Safety in Mines Research Advisory Committee

Final Project Report

Experimental validation of a mine-wide continuous closure monitoring system as a decision making tool for gold mines

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Executive summary

Previous fundamental research projects have indicated the value of continuous closure measurements for improved support design and hazard assessment and for quantifying the effect of seismicity on stope closure. This project examined the feasibility of a mine-wide continuous closure monitoring system. A RMT remote reading telltale system was modified to operate as a closure system and installed at Mponeng Mine. Unfortunately, this system did not succeed in collecting data from a large number of closure stations. Nevertheless, some valuable lessons were learnt. The two most serious problems experienced were communication problems from underground to surface and maintaining continuity of the cabling in the stope.

Three types of closure meters were designed and evaluated during the project. These designs operated satisfactorily. The cable network used in the stope presented a major challenge in terms of maintenance. Mining activity and falls of ground resulted in frequent cable damage. In conclusion, cable connections in the stope for a mine- wide closure system is not seen as a viable option. Radio communication is probably the best method to link closure meters to a data logger located elsewhere in the stope. Further problems were experienced with the communication system to surface. The RMT system required a copper link to surface. This was not available at Mponeng and attempts to use the fibre optic network were not successful. In future, mine-wide closure systems should be designed with the necessary flexibility to link-in with the existing mine communications systems, whether it is fibre optic, copper of leaky feeder.

Following the problems experienced with the RMT system, SIMRAC requested Miningtek to use the remaining funds to collect data from one site only using stand-alone closure meters. The site chosen was the 109/51 area at Mponeng Mine. Four panels were instrumented with CSIR closure meters. During the three month period of monitoring, only two significant events occurred. These were seismic events on 21 November 2002 and 17 January 2003 causing significant falls of ground in some of the panels. A very significant finding for mine-wide closure monitoring was that there is a very good correlation between the amount of instantaneous seismic closure in the panels and where the damage occurs. In both cases the falls of ground occurred in the panels with the highest amount of instantaneous seismic closure, even though the seismic events located closer to other panels that remained undamaged. For both seismic events, some increase in the steady-state closure rate was observed for some hours preceding the event. There is, however, not enough evidence to prove that this increase in closure rate can be used as a precursor to damaging seismic events.

A useful parameter calculated from the closure data is the closure ratio (CR), which is the ratio of the instantaneous blasting closure to total closure following a blast. Note that this parameter is only defined for the closure following a blast and not a seismic event. Calculation of this closure ratio for closure data collected in earlier projects showed that it is a very good measure to identify different ground conditions and possible hazards. Closure ratio values greater than 0.4 (measured in VCR stopes with a hard lava hangingwall) are typically associated with strain bursting conditions, while low values (< 0.1) are associated with significant risks of falls of ground. The typical closure ratio calculated for the experimental site at Mponeng Mine was 0.5. Fortunately no face bursting occurred during the period of monitoring but any possible changes in closure ratio preceding bursts could therefore not be investigated.

Another preliminary finding is that it appears that the closure ratio is relatively independent of position along the stope face. This implies that the exact position of the closure meter in the panel might not be critical when calculating the closure ratio, while the exact position must be known when analyzing the total amount of closure. This hypothesis requires further validation.

Some numerical modelling using DIGS was conducted to verify the usefulness of the CR parameter. It was found that these initial results support the utility of the closure ratio in discriminating the response of different geotechnical environments. However, the present numerical simulations do not support more definite trends of the closure ratio as a function of time or as a predictor of incipient face stability.

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Glossary of abbreviations, symbols and terms

Abbreviations

RF   Radio frequency
CR   Closure ratio

Terminology

As much confusion surrounds the terminology used with closure measurements, the following terms as defined in Malan (1999b) will be used in this report.

Closure
Relative movement of the hangingwall and footwall normal to the plane of the excavation.

Ride
Relative movement of the hangingwall and footwall parallel to the plane of the excavation.

Convergence
Elastic component of closure.

Long period closure measurements
Discrete closure measurements with a typical interval of 24 hours or longer between successive data points.

Continuous closure measurements
Closure recorded in a continuous fashion with suitable instrumentation such as clockwork closure meters. Closure collected with electronic data loggers with a sample frequency of greater than 1 sample/15 minutes will also be referred to as continuous.

Time-dependent closure
Slow ongoing closure observed between successive blasts when there is no change in the mining geometry. It consists of a primary and steady-state phase.

Primary closure phase
This is the component of time-dependent closure following a blast and is characterized by a period ($\approx$ 3 to 5 hours) of decelerating rate of closure. It is also observed after large seismic events.

Steady-state closure
The component of time-dependent closure following the primary closure phase. The rate of steady-state closure appears to be constant in the short term but it gradually decreases when there is no blasting or seismic activity.

Instantaneous blast closure
The instantaneous closure component occurring at blasting time. Due to the delays in the detonation sequence between adjacent blast holes in the face, this closure phase is not really instantaneous at blasting time but can last for several minutes.

Instantaneous seismic closure
The instantaneous stope closure occurring during a seismic event. Similar to the blast closure, the instantaneous seismic closure is followed by a primary and steady-state closure phase.

Closure ratio
The ratio of the instantaneous blast closure to total closure following a blast. Note that this parameter is only defined for the closure following a blast and not a seismic event.

1 Introduction

Work in the SIMRAC projects GAP332 and GAP601b indicated that continuous stope closure measurements may be a very valuable diagnostic tool in the interpretation of rock mass behaviour. Especially in the areas of hangingwall stability, the risk of falls of ground and effective support design, little information can be obtained from existing seismic systems. Much can be gained from a systematic programme of closure measurements to complement the seismic data. Some specific examples where continuous stope closure measurements may be useful include:

- Identification of different geotechnical areas (Malan and Napier, 1999)
- Identification of areas with high face stresses and therefore prone to face bursting (Malan, 1999a)
- Identification of areas with a large rock mass mobility leading to unstable hangingwall conditions (Malan, 1999a)
- Estimation of closure rates at different mining rates needed for effective support design (Malan, 1999b)
- To assess the effectiveness of preconditioning (Malan, 1999a)
- To assess the effect of seismicity on stope closure (Malan, 1998)

From these studies, the concept of a continuous real-time mine-wide closure system was born as it was felt that the design parameters and hazard identification tools available to rock mechanics engineers would be greatly enhanced by such a system.

In spite of the enormous benefits of such a system, from the onset it was known that such a closure system could be difficult to maintain, as the closure transducers would have to be moved forward on a regular basis as faces were blasted. Studies by Malan (1998) also indicated that the distance to face for each instrument on a particular day would be needed to perform an effective analysis of the closure data. To further examine the practical problems associated with these systems, the SIMRAC project GAP705 (Malan et al, 2000) investigated the feasibility of a mine-wide closure system for gold mines. The logical next step was then to develop a small-scale prototype to test the various hardware options in underground conditions.

As a continuation to GAP705, SIMRAC proposed collaboration between CSIR Miningtek and Groundwork Consulting (Pty) Ltd and the use of an existing RMT remote-reading telltale system to collect the closure data. Unfortunately, due to problems experienced with the RMT closure system, only limited data was collected for the period from April 2001 to March 2002. This data was not suitable to achieve the objectives of this project. After a meeting was held between SIMPROSS and members of the industry on 10 June 2002, it was decided that no additional funding would be given to this project. The request from SIMRAC was that Miningtek use the remaining funds to collect significant data at one site only. There should also be no attempt to collect data in real time. This data should be used as further validation of the benefits of such a system.

Although insufficient data could be collected from the RMT system, valuable lessons were learnt from the implementation of this system and these are summarised in Chapter 2.

Additional closure data was subsequently collected at Mponeng Mine using stand-alone closure meters over a period of three months. The closure collected and the value of these measurements are discussed in the report.

2 Implementation of a pilot-scale, real-time, remote monitoring closure system

2.1 THE RMT REMOTE READING TELLTALE SYSTEM

2.1.1 System Overview

The RMT system was originally designed to remotely monitor roof displacement and bed separation in collieries using electronic telltales as transducers. Telltales have become established worldwide as an effective means of identifying and measuring roof deformation in underground coal mines, providing a major contribution to safety. Mechanical telltales, which are anchored in small diameter boreholes and operate in a similar manner to extensometers, give a visual warning of rock deformation through the movement of an indicator.

With the Remote Reading Telltale system designed by RMT, up to 400 telltales can be integrated into a mine-wide monitoring system to provide real-time data of roof condition on a surface computer. The system allows up to 100 telltales to be strung together along 4 separate tunnels in a simple "daisy chain" configuration using a twin core connection cable. As each tunnel advances, new transducers can be added. At the other end, the cable of each transducer chain is connected to an underground interrogation and communications unit. This sends data to the surface computer using a twisted wire pair and provides local interrogation and diagnostic facilities. Up to four interrogation units can be connected to a single computer.

Software is available to provide a simple user-friendly interface. The standard display provides information on the current reading and recent deformation history of all the installed telltales. The software provides an archiving facility to allow a subset of the data to be stored for later access. In addition, the Boltmon software must be loaded onto the surface computer to control the entire system. This captures the data from each transducer at a regular time interval as required by the system operator.

2.1.2 Communications architecture

To address and interrogate each transducer in turn, the underground communications unit uses a frequency-based method. This overcomes the danger of sensitivity to poor connections in the harsh underground environment. The transducers can be installed and connected by the mining workforce without the need for electrical specialists.

Each transducer is supplied with a unique pre-programmed address from 1 to 120 and can be connected in any order. The 20 additional addresses are provided to allow any units which develop faults, to be replaced by a spare without the need to use the same address for the replacement. This reduces the number of transducers that are held in stock by the mine.

The communications interface unit build into the telltale, uses a modem chip controlled by a micro controller to generate and receive frequency shift keying (FSK) communications.

2.2 System components

2.2.1 The Underground Interrogation Unit (UIU)

The interrogation unit used for local interrogation and diagnostic purposes is housed within a wall-mounted steel case with lockable access to the inner control panel (see Figure 2.2.1a).

Although the electronic modules, located behind the inner control panel, are sealed against any penetration of mine dust, the front access should always be kept closed and locked. The RMT system has intrinsic safety approval.

The interrogation unit must be connected to an approved 12V DC power supply. The power supply cable, communications cable and transducer linking cable enter the wall-mounted case via a cable point to a labelled terminal block situated on the lower part of the interrogation unit front panel.

The function of the Underground Interrogation Unit is to:

- Generate transducer selection signals and process the returning signals from the activated transducers. The transducers can be activated either by using the local channel select control or remotely from surface by computer instruction. There is a knob on the UIU to select local or remote mode (see Figure 2.2.1b).
- Provide a means of locally controlling and viewing each transducer.
- Interface with a dedicated communication link (twisted copper pair) to a surface computer.
- Provide a power supply to the transducer cable line and to the interrogation unit's internal circuitry.

(a)	*(b)*

Figure 2.2.1 a) The UIU in protective casing and b) the UIU control panel.

2.2.2 The Surface Interrogation Unit (SIU)

The main function of the Surface Interrogation Unit is to convert FSK, which is the communication medium between the SIU (surface) and UIU (underground), into RS232, which is standard computer protocol used for communication purposes. This enables the closure data from the transducers to be interpreted and stored by the computer. The RS232 signal can only be reliably conveyed over a limited distance of up to 3 m and hence the SIU has to be located in close proximity to the computer.
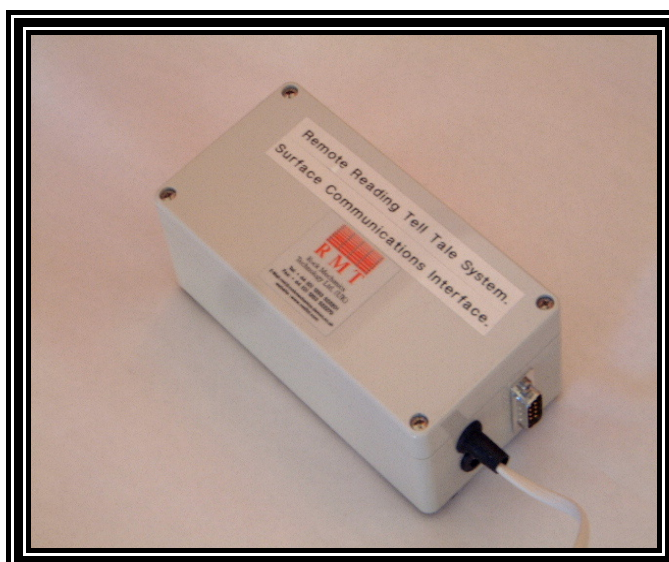
Figure 2.2.2 The Surface Interrogation Unit.

2.2.3 The Cabling Network

The transducers are interlinked by means of a twisted copper pair, which in turn is connected to the UIU. The system was designed such that the UIU can be connected to the SIU via a single pair of copper cable (typically a telephone line on the mines). The SIU is then connected to the computer by means of a normal serial cable.

2.2.4 The Telltale Transducers

The transducers are designed to give an on-site visual indication of the displacement as well as an electronic signal for remote reading. Two cylinders are attached via stainless steel wires to anchor springs installed at different heights in a 35 mm borehole. The upper cylinder ("A" in Figure 2.2.3) is attached to the lower spring, which is anchored near the collar of the borehole. The lower cylinder (B) is attached to the upper spring anchored at a depth that is typically at least twice the depth of the installed bolts in the area. Movement of the rock within the typical depth of rockbolting is registered on the A indicator and is displayed visually by the plastic reference tube. Movement of the rock at a depth greater than the installed rockbolts is displayed on the B indicator and read relative to the bottom of the A indicator.

Each indicator cylinder is marked with 3 different colour bands at 25 mm increments. A millimetre scale is also included. The colour bands allow instant recognition of the magnitude of movement by any person passing the transducer. If the green band can be seen, less than 25 mm of movement has occurred. If the yellow band can be seen but not the green band, between 25 mm and 50 mm of movement has occurred. If only the red band is visible, more than 50 mm of movement has occurred. The millimetre scale allows for accurate reading of each indicator.

In addition to the visual indications of movement described above, the transducer measures the displacements of the two indicator cylinders electronically. It uses the principle of changing inductance of a coil as a ferrite rod moves through it. This measurement method has the advantage of no moving contacts and is superior to low cost measuring devices using the measurement of changing electrical resistance.

The onboard electronics include an address recognition system and a measurement circuit, which converts the measured inductance to a frequency for transmission to the underground

interrogation unit. The accuracy is better than 0.5 mm. The circuit is designed to be intrinsically safe and to have extremely low power consumption. In the dormant mode, the current consumption per transducer is only 0.6 mA. All power can be supplied from a single 12 V power supply connected to the underground interrogation unit. The transducers do not use any on-board batteries and are therefore maintenance free.
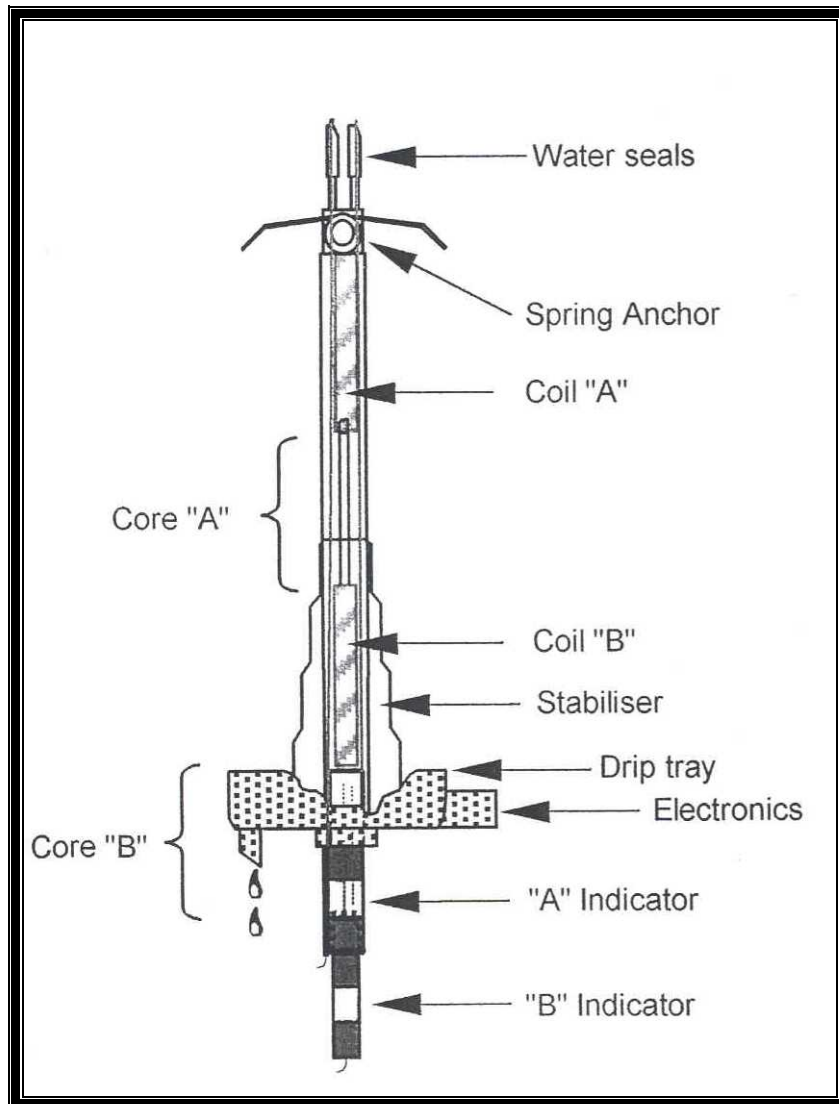
Figure 2.2.3 The RMT roof mounted remote reading telltale.

2.3 Required modifications to the RMT system

2.3.1 The transducers

The RMT transducer design was not considered suitable for the purposes of the GAP852 project. The closure meters were to be installed in the stope as opposed to the coal mining application where the transducers were installed in the roof. Therefore, the transducer design had to be more robust and able to withstand mining operations and the harsh environmental conditions. The need to place the transducers within 4 to 5 m of the advancing face placed particular demands on the closure meter design. Between the period May and July 2001, a significant amount of time was spent on modifying the transducer. The transducer consisted of the same inductance circuit (a ferrite rod and coil combination) as the RMT telltale, a gearing mechanism to drive the ferrite rod in and out of the coil and the standard RMT circuit board to

convert the inductance measurement into a frequency signal that could be interpreted by the UIU. The transducer casing had to be manufactured from a non-ferrous material to prevent interference with the sensitivity of the inductance circuit (Figure 2.3.1).

Figure 2.3.1 The modified transducer in a plastic housing.

2.3.2 The closure meter design

Since the closure meters had to be kept as close to the face as possible, the housings were designed to be as blast resistant and robust as possible. The Mark I closure meter was a spring-loaded telescopic unit designed to ensure hangingwall and footwall contact and was manufactured from mild steel (see Figure 2.3.2). Initially three closure meters of this type with channel numbers 7,14 and 89 were installed ahead of the backfill approximately 4 m back from the face directly exposed to the blast. After the second blast, two of the closure meters were damaged by the blast and had to be replaced. Although it was decided that the closure meters were to be installed in a rib left open between the backfill to protect the instruments from blast damage, it meant that the instruments could only be moved forward once an open rib was made available closer to the face. This compromised the requirement that the instruments should be kept as close to the face as possible and within the 15 m distance to face limit. After a month of monitoring, a few changes were necessary which led to the design of the Mark II housing (See Figure 2.3.3). It was decided to change the inner tube from mild steel to stainless steel since corrosion of the mild steel could interfere with the free movement of the inner tube as closure took place causing it to stick, resulting in inaccurate closure profiles. A removable seal was also designed to allow for any grit that may have accumulated between the two tubes to be removed. The Mark II closure meters were then installed in the second panel to be instrumented. Although this design was well suited to the stoping environment, it proved very costly and time consuming to manufacture. However, it should be noted that these closure meters are still operational after 18 months in the stoping environment.

A third type of closure meter, the Mark III was designed to be cost effective without compromising its durability and ability to produce reliable results. HDPE was selected as a cheap, light and durable material that is normally used for the manufacture of blast barricades. Unfortunately, HDPE in the form required was not always readily available so it was decided to use an alternative plastic material, Polypropylene. This material is just as durable as HDPE, but is more brittle. For this reason it was decided to install these closure meters behind a backfill rib. For the Mark III instruments, a bolt type of attachment of the closure meter to the hangingwall was used to ensure contact at all times, as the design did not include the spring load mechanism. The three types of closure meters can be seen in Figures 2.3.2 to 2.3.4.

Figure 2.3.2 The Mark I telescopic closure meter.

Figure 2.3.3 The Mark II Telescopic Closure Meter.
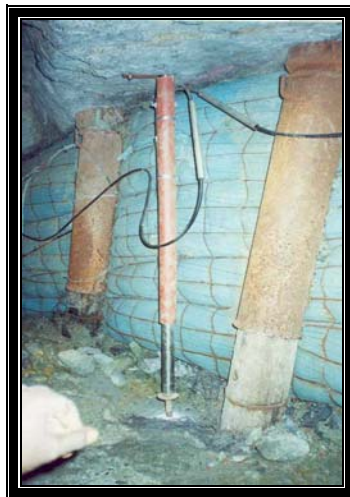
Figure 2.3.4 The Mark III Telescopic Closure Meter.

2.3.3 Cabling

Cabling as part of a remote reading system was always anticipated to be a problem. Since it would be exposed to blasting, cabling that was blast resistant, easy to transport, install and easy to replace in sections was required. SMX blast cable (LTM) consisting of a single copper pair of wire and RCA plug connectors on either end (Figure 2.3.5) was used. This made it easy to connect. It was also available in various standard lengths (3 m, 5 m, 10 m and 20 m). Used on its own, this cabling is not blast resistant and is prone to physical damage. Therefore, it was inserted into a steel protective sheath (DB10), improving its durability and blast resistance (see

Figure 2.3.6). Due to manufacturing limitations, the DB10 could not be fitted right to the ends of the LTM cabling and so connector covers were developed to protect the exposed copper cabling and the joint between the plugs (see Figure 2.3.7). Each cover was fitted with a chain link for ease of attachment and a screw on either end for secure attachment to the DB10. Furthermore it prevented any force or tension on the cable from being exerted directly on the copper cabling or plug connections which could result in them being disconnected. This DB10 cabling was used in all the high-risk areas and was extended from the centre gully or raise to the face area. From the centre gully, normal LTM cabling (blasting cable) was extended all the way through to the cross-cut, attached behind existing electrical cable, reducing the risk of physical damage.
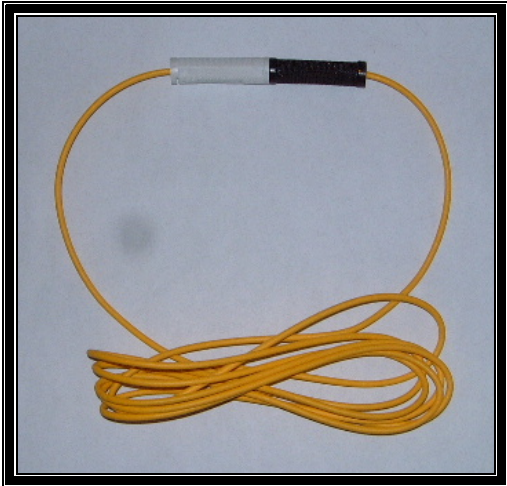
Figure 2.3.5 The LTM cabling and RCA plugs.

