Safety in Mines Research Advisory Committee

Final Project Report

The feasibility of a mine-wide continuous closure monitoring system 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 examines the feasibility of a mine-wide continuous closure monitoring system and proposes solutions to the practical problems associated with such a system. It is envisaged that the system would consist of a closure meter in every panel of the mine, connected to a data communications system to transfer the data to surface for analysis. This study focused on two main areas, namely, generic issues applicable to all mine-wide closure systems and some actual hardware designs.

The first generic issue addressed was the number of closure meters required in each panel. Underground data and numerical modelling indicate that closure is a very complex function of position in the panel and of the sequence of blasting in adjacent panels. Owing to the cost and the difficulty of moving these meters, it is suggested that only a single closure meter be installed in the centre of each panel. This can be supplemented with numerical modelling to estimate differences in closure for other positions in the panel.

The second generic issue investigated was the regular measurement of the distance to face as this information is required for the data analysis. Owing to problems with commercial range finders requiring a direct line of sight to the face, a magnetic field ranging device is proposed. As an alternative, a method of estimating the distance to face with reasonable accuracy is proposed.

The third generic issue was assigning responsibility for moving the meters (typically every two weeks) as the faces migrate forward. Interviews conducted at the mines indicated that shiftbosses are best suited for this role. The meter should be lightweight and easy to install and move.

For the actual hardware design of the closure meters, specifications were compiled by investigating the required sensitivity of the meters, required operating heights and mechanical design considerations. The advantages and disadvantages of various transducers were also investigated.

Radio communications have obvious advantages over cables in the stope area for transfer of data from the closure meters to a centrally located data logger. The feasibility of using cheap commercial 430 MHz transmitters and receivers was tested in an underground experiment. A range of 30 m was achieved. To increase the communication distance, a 2-3 MHz through the earth communications channel is proposed. Such a system would, however, require the use of bulky loop antennas. Both systems should be integrated with a closure meter and tested in underground conditions. It should be noted that the transmission power used by these designs are low and there is no risk of accidental detonation of explosives.

For data transmission to surface, the use of existing data communications systems were investigated. The AEL electrodet system for stope blasting appears very promising for integration with the closure system as it has a face termination box installed in every panel. As an alternative, the Multi Seismometers of the ISSI seismic system can also be configured to receive data from the closure system. If required, a dedicated data network can be built using mine telemetry components of which GST is a possible supplier.

It appears from this study that the necessary hardware for a mine-wide closure measurement system could be developed. The problem areas would be the automatic measurement of the distance to face and the human issues involved such as the regular moving of the meters. The next step would be to develop a small scale version of the system to test all the new concepts and to prove the benefits of the system.

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Glossary of abbreviations, symbols and terms

Abbreviations

IR	Infrared
LF	Low frequency
LED	Light emitting diode
LVDT	Linear voltage differential transformer
MF	Medium frequency
RF	Radio frequency
TEC	Through the earth communication
VHF	Very high frequency
UHF	Ultra high frequency

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 closure
The instantaneous closure component occurring during a seismic event or 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.

1 Introduction

A significant decrease in the number of rock-related fatalities in deep gold mines has not been achieved to date, although many expensive and varied research projects have been completed in recent years. One possible factor contributing to this apparent failure, is the lack of in-stope instrumentation to continuously monitor the behaviour of the rock mass. This lack of objective information makes any hazard assessment very difficult. Although seismic systems play a very important role in this regard, these systems give no information about hangingwall stability, the risk of falls of ground or stope closure rates, needed for effective support design.

Recent work in the SIMRAC fundamental research projects GAP332 and GAP601 indicated that continuous stope closure measurements (see Malan,1999b for an illustration of the difference between continuous and long period closure measurements) might be useful to:

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

From these studies it is clear that the design parameters and hazard identification tools available to rock mechanics engineers would be greatly enhanced by a continuous real-time mine-wide closure monitoring system. It is envisaged that such a system would consist of a closure meter in every panel. It is further envisaged that each meter be connected to a computer system in the rock mechanics offices on surface (see Figure 1.1). This would enable the generation of daily closure maps of the entire mine, indicating possible hazardous conditions and also areas where the existing support design might not be adequate.

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) 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. A further issue addressed in the project was the density of closure transducers needed in every stope panel. It was not clear if a single transducer per panel would be sufficient to characterize the entire panel.

The primary output of this project was to examine these problems and to suggest practical solutions. It was important to establish whether an automated mine-wide system would be feasible or if the closure measurements would be better conducted on a smaller scale with independent closure meters and the manual collection of data. One proposed solution for the mine-wide continuous closure monitoring problem would involve the installation of a set of autonomous and automatic closure transducers. This data would be transmitted to a central location in the longwall where it could be logged and transmitted to the surface regularly or on request. At present, the foreseeable problems in terms of hardware are the possible automated means of measuring the distance to the face, and the communication channel between the transducer and the data logger. The electronics for the actual closure measurements and the data logging, although not elementary, should not pose a major problem.

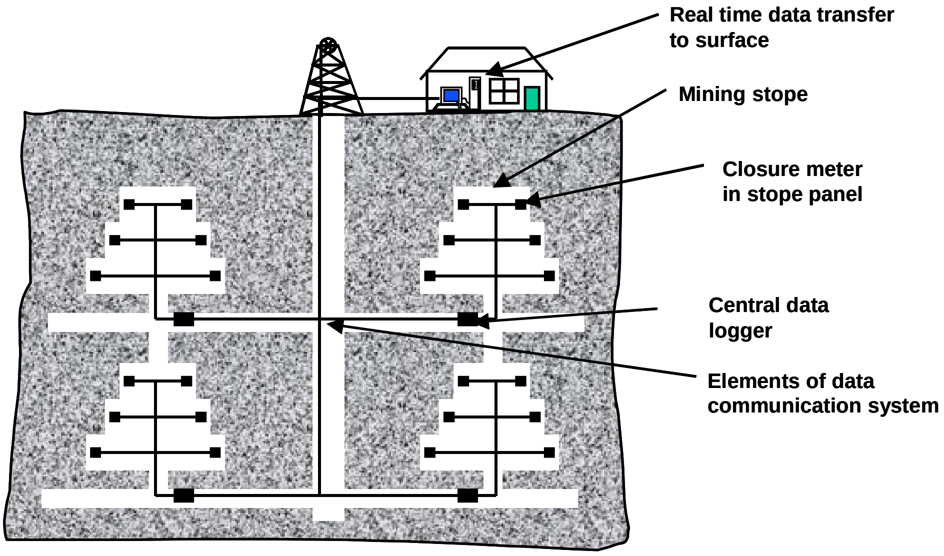


Figure 1.1 Idealized representation of a mine-wide closure system with a closure meter installed in every panel.

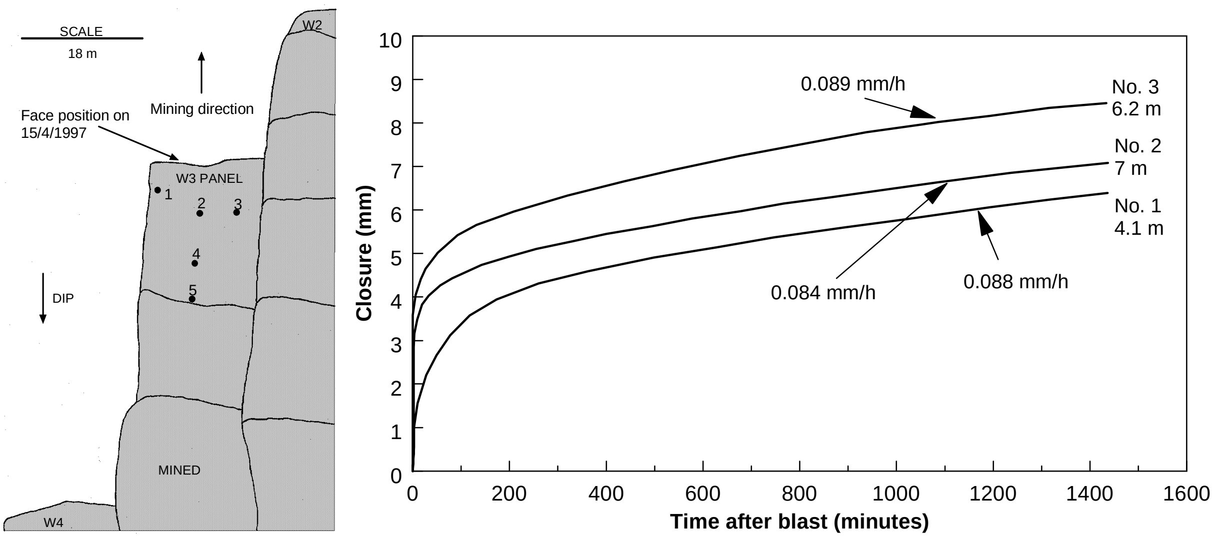
2 General requirements for a mine-wide closure system

2.1 The required density of transducers

2.1.1 Previous knowledge

The essence of this feasibility study was to examine the possibility of installing at least one closure meter in every working panel of a mine. At the outset of this study it was not clear if a single transducer per panel would be sufficient to characterize the closure behaviour or if more would be needed. A single closure transducer per panel is preferable when considering practical issues such as cost, maintenance of the network and the need to continually move the meters forward. This, however, requires a clear understanding of the effect of the position of the closure meter on the recorded data. It is well known (e.g. Leeman, 1958; Malan, 1999a) that the rate of total closure decreases as the distance of the measurement point to the mining face increases. What is not clear is how the rate of closure differs at positions parallel to the mining face (e.g. Is installing the meter close to the top or bottom of a breast panel important?).

From his experiments at ERPM, Leeman (1958) found some evidence that the rate of closure was greater near the top of the stope. Malan (1998) collected some data on the effect of spatial position on closure behaviour for the SIMRAC project GAP332. Three closure meters were installed in an up dip panel at Mponeng Mine (Figure 2.1.1a). There is a noticeable difference in the amount of total closure from the tight to the loose ends of the panel (Figure 2.1.1b). The difference at these three positions was caused by the magnitude of primary closure (see the glossary of terminology) and not the rate of time-dependent closure which was similar for all three positions. Note that for this particular case, the lead-lag distances of this panel were very large.



(a) (b)

Figure 2.1.1 (a) Plan view of the W3 up-dip panel in the 87-49 longwall at Mponeng Mine with the positions of the closure meters indicated (after Malan, 1999a). (b) Closure as a function of time for different positions approximately parallel to the face following the blast on 15/4/1997. The distances given in the graph are the distances from the closure instruments to the face before the blast.

For stiff environments such as the VCR with a hard lava hangingwall, it appears that the total closure in panels with large lead-lags is strongly affected by how close the point is to the abutment . For the high closure areas on the Vaal Reef, however, Roberts (2000) noted that the rate of closure at a specified distance to face is similar for points in the middle of the panel and close to the abutment. This was noted even for panels with large lead-lag distances.

2.1.2 Experimental site at Mponeng Mine

For this feasibility study, the earlier work by Malan was extended by conducting a closure experiment on the VCR for a panel where the lead-lag distance was small. A suitable site at Mponeng Mine was instrumented as indicated in Figure 2.1.2. An enlarged view of the panel is given in Figure 2.1.3. Figures 2.1.4 to 2.1.6 illustrate some of the closure data collected in three separate weeks of monitoring.

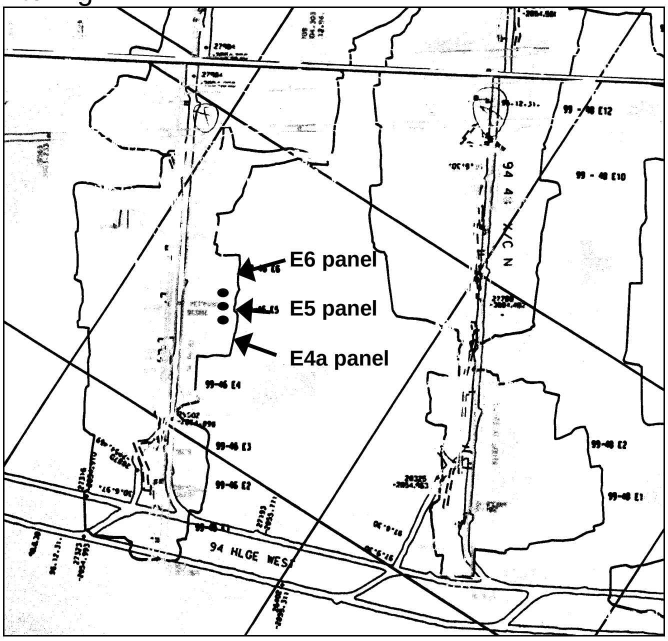


Figure 2.1.2 Installation of the three closure meters in the 99-46 E5 panel at Mponeng Mine (indicated by the black dots in the figure). The meters were installed in a line parallel to the face. The distances between these meters on dip were 6 m (between meters 1 an 2) and 7.5 m (between meters 2 and 3). At the time of the measurements, the lead lag distances between the E5 panel and the E6 and E4a panels above and below it were very small.

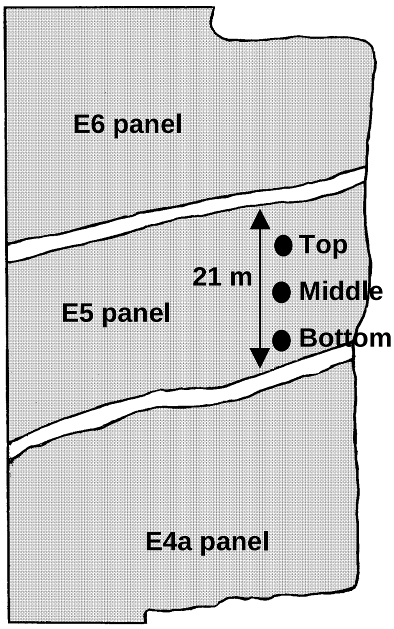


Figure 2.1.3 Enlarged view of the E5 panel and the positions of the closure meters (indicated by the black dots). Note the absence of any lead-lags between the panels.

