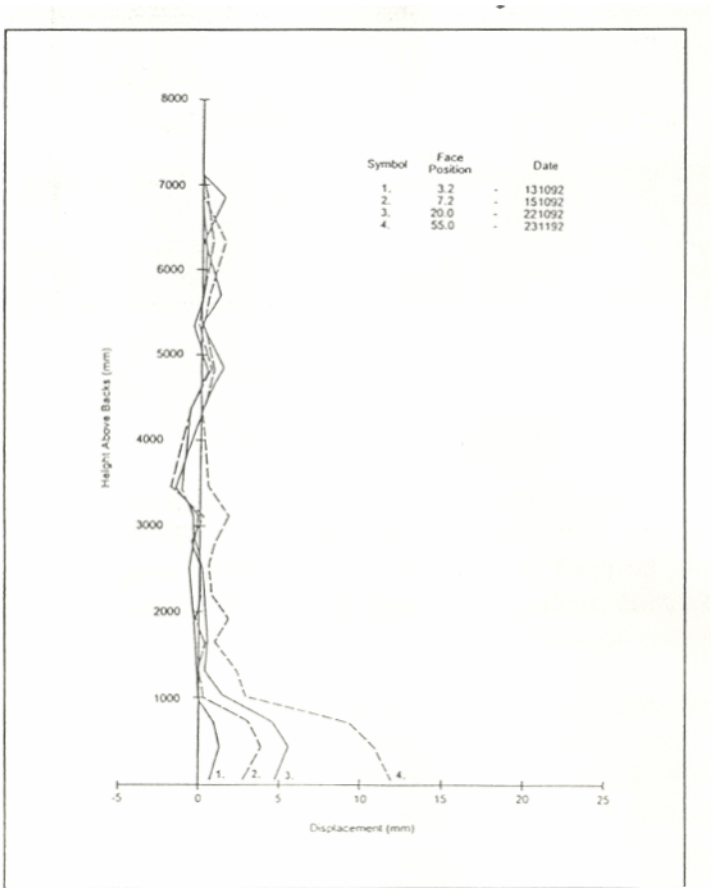

Figure 13: Monitoring results from the sonic probe extensometers.

d) Practical Implications

The results of monitoring clearly indicated the progressive failure mechanism which was occuring into the hangingwall.

The resin rockbolting system only achieved encapslation of the back metre of the rockbolt and deformation was taking place in the ungrouted part of the hole immediately after development.

Increasing the stiffness of the bolts in the front 1.5m of the hole would potentially reduce the hangingwall deformations and limit progressive failure.

The stiffer reinforcement would increase the likelyhood of the drift remaining stable for its required life without the requirement for additional support by limiting progressive failure. Fully encapsulated rockbolts installed immediately behind the face of the advancing drift were therefore identified to be a major improvement in the reinforcement system. A practical method of installation is vigorously being followed up.

e) Cost

The extensometers cost $510 each and the hire of the sonic probe (the most expensive part of the system to purchase) cost $200/week. With drilling and grouting costs it is estimated that the initial monitoring programme using sonic probe extensometers cost $3,000.

The cost of monitoring was justified as results clearly indicated areas in which rockbolt performance could be improved.

6.2.3 Rockbolt Monitoring

a) Aims

The monitoring of rockbolt behaviour was carried out in order to determine the load bearing characteristics of the reinforcement system in tension and in shear. The load bearing patterns give an indication of the local failure mechanisms occurring around the drift and allow the design of reinforcement to be improved.

b) Type

Three, 2.4m long, instrumented rockbolts were installed in the configuration shown in Figure 13. The instrumentation consists of nine pairs of strain gauges installed on opposite sides of the bolt every 20cm.

The strain gauges were monitored using a remote readout unit.

c) Results and Interpretation

The axial force and bending moment for a bolt are shown in Figure 14. The results show that a pretension of 20-30kN was achieved on installation with an indicated encapsulation length of50-100cm, indicated by the zero load transfer zone in the bolt. The size of the encapsulated area indicated an effective hole size of 30-31mm.

During the first six weeks ofmonitoring the sonic probe extensometer showed 12mm deformation in the hangingwall while the rockbolts showed an increase in axial load of less than 60kN. This indicated the load transfer characteristics of the bolt were poor.