Figure 2.3.6 The LTM Cable inside the DB10.

Figure 2.3.7 The Connector Cover.

2.3.4 The UIU power management system

The UIU box was installed inside an electrical enclosure as an additional protective measure. The UIU required a 12 V DC power supply. Initially a 12 V, 18 AH battery was used as a power source for the UIU. The idea was to use two 12 V batteries interchangeable on a fortnight basis. However, this did not prove to be reliable and hence a permanent power management system was developed to ensure that the system had a reliable power source (Figure 2.3.8). A transformer was installed next to the UIU, which converted the 550 V power supply from the gully rig to 220 V. An internal transformer, part of the power management system, converted the 220 V to a 12 V DC supply.

The power management system included three sealed lead acid batteries (7 AH) as can be seen in Figure 2.3.8. The batteries acted as a back-up power supp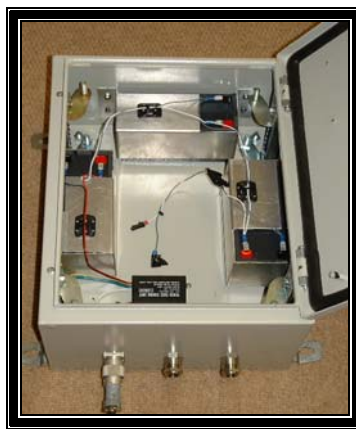ly in the event of a power failure. The circuit also incorporated a battery charging function. Note that the power management system was incorporated into the existing UIU box.

Figure 2.3.8 The power management system.

2.3.5 The Boltmon Software

As mentioned above, the Boltmon software had two main functions; to control the interrogation of each transducer and facilitated the recording and storing of the transducer data and to provide a visual display of the data as a frequency measurement and operational status of the system. Although the transducers could be connected in any order, Boltmon interrogated each transducer in numerical order in terms of the channel number.

Boltmon was designed to store the data in a text format, which was written to the same folder as where the Boltmon software was stored. The recording interval could be selected in multiples of 15-minute intervals, up to an hour, depending on the application. However, the data was stored as a frequency value rather than a displacement measurement. Therefore, a new program called Monitor was developed to convert the frequency measurement into a displacement measurement, as per the calibration curves for each of the transducers, and to provide a graphic interpretation of the closure data as a function of time.

Initially Monitor was designed to import the frequency data from the text file at a delayed rate of 16-minute intervals as opposed to the 15-minute interval recording rate selected in Boltmon. This 1-minute delay was to ensure that all the readings in the text file had already been stored before importing into Monitor. Unfortunately, this approach caused a problem. Although the text file would store the data as per the recording interval, Boltman did not write the data to the text file at the exact time as recorded. The data would be stored in the background and would

only be written later, at an unknown time. This meant that when Monitor imported the readings from the text file at a particular time, it would import zeros since the data had not yet been written to the text file.

To solve this problem, the Boltmon software had to be modified. The latest version of Boltmon allows the selection of the rate at which the text file is updated. The best option is to select a 1-minute update interval to ensure that the readings are already stored in the text file by the time Monitor imports the data.

Another minor problem with Boltmon was that if any of the settings were changed, such as the recording rate or the addition or deletion of any transducers, the changes would only take effect when a new text file was opened or when Boltman was closed and re-opened.

2.4 The Mponeng site

2.4.1 Site Description

The 94/44 area at Mponeng Mine was initially chosen as the project site. Three closure meters were installed in the E3 panel. However, due to delays in establishing the communication link to surface and poor grade in this area, the site had to be moved further down the raise line. This was ideal in terms of the project objectives since the panels on the east side were advancing towards a dyke, which meant that a significant amount of seismic activity was expected in this area.

2.4.2 Installation of the UIU

The UIU was installed in the cross-cut at the stope entrance where an existing gully rig was present. The area was well illuminated, secure and out of the way of mobile machinery. To avoid tampering, the electrical enclosure was painted orange to match the colour of the gully rig to make it as inconspicuous as possible (see Figure 2.4.1).
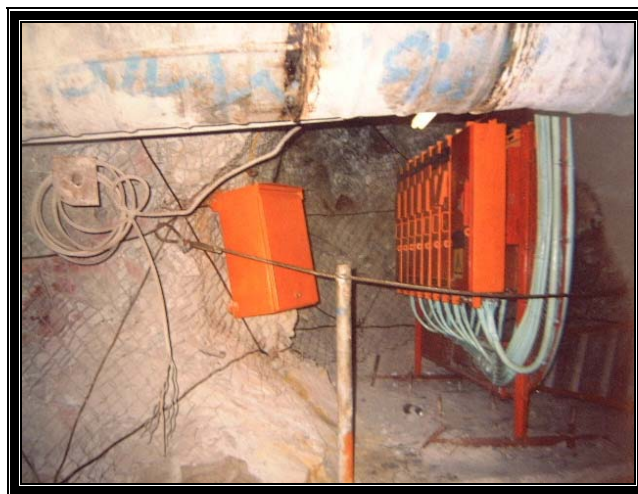
Figure 2.4.1 The UIU at the stope entrance.

2.4.3 The transducer locations

Three closure meters were to be installed per panel, one at the top, one in the centre and one at the bottom of the panel. Previous studies (Malan et al, 2000), showed that it was necessary to keep the closure meters no further than 15 m behind the face. Therefore, the meters had to be moved forward on a regular basis. Initially they were installed ahead of the backfill and although the closure meters proved to be blast resistant, the cabling was a problem. If the closure meters were installed ahead of the backfill, it was difficult to gain access to them as the broken ore accumulated in the back area, which meant that they could only be moved forward once the back area was cleaned. This made them very prone to scraper damage and difficult to move forward on a regular basis. The cabling was also at high risk of being damaged by scraper activity during the cleaning operation. If the cabling was damaged at a particular point, the entire system could be rendered non-functional. It was therefore decided to install the closure meters behind a backfill rib, which protected them from blast and scraper damage and provided convenient access. However, an open backfill rib had to be available first before the closure meters could be moved forward, during which time the maximum distance to face of 15 m could be exceeded. Further problems associated with this method will be discussed later in the report.

2.4.4 The cabling layout

A schematic representation of the cable layout can be seen in Figure 2.4.2. A main cable (a combination of DB10 and LTM) was extended down the centre raise along existing electrical cabling to offer added protection and to make it as inconspicuous as possible. DB10 cabling, which was connected to the main line by means of connector pieces, was further extended down the strike gullies of the panels and attached along the backfill to the closure meter positions. As the faces advanced, the closure meters would be moved forward and cables extended along the strike gullies. This layout provided a permanent, once-off installation for most of the cabling.
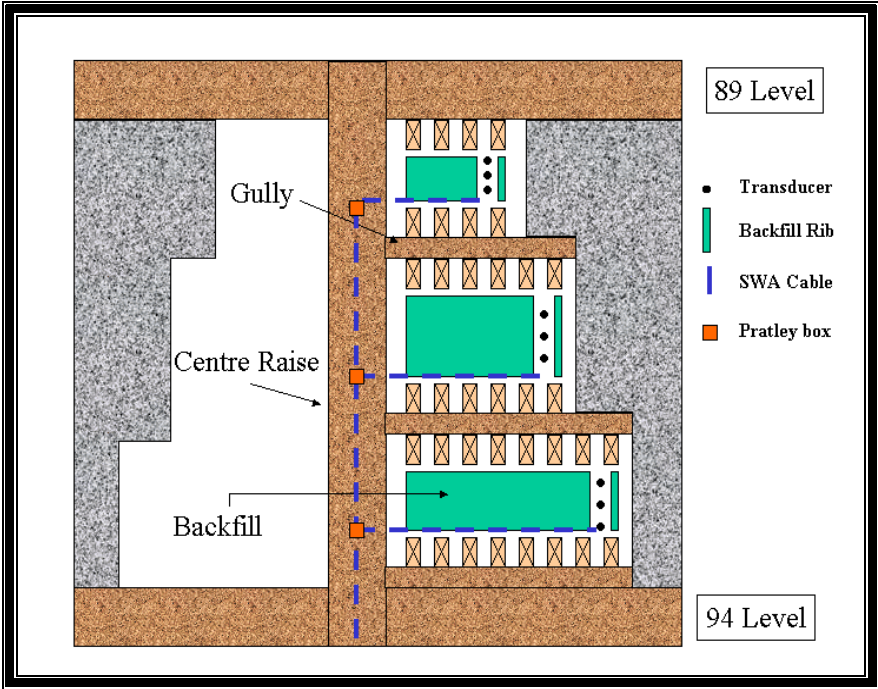
Figure 2.4.2. The cable layout.

2.4.5 The communication link to surface

The RMT system was designed so that a single copper wire pair can be used for the communication between the SIU (surface) and the UIU (underground). Unfortunately, Mponeng Mine did not have a spare copper cable pair available at the position where the UIU was situated underground, to the Rock Engineering Department on surface. The only communication channel available was a fibre optic network which was part of the mine-wide seismic system. It was therefore decided to use the seismic system communication infrastructure since it already had an established copper cable network on various levels in the haulages and a communication link to the Rock Engineering Department.

From the UIU in the 94/44 cross cut, LTM and DB10 cabling (in high risk areas) was extended along the crosscut to the haulage where it was connected to a spare copper pair of the seismic cabling. This cabling extended all the way to 81 level. From 81 level, it was connected to the surface interrogation unit, which in turn was connected to a modem using a copper to fibre interface. The fibre optic link extended all the way to the Rock Mechanics department on surface (see Figure 2.4.3).

Figure 2.4.3 The communication link to surface.

Normally the SIU would be situated on surface in close proximity to the computer. The SIU can only operate by means of a copper link and since there was only a spare copper cable pair available up to 81 level, it meant that the SIU had to be situated underground rather than on 81 level. The problems associated with this link will be discussed later in the report.

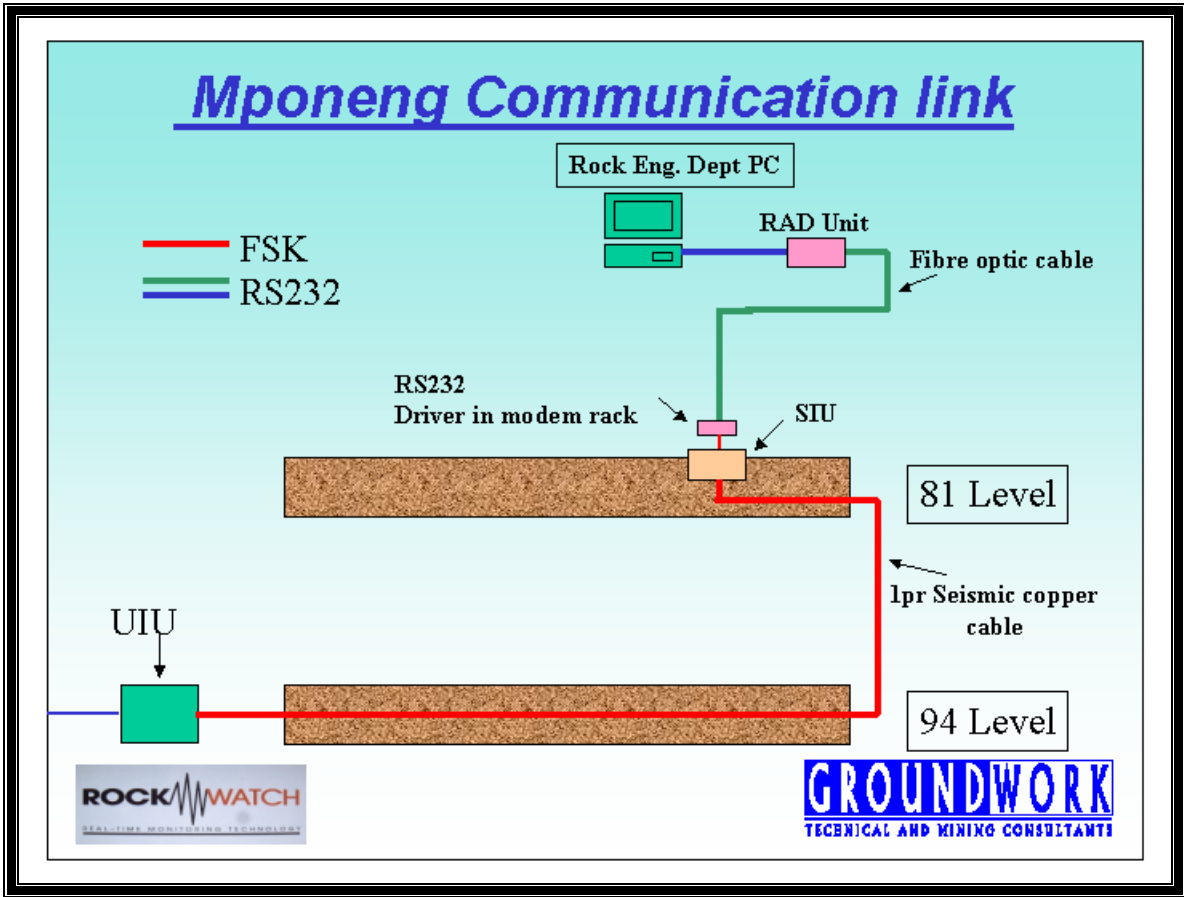## 2.5 Data collection

2.5.1 Initial results

The RMT monitoring system was commissioned during October 2001. The first three transducers were installed and the continuity and quality of the data proved to be very promising. The plan was to gradually increase the number of transducers by instrumenting two panels per month until six panels were monitored. The graph below shows the data obtained from the three closure meters in the E3 panel between 23 October 2001 and 7 November 2001.
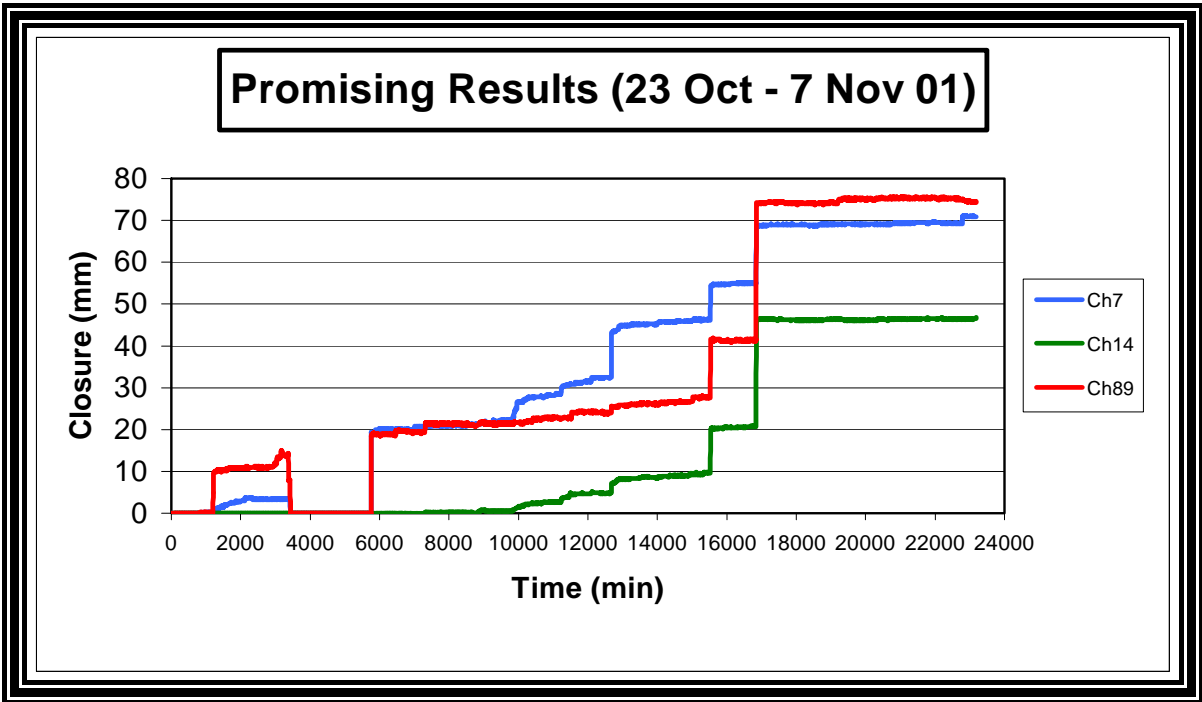
Figure 2.5.1 Initial closure data collected.

Although there was no data collected between 4000 and 6000 minutes, because of cable damage, the remaining recordings illustrated that the system had the potential to deliver good quality data.

2.5.2 Monitoring problems

Unfortunately, significant monitoring problems started as soon as additional closure meters were added to the system. A major problem was in terms of communication and maintaining continuity of the cables in the stoping environment. The more closure meters that were added to the system, the higher the risk of damage due to the expanding network of cabling. This is demonstrated by the loss of data in the graph in Figure 2.5.2 between the period 8 November and 6 December 2001.
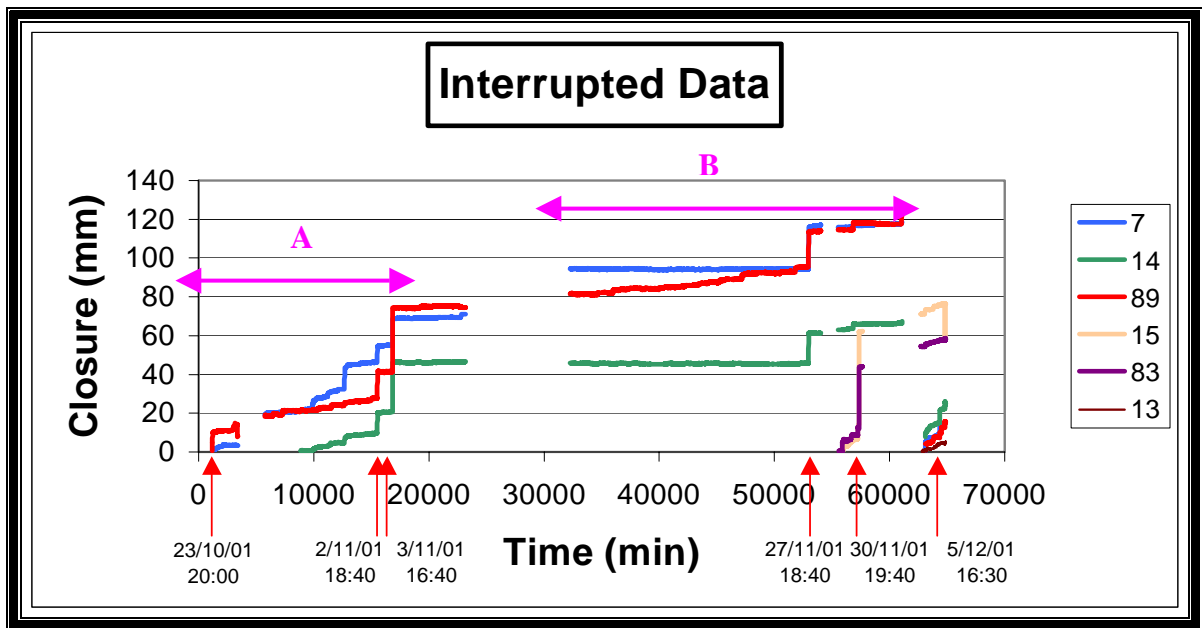
Figure 2.5.2 Problems in maintaining continuity of data.
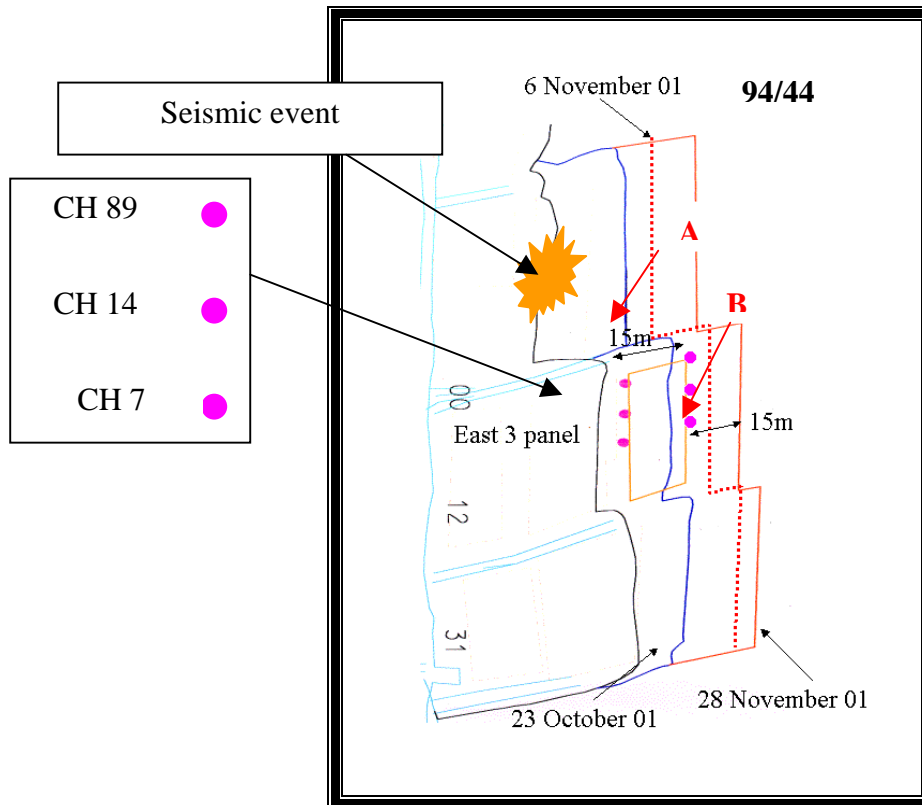
Figure 2.5.3 Position of the closure meters.