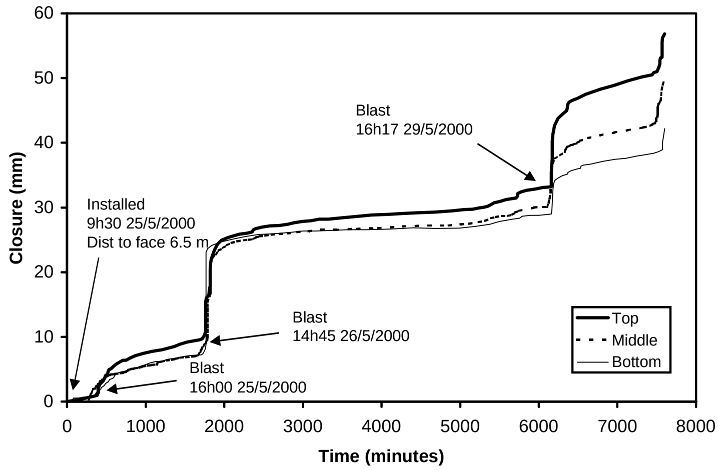


Figure 2.1.4 Closure data collected at the top, middle and bottom positions in the 99-46 E5 panel at Mponeng Mine for the period 25/5/2000 to 30/5/2000. At the end of the period, the total closure for the week was: Top = 57 mm, Middle = 49 mm, Bottom = 42 mm.

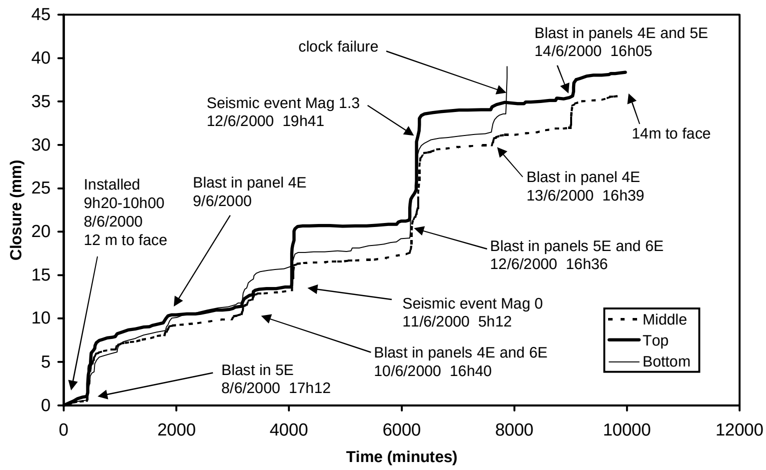


Figure 2.1.5 Closure data collected at the top, middle and bottom positions in the 99-46 E5 panel at Mponeng Mine for the period 8/6/2000 to 15/6/2000. At the end of the period, the total closure for the week was: Top = 38 mm, Middle = 35 mm, Bottom = 39 mm.

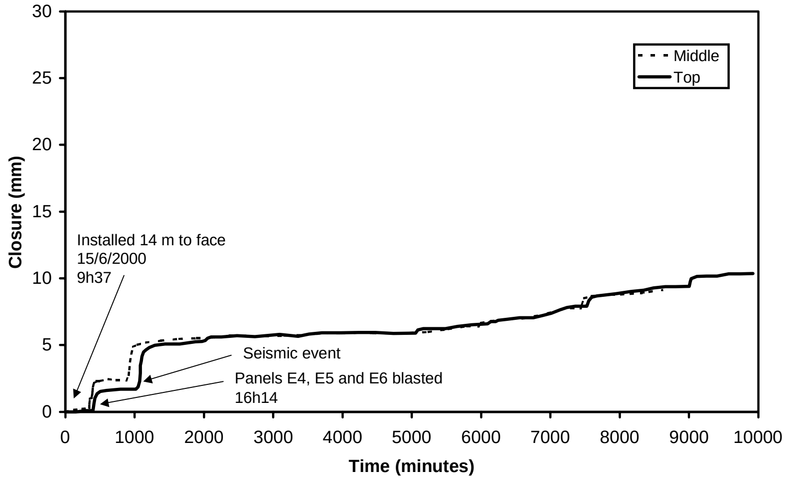


Figure 2.1.6 Closure data collected at the top and middle positions in the 99-46 E5 panel at Mponeng Mine for the period 15/6/2000 to 22/6/2000. At the end of the period, the total closure for both positions was 10 mm.

When examining the data in Figures 2.1.4 to 2.1.6, it is again very evident that the weekly rate of closure decreases as the distance to face increases. From Figure 2.1.4 it is interesting to note that the closure at the top of the panel during this period was 15 mm more than at the bottom of the panel. The reason for this is not clear as there was virtually no lead-lag between this panel and those above and below it. It can be seen from the graph that during the period from 26/5/2000 to 29/5/2000, when there was no blasting, the rate of steady-state closure was higher at the top position. The rate of closure was, however, not always the highest at the top position as can be seen from Figures 2.1.5 and 2.1.6. From Figure 2.1.5, the rate of closure was very similar in magnitude at all three positions.

2.1.3 Simulating the effect of 3D stope geometry on elastic convergence

To further illustrate the effect of a lead-lag geometry on the measured closure, some numerical studies were completed using the 3DIGS displacement discontinuity code, recently developed by Napier (2000). Figure 2.1.7 illustrates the stope geometry simulated. Note that the model assumed an elastic rock mass. The number of square shaped (2 m x 2 m) displacement discontinuities used to simulate this geometry was 2205. The depth below surface was 2200 m and the dip was 0°. Other parameters used were a Young's modulus of 70 GPa and a Poisson's ratio of 0.2. The faces 1, 2 and 3 were advanced by an increment of 2 m and the increase in convergence along the sections 1-2 and 3-4 was investigated.

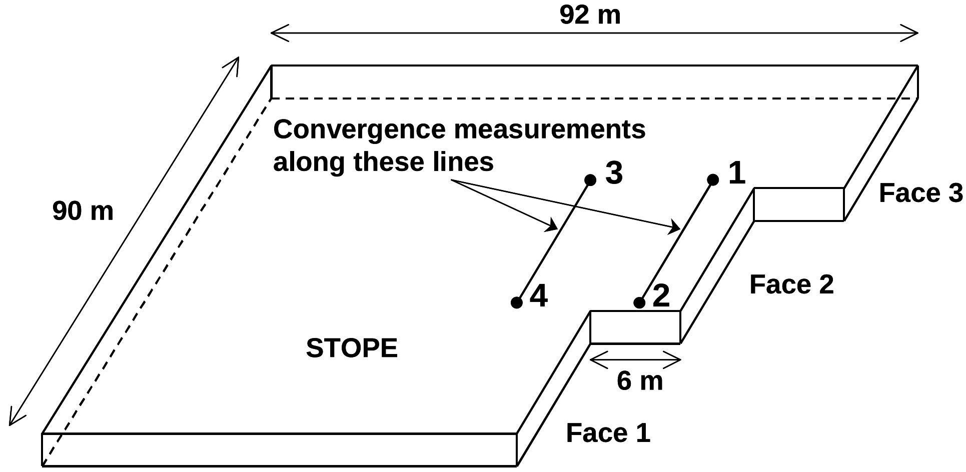


Figure 2.1.7 Lead-lag stope geometry simulated in 3DIGS. The convergence calculations were taken along section 1-2 (3 m from the face) and section 3-4 (9 m from the face).

The total convergence along the two sections of the geometry shown in Figure 2.1.7, before any face advance, is given in Figure 2.1.8. As expected the convergence close to the lead-lag abutment between faces 1 and 2 (sides 2 and 4 of the sections) is less than on the other side. Also note that this effect becomes less pronounced as the distance to face increases. For section 1-2, the difference in closure between sides 1 and 2 is 23.7 mm while it is only 15.2 mm for sides 3 and 4.

The increase in closure along section 1-2 when the faces are advanced in different combinations is given in Figure 2.1.9. A face advance of 2 m per blast was used in the simulation. The increase in convergence (and not the total convergence) is important as this is the closure measured by any closure meter which is installed when the stope has already reached a certain span. Figure 2.1.9 illustrates the convergence in panel 2, the increase in convergence in this panel is the smallest when only panels 1 and 3 are advanced. From this graph it is clear that the amount of closure measured by the closure meter is strongly affected by its position parallel to the face and by which of the adjacent panels is blasted. If only a single closure meter is installed, it might therefore be useful to install it approximately in the middle of the panel (distance 45 m in the graph) as at this point the measured convergence is least affected by blasting in adjacent panels. Figure 2.1.10 illustrates the increase in closure for section 3-4 for the different combinations of face advance. Note that the convergence behaviour at the different positions is slightly different from that along section 1-2. Again it is evident that the increase in closure measured by any closure meter in a stope will be a complex function of its location in the stope and which of the adjacent faces is advanced.

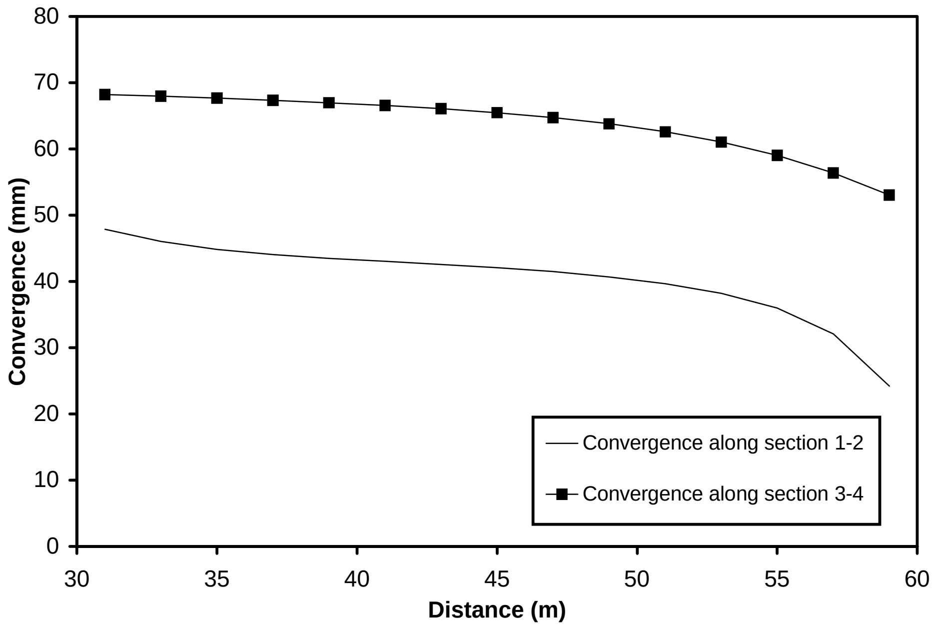


Figure 2.1.8 Total convergence along the sections illustrated in Figure 2.1.7. Sides 1 and 3 of the respective sections are on the left side of this graph.

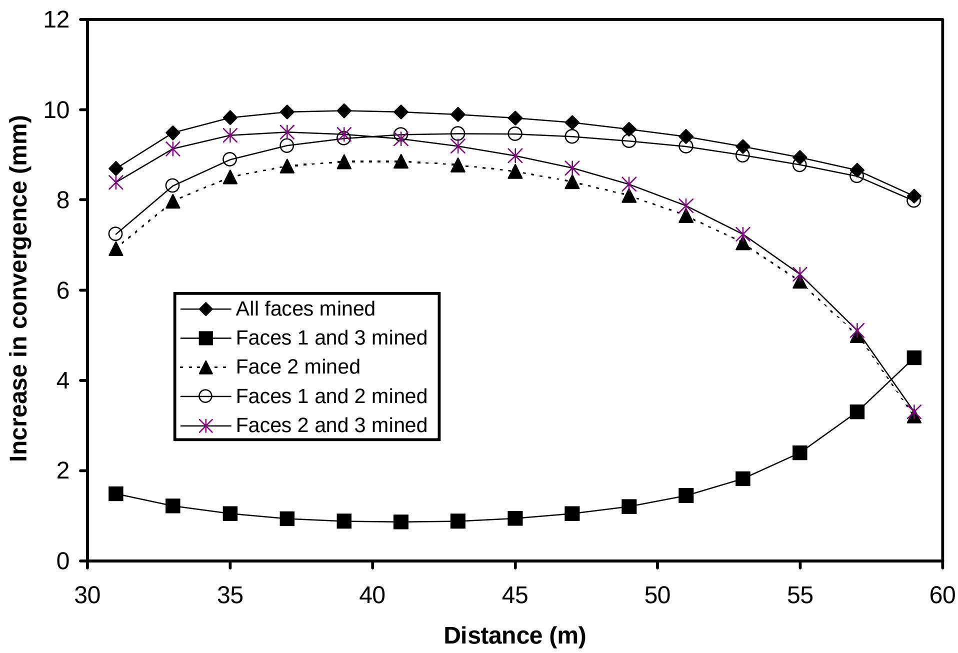


Figure 2.1.9 Increase in convergence along the section 1-2 when advancing the three faces in different combinations. Sides 1 and 3 of the respective sections in Figure 2.1.7 are on the left side of this graph.

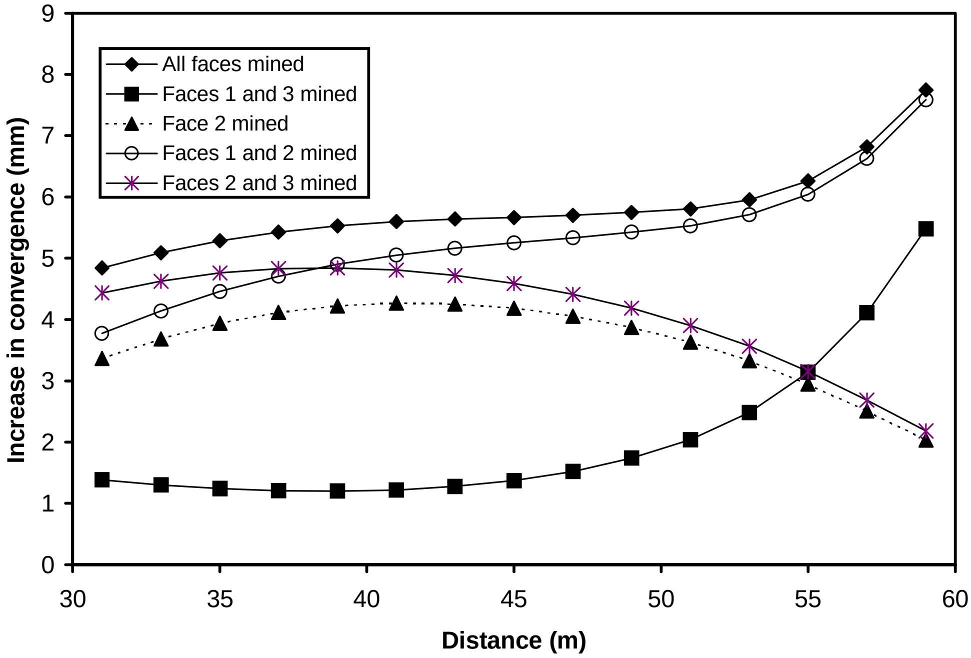


Figure 2.1.10 Increase in convergence along the section 3-4 when advancing the three faces in different combinations. Sides 1 and 3 of the respective sections in Figure 2.1.7 are on the left side of this graph.