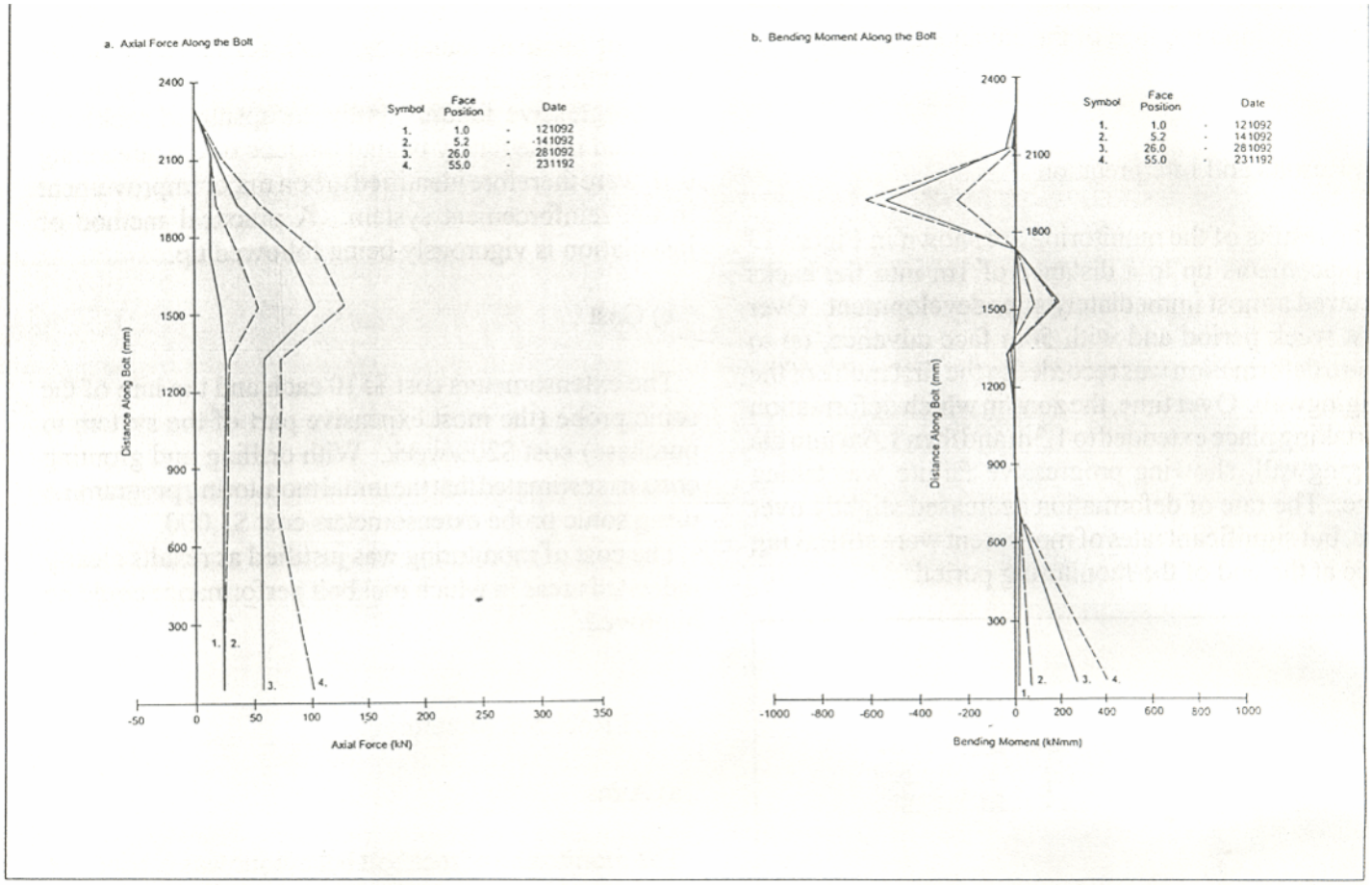

Figure 14: Monitoring results from instrumented rockbolts.

The bending movements in the bolt indicated a large shear movement was taking place at a depth of approximately 2.0m into the hangingwall.

d) Practical Implications

The rockbolt monitoring indicated the pull out load of the bolts was much lower than anticipated. This was partly due to hole size being larger than design. A consequence of this was the recommendation to use a rotary drill rather than a rotary percussion drill.

Significant bending movements on the rockbolts confirmed the requirement for fully encapsulated bolts to improve their performance in shear.

e) Cost

The cost of the instrumented rockbolts was $1,650 each. A total of three bolts were installed using the standard methods employed on the mine. The total cost of the programme was around $5,100. The improved method of drilling and the resulting increase in the load transfer characteristics of the rockbolt justified the expenditure.

7 CONCLUSIONS

a)The individual instrumentation types each had practical implications to the operation. The results could be used to improve and modify the design of extraction methods and sequences and to increase the effectiveness of reinforcement.

b)Instrumentation results were used to confirm failure mechanisms on both a regional and local scale.

This is important as a poorly designed monitoring programme may not have provided the appropriate results.

c)The integrated use of a number of individual monitoring methods allowed additional conclusions to be drawn on local and regional failure mechanisms.

d)Monitoring has been used successfully to confirm the results of numerical modelling and thereby improve the confidence for using these models in future design.

e)Routine closure monitoring is used to assess the ongoing stability of mining areas throughout the operation. The results are used by management to determine safe working conditions.

f)The total cost of monitoring instrumentation was around $40,000. The information from the monitoring allowed decisions to be taken by management which involved mining millions of dollars worth of ore.

The increased certainty with which decisions can be made more than justifies the cost of instrumentation.

Decisions not to leave regional pillars and to extract the barrier pillar have significant financial implications to the operation, far in excess of the expenditure on instrumentation.

8 ACKNOWLEDGMENTS

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