Figure 2.5.3 shows the locations of the closure meters in the E3 panel relative to the advancing face for periods A and B between 23 October and 28 November 2001. For both periods, maximum distances to face of less than 15 m were maintained. Although the closure profiles for closure meters 7,14 and 89 looked very promising, the stick-slip problem with the Mark I type closure meter appeared towards the end of period A. As time passed by, the corrosion of the mild steel inner tube of the Mark I Closure meters increased, resulting in the poor closure data for channels 7 and 14.

The Mark II closure meter (Channels 13,15 and 83) was re-designed with the intention of overcoming the stick-slip problem and these meters were installed in the 99/44 E7 panel on 5 December 2001. Eventually the three closure meters, Channels 7,14 and 89 from the 94/44 E3 panel, were moved to the 99/44 E6 panel. The remaining two panels were instrumented with the Mark III closure meters. Unfortunately, problems with the communication link and regular occurrence of cable damage due to the expanded cable network persisted. These problems were compounded by software problems to such an extent that no meaningful data was collected after December 2001.

2.5.3 Termination of the real-time monitoring experiment
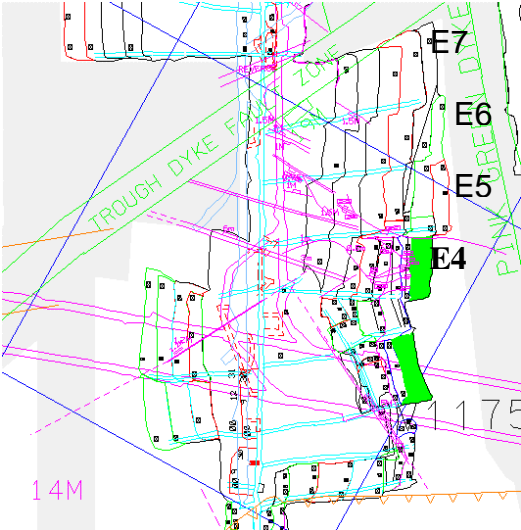
Figure 2.5.4 Positions of the panels at termination of the real-time monitoring experiment.

During the time interval taken to solve the communications problem and maintain continuity of the cabling, the E7 and E6 panels reached the pillar boundary against the dyke. The E5 and E4 panels were also reaching their limits, with E5 having only one more month of mining to go and E4 only two. This created a problem since Miningtek required at least three months worth of quality data for analysis. At the time there was no indication of how long it would take to resolve the communications problem.

Originally two sites were chosen for data collection, Mponeng and East Driefontein. With the problems experienced at Mponeng it was suggested by Miningtek that all efforts should be made to get the Mponeng site up and running before starting at East Driefontein. East Driefontein had the same communications infrastructure as Mponeng and hence the same communications problems were anticipated. Unfortunately, the time taken to resolve the problems at Mponeng spanned over the duration allowed for the entire project. This ultimately meant that the project had to be suspended and eventually terminated due to depleted funds.

2.6 Evaluation of the modified RMT system

Although the RMT system appeared to be successful initially, a number of problems were experienced with the system. The two most serious problems were the communications from underground to surface and maintaining continuity of the cabling. The experience gained and problems encountered with each of the system components are addressed individually below.

2.6.1 The transducers

Problems were experienced with some of the circuit boards in the closure meters, resulting in the data being corrupted. It was not clear what caused this and the phenomenon could not be reproduced in the laboratory. The faulty circuit boards were replaced and the problem did not reappear.

2.6.2 The closure meter design

The advantages and disadvantages of the three types of closure meters that were developed and evaluated during the project are considered below:

Mark I

ADVANTAGES	DISADVANTAGES
• Relatively blast resistant	• Manufactured from mild steel, therefore not corrosion resistant
• Relatively cheap	• Due to the corrosion problem, it tended to stick resulting in inaccurate closure profiles
• Easy to install	• Grit accumulated between the two telescopic tubes, hence also contributing to the stick-slip problem
• Spring loaded to maintain contact between the hangingwall and footwall	• Housing plugs were not well designed, therefore it was difficult to connect interlinking cabling and maintain connectivity
• Very rigid	• The protective plate (to protect the plugs when exposed to blasting) interfered with the installation when installed close to support units
• Relatively lightweight	

Mark II

ADVANTAGES	DISADVANTAGES
• Relatively blast resistant	• Expensive
• Easy to install	
• Spring loaded to maintain contact between the hangingwall and footwall	
• Very rigid	
• Plugs well designed for easier attachment to the cabling	
• Removable seal to prevent grit from accumulating between the telescopic tubes	
• Narrow profile allowing installation close to a support unit for additional protection	
• Relatively lightweight	
• Stainless steel inner tube which eliminated the corrosion problem and hence ensured free movement of the inner tube as closure took place	

Mark III

ADVANTAGES	DISADVANTAGES
• Cheap	• Not very rigid, therefore susceptible to buckling
• Lightweight	• Not spring loaded, therefore it had to be attached adjacent to an elongate or backfill for support which could affect the accuracy of the readings
• Easy and cheap to replace components if damaged	• Not as resistant to damage as the steel housings
• Not susceptible to corrosion	

2.6.3 Cabling

It was anticipated that in-stope cabling was going to be a challenge. Where possible it was attempted to attach the cabling to existing cables in such a way that it would be further protected. However, mining activity and rock falls in the stopes contributed the most to cable damage. For example, when panel E7 reached its boundary limit, the reclamation of pipes and power cables resulted in most of the cabling being damaged. Furthermore, when the travelling way was wire meshed and laced, it also resulted in the cabling being damaged. When any cabling was damaged, it was often very difficult to replace it immediately and it normally took at least a day or two to re-establish the connection to surface.

Short lengths of cable were selected to facilitate replacements. However, the problem with this approach was that the 10 m lengths of DB10 cabling were connected in a series fashion resulting in many connection points. Although the RCA plugs were easy to connect to one another, the connections were not very strong, which made it very susceptible to be being disconnection. As a result of the multiple connections, it was very difficult and time consuming to locate any break in the cabling. This meant that a cable system such as the one at Mponeng

would require high maintenance and hence result in costly labour requirements. Three hundred man-days were spent underground between September 2001 and February 2002. If a system like this were to be installed on a mine on a routine basis, this would not be feasible due to the costly labour requirements. If cabling were to be installed in areas where the risk of damaged is high, then it is suggested that a continuous cable be used with a limited number of junction points. Cabling can definitely be considered in applications where the positions of transducers are fixed such as in backfill monitoring applications and shaft pillar extractions. For these applications, cabling does not have to be extended continuously and the junction points can be limited to the minimum.

Since there is always human activity in the stoping environment, any cabling is at risk of being damaged. The transducers were connected to a main cable line in the centre raise and if this cable was damaged, any transducers beyond the break would then be isolated from the system. Also, if a cable is damaged and a short circuit occurs, all the data is corrupted until the problem is resolved. A wireless system would have the advantage of each transducer being independent with greater reliability than the current RMT system.

2.6.4 Communication to Surface

As mentioned already, the RMT system design required a copper link between the SIU and UIU. Mponeng Mine could not provide a copper link to surface and therefore the system had to be linked to a fibre optic network. This interface proved to be problematic.

The communication protocol between the modem rack underground and RAD unit on surface as illustrated in Figure 2.4.3, is RS232. The RAD unit is also a modem rack, which is an interface between the fibre optic and copper cables. The output signal from the surface interrogation unit was assumed to be RS232 and hence it was thought that it was possible to connect it to the RAD unit underground instead of on surface. However, the problem arose that the RS232 output from SIU was not strictly speaking RS232. The RAD unit accommodated a RS232 signal with a voltage range between −12 V and +12 V, whereas the output from the SIU had a voltage range between 0 and +5 V, resulting in a communication delay between the outgoing signal from Boltmon and the return signal from the UIU. Hence, the time taken to scroll through the closure meters was significantly longer than anticipated. Initially this was not a problem with only three transducers installed. However, when there were 18 transducers linked to the system, the time taken to scroll through all 18 transducers was longer than the maximum recording time window of fifteen minutes. The readings for all 18 transducers could not be written to the text file within the recording interval of fifteen minutes. This resulted in the loss of continuous data. RMT subsequently manufactured a RS232 rectifier to improve the communication problem and although it did improve matters, the time taken to scroll through all 18 transducers was still considerably longer than the maximum 15 minutes interval time. For this reason it is believed that the RMT system is only suited to applications where a direct copper link is available to surface.

2.6.5 The software

Although the current software can be used effectively, it requires that the Monitor program be running continuously for it to be operational. If the program were to run efficiently, it would be best if the program were installed on a dedicated computer with little interference. When other applications are opened on the same computer, the Monitor program becomes unstable. It was subsequently decided to import data only once a day. The data would be imported from the text file at 01:00 in the morning, which reduces the risk of the program becoming unstable due to the operation of other software applications.

2.7 Recommendations

2.7.1 Suitability of the current system

Although not successful, the trial application of the RMT system as a mini mine-wide stope closure monitoring system has highlighted important issues for the design and implementation of a mine-wide remote reading closure system. The system has demonstrated that remote reading is possible and can be successful. This has laid the foundation for the successful enhancement of the current system or development of a new system, which will be reliable enough to provide continuous real time closure data on surface.

The main area of concern is the communication network. The RMT system has demonstrated that cabling does not work well in the stoping environment since transducers have to be moved. This is a high maintenance, labour intensive and unreliable method of communicating in the stopes. Furthermore, the RMT system has also demonstrated that a remote reading system needs to be flexible in terms of communication infrastructure. It has to be able to be incorporated into existing infrastructure on any mine and should not be dependent on only one communication type. Most mines today are moving towards new generation communications networks such as fibre optics and leaky feeder systems and any mine-wide closure system should be able to use these networks. For these reasons, the RMT system is not well suited to mine-wide stope closure monitoring applications.

The RMT system should only be considered when:

1. There is a copper link available between underground and surface,
2. There is limited human activity in the area to be monitored,
3. The transducers are stationary and do not have to be moved,
4. The cabling is a once-off installation and the likelihood of damage is minimal.

2.7.2 Future developments

The ideal closure monitoring system should incorporate the following:

1. A cable free communication network in the stoping environment. This fact was already identified by Malan et al (2000) in the project GAP705 which examined the various options such as infrared or radio communication.
2. Simple communication protocols that can be incorporated easily into existing communication infrastructure on the mines.
3. The transducers and housings must be low maintenance and rugged enough to withstand the harsh underground conditions in terms of humidity, heat and mining operations.
4. Software that makes the stope closure data readily available and easy to interpret.

The modified transducers proved to be very reliable and require very little further development. More care needs to be taken in protecting all the electronic components of the transducer. In future, it would also be advisable to mould the transducer housings so that the manufacturing can be standardised. This will ensure that each transducer is manufactured to the same specifications and hence all the transducers can have one calibration curve which will simplify the software. The closure meter housings that were developed for the project worked well. It is recommended that these types of housings be used in the future.

In-stope cabling needs to be replaced by wireless communication means, which will reduce the maintenance requirements and improve the reliability. This still requires further research.

In future, it is necessary that a reputable local manufacturer of instrumentation with the necessary electronic and communications expertise should be identified to further develop a remote reading system. This is important not only in terms of technical back up, but also in terms of an understanding of how a remote reading system can be incorporated into existing communication networks on different mines.

The RMT system requires some modifications and is only suited to specific applications. It is suited to applications where cabling is at low risk of being damaged and where the transducers will be stationary. The system can be used to monitor shaft movement during shaft pillar extraction or pillar behaviour in mined out areas, provided copper cabling is available to communicate to surface.

3. Data collection using stand-alone closure meters

3.1 Introduction

As described above, no closure data could be collected during the period from April 2001 to March 2002 due to problems experienced with the RMT closure system. After a meeting was held between SIMPROSS and members of the industry on 10 June 2002, it was decided that no additional funding would be given to this project. The request from SIMRAC was that Miningtek should use the remaining funds to collect significant data at one site only. This data should be used to further verify the value of continuous closure data as a decision making tool to rock engineers and mine management. There should also be no attempt to collect data in real time.

3.2 Description of the CSIR closure meters

Until recently, the only reliable method to collect continuous stope closure was to use mechanical clockwork closure meters. These units recorded the data on graph paper. Converting the data into digital format was very tedious and a reliable electronic closure meter was needed. The specifications and requirements of such a meter is given in Malan et al. (2000).   One particular design of a telescopic closure meter, developed at CSIR Miningtek, is shown in Figure 3.2.1. This design provides a robust meter as all the electronic components, data logger and batteries are contained within the telescopic tubing, It is also lightweight, easy to install and to move as the main body of the meter is manufactured from rigid PVC piping. It allows a maximum deformation of 300 mm, and can be used in stope widths ranging from 990 mm up to 3 m by adding an additional section of PVC tubing. This is indicated in Figure 3.2.1. This extension piece can be cut in the stope to the required length. These meters are not blast resistant and should be installed behind support units to protect them from damage. For the purposes of this project, 13 of these meters were installed in panels as indicated below. The reliability of the meters was found to be adequate, apart from the occasional problems such as loose battery connections or batteries running flat. The meters have the ability to be downloaded underground with a handheld controller. This option was not used, however, due to initial reliability problems with the handheld unit. The observer also experienced too many problems with the complex operation of the unit. A simpler unit is currently being designed. To download the data, the observer took three additional meters underground during every shift and replaced three of the installed meters. These three meters were brought to the surface for downloading. Although this system of meter rotation increased the workload of the observer, the supply of data became more reliable. The revised design of the handheld unit will solve this problem in future.
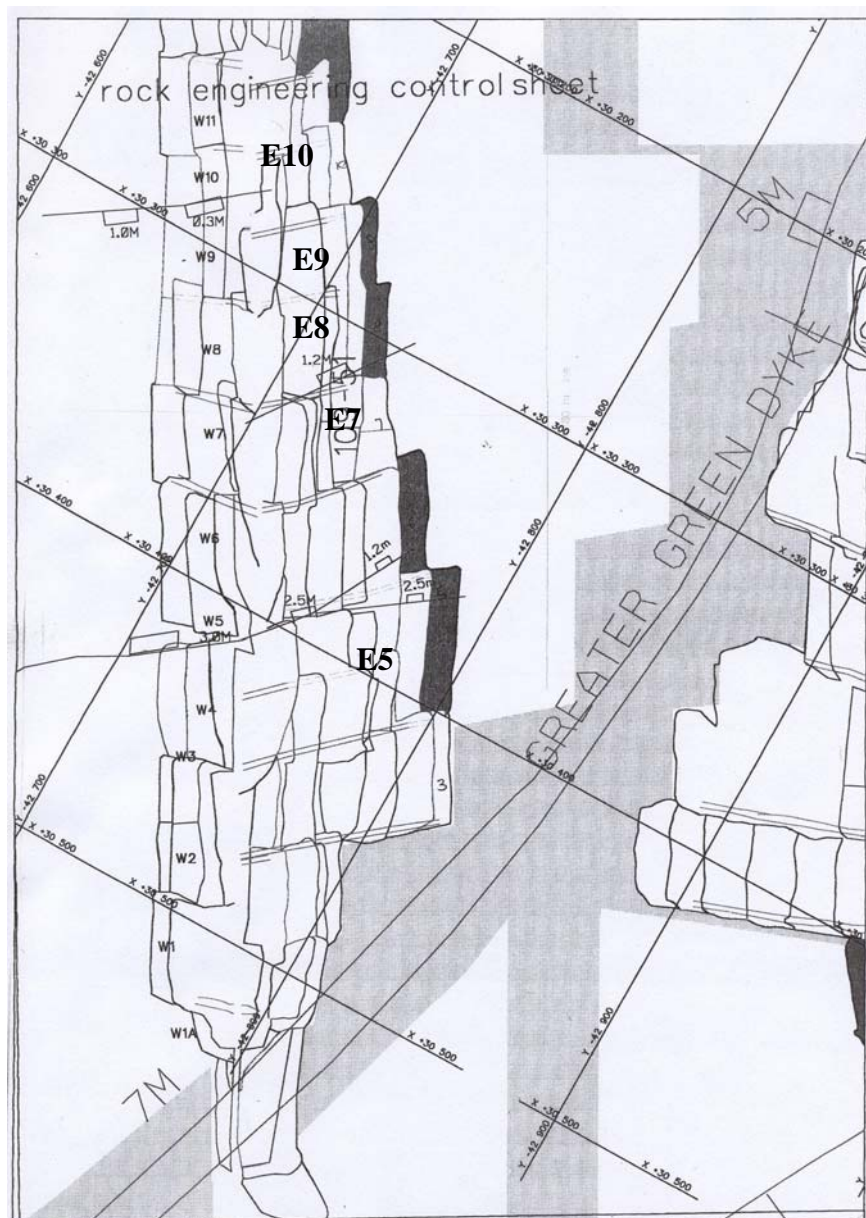
(a)   **(b)**

Figure 3.2.1 (a) Telescopic closure meter developed at CSIR Miningtek and (b) installation underground.

3.3 The experimental site at Mponeng Mine

A new site was chosen at Mponeng Mine in the 109/51 area. A map of the area is given in Figure 3.3.1. The depth ranged from 3423 m at the top of panel E10 to 3481 m at the top of panel E5. The dip of the area was 22°.

Figure 3.3.1 The 109/51 area at Mponeng Mine.

Closure meters were installed in the E10, E9, E8 and E7 panels. Three meters were installed at the top, middle and bottom of each panel. It is of interest that these panels are mining towards the Greater Green Dyke. The effect on the closure data of mining towards this dyke needs to be investigated and therefore a further closure meter was installed in the E5 panel, which is closer to the dyke than the panels above. Although not all closure meters remained operational during the entire monitoring period, this was the largest number of continuous closure meters ever installed in a single raise connection. Data was recorded from the beginning of November 2002 to March 2003.

The support in these panels consisted of elongates, backfill and camlock props as temporary support in the face area. Rockprops were also used in certain areas where the stoping width exceeded a certain maximum height. Figure 3.3.2 illustrates typical backfill support and hangingwall conditions. Typical hangingwall conditions are further illustrated in Figure 3.3.3 and the face area is shown in Figure 3.3.4.

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Figure 3.3.2 Backfill in the E9 panel.
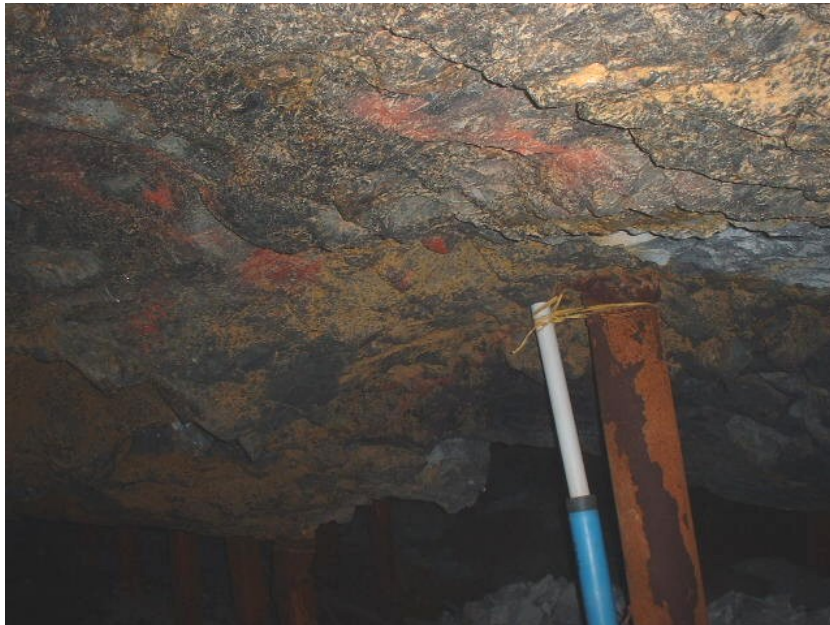

*Figure 3.3.3 Typical hangingwall conditions in the E8 panels.*
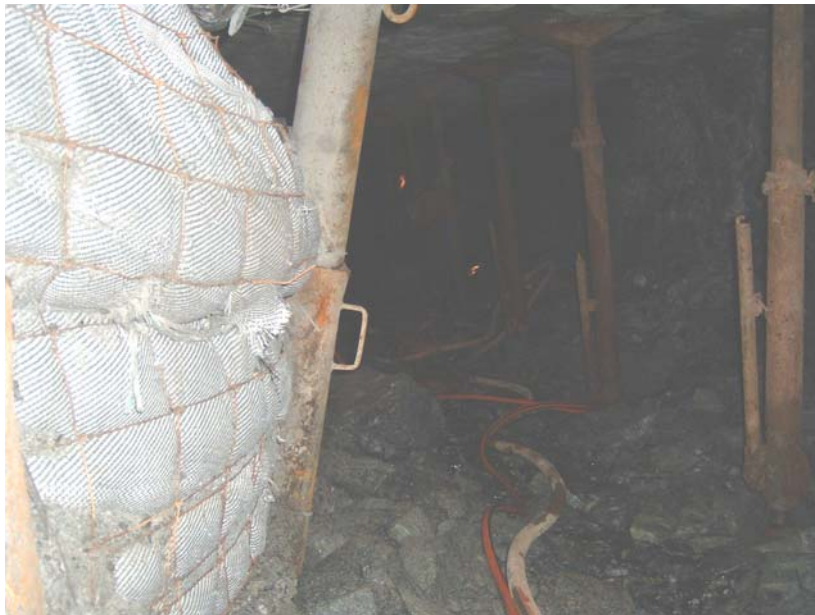
Figure 3.3.4 Conditions in the face area. Note how close the backfill is installed to the face. This often made it difficult to find a suitable location to install the closure meters.