2.1.4. Summary

The ability of rock mechanics engineers to continuously assess and optimize their support designs would be greatly enhanced with a mine-wide closure system consisting of at least a single closure meter in every panel of the mine. Fewer closure transducers would greatly reduce the effectiveness of such a system as local geotechnical conditions (such as rolls in the VCR) could result in large differences of closure rate, even for panels in the same longwall. On the other hand, a larger number of instruments would be impractical owing to factors such as continually moving the meters forward, cost of the closure instruments and maintenance of the system. For initial versions of the system it is therefore advisable to install only a single closure meter per panel. As more experience is gained with such a system, the number of meters could be increased or decreased in future.

It should, however, be noted that when using a single closure meter in panels with large lead-lags, the rate of closure measured is affected by how close the instrument is installed to the solid abutment (for a particular distance to face) and by which of the adjacent panels is blasted. This effect is more prominent in the stiff environments such as the VCR (hard lava) stopes than in stopes with high time-dependent closure rates such as in the Vaal Reef. If only a single closure meter per panel is used, it should be installed in the middle of the panel as at this point the closure is least affected by blasting in adjacent panels. Three dimensional elastic modelling should then be used to estimate how much the closure may vary for different positions in a particular panel. It is clear that a mine-wide closure system will only be effective if an accurate record of all installed closure meter positions is available.

2.2 Monitoring the position of the closure transducers

As described above, the measured closure behaviour is very dependent on the spatial position of the closure meter in the stope panel and in particular on the distance to face. A central registry of closure meter positions should therefore be created in the rock mechanics departments. When moving these meters, the responsible people should measure the distances from the meter to the face and the bottom gully and enter these values in the register. The rock mechanics engineers also need to know the updated distances to face on a daily basis. An accuracy of ± 1 m would be adequate. Three options for measuring the distance to face are available:

Automated distance measurements
Ideally, it would be very convenient if the distance measurements could be automated and these values transmitted together with the closure data to surface. As described in Section 3.2, commercial devices based on ultrasonic and laser techniques are available to measure distances. Unfortunately these devices all require a clear line of sight to the face. This cannot be guaranteed in the stope environment as the movement of broken rock and support elements can obstruct this path at any time as illustrated in Figure 2.2.1. Any measurement technique based on receiving reflected signals from the face is therefore not suitable. Another novel technique which holds some promise is a magnetic field ranging device as described in Section 3.2. This, however, would require a low frequency transmitter to be worn by the drill operators which would significantly increase the complexity and maintenance requirements of the closure system.

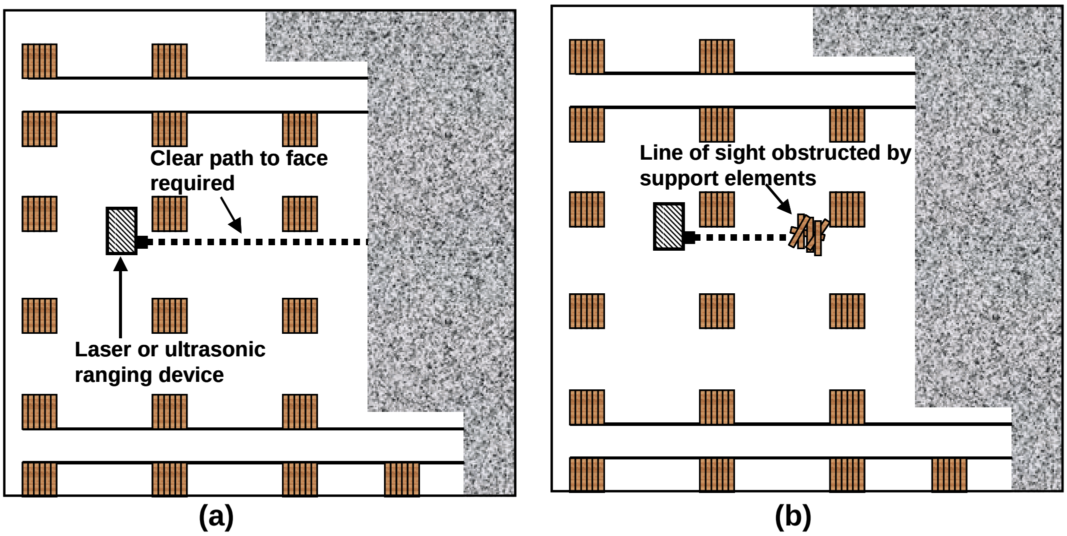


Figure 2.2.1 a) Laser or ultrasonic devices measuring the distance to face need a clear line of sight to the face. (b) This path will frequently be obstructed by broken ore or support elements.

Manual measurements
The second alternative would be to measure the distances to face manually. Ideally these measurements should be taken daily. As rock mechanics departments often do not have the human resources to do this, the only alternative is for the miners or shiftbosses to record the distances and report the values to the central registry. This is not seen as a viable option as the correct distance to face may not always be reported by production people owing to pressure on them to blast as frequently as possible.

Estimating distances from initial measurements and the number of blasts
Another option is to estimate the distance to face. This would require that the person installing the closure meter take an initial distance measurement. From this initial measurement, and by counting the number of blasts since the installation, the distance could be estimated provided the average face advance per blast is known. This would, however, require that reliable information on the number of blasts is available. One method to obtain this is from the actual closure data.

To illustrate the usefulness of this method, the data in Figure 2.2.2 was used to estimate the distance to the face at the end of the period in question. The closure meter was initially installed 6.5 m from the face. From the data, there were 4 blasts during this period. The average face advance per blast from earlier measurements appeared to be 0.7 m. The distance to face at the end of the period can be calculated as: d = 6.5 + (4*0.7) = 9.3 m. The actual measurement of the distance underground indicated a value of 9.5 m, showing the usefulness of this technique to determine the distance. This technique could easily be incorporated into the planned software which would be used to analyse the data on surface.

This method is not foolproof as the number of blasts can easily be misjudged from the closure data. Even if the particular panel is not blasted, jumps in the closure data of the panel may appear during large seismic events or when neighbouring panels are blasted. This can be illustrated by examining the data in Figure 2.1.5. Blasting in the adjacent panels 4E and 6E caused the jump in the closure data measured in panel 5E on 10/6/2000 at 16h40. This jump in closure can easily be mistaken for a blast in the 5E panel, leading to wrong estimates of the distance to face. In mines using the electrodet system, this problem would be solved as accurate records of which panels were blasted are available. Strict discipline would also be required from the people responsible for moving the closure meters, to measure the distance to face after each move and to enter this data into a central data base.

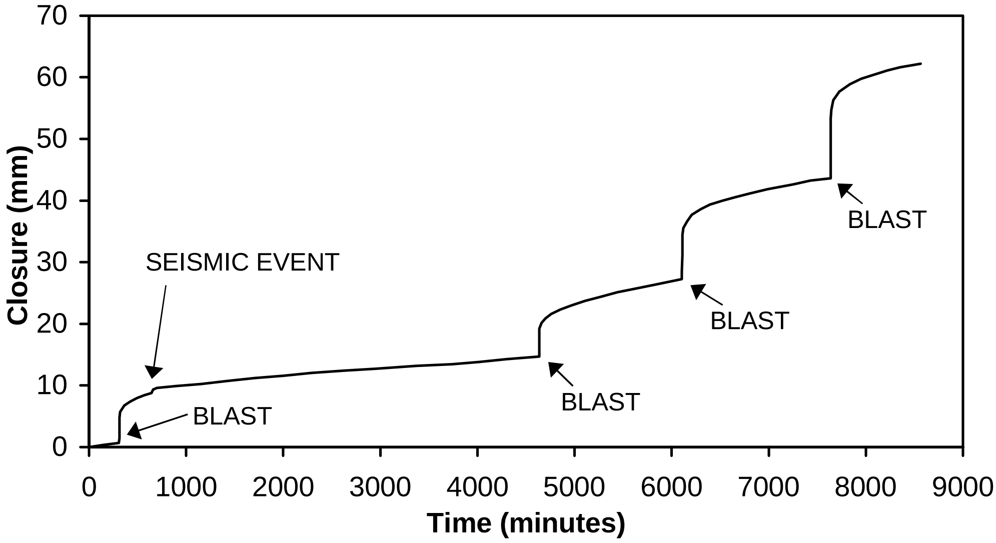


Figure 2.2.2 Counting the number of blasts from the continuous closure data.

2.3 Responsibility for moving the transducers forward on a regular basis

A difficult problem associated with a mine-wide closure system is the need to move the closure transducers forward on a regular basis as the faces are mined. This requirement makes such a system much more difficult to operate and maintain compared to a seismic system where the transducers remain in fixed positions. The value of a closure system is greatly reduced if there is any indiscipline from the people responsible for relocating the transducer array. It is therefore important that the people responsible for this task gain some benefit from the closure data and know the reason for collecting it. During this project, it was suggested to the authors that the data loggers installed in the stopes should have a display indicating relevant information to the people underground. The moving of the closure meters would be more successful if the workers in the stope assumed joint ownership of the system. From previous measurements, it was noted that the closure meters should ideally not be positioned further than 15 m from the face. For safety reasons they should not be installed behind the sweepings line. The area of installation should be chosen carefully so that the meters do not get damaged during any blasting, cleaning or sweeping operations. They should initially be installed as close as possible to the face, typically 5 m to 7 m. For a face advance of 10-15 m/month, this implies that the meters would only have to be moved every two weeks.

Interviews were conducted with rock mechanics personnel at various mines to establish if a mine-wide closure system is a viable proposition. The people interviewed were: T. da Silva (Driefontein Mine), S. Murphy (TauTona Mine), J. Oelofse (Great Noligwa), T Steyn (Great Noligwa), G. Mungar (Kloof Mine), D. Ras (Target), R. Mcgill (Mponeng) and L. de Klerk (Mponeng). It was striking how positive the response to such a system was from these people who were interviewed. The general feeling was that the data would be very valuable, especially for improved support design. With regards to the responsibility of moving the transducers, the feeling was (with one exception) unanimous that the shiftbosses should be responsible. As the shiftbosses enter their respective panels almost every day, it would be easiest for them to verify the status of each transducer regularly and move it forward if required. This would, however, require that the closure meter design be such that it is very easy to handle and move, otherwise resistance against its usage would build up very quickly. One interviewee felt that the responsibility for moving the meters should rather be given to rock mechanics observers. When discussing the issue with production personnel, they appeared to be willing to move these meters, especially after the value of such a system was explained to them. It, however, remains to be seen if this will work in practice. If the shiftboss gets the responsibility, it may be advisable for him to move the meters on a weekly basis so that it becomes part of a weekly routine.

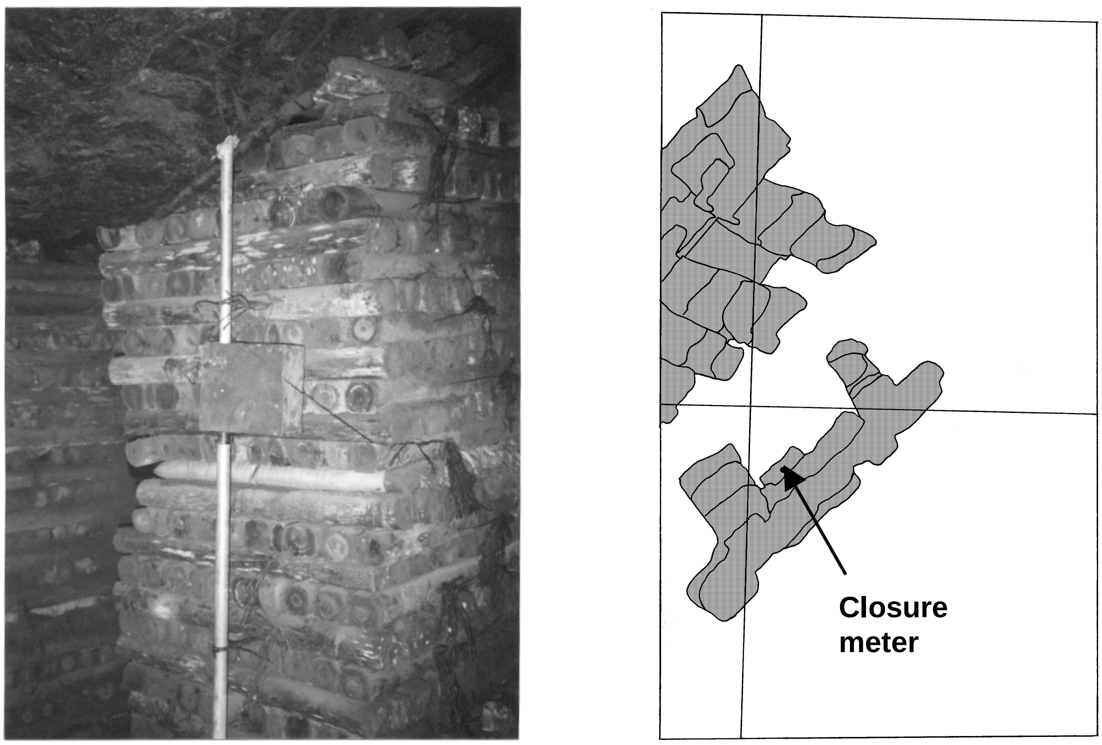
3 Alternative hardware designs for a mine-wide closure system

3.1 Specifications for the closure transducers

3.1.1 Required sensitivity

Previous data collected by Malan (1999a) indicated that daily closure rates were in the range of 1 mm/day to 30 mm/day. Adams and Gurtunca (1990) also reported closure rates as high as 30 mm/day in some cases. With regards to the rate of steady-state closure, Malan measured values as high as 1 mm/h.

The objective of this study was to investigate the feasibility of a mine-wide closure system at a variety of depths. As no continuous closure data was available from any of the shallow workings, an experimental site was established at Driefontein Consolidated No 7 shaft. The depth below surface was approximately 850 m. As the stope span was small (see Figure 3.1.1), this site is a good representation of an area with a low rate of closure.



(a) **(b)**

Figure 3.1.1 (a) Installation of the closure meter. (b) Position of the closure meter in the 1-54-4W panel at Driefontein Consolidated Mine.

Some of the closure data collected is given in Figures 3.1.2 to 3.1.5. From Figure 3.1.2 the total closure over a period of 4 days was approximately 2 mm. This implies that the closure meter should ideally have a sensitivity of at least 0.5 mm/day if it is going to be used in these shallow areas.