In terms of seismicity, Figure 3.3.5 illustrates all the events bigger than magnitude -1 recorded for the period from 21 January 2002 to 13 March 2003. As expected, the seismic activity tends to cluster around the active faces. The largest event recorded during the entire period of monitoring had a magnitude of 1.9. The largest proportion of events appeared to be located in the footwall as indicated in Figure 3.3.6.
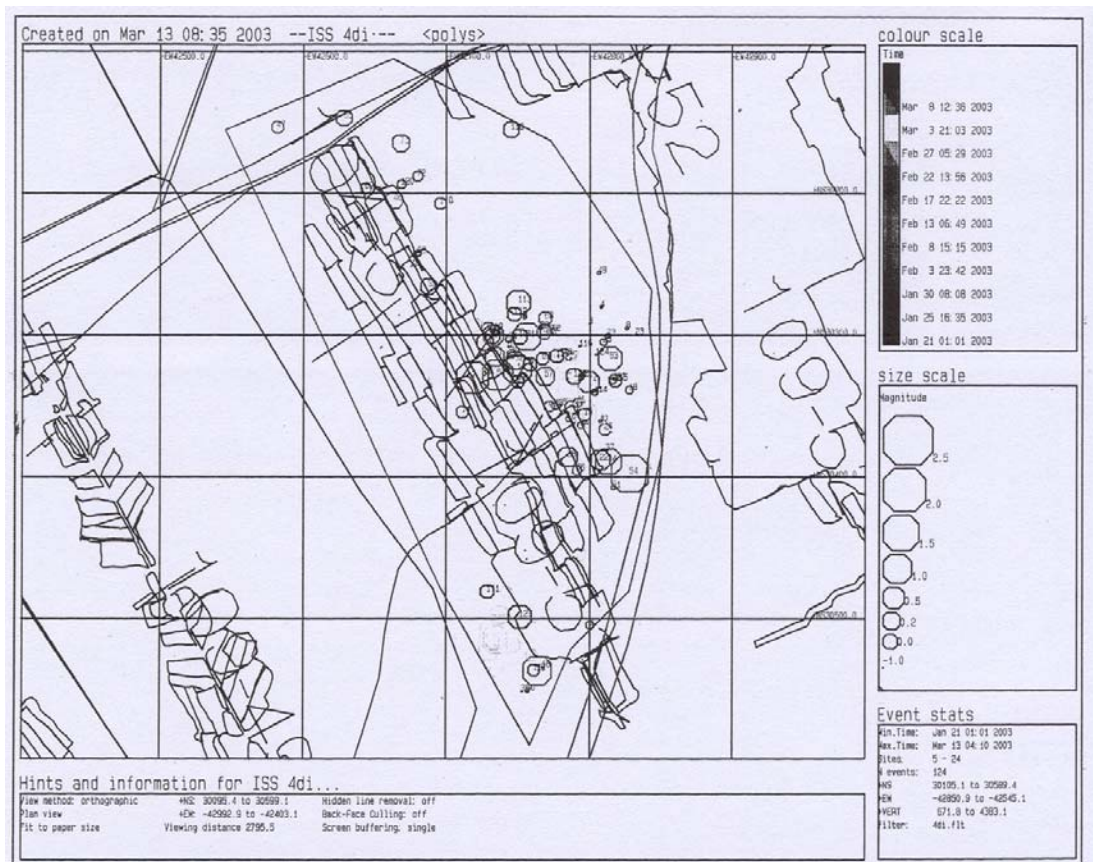
Figure 3.3.5 Seismic data recorded for the period from 21/1/2003 to 13/3/2003.
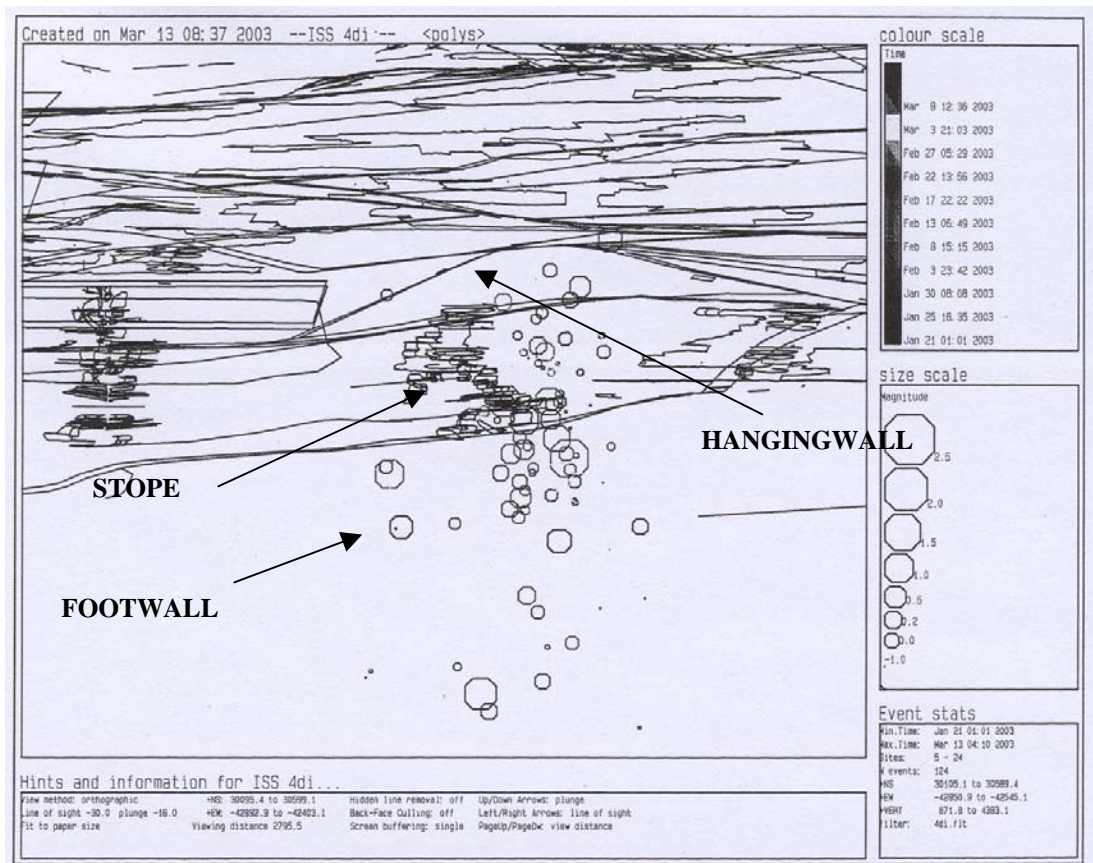
Figure 3.3.6 Vertical location of the seismic events shown in Figure 4.3.5.

3.4 Examples of data collected

Similar to results shown in earlier studies (Malan, 1999b), the closure data following a panel blast consisted of an instantaneous component, a primary closure phase and a steady-state closure phase. Figure 3.4.1 shows some good data collected with a total amount of closure of 85 mm over a period of 6 days. The closure pattern can be more complex, however, as indicated in Figure 3.4.2. If there is no blasting activity, the closure rate becomes very small as illustrated in Figure 3.4.3 where a total closure of only 2.3 mm was recorded over a period of 8 days. In some cases, however, even if a specific panel is not mined, blasting in a neighbouring panel can cause an increase in closure as indicated in Figure 3.4.4.
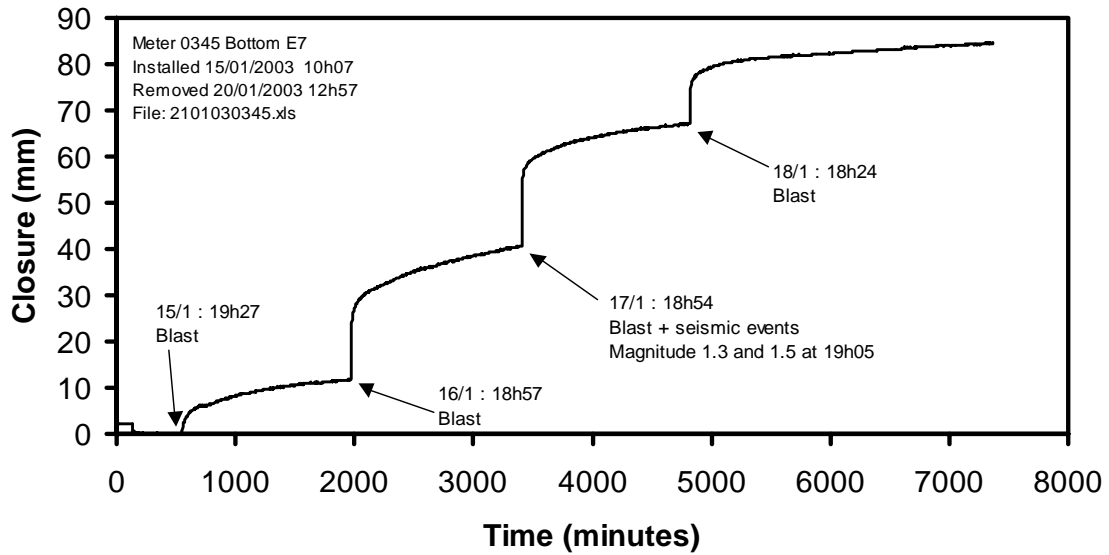
Figure 3.4.1. Data collected in the E7 panel where the meter was installed at a distance of 6 m to the face.
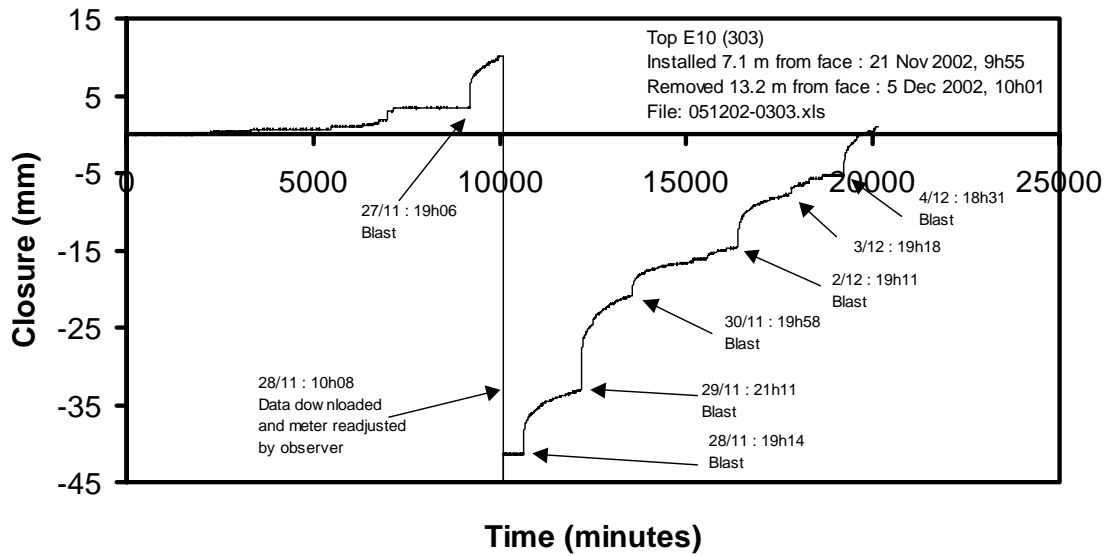
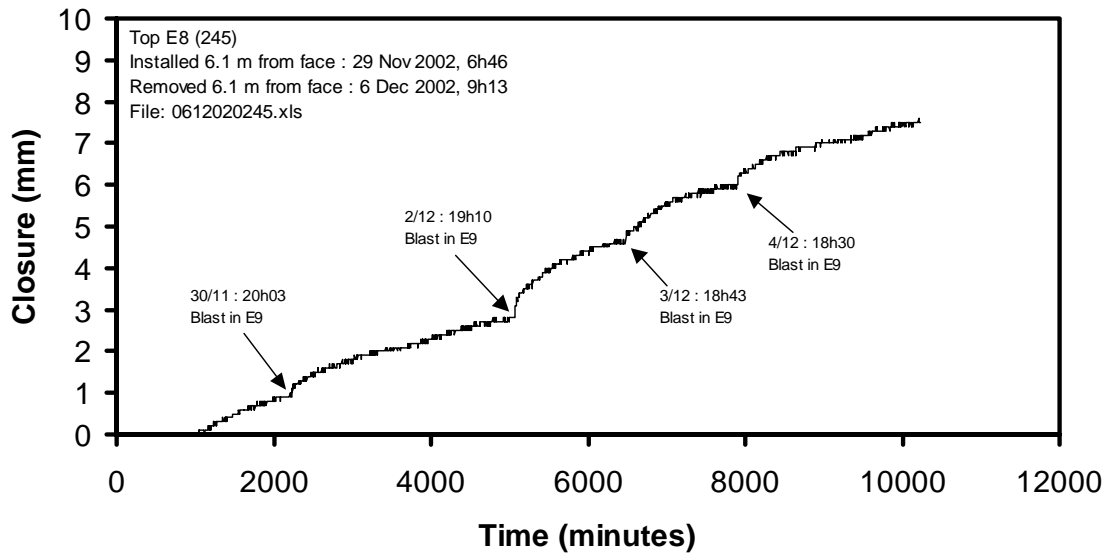*Figure 3.4.2 Data collected in the E10 panel.*
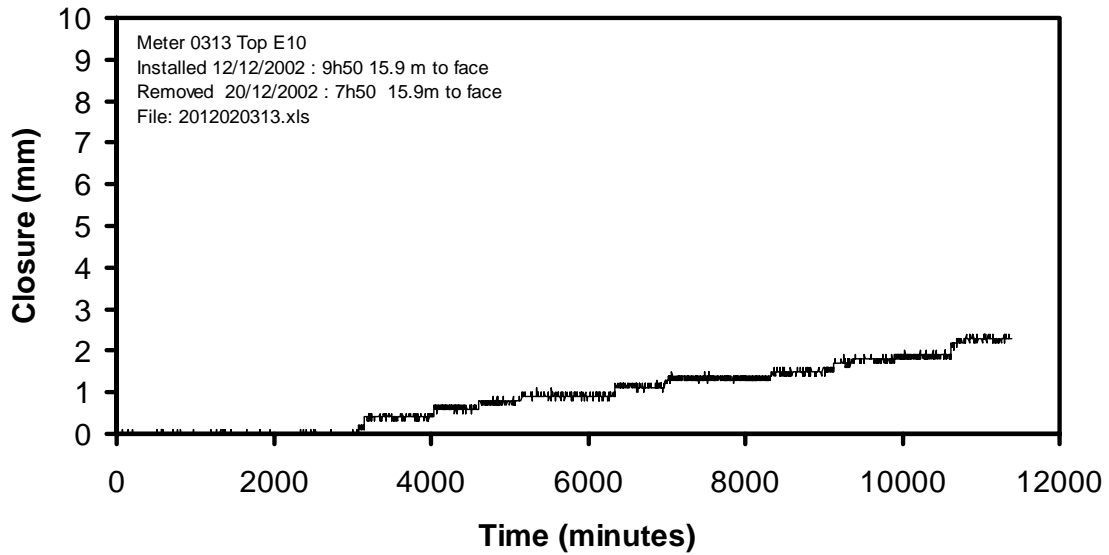
Figure 3.4.3 Closure in the E10 panel when there was no blasting activity.

Figure 3.4.4 Closure in the E8 panel when there was no blasting activity. The increase in closure was caused by the blasting in the neighbouring E9 panel.

4. Effect of seismic events on continuous closure data

4.1 Introduction

The effect of a seismic event on the continuous closure data is very similar to that of a blast where the seismic closure is characterised by an instantaneous, primary and secondary component. As an example, Figures 4.1.1, 4.1.2 and 4.1.3 illustrate the effect of a magnitude 1.9 seismic event on the closure recorded in the top, middle and bottom of panel E9. The magnitude of instantaneous seismic closure is relatively small as the event located some distance away at the top of the raise line ahead of the panels mining in the westerly direction.
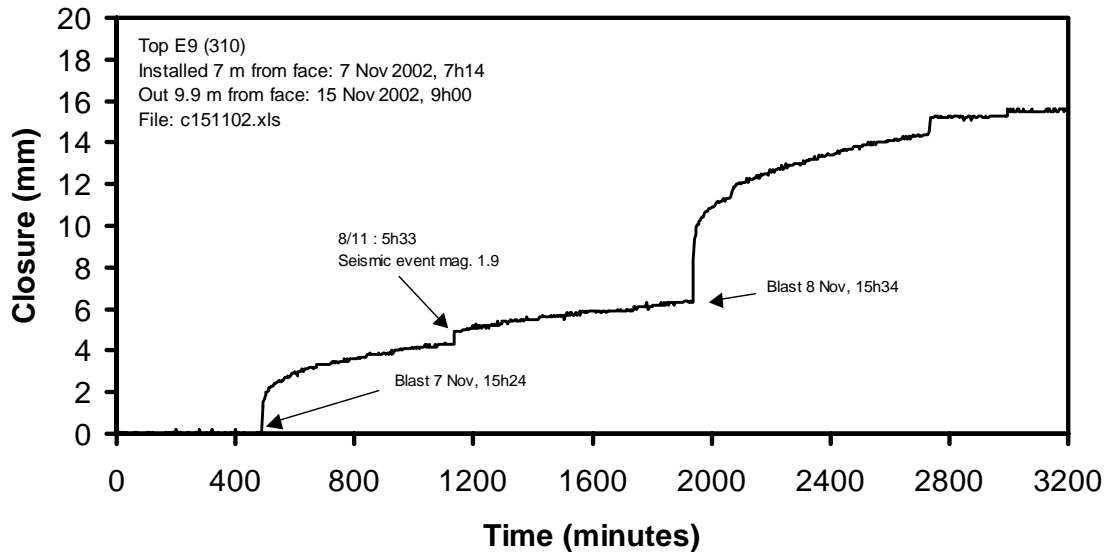
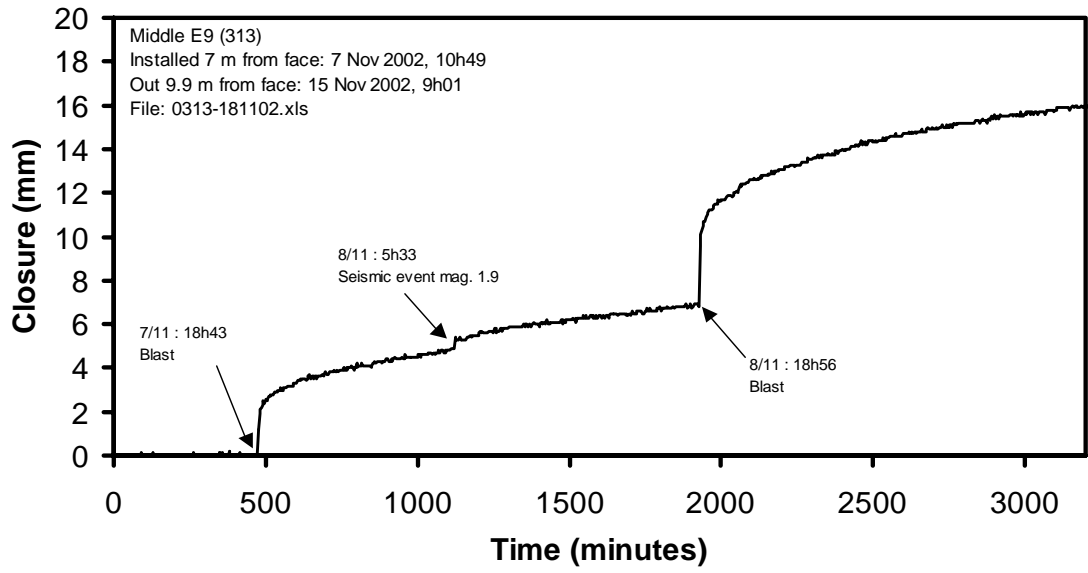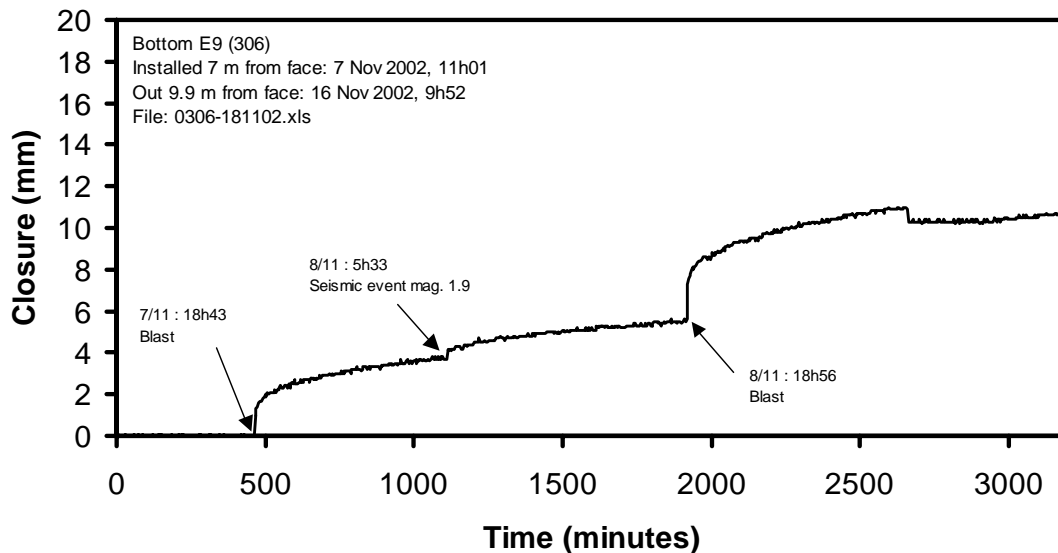

Figure 4.1.1 Closure recorded at the top of panel E9.

**Figure 4.1.2 Closure recorded in the middle of panel E9.**

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Figure 4.1.3 Closure recorded at the bottom of panel E9.

In terms of the implementation of a real-time mine-wide continuous closure system, a key question was whether there is a good correlation between the amount of instantaneous seismic closure measured in a particular panel during a damaging seismic event and the amount of damage in this panel. If this is the case, a real-time closure monitoring system will be very valuable to direct search and rescue efforts after big seismic events. The current method of using the location of seismic events to estimate where damage occurred is often not satisfactory. As an example, a case study is given in Jager and Ryder (1999) where a magnitude 2.5 seismic event caused a violent shakedown in panels in a Carbon Leader Reef stope. The most severe damage was found in the W3 panel while the W1 and W2 panels, which were located closer to the event, were virtually undamaged. The location of a seismic event is therefore not a good indicator of where to expect damage.

During the monitoring period, only two seismic events caused falls of ground in the five panels being monitored. As both these events occurred shortly after blasting time, no personnel were injured. These events are described below.

4.2 Effect of the seismic event on 21 November 2002

On 21 November at 19h51, a seismic event of magnitude 0.6 was recorded ahead of the E5 panel (co-ordinates: x=30365, y=-42790, z=3193). This is indicated in Figure 4.2.1.

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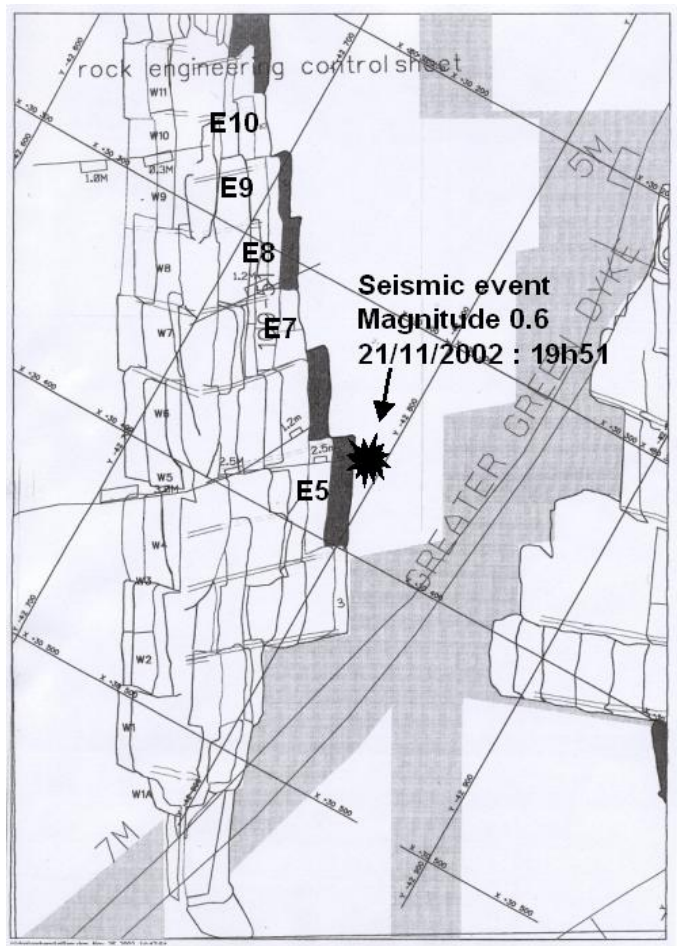
Figure 4.2.1 Location of the seismic event on 21/11/2002.

Significant falls of ground were observed in the E8 panel as shown in the schematic diagram (Figure 4.2.2) and in Figures 4.2.3 to 4.2.6. No damage was observed in the other panels. From Figure 4.2.1, the location of the seismic event, as given by the seismic system, was ahead of panel E5. It is therefore not clear why the most damage occurred in panel E8.
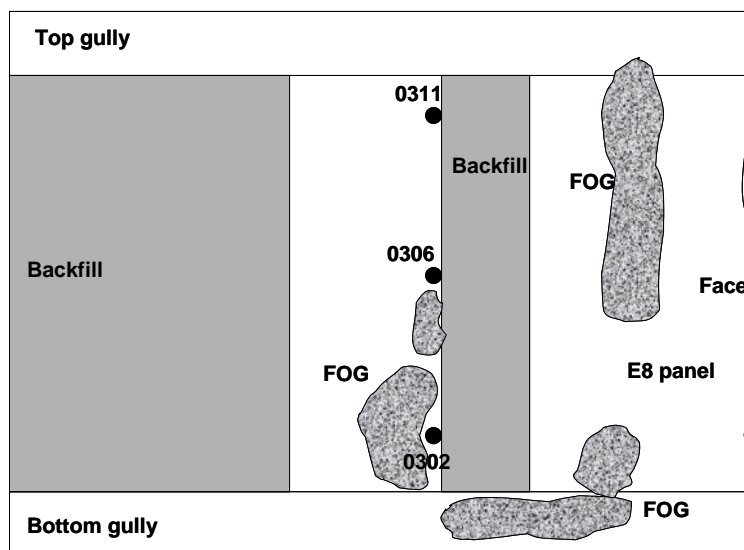
Figure 4.2.2 Illustration of the area of the falls of ground in the E8 panel following the seismic event.

38

Figure 4.2.3 Fall of ground in the E8 panel next to the 0306 closure meter (looking down dip).

Figure 4.2.4 Fall of ground in the E8 panel next to the 0302 closure meter (looking down dip).

Figure 4.2.5 Fall of ground in the E8 panel close to the bottom gully.

Figure 4.2.6 Fall of ground in the E8 panel showing the zone of influence of the support unit.

In terms of closure measurements, Figures 4.2.7 to 4.2.13 illustrate the closure measured in panels E9, E8, E7 and E10. On the day of the seismic event, only panel E9 was blasted. Note the large amount of instantaneous seismic closure in panel E8 (Figure 4.2.11) while the event had no effect on the closure in E10 (Figure 4.2.13). Table 4.2.1 illustrates the instantaneous closures recorded in the various panels. Note that the falls of ground occurred where the largest amount of instantaneous closure was recorded. Of further interest is the acceleration of the rate of steady state closure on the day preceding the damaging seismic event in panel E9 as seen in Figures 4.2.7 and 4.2.8. It is also seen to a lesser extent in panel E8 (Figures 4.2.10 and 4.2.11).
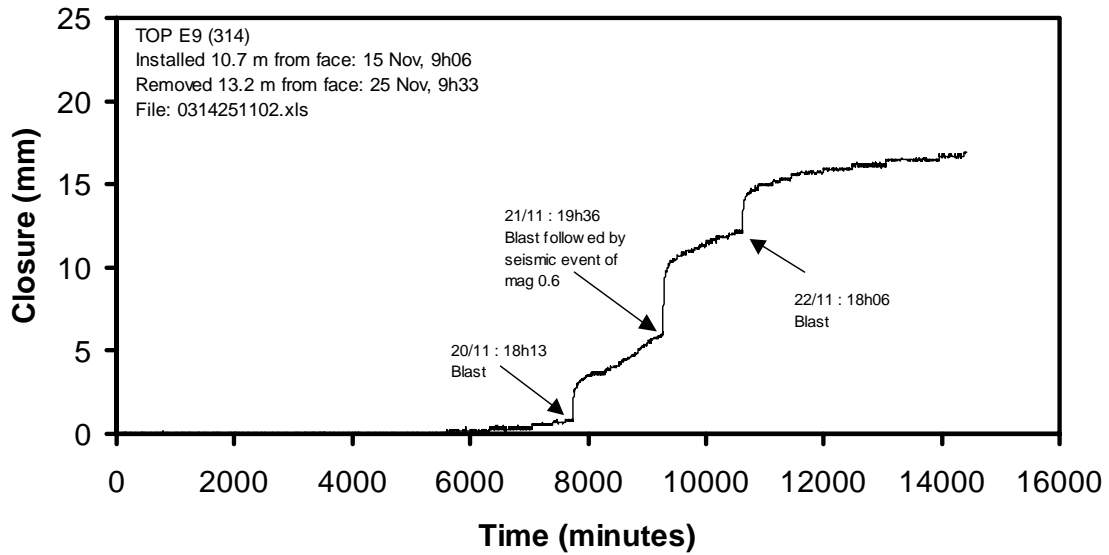
Figure 4.2.7 Closure recorded at the top of E9. Note the acceleration of the rate of steady state closure on the day preceding the damaging seismic event on 21 November.
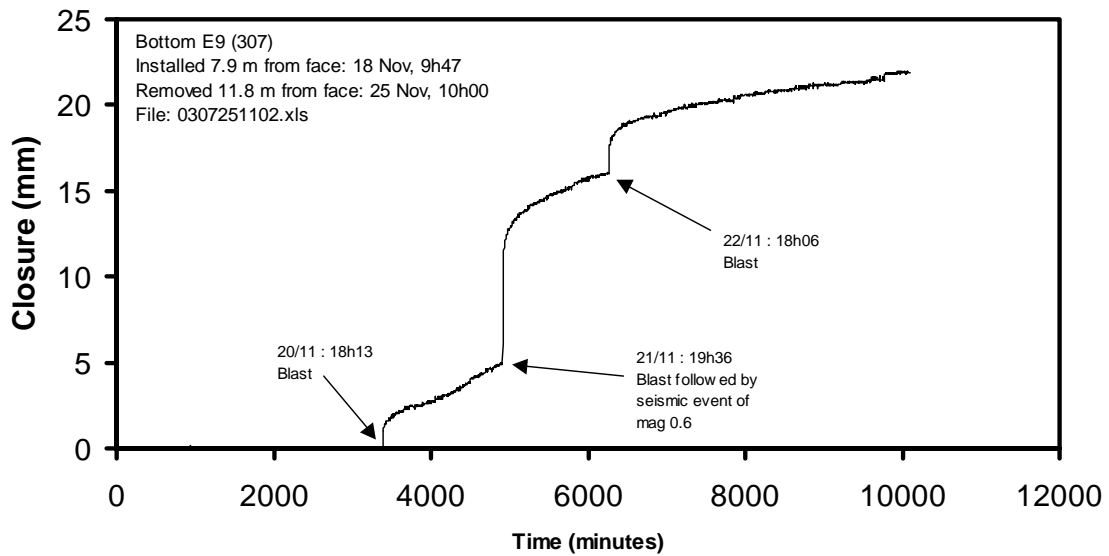
Figure 4.2.8 Closure recorded at the bottom of E9. Note the acceleration of the rate of steady state closure on the day preceding the damaging seismic event on 21 November.

Figure 4.2.9 Closure recorded at the top of panel E8.

Figure 4.2.10 Closure recorded in the middle of panel E8.

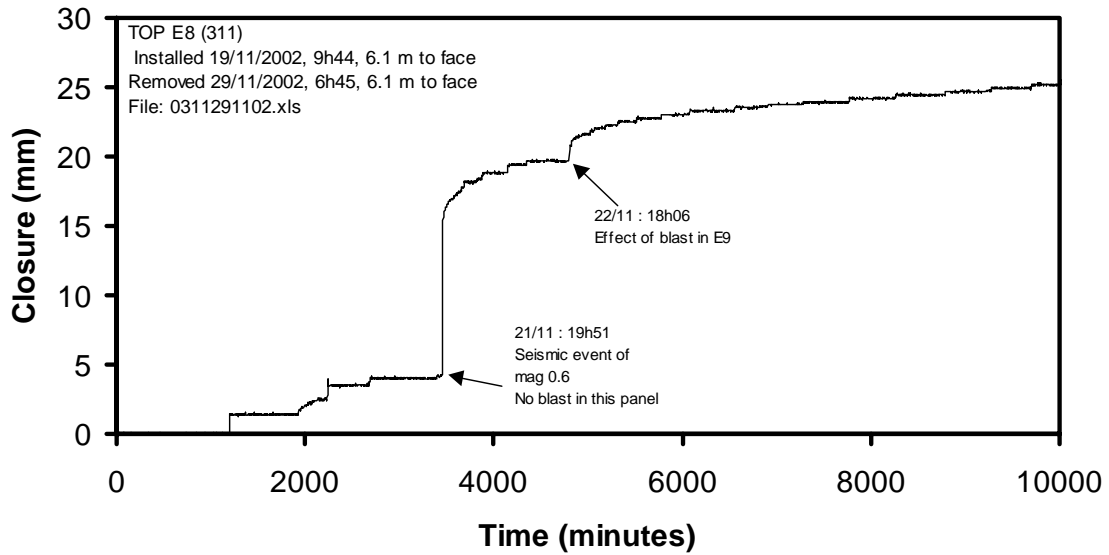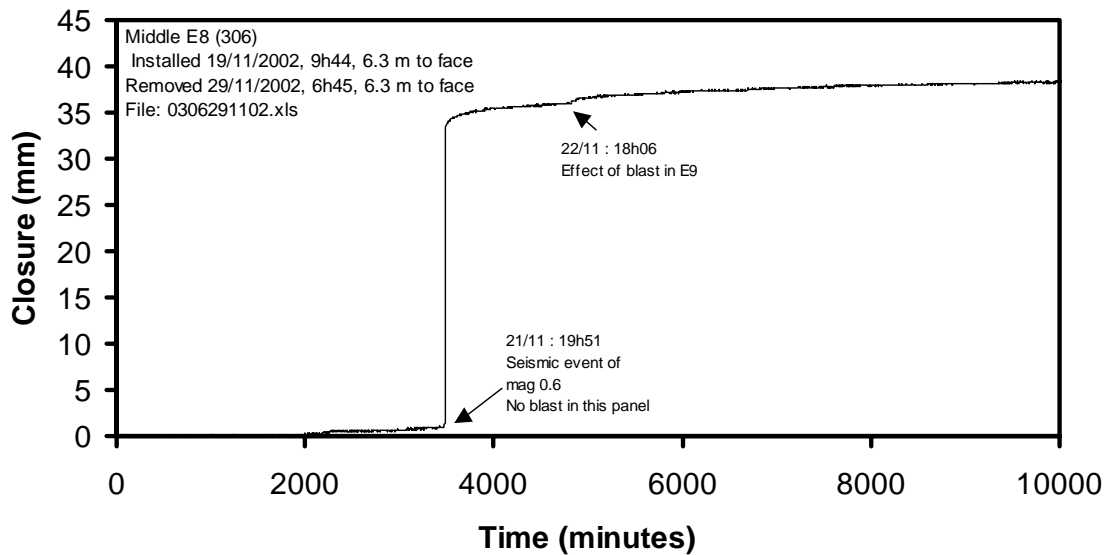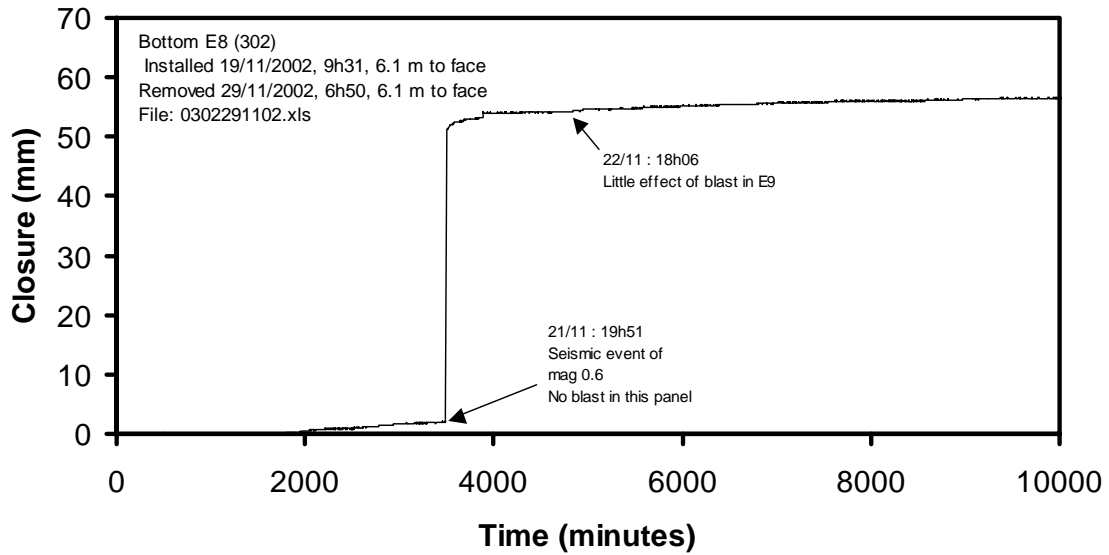42

Figure 4.2.11 Closure recorded at the bottom of panel E8.
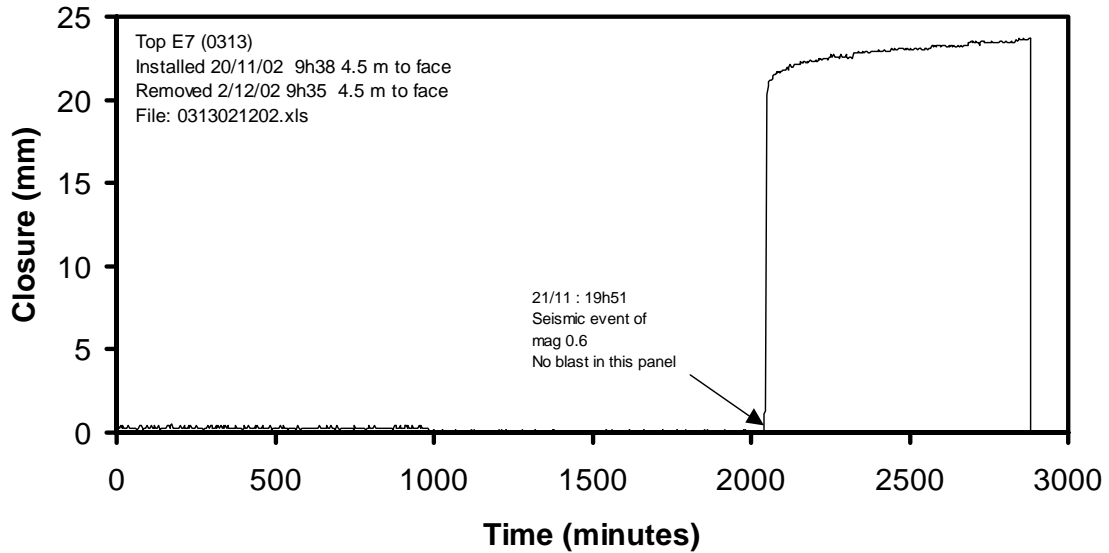
Figure 4.2.12 Closure recorded at the top of panel E7.

43
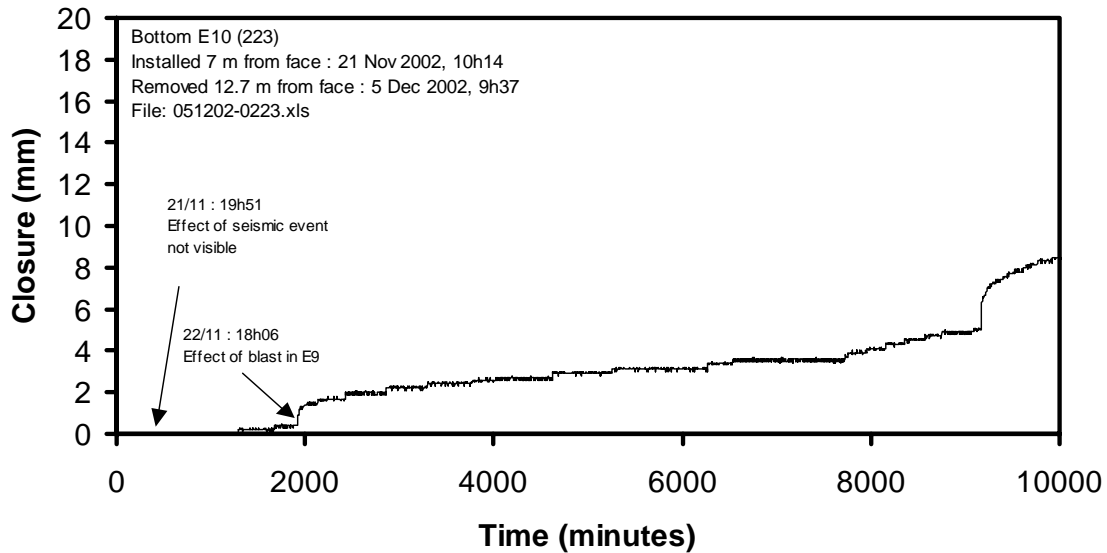
Figure 4.2.13 Closure recorded at the bottom of panel E10.

Table 4.2.1 Listing of the instantaneous closure recorded in the various positions at the time of the seismic event

Closure meter position	Instantaneous closure at time of event	Blast	Damage in panel
Bottom E10	0 mm	No	No
Top E9	3.7 mm	Yes	No
Bottom E9	7 mm	Yes	No
Top E8	11.7 mm	No	FOG
Middle E8	32.7 mm	No	FOG
Bottom E8	50.1 mm	No	FOG
Top E7	20.5 mm	No	FOG in top gully

4.3 Effect of the seismic events on 17 January 2003

Another major fall of ground was caused by two seismic events recorded on 17 January 2003 (see Figure 4.3.1). The first event of magnitude 1.3 occurred at 18h57 at co-ordinates x=30319, y=-42759, z=3194. This was followed by a second event of magnitude 1.5 at co-ordinates x=30288, y=-42708, z=3168. A third event of magnitude 1 was recorded at 18h57, but was located at the top of the raise line ahead of the panels mining westwards and is not considered in this discussion. Significant fallouts occurred in the E10 panel as illustrated in the schematic diagram (Figure 4.3.2) and the photographs in Figures 4.3.3 to 4.3.7. The only other panel where damage occurred was in E8 with the fallout illustrated in Figure 4.3.8.
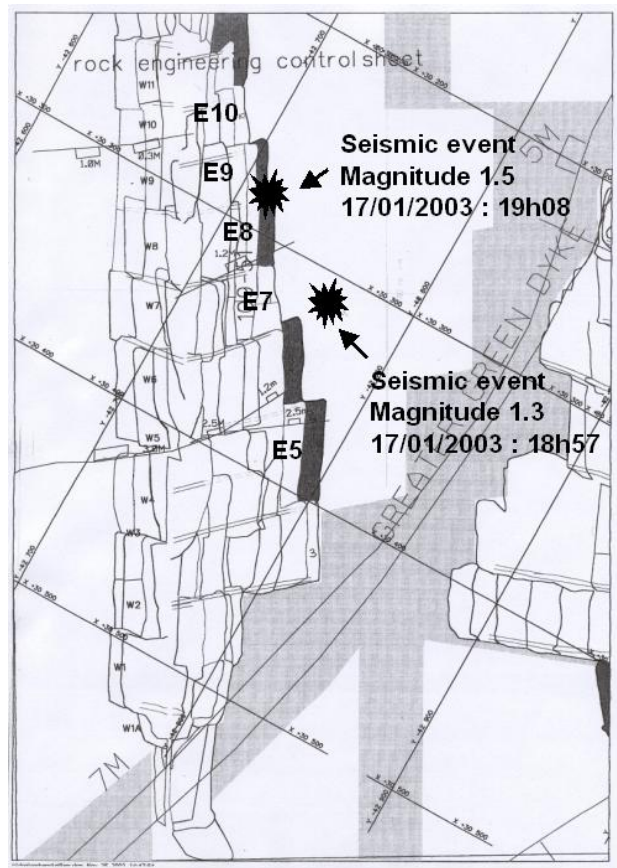
Figure 4.3.1 Location of the seismic events on 17/1/2003. Note that the same map is used as in Figure 4.2.1. The faces were advanced during the period from 21/11/2002 to 17/1/2003 but the map is not updated to show this.
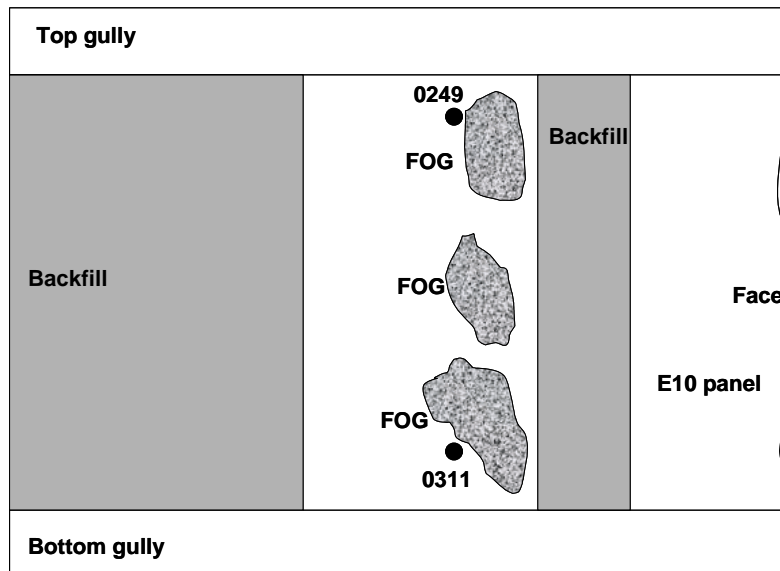
Figure 4.3.2 Illustration of the area of the falls of ground in the E10 panel following the seismic events.