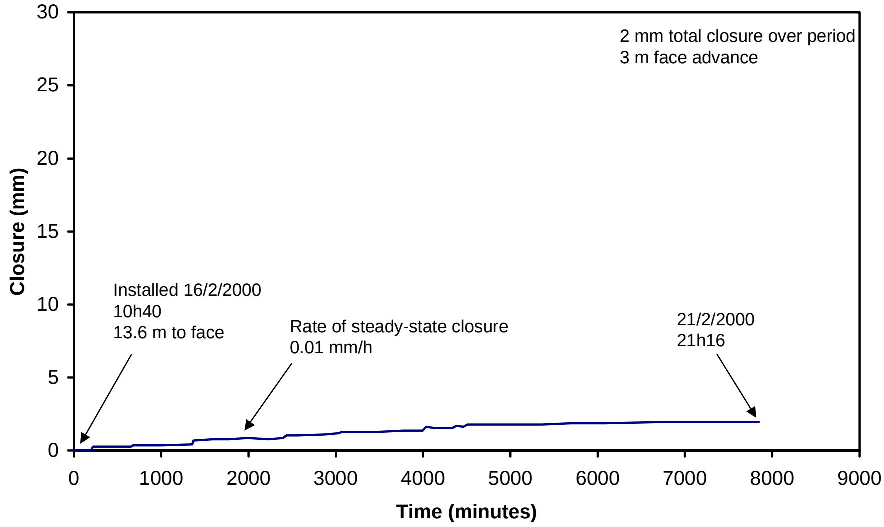


Figure 3.1.2 Closure data collected in the 1-54-4W panel at Driefontein Consolidated Mine for the period 16/2/2000 to 21/2/2000.

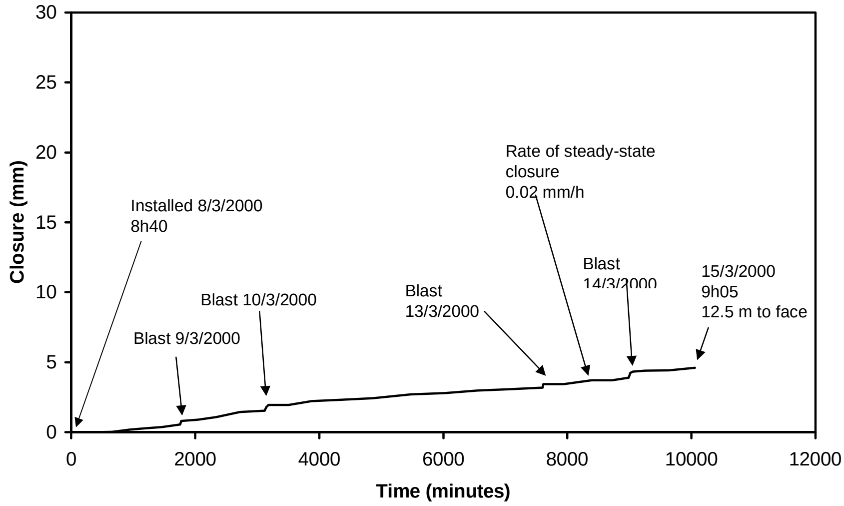


Figure 3.1.3 Closure data collected in the 1-54-4W panel at Driefontein Consolidated Mine for the period 8/3/2000 to 15/3/2000.

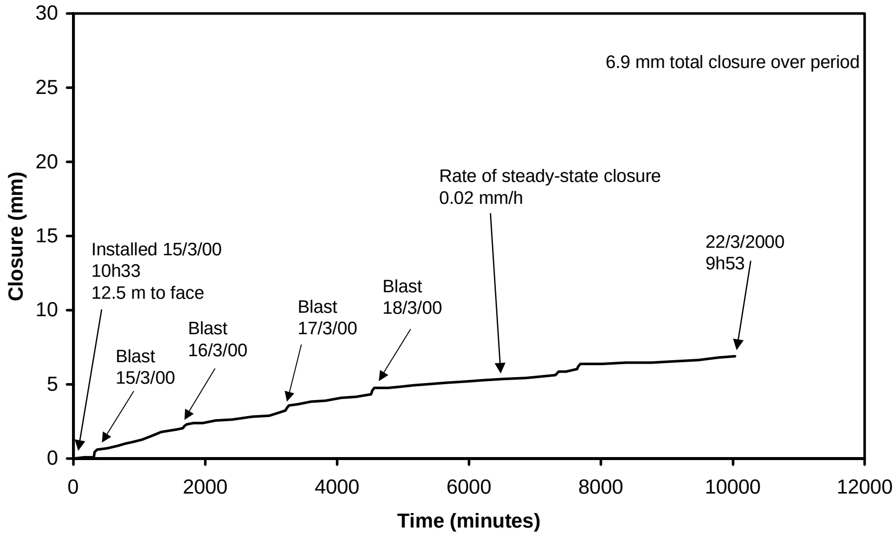


Figure 3.1.4 Closure data collected in the 1-54-4W panel at Driefontein Consolidated Mine for the period 15/3/2000 to 22/3/2000.

3.1.2 Operating height (stoping width)

In 1980 the average stoping width in the South African gold mining industry was estimated to be 1.33 m (Gay and Jager, 1980). Quite a significant variance in this average stoping width is, however, encountered underground. From earlier closure measurements on the Carbon Leader with a stoping width of 90 cm, it was noted that it was very difficult to install the mechanical closure meters as they were designed for larger stoping widths. When designing the closure meters, it is therefore important to account for minimum and maximum widths that may be encountered. Values of minimum and maximum stoping widths were compiled for the different mining areas and are given in Table 3.1.1.

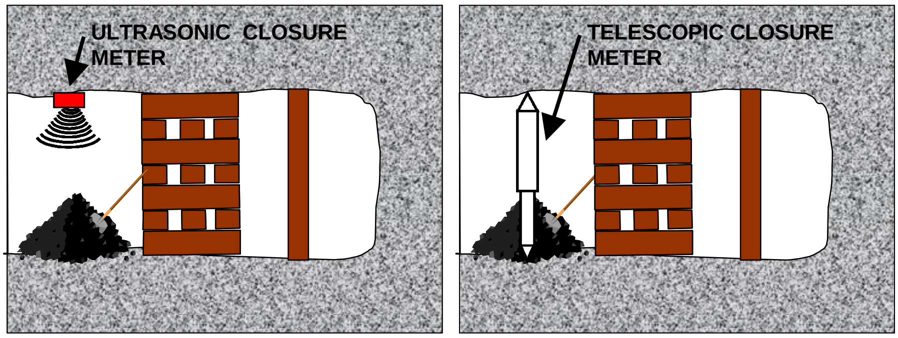
Table 3.1.1 Typical stoping widths in the various areas of the gold mining industry.

Area	***Stoping width***
Klerksdorp area	
Vaal Reef	100 cm - 120 cm
VCR	110 cm – 200 cm
Carletonville area	
Carbon Leader	90 cm – 120 cm
VCR	110 cm – 300 cm
Kloof Reef	90 cm – 120 cm
Free State	
Basal Reef	90 cm – 120 cm

It appears then that any instrument needs to cater for stoping widths in the range of 90 cm to 300 cm. As the rate of closure can be as high as 30 mm/day in some extreme cases, the instrument should allow for a total deformation of at least 300 mm (installed in a particular position for at least 10 days).

3.1.3 General requirements

A closure meter design consisting of a small device that adhere to the hangingwall and measure the distance to the footwall using laser or ultrasonic techniques is very appealing. These devices have the advantage that they are easy to install and less prone to damage during scraping and other cleaning operations. These designs will unfortunately always be prone to false readings if the underlying rock or material datum is moved (see Figure 3.1.5a). Therefore, it is suggested that the closure meter design would have to be such that mechanical contact is maintained with both the hangingwall and footwall (Figure 3.1.5b). The drawback of the telescopic meters is that they are more bulky and heavier to carry around. They also require some effort to install in areas where the sweepings are not done, as holes need to be dug to ensure contact with the solid footwall. One particular design of a telescopic closure meter developed at CSIR Miningtek before the onset of this feasibility study is given in Figure 3.1.6. (patent pending). 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 as indicated in Figure 3.1.6. This extension piece can be cut in the stope to the required length.



(a) (b)

Figure 3.1.5 False closure readings caused by the closure meter (using ultrasonic or infrared/laser distance measurement) in (a) when rock or material is moved below the transducer. This will not be the case in (b) where the closure meter makes physical contact with both the hangingwall and footwall.

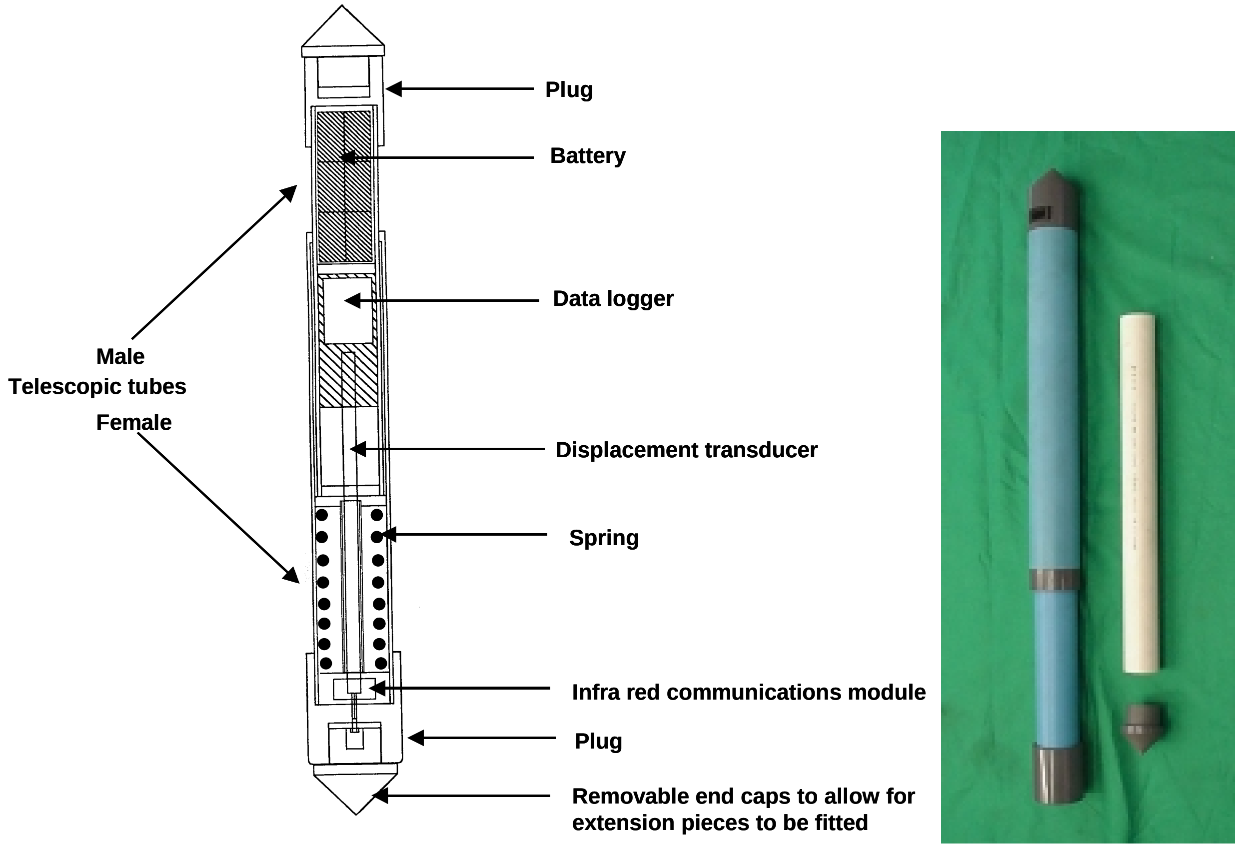


Figure 3.1.6 Telescopic closure meter developed at CSIR Miningtek (patent pending).

A further additional requirement of the closure meter is that it should be waterproof to protect the electronic components. As it is not feasible to design a blast-on closure meter without significantly increasing the weight and cost, it would be necessary to protect the closure meters from blasting damage. In stopes where packs are used, this can easily be achieved by installing the meter behind a pack. Protecting the meter becomes more difficult where backfill or elongates are used. A solution that worked well in the past was to ask the workers to install two elongates right next to each other. Installing the closure meter behind these two elongates provides adequate protection from the blast as indicated in Figure 3.1.7.

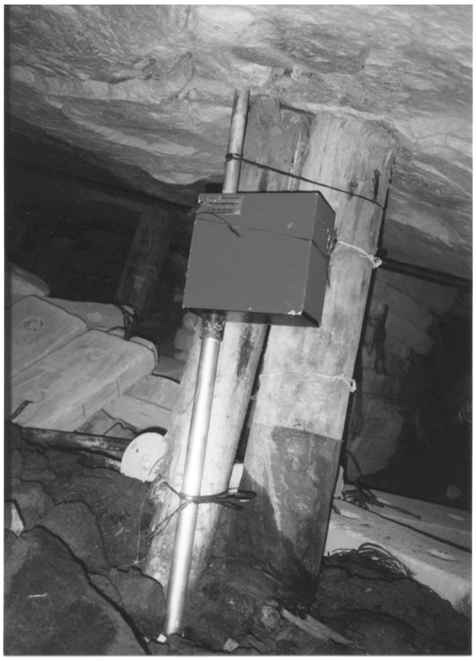


Figure 3.1.7 Protecting the closure meter from blast damage by positioning it behind two elongates which were installed next to each other.

3.1.4 Transducer options

Different transducers, which are commercially available, were investigated and the most promising candidates are given in Table 3.1.2. LVDTs (linear voltage differential transducer) were investigated but are not considered to be suitable as they require bulky signal conditioners and their power consumption is relatively high. They are also expensive with a typical LVDT and signal conditioner costing approximately R 6000. From the table it appears that the linear potentiometers or cable-actuated potentiometers are most suited for development of the closure meter. A linear potentiometer is used in the CSIR closure meter depicted in Figure 3.1.6. Of some concern is the high price of these transducers. Consideration will have to be given to developing a cheaper alternative. At the current price of approximately R 3000 a unit, the transducers for 100 closure meters (the number typically needed for a single mine) will cost R 300 000. The cable-actuated potentiometers were used previously in many closure measurements underground. A locally supplied wire pull closure meter from Qualitec Engineering (Figure 3.1.8) uses a cable-actuated potentiometer and sells for approximately R 2700. The instrument is bolted against the hangingwall and the end of the cable anchored into the footwall. As the wire is prone to damage, Qualitec also sells a telescopic closure meter using the same transducer with the cable protected inside a telescopic pipe (Figure 3.1.9).