Figure 4.3.3 Fall of ground in the E10 panel next to the 0249 closure meter. The fallout height was approximately 1 m.

Figure 4.3.4 A different view of the fallout in Figure 4.3.3 to illustrate the fallout height.

Figure 4.3.5 Fall of ground in the back area of E10.

Figure 4.3.6 Fall of ground in the back area of E10.

Figure 4.3.7 Fallouts around the 0311 closure meter in panel E10.

Figure 4.3.8 Fall of ground at the bottom of E8.

Figure 4.3.9 Hangingwall conditions in the E7 panel after the seismic events showing very little damage.

In terms of closure measurements, Figures 4.3.10 to 4.3.15 illustrates the closure measured in panels E10, E9, E8 and E7. On the day of the seismic events, only panels E8 and E7 were blasted. Table 4.3.1 illustrates the instantaneous closures recorded in the various panels. Similar to the event described in Section 4.2, the most damage occurred where the largest amount of instantaneous closure was recorded. Although expected intuitively, the events described in Sections 4.2 and 4.3 and the accompanying closure data are therefore some of the first data supporting the hypothesis that during damaging seismic events, areas with the largest instantaneous seismic closures experience the most damage. If mine-wide closure systems can become a reality, this would therefore greatly assist mine personnel to immediately assess where damage could have occurred after large seismic events.

Of further interest is the acceleration of the rate of steady state closure on the day preceding the damaging seismic event in panel E8 as seen in Figures 4.3.14. A similar phenomenon was seen for the event described in Section 4.2 and warrants further investigation.
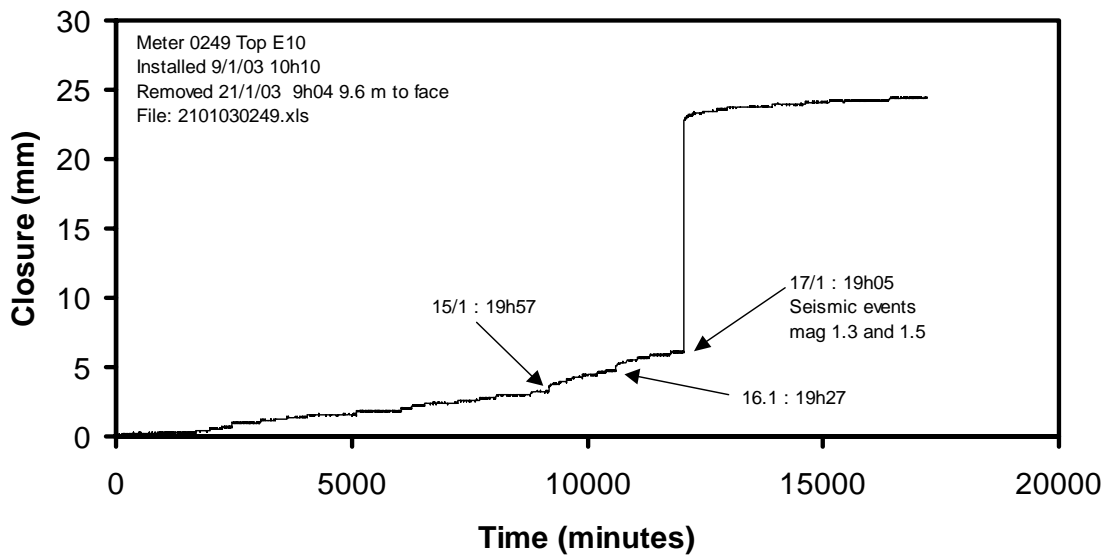
Figure 4.3.10 Closure recorded at the top of panel E10.
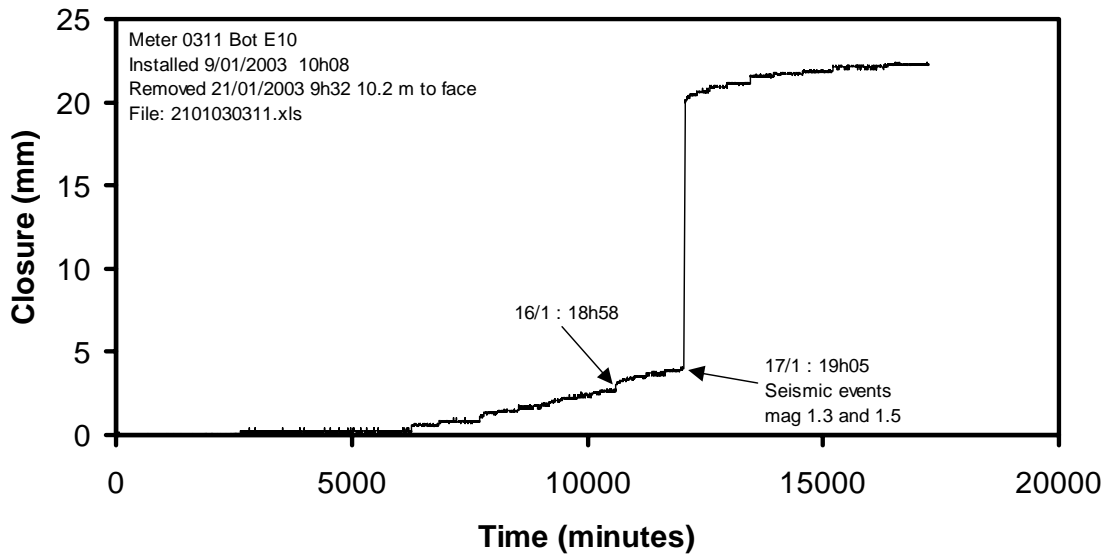
Figure 4.3.11 Closure recorded at the bottom of panel E10.
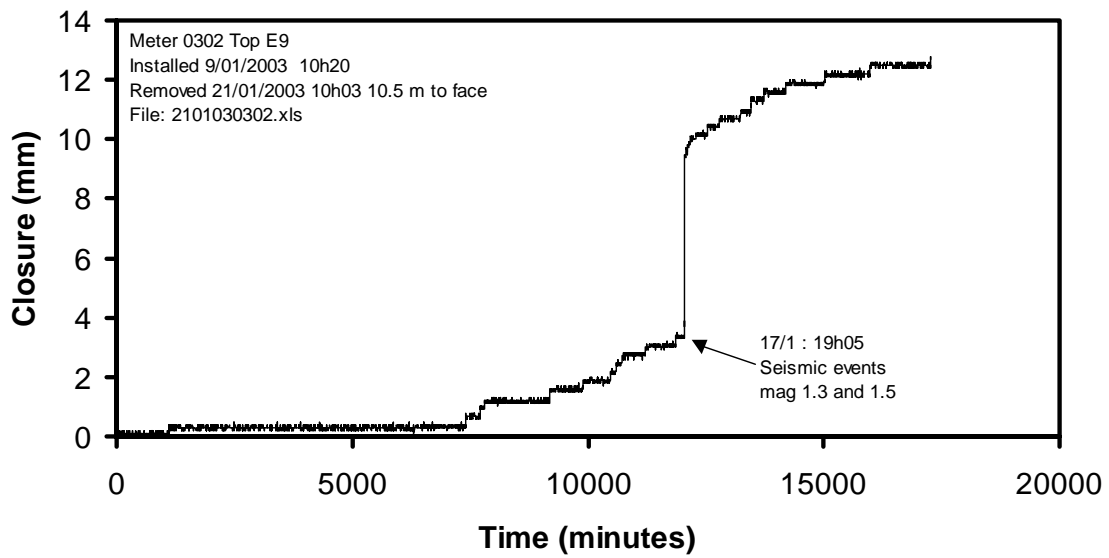
Figure 4.3.12 Closure recorded at the top of panel E9.
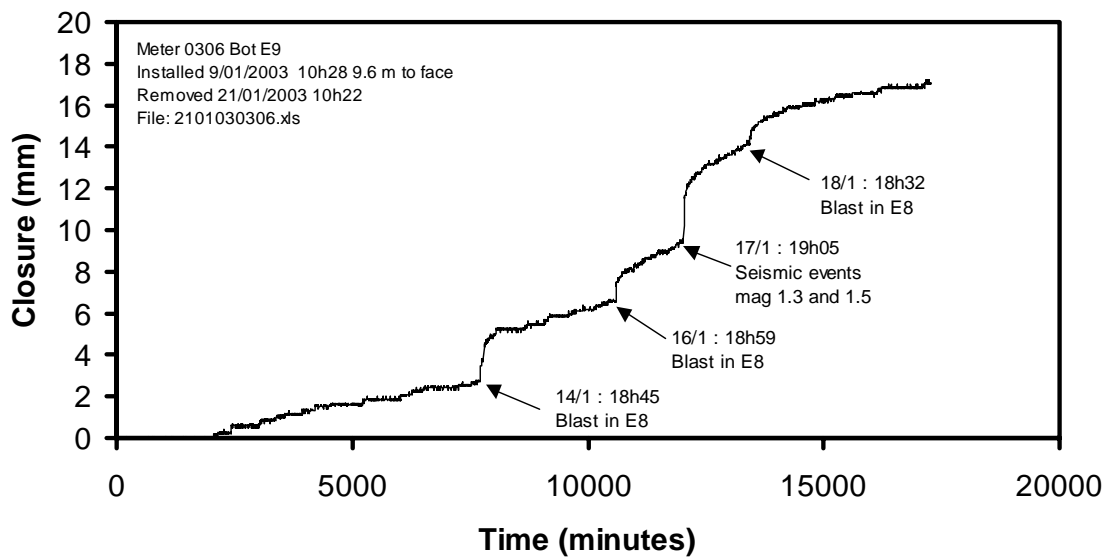
Figure 4.3.13 Closure recorded at the bottom of panel E9.

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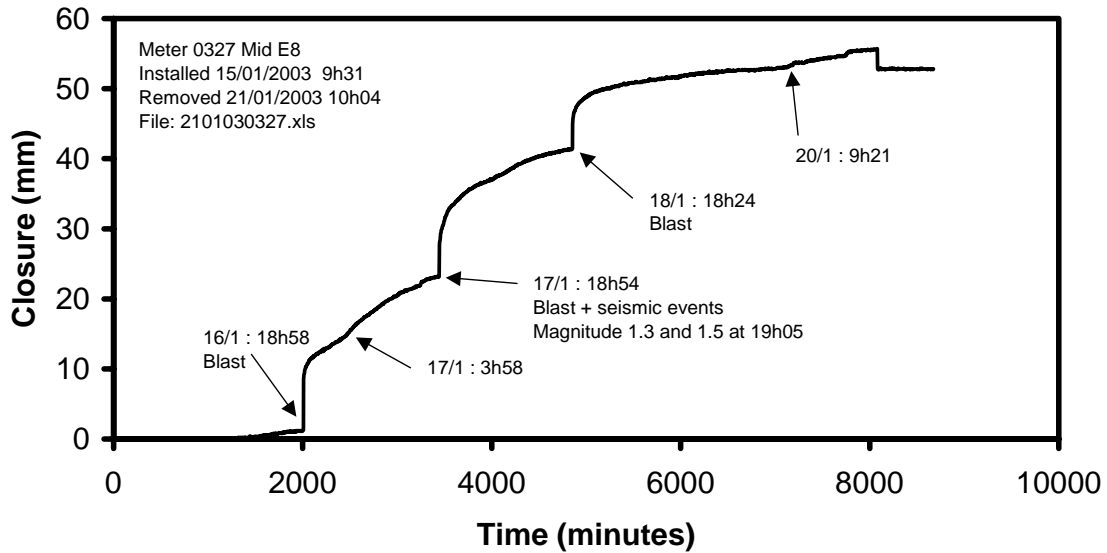
Figure 4.3.14 Closure recorded in the middle of panel E8. Note the acceleration of the rate of steady state closure on the day preceding the damaging seismic events on 17 January.
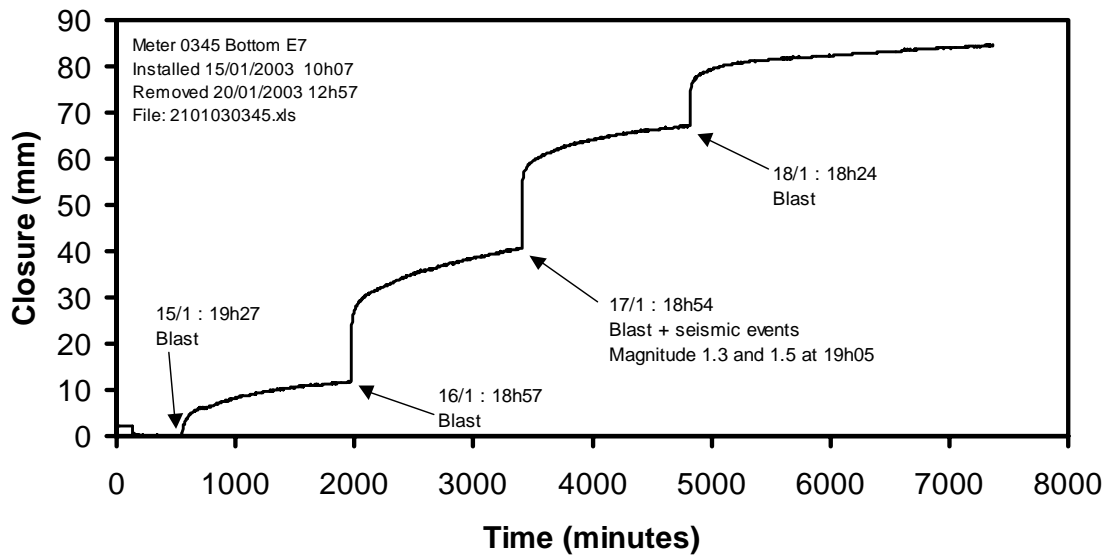
Figure 4.3.15 Closure recorded at the bottom of panel E7.

Table 4.3.1 Listing of the instantaneous closure recorded in the various positions at the time of the seismic events.

Closure meter position	Instantaneous closure	Blast	Damage in panel
Top E10	16.6 mm	No	FOG
Bottom E10	16.1 mm	No	FOG
Top E9	6.3 mm	No	No
Bottom E9	2.5 mm	No	No
Middle E8	5.4 mm	Yes	FOG at bottom of panel
Bottom E7	16.1 mm	Yes	No

5. Calculation and use of the closure ratio

5.1 Definition of the closure ratio

One closure parameter suggested in earlier work (Malan and Napier, 1999) as a possible risk parameter, is the closure ratio CR. For a single mining increment j, CR is defined as the ratio of instantaneous blast closure to total daily closure given by (from Figure 5.1.1)

$$CR_j = \frac{\Delta S_i^{\ j}}{\Delta S_T^{\ j}} \qquad (5.1.1)$$
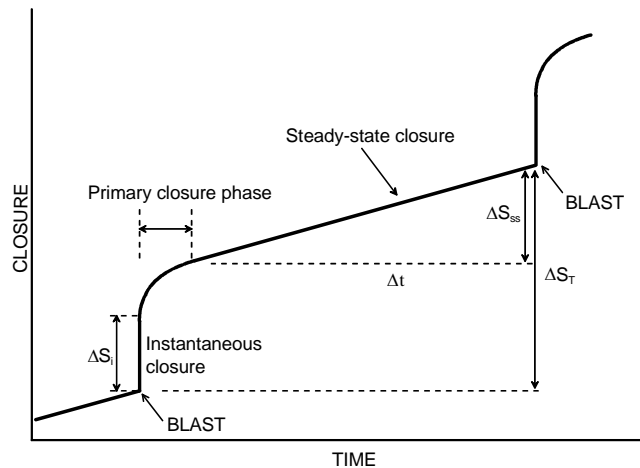
Figure 5.1.1 Typical continuous stope closure after blasting and the definition of closure terms.

For n successive blasts, equation (5.1.1) can be written as

$$CR = \frac{1}{n} \sum_{j=1}^{n} \frac{\Delta S_i^{\ j}}{\Delta S_T^{\ j}} \qquad (5.1.2)$$

The period Δt used for calculating ΔS_T is taken as 24 hours. In some cases, this period might be slightly shorter if the next blast occurs before the full 24 hours has expired since the previous blast. Note that the closure ratio is only defined for the closure following a blast and not a seismic event. As it might be difficult in practice to determine the magnitude of the instantaneous closure from the graphs, it is suggested that $\Delta S_i^{\ j}$ be taken as the increase in closure during the 5 minute period following the blast.

5.2 Calculation of closure ratio using historical data

As an example of calculating closure ratio, data from three different geotechnical areas described by Malan and Napier (1999) is analysed in this section. Figure 5.2.1 illustrates closure data collected at Mponeng Mine. The hangingwall of the VCR mined in this area consisted of hard lava and the area was prone to face bursting. The competent lava has a strong influence on the closure behaviour and the general rock mass behaviour of the stopes. When applying equation 5.1.2 to this data set, a closure ratio of CR = 0.46 is obtained. It should be noted that this is an average value as the closure ratio for the first blast is 0.36, the second 0.51 and the third 0.52. As a possible hazard parameter, it is therefore important not to look at an isolated CR value after a single blast, but rather an average over a period of time.
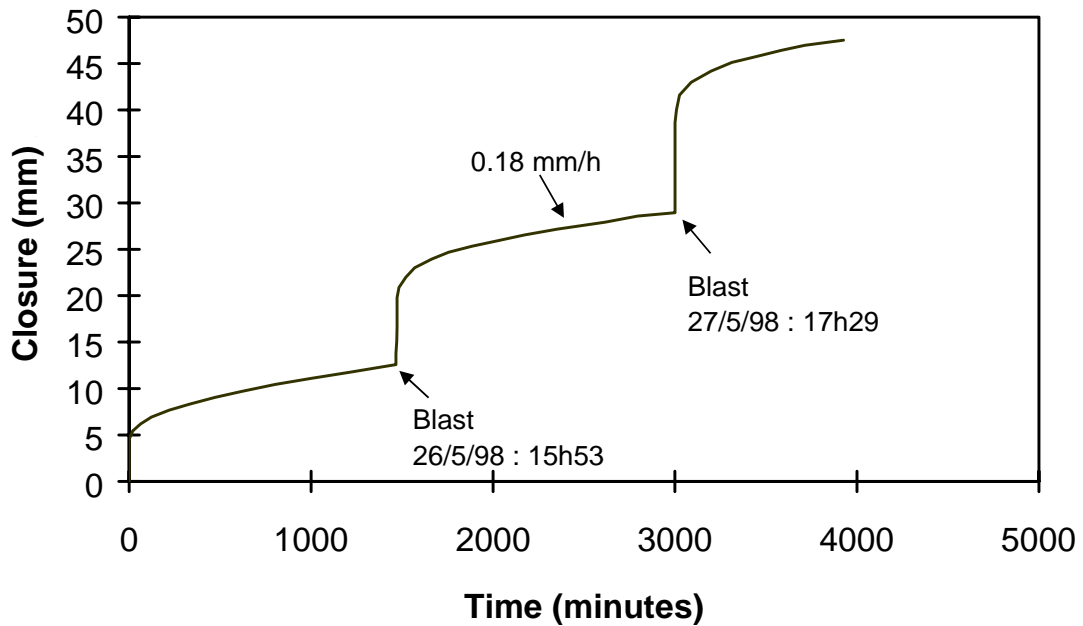
Figure 5.2.1 Time-dependent closure measured at Mponeng Mine (after Malan and Napier, 1999). The closure instrument was 8.1 m from the face before the blast on 26/5/98.

Continuous closure data was also collected at Kloof Mine where the hangingwall of the VCR consisted of soft lava. The rock mass behaviour and the closure response in this area were dominated by the time-dependent disintegration of the soft lava in the hangingwall. It was very difficult to support the hangingwall with significant fallouts between packs. The risk of strain bursting was low in this area, although the risk of falls of ground was very high. When applying equation 5.1.2 to this data set, a closure ratio of CR = 0.04 is obtained.
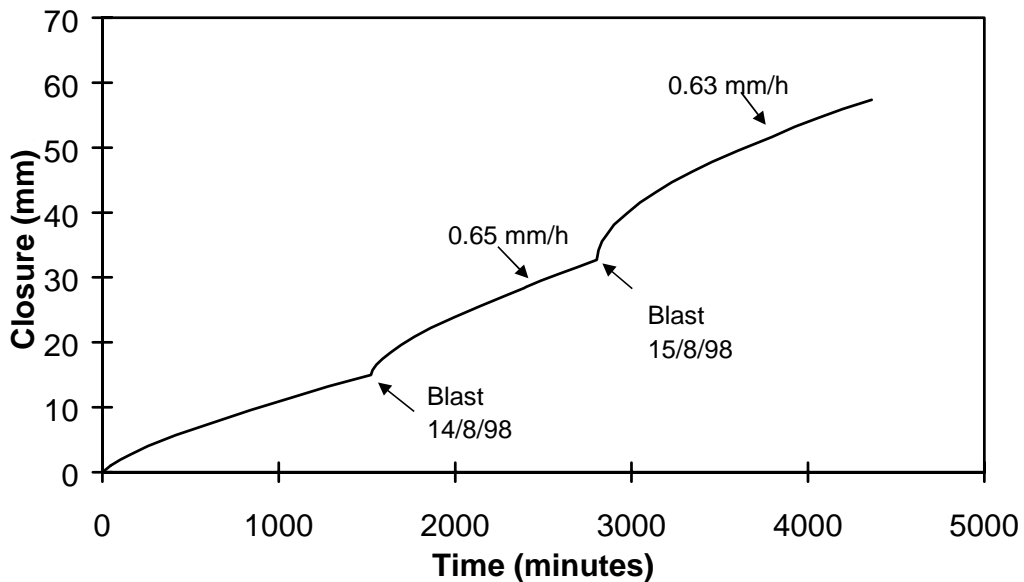
Figure 5.2.2 Time-dependent closure measured at Kloof Mine (after Malan and Napier, 1999). The closure instrument was 8.5 m from the face before the blast on 14/8/98.

Data from a third geotechnical area, the Vaal Reef at Hartebeestfontein Mine, is shown in Figure 5.2.3. Well-defined bedding planes in the quartzite of the hangingwall dominate the rock mass behaviour and closure response of the stopes. These areas appeared to be prone to falls of ground while the risk of strain bursting was very low. When applying equation 5.1.2 to this data set, a closure ratio of CR = 0.06 is obtained.

Figure 5.2.3 Closure measured at Hartebeestfontein Mine (after Malan and Napier, 1999). The instrument was 10.9 m from the face before the first blast.

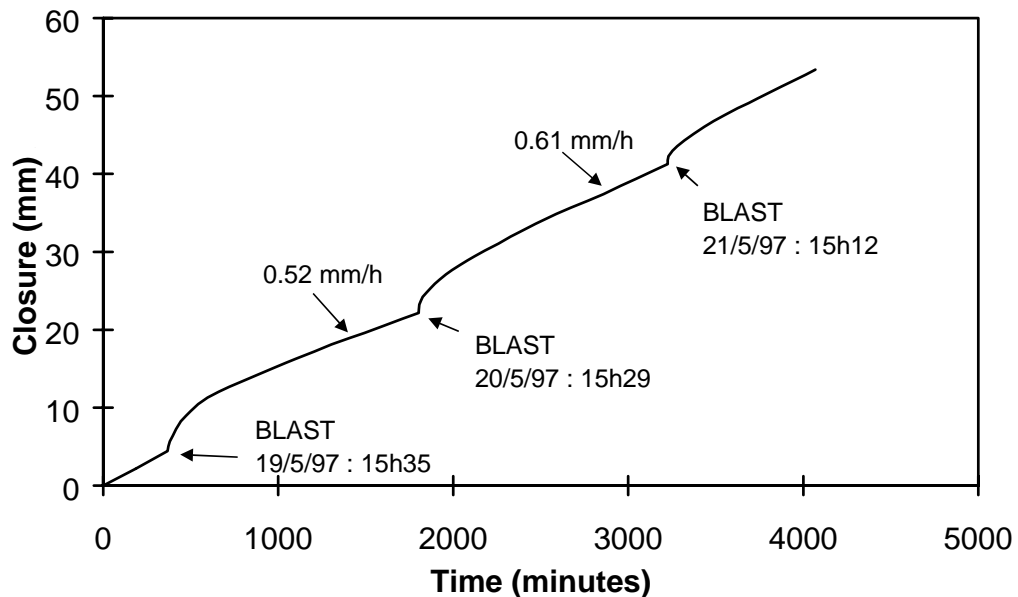In summary, from this historical data, it appears that the closure ratio is a good measure to identify different geotechnical conditions. The results are summarised in Table 5.2.1. Low values of closure ratio are typically associated with poor hangingwall conditions and a high risk of falls of ground whereas high values of closure ratio are associated with areas prone to face bursting. As mentioned above, however, the closure ratio does not stay constant for every blast but shows some statistical variation. It is therefore important to calculate an average value and use this as a base value to investigate possible changes in conditions in the stope over a period of time.

Table 5.2.1 Typical values of closure ratio for different geotechnical conditions.

Area	Closure Ratio	Conditions	Reference
VCR (hard lava) : Mponeng Mine 87-49 area	0.46	High risk of face bursting, Significant seismicity,	Malan and Napier, 1999
VCR (soft lava) : Kloof No 1 Shaft 31-34 area	0.04	Very high risk of falls of ground, low risk of strain bursting	Malan and Napier, 1999
Vaal Reef : Hartebeestfontein No 6 Shaft, 78N23 longwall	0.06	High risk of falls of ground, low risk of strain bursting	Malan and Napier, 1999
Carbon Leader : TauTona 102 E3 area	0.35	Good backfill installation, stable hangingwall conditions, seismically active area	Malan et al, 1999
VCR (soft lava) Kloof No 1 shaft 37-61 longwall	0.15	More stable hangingwall conditions than 31-34 area	Malan and Van Rensburg, 1999

5.3 Closure ratio for the 109/51 area at Mponeng Mine

For the recently collected data in the 109/51 area at Mponeng Mine, the closure ratio was calculated as 0.5 for the closure data given in Figure 3.3.1. This is very similar to the value of 0.46 calculated for the data collected in 1998 in a different part of the mine (Table 5.2.1).

5.3.1 Effect of spatial position on closure ratio

In Section 4.2 of this report, Figures 4.2.7 and 4.2.8 illustrated the closure recorded at the top and bottom of panel E9. Using equation 5.2.1, the closure ratio for these data sets were calculated giving values of 0.46 at the bottom and 0.48 at the top of the panel. The values are very similar even though the total closure at the top was 16.1 mm and 21.9 at the bottom. This appears to show that the closure ratio is independent of total closure measured in the various positions of the panel. A further example is given in Figures 5.3.1 and 5.3.2. The total closure at the top position in E7 just before the blast on 28/2/2003 was 22.9 mm while it was 18.8 mm for the meter in the middle of the panel. The closure ratio for the top position after the first three blasts was calculated as 0.57 while it is 0.55 for the data collected in the middle of the panel.
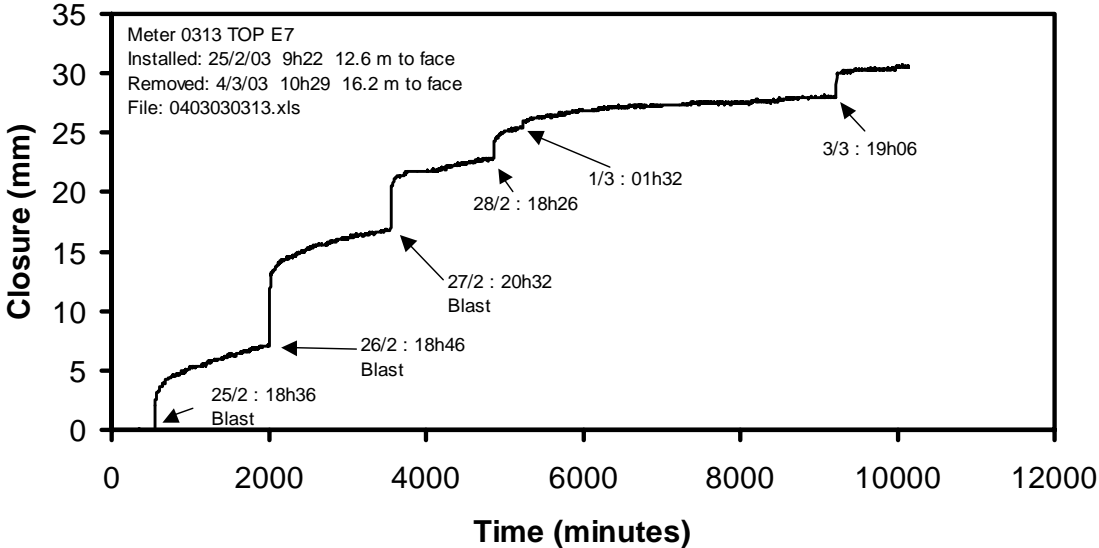
Figure 5.3.1 Closure collected at the top of panel E7.
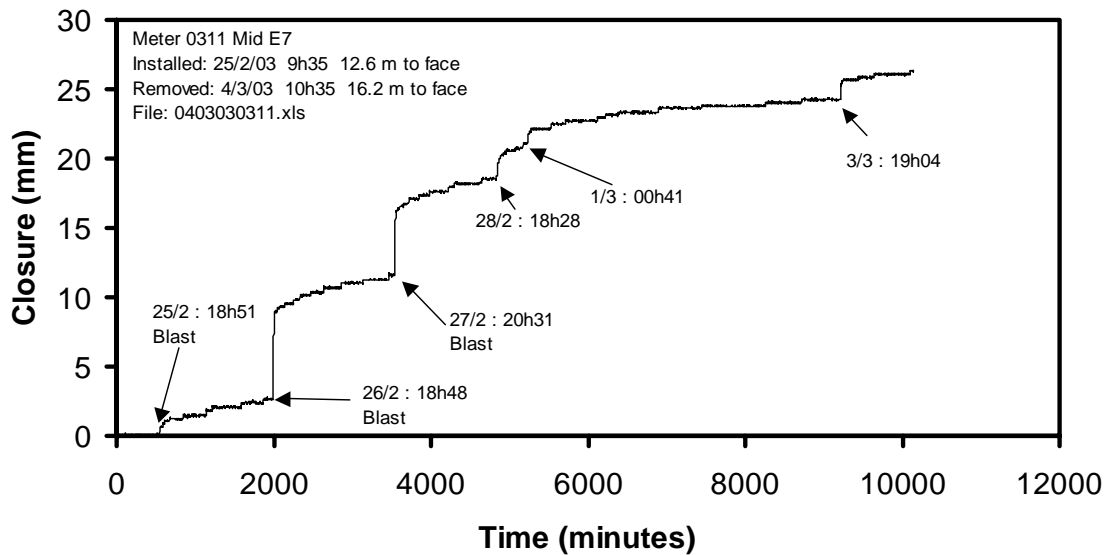
Figure 5.3.2 Closure collected in the middle of panel E7.

In both the examples used above, the closure meters were positioned at the same distance to face. A further question investigated was the influence of distance to face on closure ratio. Unfortunately, due to the backfill used in the experimental area, usually only one open area at a certain distance to face between backfill ribs was available to install the closure meters. It was therefore not possible to have closure meters at different distances to face for one particular blast. It was nevertheless possible to calculate the closure ratios for the entire data set during different blasts and these are plotted Figure 5.3.3 as a function of distance to face. Note that there is no clear trend as the distance to face increases. The closure ratio ranged from 0.26 to 0.74 with an average of 0.49.
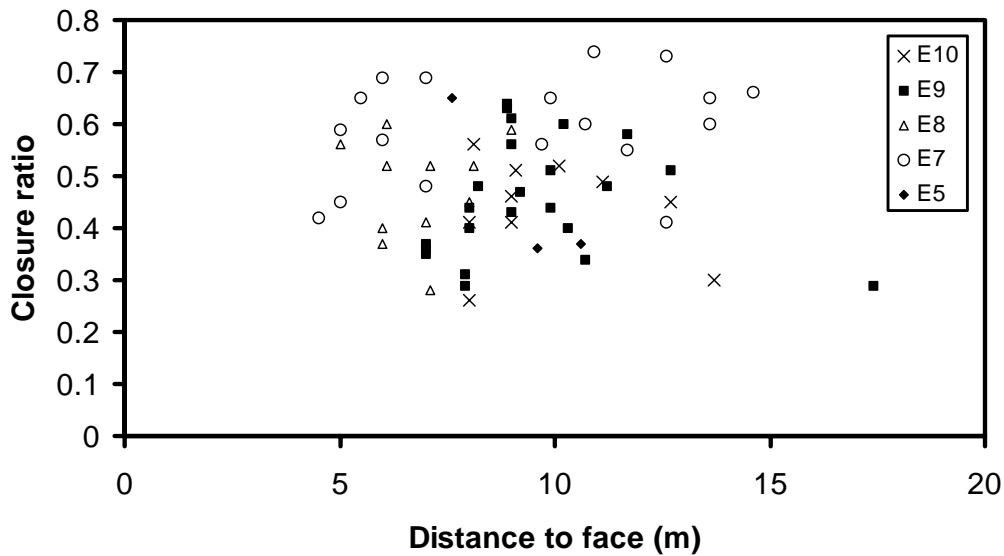
Figure 5.3.3 Closure ratio versus distance to face for the various panels.

5.4 Numerical modelling of stope closure and closure ratio

In order to gain further insight into the use of the closure ratio in determining the geotechnical condition of the rock mass, a two-dimensional numerical modelling study was performed using the computer code DIGS. The DIGS program has been developed to model fracture zone development near the edges of tabular stopes. The analysis technique is based on the displacement discontinuity method and has been described previously by Napier and Malan (1997). In the present study, fracture zone development was modelled by extending one side of a parallel-sided, horizontal mining panel towards a region covered by a random mesh of potential cracks. The random mesh was generated as a Delaunay triangulation having an average side length of one metre. The failure properties of the mesh positions are determined by a Mohr-Coulomb criterion with specified cohesion and internal friction angle. Two cases were considered: a "low" strength rock with cohesion equal to 15 MPa and a "high" strength rock with cohesion equal to 25 MPa. In each case the internal friction angle was chosen to be 45 degrees. The mining simulation was carried out in 25 face advance steps of one metre starting from an initial span of 50 m. Following each mining step, twenty four time relaxation steps were allowed to occur. Within each time relaxation step, the stress state is examined at each element of the random mesh and, if the stress exceeds the specified Mohr-Coulomb intact limit, these elements are allowed to slip at a rate that is proportional to the difference between the shear stress and a specified residual frictional resistance. (The residual friction angle was set to 30 degrees). Closure "measurements" were performed by computing the difference in vertical displacement arising between benchmark points located 2 m in the hangingwall and 2 m in the footwall at each of five monitoring positions. These closure "stations" were spaced at intervals of 5 m with the measuring points of the first station aligned vertically above and below the centre of the first excavation increment.

Figures 5.4.1a and 5.4.1b show the fracture zone developed after 25 mining steps in the random mesh for the "low" and "high" strength rock environments. In these plots, the hangingwall region is separated from the footwall region to display the distorted deformations more clearly. It can be seen that a much larger region of rock is activated in the low strength material as would be expected intuitively. It is apparent also that considerable fragmentation of the rock occurs at the boundaries of the hangingwall and the footwall. This arises from the particular assumption of the Delaunay tessellation grid and the validity of this fracture pattern must be judged according to actual field observations and the installed internal stope support performance. Detailed simulation of support effects are not considered in the present study. However, the modelled block detachments do not contribute to stress changes in the intact rock body but do need to be considered in the monitoring of detailed closure movements. For this reason "internal" monitoring points, located 2 m into the hangingwall and the footwall respectively, were chosen to record the effective stope closure behaviour.
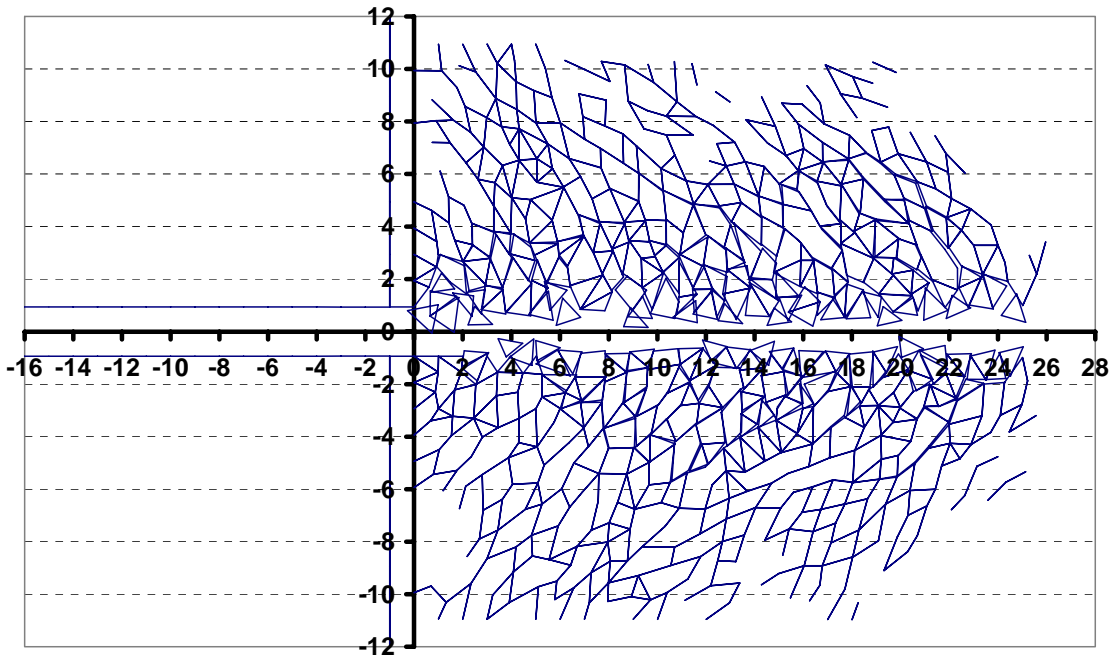
(a)
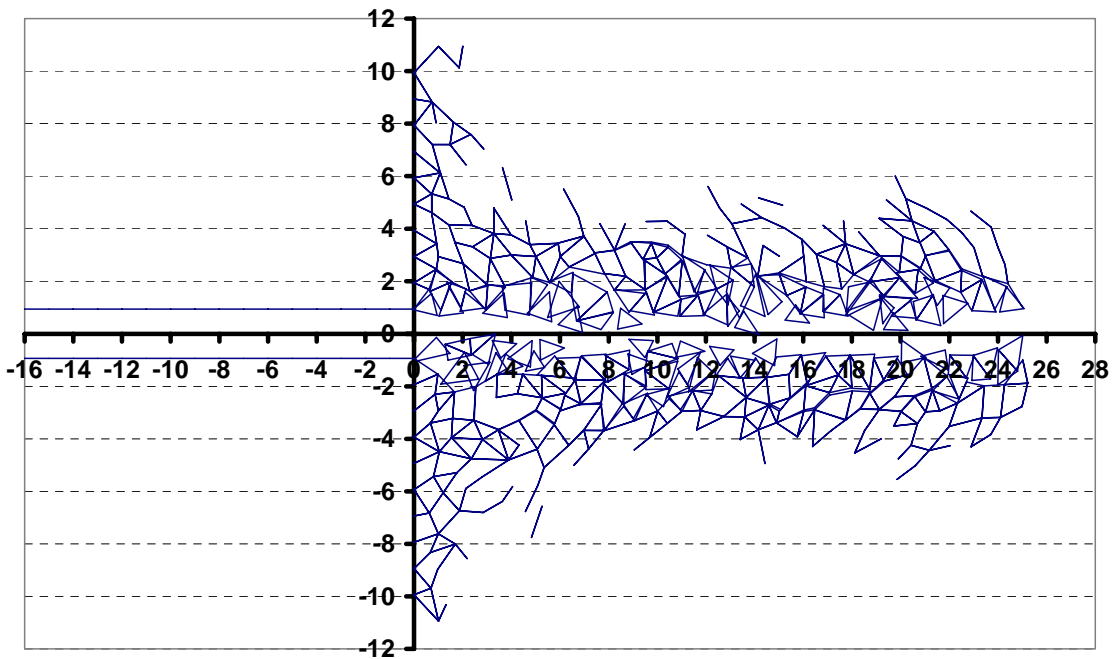
(b)

Figure 5.4.1   Distorted grid plots of fracture zone formation after twenty five mining steps in (a) "low" strength and (b) "high" strength rock.

Two closure profiles observed at Station 4 (located 15.5m to the right of the origin in Figures 5.4.1a and 5.4.1b), for the low and high strength rock cases, are shown in Figure 5.4.2. These profiles show a marked difference in deformation behaviour between the two material models. It is of interest to contrast this behaviour with the changes in incremental energy release (effective seismic activity) that are computed in each case. (The simulated energy release increments may also be interpreted as a measure of the incremental stability of the overall rock mass). The cumulative energy release increments are plotted in Figure 5.4.3 for face advance steps 16 to

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25 (time 480 to 720) and, interestingly, show little difference between the low and high strength rock cases. The cumulative energy release increments that are computed when explicit fracturing is considered are, however, much greater than the case where no fracturing is allowed to occur (elastic rock), depicted in Figure 5.4.4. More importantly, it is apparent that the commonly computed elastic energy release rate (ERR), which can be deduced from Figure 5.4.4 as the elastic energy release per unit area mined, will **not** provide a useful measure of the effective fracture zone size in the "low" and "high" strength cases shown in Figure 5.4.1. This motivates strongly the need to assess supplementary measures of the geotechnical rock response. One particular form of such a measure is the Closure Ratio as defined in Section 5.1.

A useful test of the performance of the closure ratio as a measure of geotechnical behaviour and, simultaneously, a check on the validity of the numerical procedure in relation to observed behaviour is obtained by computing the closure ratio for the low and high strength rock simulations shown in Figure 5.4.1. (The "numerical" closure ratio is computed as the ratio of the closure that is measured after the first time interval, following a mining step, to the total closure after 24 time steps. Since the sampling frequency is much lower than the "instantaneous" field measurements, it may be expected that the simulated closure ratios will be generally greater than field observations.). Figure 5.4.5a shows a plot of the closure ratio as a function of the absolute observation time. In this case the earliest observations are obtained at Station 1, followed by observations at successive stations as they are installed. The data in Figure 5.4.5a are re-plotted in Figure 5.4.5b as a function of the distance to the mining face position relative to when each meter is installed. A fairly wide scatter in the results is observed with no clear trends of the closure ratio as a function of time or relative position to the mining face. The average closure ratio is approximately equal to 0.5 which may be compared to the observed values quoted in Table 5.2.1.