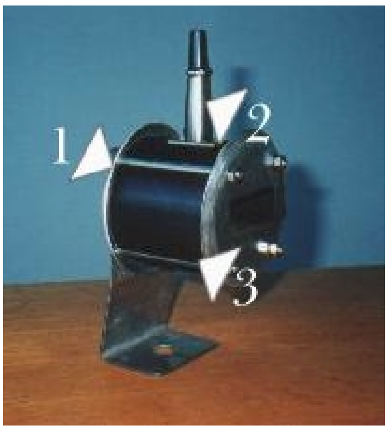


Figure 3.1.8 A wire-pull closure meter from Qualitec Engineering (courtesy Qualitec Engineering).

Table 3.1.2 Different transducers available for installation in the closure meter.

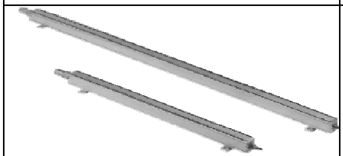
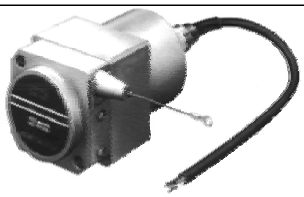
TRANSDUCER	MEASUREMENT RANGE	RESOLUTION	ACCURACY	POWER REQUIRE-MENTS	REMARKS
 **SONIC**	1 to 18 metres	10 mm	= ±5.0% FS	9 V	Cost : R485 Not suitable as the resolution and accuracy are too coarse for a closure meter
 **LINEAR POTENTIOMETER**	0.5 to 1 metre	Infinite resolution	= ±1.0% FS	0.6 W to 2 W power consumption	Cost : R3700 Long life, very low noise, waterproof and dustproof . Suitable for use in the closure meter.
CONTACTLESS  **MOTION POTENTIOMETER**	15 mm to 50 mm	Almost infinite resolution	= ±1.0% FS	Any voltage up to a maximum of 7 V	Cost : R1000 Travel too short for application as transducer in closure meter
 **CABLE ACTUATED POTENTIOMETER**	200 mm to 500 mm	Infinite resolution	Standard Linearity = ±1%	Power rating, 3W	Cost : R3000 Low noise and rugged construction. Suitable for use in the closure meter.
 **LASER**	600 mm to 15 m	5 mm	95% of max. range	9 V	Cost : R1100 Power consumption too high for closure meter. Difficult to interface with other logging instrumentation.

Figure 3.1.9 Telescopic closure meter using a cable actuated potentiometer as transducer.

3.1.5 The effect of seismic events

As noted in Malan (1999b), an advantage of taking continuous closure measurements rather than long period closure measurements is that the effect of seismicity on stope closure can be quantified. This is illustrated in Figure 3.1.10.

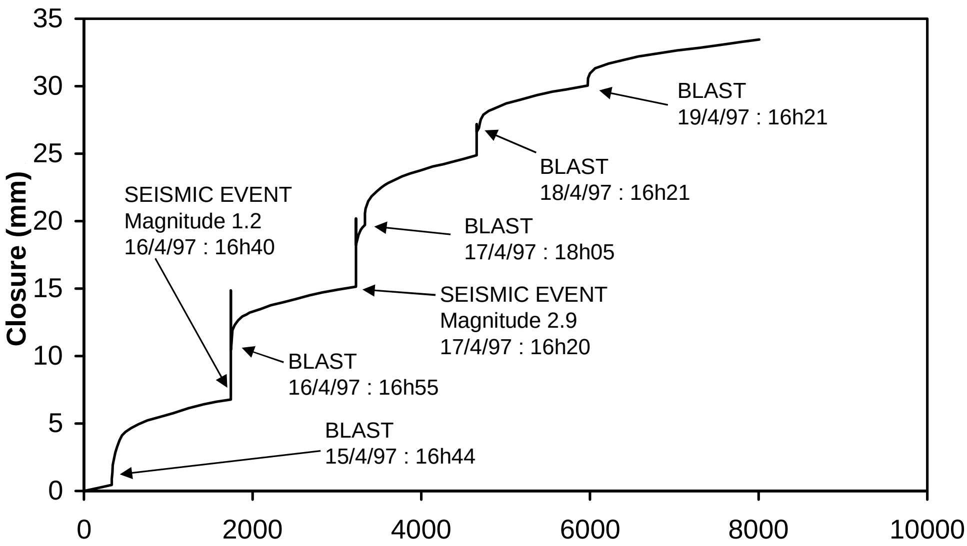


Figure 3.1.10 Continuous closure recorded in a VCR stope. The additional closure due to seismicity can be easily identified from the data. For the period over which the data was collected, the total closure was 33 mm of which the seismic events contributed approximately 8 mm.

As the closure meters will be subjected to seismic events, it is important that the mechanical design is such that it can withstand the accelerations associated with these events. It should be noted that a closure meter such as that illustrated in Figure 3.1.6, using any of the suitable transducers in Table 3.1.2, will be able to measure the total stope closure associated with a particular event. It will, however, not be able to give the high frequency response of the closure behaviour during the seismic event as the sampling rates of the loggers are too low. The maximum velocity under which the transducers give reliable readings is also less than what may be experienced during a seismic event (e.g. for some of the linear potentiometers the maximum velocity for reliable readings is 1.8 m per second). As the high frequency content of the closure behaviour during seismic events should still be investigated in other research projects, it is not considered worthwhile for the initial versions of the mine-wide closure system to aim for very high sampling rates as this would increase the cost unnecessarily. The initial focus should rather be solving all the practical problems associated with such a system.

3.1.6 Summary

Summarizing the findings given in previous sections, the closure meters need to meet the following requirements to enable their use in all geotechnical environments in the gold mining industry:

Table 3.1.3 Closure meter specifications

Design parameter	***Value***	***Comments***
Sensitivity	< 0.5 mm	
Operating height	900 mm to 3000 mm	
Maximum deformation	> 300 mm	
Mechanical construction	Telescopic tubing preferable Waterproofing necessary Sufficiently robust	Design must provide for mechanical contact with both hangingwall and footwall
Transducer options	Linear potentiometer or cable actuated potentiometer	These transducers are relatively expensive

3.2 Automated measurement of the distance to face

A number of commercially available ranging devices were considered and are described in this section. A novel method of distance measurement is also proposed. From previous measurements it is known that the maximum desirable operating range is 20 m with an acceptable accuracy of ±1 m. Details regarding some of the commercially available equipment are presented in Tables 3.2.1, 3.2.2 and 3.2.3. The technique used by all the commercial devices is to measure the time interval between a radiated and reflected impulse. Knowing the impulse propagation speed, the distance to the reflected surface is calculated. As mentioned in Section 2.2, these devices require a clear line of sight to the face, which will always be problematic. For the record, the following alternatives are available:

Ultrasonic ranging devices
Commercially available ultrasonic devices are unable to achieve the operating distances required. A maximum range of about 10 m can be expected from these devices. The wide beam divergence (roughly 8 degrees off the firing axis) will also be problematic if a high degree of directivity is required in obtaining a clear path to the face. These devices are very sensitive to the level of humidity in the air.

Laser ranging devices
Commercially available laser range finding devices satisfy both the range and accuracy requirements. With beam divergences typically being a fraction of a degree to either side of the firing axis, it is easier to obtain a clear path to the face than with the ultrasonic devices. The cost of these devices is a problem, being in the region of a few thousand rand.

Microwave ranging devices
Although these devices satisfy both the range and accuracy requirements, they are completely impractical owing to their size, weight and cost.

Table 3.2.1 Microwave rangefinders

Device Name	*Range and Resolution*	*Other Details*
Saab TankRadar REX RTG 3900 radar gauge	Range: 0.85-20 m Resolution: 0.5 mm	Weight: 30 kg

Table 3.2.1 Ultrasonic rangefinders

Device Name	*Range and Resolution*	*Other Details*
5600-0157 Ultrasonic Level Sensor (Sutron)	Range: 0.3-4.9 m Resolution: 1.3 mm	Beam pattern: 9 degrees off axis. Power requirements: 7 mA at 24 V.
Lundahl IRU-1001 (C&G Industrial Supply)	Range: 0.2-3 m Resolution: 6 mm	Beam pattern: 8 degrees off axis.
Senix Corporation	Range:0.05-10 m	
Omni Beam Q45UB Ultrasonic sensor	Range: 0.25-3 m	

Table 2.2.3 Laser rangefinders

Device Name	*Range and Resolution*	*Other Details*
Impulse Laser Rangefinder (Laser technology inc.)	Maximum range: 575 m Accuracy: 3 cm Resolution: 0.01m	Dimensions: 15.2×6.4×12.7 cm^3 Weight: 1 kg Power requirements: 2 AA batteries providing up to 20 hours of use. Waterproof to IP67
Easy Ranger LM 1000 (Directional Explosives)	Range: 0.5-500 m Resolution: 0.1m	Dimensions: 23×20×11 cm^3 Power requirements: 1 A at 220 volts AC 50 Hz. Environmental protection IP65 Beam divergence: <0.15° Price: Approximately R 7000 to R 10000.
DME 400 laser distance meter (Laser Optronics)	0.1 m resolution up to a distance of 99 m.	Dimensions: Palm sized, small enough for a pocket. Power requirements: 9V battery provides several hours of use. Price: Approximately R 2200
Lasertape FG21-HA (C&G Industrial Supply)	Maximum range: 1000 m Resolution: 5 cm	Dimensions: Not heavier or larger than a conventional pair of binoculars. Power requirements: Built in standard batteries or size AA.
LD90-3100 series (RIEGL Laser Sensors)	Range: 1-150 m Resolution: 5 cm	Beam divergence 2 Mrad

3.2.1 Proposed magnetic field ranging device

Because of the low accuracy required from the measuring device, another method of relative measurement is proposed. This method measures the *induction field* (a name given to the near-field magnetic field) produced by a loop antenna. The strength of this magnetic field has an inverse cube relationship to distance (unlike in the far-field where the magnetic field decays linearly with distance), so even a relatively small change in the distance between the source of the magnetic field and a receiver is detectable. The magnetic field distribution should be sufficiently uniform to achieve the specified accuracy.

This method could be implemented in the following manner (refer to Figure 3.2.1). One of the drill operators could be equipped with, for example, a belt-worn low frequency (LF) transmitter with a loop antenna inside the belt. During the drilling process, the operator would work in or pass the area where the closure meter is installed. A LF receiver with a loop antenna should be installed on the closure transducer. The received signal from the transmitter would reach its maximum level with the operator closest to the closure transducer i.e. when the operator crosses the line from the transducer to the face, perpendicular to the face. This maximum signal would be used to calculate the distance between the closure transducer and the receiver. A sample of the signal strength would only be taken if the signal remained constant for a few minutes, corresponding to the time taken for the drill operator to drill a hole. Any “wandering” of the operator should thus not be picked up. The value for the distance between the closure transducer and the face would consist of the measured distance plus 1.5 m, which corresponds to an average distance between the drill operator and the face. This method would almost certainly be more cost efficient than the laser ranging device. It is estimated that the prices for the transmitter and receiver would be approximately R 300 each. The drawback of the system is that a bulky loop antenna would be required at the closure meter. Human factors would also play a role here, for example, it cannot be guaranteed that the drill operator would be wearing the correct belt. The purpose of the system should also be communicated effectively as the danger exists that the perception might form that the drill operator is asked to wear the device to check that he is working hard and efficiently.

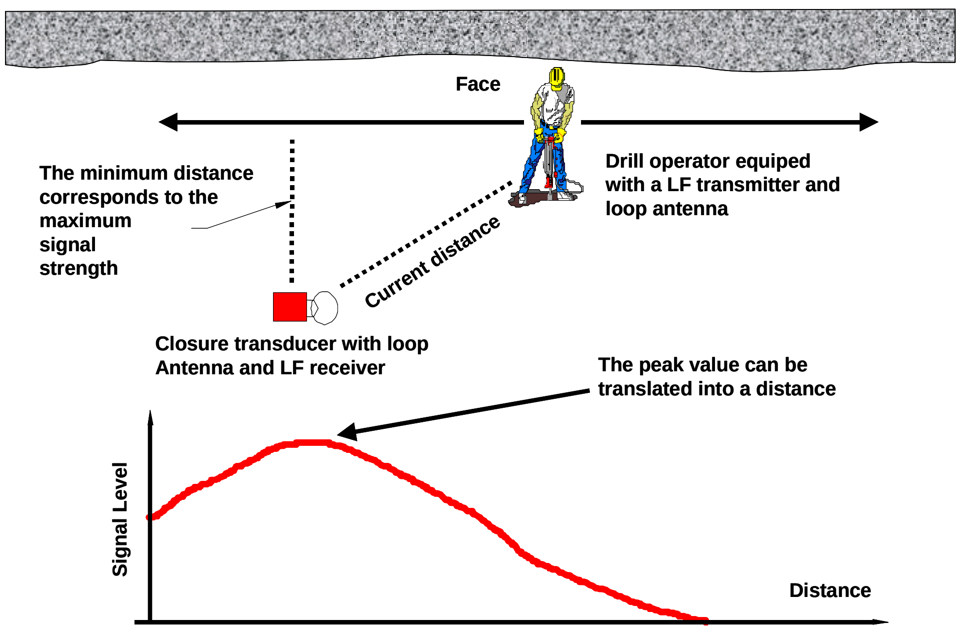


Figure 3.2.1 The positioning of the drill operator relative to the closure transducer and the face.

3.3 Communication channels for mining applications

As the mine-wide closure system is viewed as only the initial phase of a broader mine monitoring system, the possible communication channels were investigated with a broad perspective in mind. Once a proper data communications channel is established from the stope face to surface, it will have a multitude of uses such as the monitoring of temperature, methane and data from devices measuring peak particle velocities during seismic events.

3.3.1 Design considerations

Different communication channels are available for moving information from its source to the people who require it. In contrast to normal industrial applications, in the design of a communication channel for use in a South African mine, special consideration must be given to the environment in which it must operate and to a number of safety precautions pertaining to the design of equipment. Mine communication systems usually employ existing channels such as: telephone line and power cables or some dedicated physical lines such as wires, coax, fibre-optic cables or leaky feeders. Such systems operate satisfactorily under normal conditions, but are prone to damage in the event of underground disaster. To transfer data from a closure meter in a stope, down a haulage and eventually to surface, it is vital to select the proper communication channel.

When designing electrical or electronic equipment for use in mines, two important conditions have to be considered at all times. These conditions are safety and the harsh environment in which the equipment has to function. In order to fulfill these requirements, a communication channel has to satisfy the following conditions.

- *Intrinsically safe* (*when required).* Any system must provide protection against the ignition of combustible gases.

- *Mine-proof*. This means that all parts of a channel have to be protected against coal or rock dust and moisture penetration into the electronic enclosures and cables. All parts have to be robust to survive impacts caused by falling material and blasting.