Figures 5.4.6a and 5.4.6b show the equivalent closure ratios observed in the high strength rock simulation. It should be noted that a few closure ratio values greater than unity were recorded in this case but are not plotted in Figures 5.4.6a or 5.4.6b. In these instances, detached "blocks" were formed at the closure monitoring positions leading to spurious stope "opening" behaviour. Although the closure ratios plotted in Figures 5.4.6a and 5.4.6b are also scattered, the mean value is approximately equal to 0.7 and is clearly greater than the mean closure ratio of 0.5 shown in Figures 5.4.5a and 5.4.5b. Consequently, the numerical simulation of the closure ratio is in good agreement with the contrasting geotechnical behaviour exhibited in Figures 5.4.1a and 5.4.1b and is also in agreement with the observations quoted in Table 5.2.1. However, the present numerical simulations do not support more definite trends of the closure ratio as a function of time or as a predictor of incipient face stability. It is apparent though that these very encouraging initial results support the utility of the closure ratio in discriminating the response of different geotechnical environments. This should motivate further studies that incorporate improved representations of fracture patterns, which include the treatment of three dimensional layout geometries.
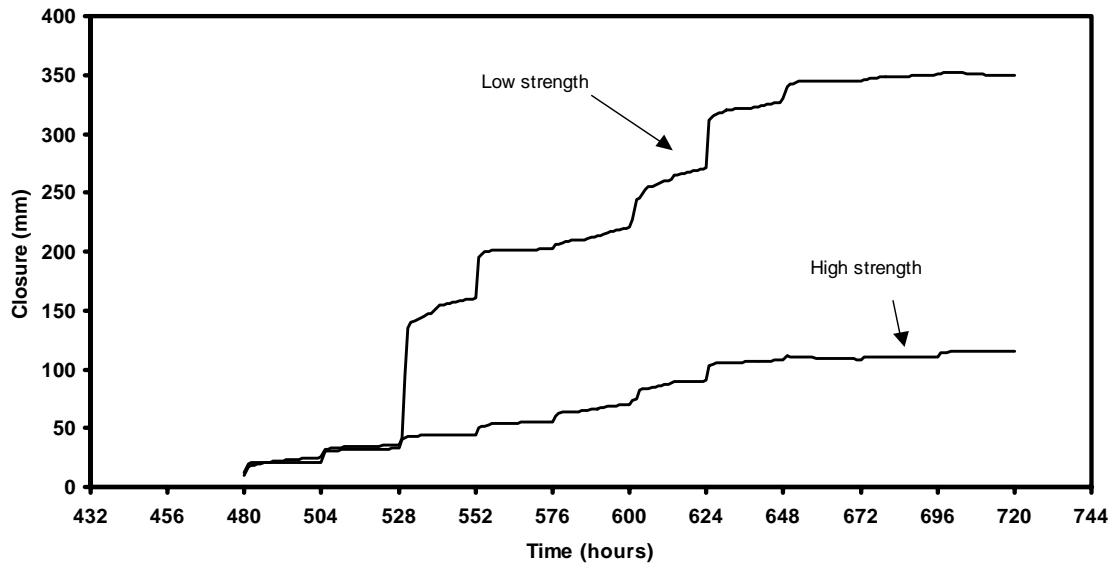
Figure 5.4.2 Closure profiles monitored at "Station 4" for "low" and "high" strength rock materials. Please note that the numerical model did not include the effect of bedding planes and therefore these results should not be directly compared to Figures 5.2.1 and 5.2.2.
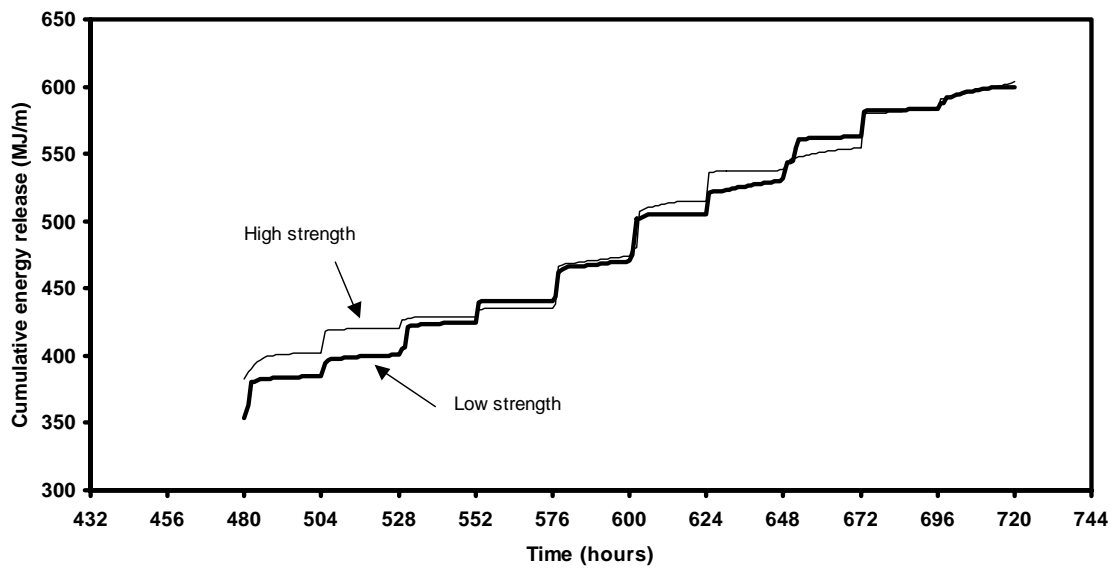
Figure 5.4.3 Comparison of cumulative energy release increments computed in the numerical simulation of mining through "low" and "high" strength rock.
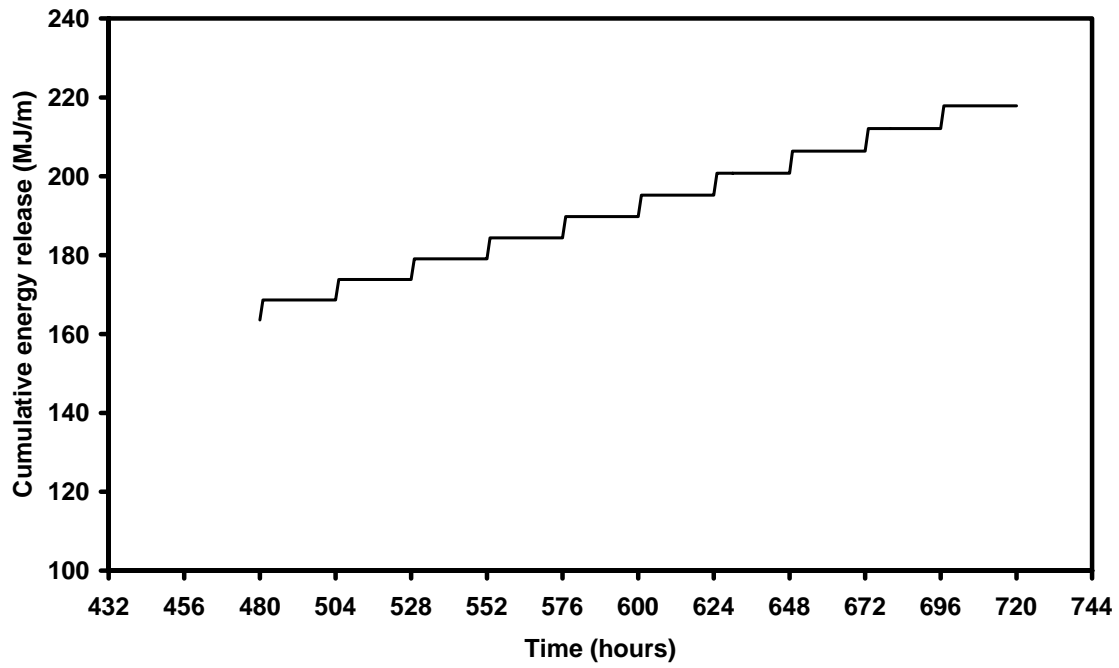
Figure 5.4.4 Cumulative energy release – no rock failure.
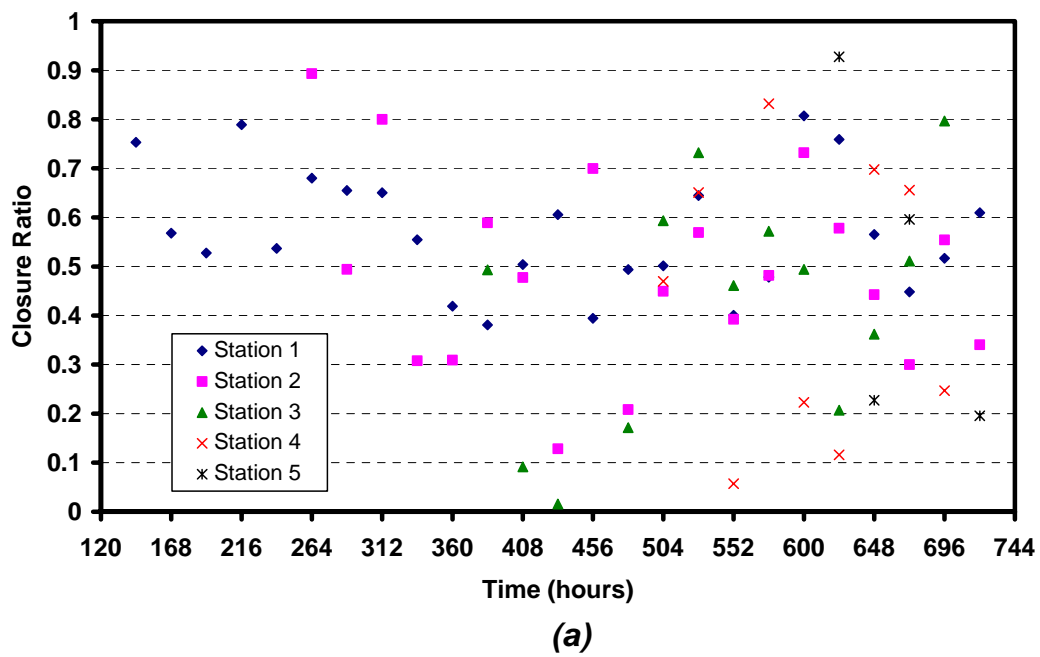
(a)
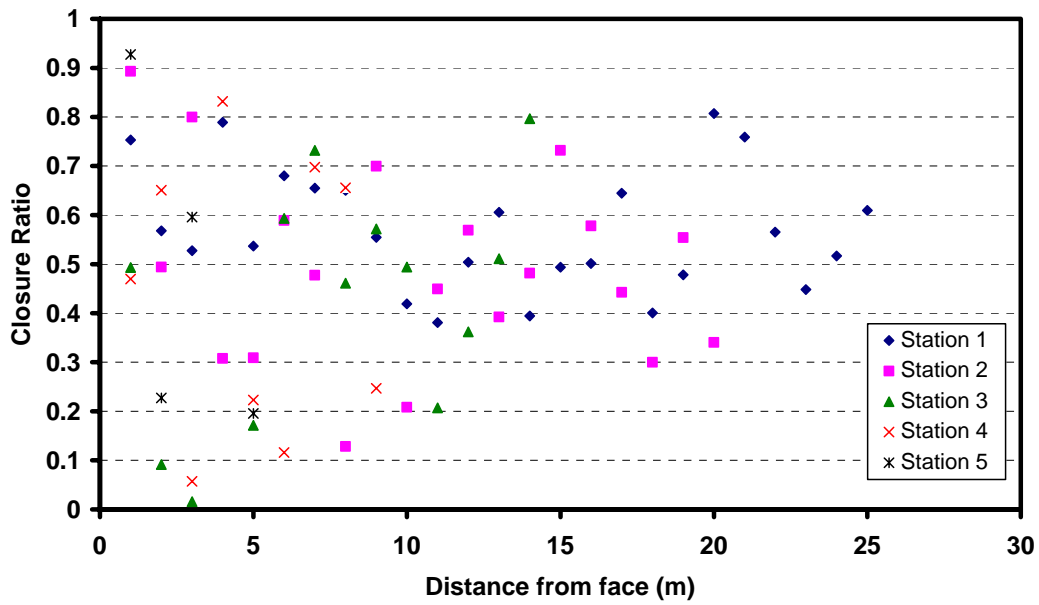
(b)

Figure 5.4.5   Observed closure ratio for low strength rock at each of 5 measuring stations plotted (a) as a function of absolute time and (b) plotted as a function of the face advance increments relative to the individual time of first observation.
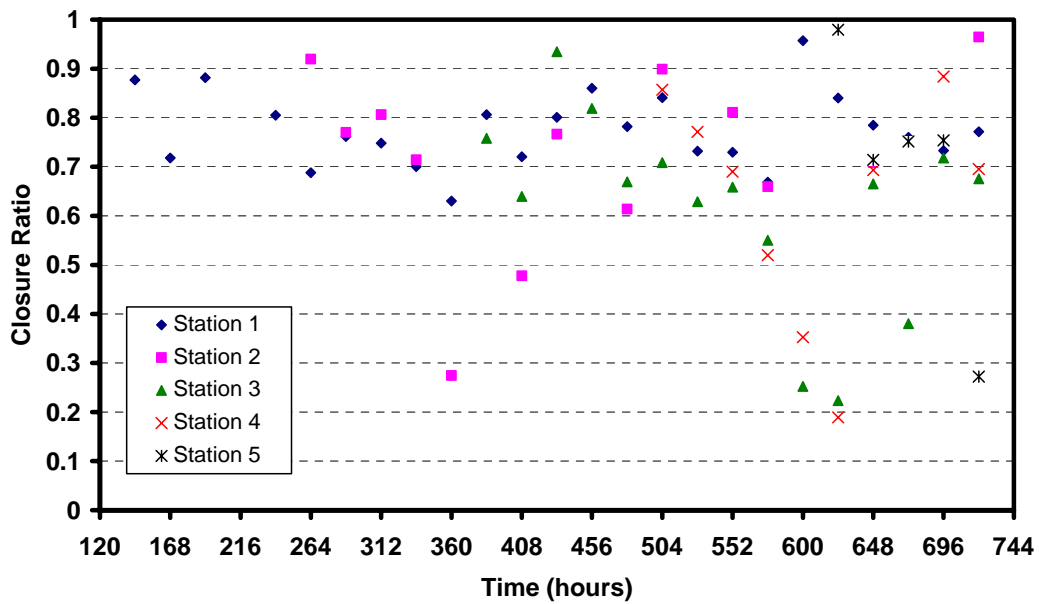
(a)
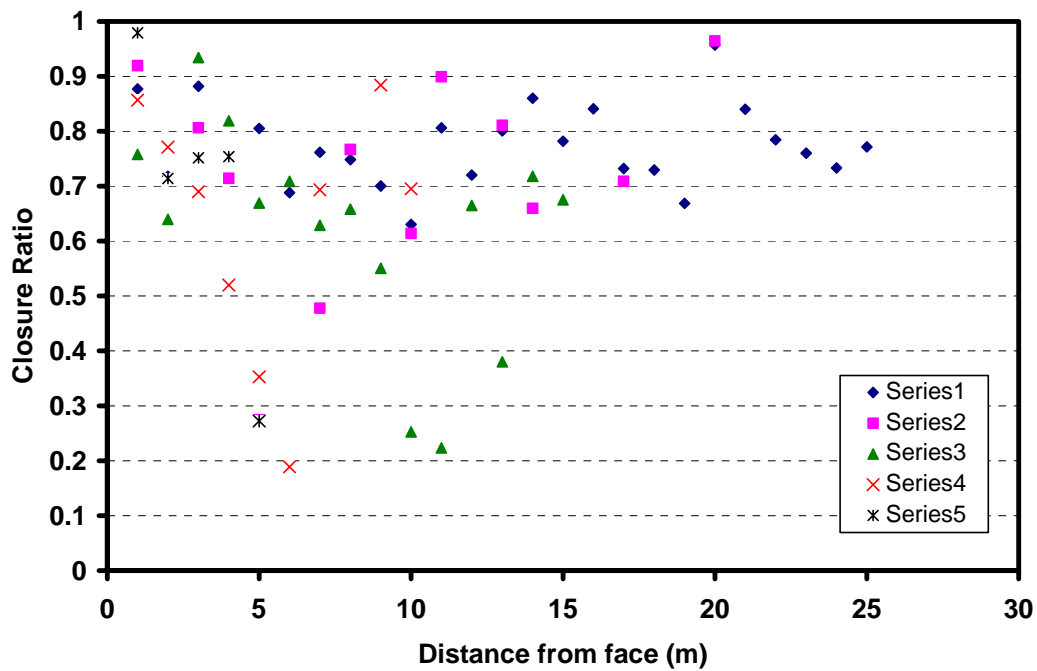
(b)

Figure 5.4.6 Observed closure ratio for high strength rock at each of 5 measuring stations plotted (a) as a function of absolute time and (b) plotted as a function of the face advance increments relative to the individual time of first observation.

6 Conclusions

The objective of this project was to investigate the feasibility of implementing a continuous real-time closure monitoring system as a decision making tool for gold mines. The first part of this report describes attempts to implement a prototype closure monitoring system. A RMT remote reading telltale system was modified to operate as a closure system and installed at Mponeng Mine. Although this system never really succeeded in collecting data from a large number of closure stations, valuable lessons were learnt. The two most serious problems experienced were communication problems from underground to surface and maintaining continuity of the cabling in the stope.

Three types of closure meters were designed and evaluated during the project. The Mark I meters manufactured from mild steel were relatively cheap and blast resistant, but suffered from corrosion problems. To overcome this problem, the Mark II meters were manufactured from stainless steel. The high cost, however, prevented widespread use. The Mark III meters were manufactured from polypropylene to be cost effective without compromising on durability. These meters were, however, not blast resistant and had to be installed behind support for protection.

The cable network used in the stope presented a major challenge in terms of maintenance. Mining activity and falls of ground resulted in frequent cable damage. In conclusion, cable connections in the stope for a mine- wide closure system is not seen as a viable option. As suggested by Malan et al. (2000), radio communication is probably the best method to link closure meters to a data logger located elsewhere in the stope.

Further problems were experienced with the communication system to surface. The RMT system required a copper link to surface. This was not available at Mponeng and attempts to use the fibre optic network were not successful. In future, mine-wide closure systems should be designed with the necessary flexibility to link-in with the existing mine communications systems, whether it is fibre optic, copper or leaky feeder.

In spite of the problems mentioned, the limited data that was captured remotely on surface illustrated the potential of such a system and was probably an industry first for remote continuous closure recording.

Following the problems experienced with the RMT system, SIMRAC requested Miningtek to use the remaining funds to collect data from one site only using standalone closure meters. The instruction was that no further attempt should be made in this project to collect data in real time.

The site chosen was the 109/51 area at Mponeng Mine. Four panels were instrumented with CSIR closure meters. Three meters per panel were installed. An observer visited the panels every day and recorded parameters such as daily face advance for each panel, falls of ground, any strain bursting and performance of the support units.

During the three month period of monitoring, only two significant events occurred. These were seismic events on 21 November 2002 and 17 January 2003 causing significant falls of ground in some of the panels. A very significant finding was that there is a very good correlation between the amount of seismic closure in the panels and where the damage occurs. In both cases the falls of ground occurred in the panels with the highest amount of seismic closure, even though the seismic events located closer to other panels that remained undamaged. If a robust real-time closure system can be developed in future, one of the big benefits of such a system will be the ability to immediately pinpoint damage after large seismic events to a greater accuracy than currently possible with seismic systems. For both seismic events, some increase in the steady-state closure rate was observed for some hours preceding the event. There is, however, not enough evidence to prove that this increase in closure rate can be used as a precursor to damaging seismic events.

A useful parameter calculated from the closure data is the closure ratio (CR), which is the ratio of the instantaneous closure to total closure following a blast. Calculation of this closure ratio for closure data collected in earlier projects showed that it is a very good measure to identify different ground conditions and possible hazards. Closure ratio values greater than 0.4 (measured in VCR stopes with a hard lava hangingwall), are typically associated with strain bursting conditions, while low values (typically < 0.1) are associated with significant risks of falls of ground. The average closure ratio calculated for the experimental site at Mponeng Mine was 0.5.

Another preliminary finding is that it appears that the closure ratio is relatively independent of position along the stope face. As an example, for a number of blasts, the total closure at the top of the panel was 16.1 mm while it was 21.9 mm at the bottom. The calculated closure ratio was, however, very similar with a value of 0.48 at the top and 0.46 at the bottom. This implies that the exact position of the closure meter in the panel might not be critical when calculating the closure ratio, while the exact position must be known when analyzing the total amount of closure. This hypothesis requires further validation, however.

Fortunately no face bursting occurred during the period of monitoring but any possible changes in closure ratio preceding these bursts could not be investigated.

Some numerical modelling using DIGS was conducted to verify the usefulness of the CR parameter. The incremental mining of a stope in a random mesh of potential fracture planes was investigated. Simulations were conducted for both a "strong" and a "weak" rock type and the closure ratios computed. A fairly wide scatter in the results is observed with no clear trends of the closure ratio as a function of time or relative position to the mining face. The average closure ratio for the "strong" material at 0.7 was, however, noticeably higher compared to that of the weaker material at 0.5 and is in qualitative agreement to the responses observed underground. It is apparent though that these very encouraging initial results support the utility of the closure ratio in discriminating the response of different geotechnical environments. However, the present numerical simulations do not support more definite trends of the closure ratio as a function of time or as a predictor of incipient face stability.

In terms of the objectives of this project, an important question to answer is whether real-time closure monitoring is necessary or will standalone closure meters be sufficient to provide the necessary data. There is no doubt that the collection of continuous closure data is very valuable to optimise support design for different mining rates, identify different geotechnical areas and the hazards associated with each area and to investigate the effectiveness of preconditioning. The data necessary to do these analyses need not be collected in real time and therefore stand-alone closure meters will be sufficient in these cases. The true value of real-time monitoring will be to immediately identify areas of possible damage after large seismic events and to warn of sudden changes in conditions that can lead to falls of ground, face bursting or rockbursts. From the available data, however, no clear precursors to rock instability could be found to date and further experimental monitoring will be necessary to justify the expense of real-time, mine-wide closure monitoring systems. It should nevertheless be emphasised that stand-alone continuous closure meters do provide substantial additional information on rock mass behaviour and their use throughout the mining industry should be widely encouraged.

6.1 Suggestions for further work

- The original objective of the project was to install prototype closure systems in two different geotechnical areas. Due to the problems experienced with the RMT system and the request from SIMRAC to collect data at one site only, no data could be collected from a Carbon Leader site. Although limited data from the Carbon Leader Reef is available, monitoring with a large number of closure instruments in a single area should be conducted to supplement some of the findings for the VCR.

- As the current work focussed on deep gold mines only, the use of closure monitoring systems to warn of unstable hangingwall conditions and possible backbreaks in shallow platinum and gold mine panels should be investigated.

- Although significant evidence exist that the closure ratio can be used to identify different geotechnical areas and the particular risks, e.g face bursting, associated with each area, the hypothesis that the closure ratio might be used to warn of an increase in risk of face bursting in a particular area is still unproven. Further measurements in areas prone to face bursting are necessary to investigate this hypothesis. This should include further measurements on the VCR.

- In terms of further development of closure monitoring equipment, it is clear that in-stope cabling is not viable and alternative methods such as radio communication must be investigated. Malan et al (2000) suggested the building of a number of prototypes using RF technology. These concepts should be further tested in underground conditions.

- Some of the practical issues associated with a mine-wide closure system need further addressing such as measuring the distance to face and the responsibility of moving the meters forward on a regular basis.

- The spatial variability of closure across panels needs to be further investigated. As mentioned above, it appears that the closure ratio is relatively independent of position along the stope face. This requires further validation.

7 List of references

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