- *Maintenance and repair*. All parts of a channel have to be light and exchangeable underground.

- *Must not restrict any mining operation*. Any kind of installation, maintenance and repair of a communication channel has to present no restriction to normal mining operations.

For an information system to be widely applicable, all units of the system, such as adaptors, interfaces and transducers, must be compatible and exchangeable to provide easy maintenance and repair. In this report, a number of different communication channels are considered from the point a view of safety and suitability to the underground environment. A typical operating mine was divided into three main areas as different communication channels would be more suitable in each of these areas.

3.3.2 Definition of different areas in the mine

When choosing the most appropriate communication channels to be used in a mine, it is useful to divide the mine into three different areas, as each area imposes it is own constraints and limitations on the channel. It should, however, be noted that the amount and type of information to be transferred by the channels in the different areas will ultimately determine the type of channel to be used.

Area A: Stopes
This area of the mine is responsible for most of the information that is generated with respect to production and safety. Typical parameters that can be monitored in this area are environmental information and rock behaviour such as rate of closure. The required information from the stope can be stored in a logging device or transmitted directly to the surface. Since the stope faces are continuously moving forward, the main requirement of the communication channel is mobility. The channel must also be robust, easy to maintain and able to convey the information without interfering with the normal mining operations or equipment.

Area B: The area between the stope and the shaft
As the stopes gradually move further away from the shaft, the main requirement for the channel in this area is extendibility. The channel must therefore be modular in order that sections can be added to the existing channel every time the section is advanced. One of the sources of information to be carried in this area would be information supplied by the environmental or rock engineering monitoring in area A. To create an efficient system, care should be taken to ensure that only relevant data is passed from area A to area B. The other possible source of information for transmission on this channel is information from the tramming operations, workshops or waiting areas throughout the mine.

Area C: The shaft and area between the shaft and the control room on surface
The information conveyed by this channel will contain data from both areas A and B. The only requirement for the channel is that it must be reliable and able to carry the volume of data that is provided by the different monitoring devices in the mine. Only relevant data must be transmitted, as a large amount of irrelevant information would require a channel with an unnecessarily large capacity.

3.3.3 Communication channels

Communication channels in mines are used typically for voice communication, environmental monitoring, seismic monitoring and centralized blasting control. Depending on the type of transmission medium, communication channels can be divided into three groups: physical line, wireless and combined. It is often claimed that only very high frequency communication channels must be used in new systems to provide the required data communication rate. This is not true for the underground environment as high communication rates can be achieved without moving to VHF, UHF or microwave bands. As very little of the electromagnetic spectrum is in use in underground mines, use can be made of a very high bandwidth at a relatively low centre frequency. Such an approach reduces the cost of the communication hardware and makes it compatible with many of the existing communication lines. The tendency to move to the higher spectrum is usually dictated when all the lower frequency bands have been occupied. This is not the case in an underground mine. Physical line communication media include:

- telephone lines or any dedicated hardwire (cable);
- leaky feeder;
- fibre optic line;
- power/control cable.

Wireless channels include:

- infrared (IR);
- conventional radio;
- through the rock electromagnetic wave communication.

Each of these channels is now discussed in more detail.

3.3.3.1 Physical lines

Telephone lines or any dedicated hardwire (cable)
These communication lines are widely used in South African mines, for example, for environmental monitoring, early warning and electronic blasting systems. The advantage of these lines is their simplicity and their common availability in many areas. As a disadvantage these lines are prone to damage, require maintenance and in some cases can restrict mining operations.

Leaky feeder
This is a contemporary communication medium, which provides voice, data and video signal transmission. Communication channels based on a leaky feeder have been used since the beginning of the 1970's, particularly for underground areas with a fixed geometry or slow mining advance. A leaky feeder is essentially an RF communications channel which requires that transmitting cables be laid out. These cables act as a waveguide with a leak and are similar to coaxial cables but with a more perforated outer sheath. Repeaters are required every 350 m and are powered by a DC supply sent along the core of the cable. Communication is possible within roughly 50 m of the leaky feeder cables. The Flexcom leaky feeder system (Mine Radio Systems) can provide up to 32 data control channels and up to 16 video channels, all operating simultaneously. Systems that use a leaky feeder (El-Equip, Mine Radio Systems, Emcom) are typical examples of combined physical line and wireless radio communication systems.

Optical IR communication is also compatible with a leaky feeder as implemented at Finsch Mine. The main disadvantage of a leaky feeder is that it should not be used in an environment where the cable is at risk of being damaged. At Finsch Mine, communication via a leaky feeder is impossible in the draw area. Emcom's mine underground radio (MUR) is based on a leaky feeder and provides speech and data communication and tracking of miners and equipment underground. The main concern of using leaky feeder systems is the high capital cost. In recent years more and more communication systems based on a leaky feeder have been installed in South African mines.

Optical fibre
With the establishment of affordable maintenance systems and expertise, the price of optical fibre systems is becoming competitive with conventional systems. With the advantages offered by optical fibre systems, it is foreseen that most copper wire systems will eventually be replaced with optical fibre systems. For the successful implementation of optical fibre as a channel, there are two options, namely a separate optical fibre cable or inclusion of the optical fibre in the power cable of the equipment. This second type of cable is becoming more readily available now, which gives access to a whole range of available channels that can be used for transmitting vast amounts of information. The advantages of optical fibres are:

- Optical fibres are fabricated from materials which are electrical insulators. This makes it ideal for communication in hazardous environments where ignitions could pose a problem.

- As an optical fibre forms a wave guide, it is free from electromagnetic interference, radio interference or switching transients. Cross-talk between fibres is negligible, even if many fibres are bundled together. It is thus possible to combine the power cable and the communication link.

- Cable structures have been developed that are flexible, compact and very robust. By installing the optical fibre in the power cable, an extremely rugged communication link can be achieved.

- Modulation of several gigahertz (GHz) over a few kilometers is possible without repeaters. The information carrying capacity and bandwidth of optical fibre systems is far superior to the best copper cable systems or wide band radio systems.

- At present, the cost of optical fibre cable is reasonable when compared to coaxial cable.

The disadvantages are:

- The electrical to optical and optical to electrical interface units are more expensive than the driver and receiver units used in copper cable systems.

- The maintenance and installation equipment is significantly more costly than the soldering iron and crimping tools necessary for installation of copper and/or coaxial cables.

Power line carrier

The principle of this channel is based on using the power cables of mining machines as a communication medium. Various options are available:

- *Direct galvanic connection through the pilot cores of a power cable.* This is based on a proposal for using the pilot cores of a power cable for remote control of a mining machine (Anon, 1991). Subsequent to this proposal, pilot cores were used for the transmission of encoded control and monitoring signals from mining machinery. A special protective unit should be used at both ends of the cable to protect the pilot core circuits against high voltage.

- *High frequency carrier injected into main or pilot cores of a power cable*. In this approach a high frequency carrier is applied through a capacitor to the main or pilot core of the power cable.

- *High frequency carrier induced in a power cable.* This method incorporates clip-on inductive antennas, which can be clamped around both sides of a trailing power cable at the machine and switchgear. This is the most attractive method, as it provides quick in-mine installation of a communication channel. The main difference when compared to a conventional radio system is the antenna system and propagation medium. A few kilometres of communication distance is possible.

The advantages of this communication channel are:

- As the existing power cable is used, there is no need for an additional line for the communication system.
- The influence of atmospheric moisture and dust has no effect on the propagation path.
- The installation of the system is fast and easy, only involving the clipping of the antenna around the trailing cable.

The disadvantage of the system is that the antenna used to couple into the power cable is more complex than for normal radio systems. This would increase the cost of a system.

The Australian company Balmoral Technologies has developed a mine monitoring system that utilizes existing high voltage power cables for data transmission through a mine, using an electromagnetic carrier. The system can also use any kind of cable, including a telephone line. The concept is attractive as it can make use of existing cables that are robust and well protected against damage and which, if damaged, can be repaired without any delay.

In terms of our gold mines, it may be possible to use the power cables running to the face scraper winches as a communication channel. Capacitors of some sort would, however, have to be connected across transformers to allow for continuity of the signal. One should be able to achieve a communication distance of 300 m using this line, after which the signal could be transferred to another medium.

3.3.3.2 Wireless communication

Infrared

Infrared (IR) radiation as a communication channel has been used since the end of the 70's. In France, it was initially used for the automatic reverse of a mining plough. Germany used an infrared channel for the remote control of monorail haulage systems. In the UK it was used for coal face alignment and roof support machine initiation. In the former USSR commercial production of infrared remote control for loaders, roadheaders and shearers took place from 1982, while research in this technology started in 1978 (Kononov, 1987).

Research and practice have shown that in the presence of dust not exceeding a level of 100 mg/m^3, reliable transmission distances of 30-40 m can readily be achieved without the need for special optical devices if a LED IR radiation power of 200 mW is used. Owing to the defused infrared radiation from road and pillar surfaces, as well as scattering from airborne particles, communication is possible even without a direct propagation path between an infrared transmitter and a receiver.

For line-of-sight communication, an infrared channel has the following advantages:

- High level of immunity from electromagnetic interference and good compatibility with other electronic and electrical equipment
- Low cost
- Harmless to human health
- Potential to deliberately restrict the area of communication

The disadvantages of an infrared channel are:

- Short out-of-sight communication distance
- Blocking of the direct infrared signal by equipment and personnel
- The transmission and receiving windows of the system need to be cleaned periodically

Conventional radio

Radio communication channels are available in LF, MF, HF, VHF and UHF parts of the spectrum. For underground mining applications, it is mostly useful for communication over short distances (100 - 200 m) unless a waveguide is used. In most cases, a leaky feeder system (described above) installed throughout the mine provides reliable links between portable radio stations, thereby eliminating the communication gap between terminals. The advantage of radio communication is:

- Easy to install
- Moderate maintenance costs
- Provides reasonable ruggedness and does not restrict day-to-day mining operations

The disadvantage is that without some waveguide, such as cables, rails, steel ropes or pipes, the radio channel cannot provide long distance out-of-sight communication.

Through the earth communication (TEC) channel

On average, about ninety per cent of South African collieries have a depth of less than 200 m. Therefore, local coal mining conditions favour such a method for sub-surface and up-link communication. The tests conducted by CSIR Miningtek indicate that the method is applicable to depths of 500 m. Therefore, in most gold mines, this method could be used only from one level to the next or for communications on one particular level. The main factors which limit the TEC channel performance (Kononov, 1997) are:

- surface and underground electromagnetic background noise
- rock attenuation
- surface and underground transmission power
- antenna parameters

In general, the TEC channel should operate at low frequencies as the attenuation of electromagnetic waves in rock increases with frequency. At the same time, the electromagnetic noise and interference from electrical equipment increases at low frequencies. Atmospheric noise and other surface electromagnetic interferences would reduce the up-link communication performance.

In-stope TEC channel for the mine-wide closure system

For the mine-wide closure system a communication distance of not more than 50-70 m is required in the stope. For TEC communication a magnetic loop antenna has proved to be the most effective (Kononov, 1998).

In order to avoid the data communication equipment interfering with normal mining operations, both transmitting and receiving loop antennae used for TEC data transmission should be relatively small. This implies that the total length of the wire used in the loop would be short for the frequency used. The effectiveness of these antennae, , is characterized solely by the ratio between radiation resistance, Rr, and total loss resistance, Rt, in Ohms (Kraus, 1950).

$$\eta = \frac{Rr}{Rt} 100\,\% \qquad (3.3.1)$$

The radiation resistance for a loop antenna is

$$Rr = 31200\left(n\frac{A}{\lambda^2}\right)^2 \qquad (3.3.2)$$

where n is the number of turns, A is the loop surface (m^2) and is the wavelength (m). Usually, it is difficult to expect more than 0.1 % efficiency for the practical sized loops. An antenna's radiation resistance, and therefore its efficiency, could be increased by increasing the number of turns or loop size or increasing the frequency used.

The mining situation does not provide a homogeneous medium for the propagation of radio waves as the field pattern is distorted, particularly if conductors, such as cables, pipes or rails, are present. Radio waves are induced in these conductors and propagate along them. As these conductors are randomly terminated, standing waves are set up, giving alternate maximum and minimum field strengths at a distance corresponding to every quarter of a wave length.

Not using the optimal frequency is a serious drawback of many trail systems using through the earth communication. In spite of the considerable information available worldwide on electromagnetic (EM) propagation through rocks, it was decided to concentrate more on research that has been carried out in South Africa, as the project results should fully comply with the local mining industry, and in particular the gold mining industry's requirements.

The effect of a finitely conducting earth on EM wave propagation was first analysed by Sommerfeld (1926) and later formed the basis for the EM through the earth communication theory. Formal expression of the theory has been made by Wait and Campbell (1953) and Sinha and Bhattacharya (1966). It is generally accepted that attenuation of EM waves by rock is prescribed by a skin depth δ. The skin depth is the distance which an EM wave has to travel via a conductive medium to be attenuated to 37 percent (-8,6 dB) of its initial amplitude.

Skin depth can be calculated as follows:

$$\delta = \sqrt{\frac{2}{2\pi f\sigma\mu}} \tag{3.3.3}$$

where μ is the magnetic permeability and σ is electrical conductivity. For relatively short communication distances (50-70 m), the effectiveness of loop antennae and of the whole communication system grows with frequency much faster that the rock attenuation. Previously obtained results indicated that a communication frequency of 2-3 MHz could be used for data transmission within a stope.

3.3.4 Underground propagation tests using conventional radio transmitters

For this project, a set of underground tests was conducted in the 70-47 P10 panel at Moab Khotsong Mine using 1 and 100 mW transmitters with a frequency of 430 MHz. These transmitters are cheap units available commercially from Radiometrix (see Appendix I). Although this is not the optimum frequency for use in a stope, the low price of these units (approximately R 200 for the transmitter and the receiver) makes them very attractive. Figure 3.3.1 illustrates the transmitter and receiver units. Their small dimensions (48 x 18 x 4.5 mm for the receiver and less for the transmitter) also make them ideally suitable for installation in a closure meter such as that illustrated in Figure 3.1.6.

Using the 100 mW transmitter it was possible to establish communication along a 30 m distance in the stope when the transmitter and receiver were between the same lines of support. A distance of only 15 m was achieved when two lines of support separated the transmitter and receiver (see Figure 3.3.2). Along the gully, the communication distance was approximately 100 m but no transmission was possible around the corner.

Based on results of some previous tests, communication could be achieved in an area 40 m in diameter in the stope using a frequency of 50 MHz, but to be effective, the size of the antennae (whip or wire about 1.5 m) was impractical for use in the stope.

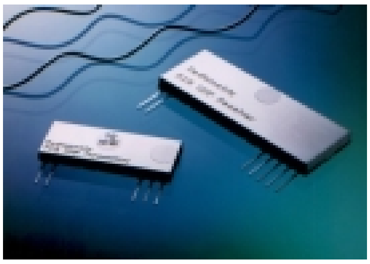


Figure 3.3.1 Data transmitter and receiver modules from Radiometrix.

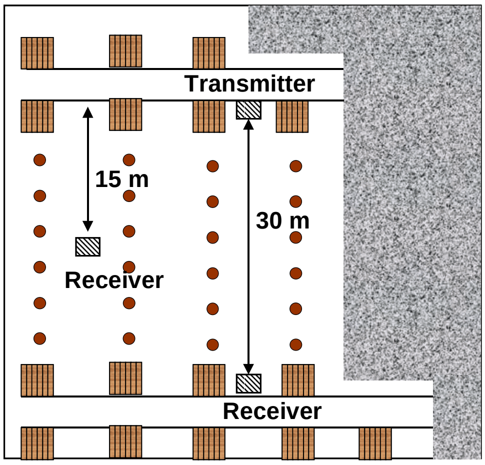


Figure 3.3.2 Communication ranges achieved with the Radiometrix transmitter and receiver in the underground experiment.

3.3.5 Recommended communication channels

Based on the above information regarding the different communication channels, the following recommendations are made for each of the areas.

- Area A : Wireless communication such as conventional radio or a magnetic through the earth channel is the preferred option in this area.

- Area B : The best approach in this area would be the use of separate optical fibre cables to move information between the stope and the shaft. The alternative is the use of a leaky feeder cable. Although the cable is cheaper than optical fibre, it would require the installation of repeaters at fixed distances to enhance the transmitted signal. Use of twisted copper wire is also feasible.

- Area C : If the requirement for this area is all the information from area A and B, optical fibre would be more suitable as a result of the greater bandwidth and higher data transmission rate. Leaky feeder cabling would be less expensive but would limit the amount of and speed at which data could be transmitted. Any type of normal industrial communication channel could be used.

3.4 Proposed communication of the closure meter with the data network

3.4.1 Communication channel

Use of the 430 MHz conventional radio channel is possible when a receiver is positioned in the same line as the closure meter or if it is not separated by more than one row of support units. The main advantage of this option is that antennae only have to be 150 mm in length. If the communication range (see Figure 3.3.2) achieved with this system is not sufficient, the other option is to use the 2-3 MHz through the rock magnetic communication channel. This would be able to cover the whole stope area. The drawback of the system is that bulky loop antennae would have to be provided. The closure meter would require a loop antenna of about 0.5 m diameter built as a “wheel” around its upper part (Figure 3.4.1). A 50 mW transmitter would be sufficient for communication with this system. At the receiver, a 1 m diameter loop should be attached to the hangingwall to receive the signal from the closure meter.

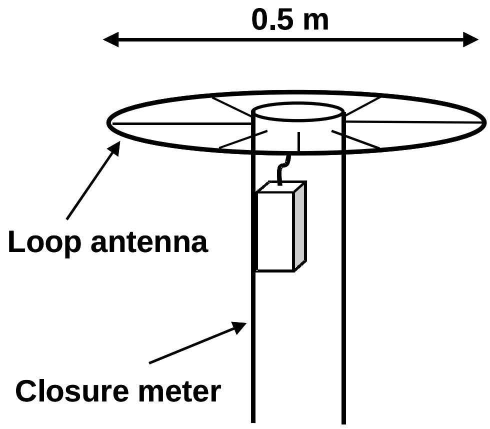


Figure 3.4.1 A loop antenna will be required when using the 2-3 MHz through the rock communication channel. Only a short whip antenna of 150 mm is required for the 430 MHz transmitters and receivers.

3.4.2 System structure and specifications

A problem with using radio communications is that the closure meter has to contain an independent battery supply. In order to provide as long as possible a period of autonomous operation, no on-board data logging should be done. The information from the closure transducer and the automated rangefinder (if used) should be transmitted to a gully where an appropriate receiver, a logging unit and a communication interface for transmitting information to the surface should be installed.

To prolong the life of the battery, the information from the closure meter would be transmitted only at pre-determined time intervals or when the rate of change of closure is significant enough to be classified as a seismic event. Should the battery be discharged to 80% of its full level, the transmitted signals would also carry a warning that the battery on the closure meter should be replaced.

It is obvious that the preferred link between a closure meter and the data logging/communication interface is radio communications to avoid the problem of possible cable damage in the stope. The proposed structure of the closure meter is given in Figure 3.4.2.

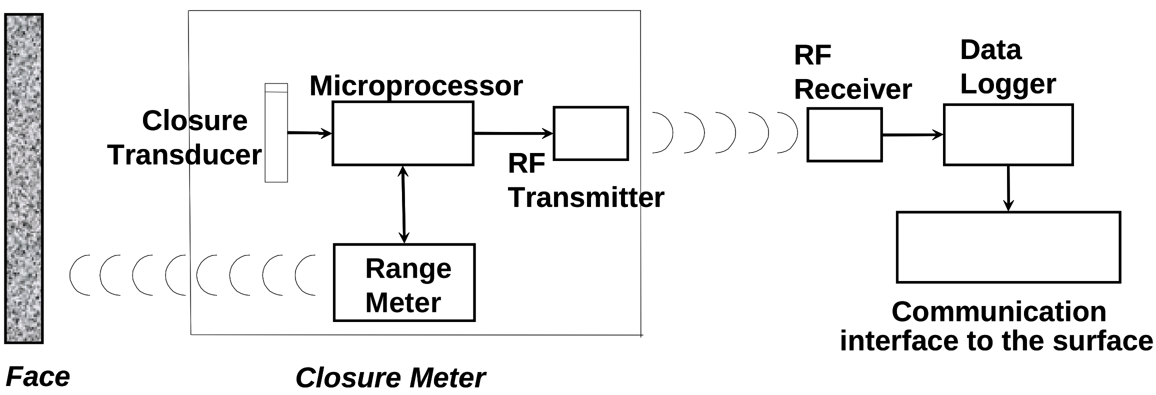


Figure 3.4.2 Block diagram of the proposed closure meter.

A simplified breakdown of the proposed operating procedure is as follows: If a seismic event occurs or if the predetermined sample period elapses, the system is roused and the microprocessor powers itself and its peripherals. The microprocessor stores the present closure value. If the automatic face distance measurement is used, a distance reading is taken. If the magnetic field monitoring device is used, frequent sampling, comparing and storing of the signals (even while the rest of the system is asleep) is required to keep track of the signal strength as the operator moves along the face. The signal processing also requires considerable intelligence to interpret stray movements of the operator. Both the closure and face distance values are transmitted to the logging unit where they are time-stamped and stored. The system goes back to sleep. The A/D conversions could be done using the microprocessors on-board A/D converters. The system could be extended to provide for the use of a number of closure transducers being monitored by a single logger. The required system specifications are presented in Table 3.4.1.

Table 3.4.1 Closure meter specifications and constraints. Some additional specifications are given in Table 3.1.3.

Characteristic	***Specification***
Power consumption	The device should be able to operate continuously off batteries (probably lithium) for two weeks
Size constraints	No rigid constraints, obviously as small as possible
Ranging device distance limit	20 m
Ranging device accuracy	±1 m
Data transmission distance	40 m

3.5 Data transmission to surface

3.5.1 Use of existing data communication systems

To reduce the cost associated with a mine-wide closure system, the use of existing mine data communication systems was investigated. Of the possible systems considered were a) the ISSI seismic system, b) the fire detection system and c) the electrodet narrow reef blasting system of AEL.

3.5.1.1 ISSI seismic system

As these seismic systems are installed in most of the deep gold mines, the feasibility of using these networks was investigated. The Multi Seismometers installed underground can have a non-seismic A/D fitted to provide a connection for the closure meters. These non-seismic A/D cards have 32 channels of which one is reserved for internal temperature measurements. If the closure meter is designed around a potentiometer type transducer, there is no need for the development of an interface other than a connection box, possibly with some form of voltage level matching. To power the closure transducers, there is a voltage source available on the non-seismic plug, but there is a limit on the amount of current that can be drawn. An independent power source might be necessary for the closure meters, depending on their design and on the length of cabling between the meter and the Multi Seismometer. A big drawback of using this seismic system would however be the large distances between the Multi Seismometers and the working panel faces. As an example, Figure 3.5.1 illustrates the positions of the geophones in a typical mine. As the Multi Seismometers are located not far from these geophone positions, it is clear that there are large distances between these stations and the working faces. The implications are that an extensive data communications network would have to be developed to connect the closure meters to the Multi Seismometers.

3.5.1.2 Fire detection system

The positions of the fire detectors at the same mine are also indicated in Figure 3.5.1. It is clear that the same difficulties apply, as with the seismic system, namely the large distances between the fire detectors and the working faces. As a fire detection system is such a vital system in the mine, there might be some resistance against its usage for other purposes.

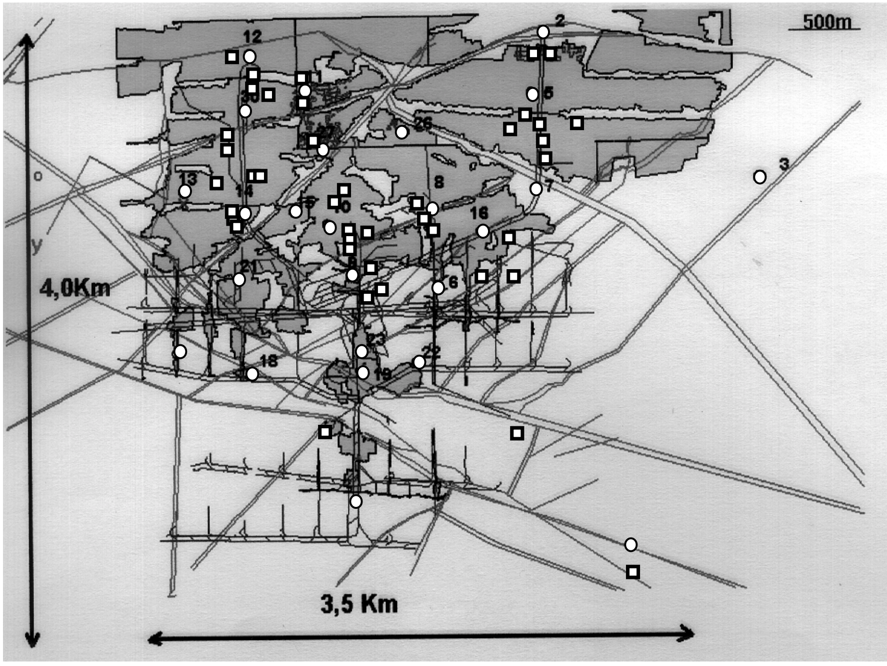


Figure 3.5.1 Positions of the geophones and fire detectors in a typical gold mine.

3.5.1.3. AEL electrodet blasting system

After discussions with the engineers at AEL (African Explosives Limited), it appears that this system has significant potential to be integrated with a mine-wide closure system. The main components of the electrodet system are the electronic detonators, face boxes and face termination boxes and crosscut control units (CCU). Information regarding the connection of blastholes per stope panel is relayed through the face boxes and CCUs to a surface based computer via a normal telephone link. Figure 3.5.2 illustrates a schematic diagram of the system. The main components of the system are shown in Figure 3.5.3. The advantages of using the infrastructure of the electrodet system as a vehicle for the closure system are:

- There is a face termination box installed in every panel. These boxes are typically kept not further than 15 m from the face. It would therefore be easy to connect the closure meter in every panel to these face termination boxes.
- A voltage source is available at the face termination boxes. This implies that the closure meter would not need an independent battery pack when using a cable to connect it to the face termination box.
- The electrodet system needs to be maintained by the mine otherwise blasting is not possible. This implies that the closure system would be more reliable as only the closure meters and their connections to the face termination boxes would require additional maintenance.
- Apart from buying the closure meters, there will be no extra cost for mines where this system is already in use.

The disadvantages of using the electrodet system for the closure system are:

- At blasting time there is a time window of approximately 2 minutes during which the system is busy with the blasting procedures and no closure data could be sent during this time. The data could however be logged and transmitted later.

- The electrodet system is not installed in every mine. Initiatives are, however, currently in place at Mponeng Mine and Great Noligwa to implement the electrodet system throughout the entire mine.

The price of the electrodet system is approximately R23 000 for a CCU, six face boxes and six face termination boxes. To install the system throughout a mine with approximately 70 panels would cost approximately R 500 000 including the cabling.

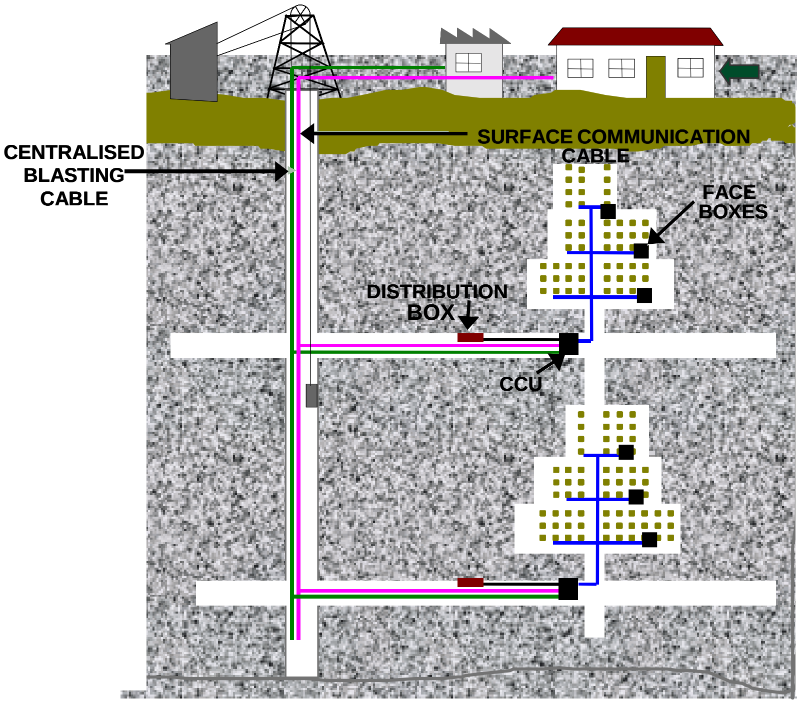


Figure 3.5.2 Schematic diagram of the components of the electrodet system installed in a mine. (courtesy AEL)

Figure 3.5.3 Components of the electrodet system (courtesy AEL).

3.5.2 Dedicated data communication lines for the closure system

As some of the existing data communication networks described above may not be available in all mines, the possibility of installing a dedicated data communications system to surface was investigated. One possibility is to build the system using telemetry components supplied by Grintek Systems Technology (GST). As these systems were specially designed for underground usage, the components are robust enough to survive the harsh conditions in the stopes. Long communication distances (30 km) are possible with the Profibus long distance wired system. One possibility is to connect the closure meters to the Telcon telemetry outstation as illustrated in Figure 3.5.4. The specifications for this outstation are given in Appendix II. It provides up to 16 digital inputs and 10 analog inputs.

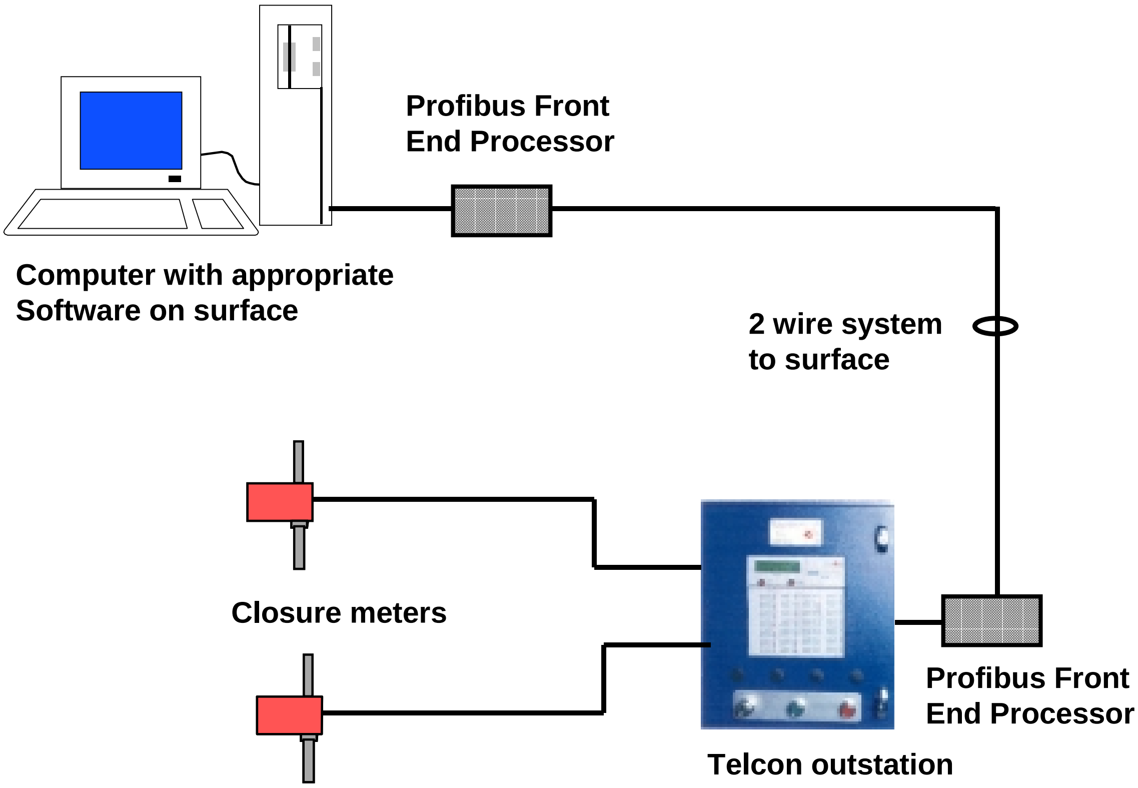


Figure 3.5.4 Use of GST mine telemetry systems to provide a data link to surface.

The prices for the various components are

Item	Price
GST Profibus Front End Processor	R 5 945
GST Mini Telcon Outstation (complete)	R 10 567

4 Conclusions

An important step to improve the hazard assessment capabilities of rock mechanics engineers would be to increase the amount of real-time data available on the rock mass behaviour in every stope panel. A good starting point would be the development of a mine-wide closure system as this would assist greatly in the design and assessment of support on a continuous basis. Data from such a system also has great potential to be used in a possible face burst hazard index, to assess the effectiveness of preconditioning and to identify areas with a large rock mass mobility leading to unstable hangingwall conditions. A spin-off could also be the automatic tracking of key face positions. It is envisaged that such a system would consist of at least one closure meter in every working panel of the mine. This study investigated the feasibility of such a system and focused on two main areas namely:

- generic issues applicable to all mine-wide closure systems independent of hardware choice
- alternative hardware designs

4.1 Generic issues

The required density of transducers
The first generic issue addressed was the density of closure transducers required in each panel. This problem was addressed by looking at historic closure data, doing an underground experiment and three dimensional numerical simulations of stope closure. It is clear from the data and numerical simulations that the measured increase in stope closure after blasting is very dependent on the position of the closure meter in the panel and also on the blasting sequence in adjacent panels. With regard to position of the closure meter, both the distance to the face and the distance to the gullies (the position of the closure meter in a line parallel to the face) play a role in determining the value of closure that is measured. The first important conclusion is therefore that very accurate records of all closure meter positions should be kept to enable meaningful data analysis. Without this data on record, the measured closure values will be of little use. As the closure is such a complex function of geometry and changes in geometry, ideally a large number of closure meters should be installed in every panel. Although this may be feasible in a few selected panels, when considering the mine-wide scale (which can include as many as 70 working panels), a large number of meters in every panel would be very expensive, difficult to maintain and very difficult to move forward on a regular basis. It is therefore suggested that for a system on a mine-wide scale, only one closure meter per panel should be installed initially. This may in future be increased as more experience is gained with such a system. On the other hand, fewer closure meters than one per panel may greatly reduce the effectiveness of such a system as local geotechnical conditions may result in large differences of closure rate, even for panels in the same longwall. If only a single meter is installed per panel, a good location for this meter would be approximately in the middle of the panel (halfway between the two gullies) as the closure in this location is least affected by blasting in the adjacent panels. It should then be realized that the closure on the loose end of the panel will be higher. Numerical modelling should be used to estimate the differences in closure for different positions in a particular panel.

Measuring the distance to face
As mentioned above, the distance to face is an important parameter needed for analysing the closure data. The second generic issue addressed in this study was to investigate the different options for measuring this distance to face, preferably on a daily basis. Three options are available:

- *Automated distance measurements:* Most of the devices considered were found to be unsuitable as they require a direct line of sight to the face. This can unfortunately not be guaranteed in an underground stope as blasted rock, blasting barricades and support material often obstruct the line of sight to the face. An alternative method of automated measurements is described below.

- *Manual measurements:* Although the miners or shiftbosses could be asked to fulfill this function, the correct distances to face may not always be reported by production people owing to pressure on them to blast as frequently as possible. If manual distance measurement is the preferred option, rock mechanics departments would have to employ special observers to take these measurements.
- *Estimating distances:* This could be done provided that the person installing and moving the closure meters took initial manual measurements of distance. From these initial measurements, knowledge of the number of blasts (which can be obtained from the closure data) and knowledge of the average face advance per blast, the new distances to face could be calculated. This technique would only be approximate as it is possible to misjudge the number of blasts from the closure data. In mines using the electrodet blasting system, accurate records of which panels were blasted and when are available.

As manual measurements will not always be feasible, the proposed method of automated distance measurement described below should be tested in the underground environment. The method for estimating the distances should only be used as a last resort.

Moving the closure meters

A mine-wide closure system will be more difficult to maintain than a seismic system as the closure meters need to be moved forward on a regular basis when the faces migrate forward. The third generic issue investigated was who should be responsible for moving these meters forward. The issue was investigated by conducting a number of interviews on various mines. All the rock mechanics people interviewed were very positive about the value of the system and, with one exception, felt that the shiftbosses should be responsible for moving these meters. When discussing the issue with production personnel, they appeared to be willing to move such meters, especially after the value of such a system was explained to them. It is vital that the design of the closure meter is such that it is easy to handle and move otherwise resistance against its usage could be encountered.

4.2 Hardware designs

Specifications for the closure transducers

For the actual hardware designs, the first issue investigated was the required sensitivity of the closure meters. An experiment was conducted in a shallow stope at Driefontein Mine. This data, together with previous closure data, indicated that the instrument should have a sensitivity of better than 0.5 mm, it should be able to operate in stoping widths from 900 mm to 3000 mm and it should allow a maximum deformation of at least 300 mm. The mechanical design should be such that the instrument maintains physical contact with both the hangingwall and footwall to prevent false readings from rock or material being moved below the meter. The study also investigated various commercial transducers for installation in the closure meters. Linear potentiometers and cable potentiometers are suitable candidates. The price of these commercial transducers unfortunately exceeds R 3000 which will make the closure meters rather expensive. Some consideration should therefore be given to the development of a cheaper alternative.

Automated measurement of the distance to face

To automate the measurement of distance to face, a magnetic field ranging device was proposed. This would require one of the drill operators to be equipped with a belt-worn low frequency transmitter. The received signal at the closure meter, as the operator passes the face, would be used to calculate the distance. Testing of such a system will have to be undertaken in future to determine if the benefits of these automatic distance measurements warrants the added complication of transmitters worn by the drill operators.

Radio communications

As the closure meters need to be moved forward on a regular basis, connecting the meters to the data communication network using cables is not seen as a viable method. The cables would complicate the process of moving the meters forward. The cables would also have to be protected from blast damage. Owing to these problems, radio communication was investigated as a means to link the closure meters to a data logger located elsewhere in the stope. An underground experiment was conducted to test the communication distance of commercial 430 MHz transmitters and receivers. Although this frequency is not ideal for underground conditions, these transmitters and receivers are cheap (R200 each) and very compact, making them ideal for installation in a closure meter. The range achieved underground was 30 m, provided there were not many support units blocking the transmission path between the transmitter and receiver.

For conditions where the 430 MHz radio communications link does not provide enough range, a 2-3 MHz through the earth communication channel is proposed. The range of this system would cover the entire stope. It would, however, require the use of a loop antenna of 0.5 m diameter for the transmitter and a 1 m loop antenna for the receiver. Both these antennae can be attached to the hangingwall.

If the radio communications link is used, the closure meter would have to contain an independent power supply. To allow for an extended battery life, the closure meter was designed to include a microprocessor. At predetermined intervals or during seismic events, the microprocessor would power the system up, take a reading, transmit the data to the data logger and go back to sleep. It is expected that a battery life of two weeks could be achieved. The price of the closure meter (excluding the closure transducer) is estimated to be R 1000 a unit.

Data transmission to surface

To simplify communication to surface, existing communication systems to surface were investigated. The use of these systems would negate the need to develop the entire communication system from scratch.

- *ISSI seismic systems:* The Multi Seismometers installed underground could be configured to provide a connection for the closure meters. Unfortunately these seismometers are often located very far from the working faces. A large amount of extra cabling would be required to develop the mine-wide closure system. An extensive communications network would have to be developed to connect the closure meters to the Multi Seismometers.
- *AEL's electrodet blasting system:* It appears that this system has significant potential to be integrated with a mine-wide closure system. The benefit of such a system is that it has a face termination box installed in every panel at a distance of typically not more than 15 m from the face. These boxes need to be moved as the faces migrate forward. This provides a convenient connection for the closure meters. A drawback of the system is that it is not installed at every mine and during blasting time there is a time window of approximately two minutes during which no closure data can be transmitted.

Alternatively, a dedicated data network can be built using mine telemetry components of which GST is a possible supplier. To conclude, it appears from this study that the necessary hardware for a mine-wide closure system can be developed, provided enough effort is directed towards it. The biggest technical problem will be the automated measurement of the distance to face if manual measurements are not taken. The solutions suggested in this report should be investigated in underground trials to test their applicability. The more problematic areas of the mine-wide closure system are the "soft" issues such as manpower to maintain the system and to move the meters forward. As such a system will only be successful if it is fully supported by both management and the underground workforce, a big communications drive would be necessary to highlight the benefits of such a system.

4.3 Suggested steps for further development of the mine-wide closure system

As a number of alternative hardware options were proposed, the next step would be to develop a small scale prototype to test the various options in underground conditions. Although prices and performance estimates for the various options are given in this report, working prototypes are required to determine the best solutions and to test the integration of the various units. In particular the following steps should be taken:

4.3.1 Hardware development

Phase 1: This initial phase will focus on the closure meters and in-stope communication.

- Prototype 1: Build a prototype of the closure meter integrated with the 430 MHz transmitter module. The receiver must be integrated with a suitable logger and the system tested underground.

- Prototype 2: Build a prototype of the closure meter integrated with the 2-3 MHz TEC communication channel. This system should also be tested in underground conditions. Both prototypes 1 and 2 should consist of a closure meter installed in a stope with a suitable data logger situated some distance away in the strike or centre gully to test the in-stope wireless communication

- Build a demonstration unit of the proposed magnetic field ranging device. For the initial tests it would not be integrated with the closure meters as the concept still needs to be proven. This should be tested in various stopes to determine if accurate distance measurements are possible.

Phase 2: If satisfactory results are obtained from phase 1, work should continue with the integration of the prototypes with suitable communication channels to surface. Different options should be tested to give reliable information on actual cost of each and ease of integration. This will include:

- Integration with the AEL electrodet system. A small scale version of the closure system would be tested where, for example, closure meters would be installed in only 3 to 4 panels in a particular longwall.

- Integration with the ISSI seismic system.

- Building an independent data network using available equipment such as the Grintek System Technologies (GST) components.

- The use of power line carriers: A prototype using the power cable of face scraper winches to move data from the stope to a nearby crosscut should be tested.

During this second phase, some consideration should also be given to developing software suitable for analysing the data.

4.3.2. Technology transfer

Before the mining industry will invest in a mine-wide closure system, the benefits of such a system will have to be clearly communicated. Parallel to the proposed hardware development, some effort must be directed towards a technology transfer stategy. The following steps are proposed:

- Produce a guide to continuous closure measurements highlighting the value that can be gained from a mine-wide closure system. This should be aimed at production personnel and management as the successful implementation of such as system will ultimately depend on them. This step should run parallel to phase 1 of the hardware development. This guide would support the seminars and workshops that should be given on this topic.

- Arrange workshops to communicate the benefits of the system. During the second phase of hardware development, the data obtained from the scaled down version of the system should be used to illustrate the usefulness of the concept.

It should be borne in mind that a mine-wide closure system will undergo the same development phases as seismic systems in the mining industry. The initial seismic systems were very crude but provided valuable data to motivate further developments of these systems. Currently, it is unthinkable to operate a deep gold mine without some seismic monitoring. It is anticipated that the closure system will go through the same development cycle.

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Appendix I

Specifications of the 430 MHz transmitters and receivers

Appendix II

Specifications of the GST Telcon telemetry outstation