Observational design of underground cable bolt support systems utilizing instrumentation

D.J. Hutchinson · V. Falmagne

Abstract The observational approach to cable bolt design uses visual observations as well as data collected from rock mass and cable bolt instruments to gain increased understanding of the response of the rock mass to the creation of mining openings and the interaction between cable bolts and the deforming or failing rock mass. Predictions of rock mass and cable bolt behaviour, made from models, can be used to determine the type of instruments required in the programme and then to compare the predicted to the measured response. Increased understanding of the interaction between the cable bolts and the rock mass can lead to changes in the type or pattern of cable bolts specified in design. A case history based on a cable bolting instrumentation programme carried out at Ansil Mine illustrates many of these principles in practice. As a result of the findings of this case history, the cable bolt design for Ansil Mine was modified to take account of the anticipated conditions of mining-induced stress change.

Résumé. L'étude de terrain pour la conception de renforcements par câbles d'ancrages utilise des observations visuelles ainsi que des données provenant d'une instrumentation du massif rocheux et des câbles d'ancrages, permettant d'obtenir une meilleure compréhension d'une part de la réponse d'un massif rocheux à des opérations minières de creusement, d'autre part de l'interaction entre un dispositif de renforcements par câbles d'ancrages et un massif rocheux en cours de déformations ou de rupture. Des prévisions des comportements de masses rocheuses renforcées par câbles d'ancrages, réalisées à partir de modèles, peuvent être utilisées pour déterminer le type d'instrumentation nécessaire pour la surveillance, puis comparer la réponse prévue à la réponse mesurée. L'amélioration de la compréhension de l'interaction masse rocheuse-renforcement par câbles d'ancrages peut conduire à des modifications des types ou des schémas de renforcements mécaniques prévus à la conception. Une étude de cas, basée sur un programme d'instrumentation d'un dispositif de renforcement par câbles d'ancrages, réalisée à la mine d'Ansil, illustre plusieurs de ces principes de façon concrète. À partir des résultats de cette étude, un projet de renforcement par câbles d'ancrages pour la mine d'Ansil a été amélioré pour prendre en compte les modifications du champ de contraintes induites par le creusement minier.

Key words Cable bolt · Observations · Rock mass · Instrumentation · Design

Mots clés Cable d'ancrage · Observations · Massif rocheux · Instrumentation · Conception

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Introduction

Cable bolts are used to support mining excavations throughout the world. Usually one or more steel cable bolt strands are inserted into each borehole and grouted using Portland cement with a water:cement (w:c) ratio ranging between 0.30 and 0.45. A conventional or plain strand cable bolt consists of six drawn steel wires helically wound around a straight centre wire and stress relieved by heat treatment.

Modifications to this plain strand design have been made whereby the steel strand is deformed to increase the geometric interlock between the cable bolt and the grout, thereby increasing the bond strength and stiffness. Such strands are fabricated by unravelling and reforming the wires (birdcage), by attachment of anchors (swages or buttons), by insertion of a nut (nut cage) or by a slight kinking of the outer wires (bulbed) (see Fig. 1). In addition, a section of strand may be decoupled from the grout, using grease or a plastic sheath, to increase allowable deformations as required. Cement grout mixtures may include additives such as sand or plasticisers, while the strand itself may have restraining elements such as plates or straps attached at the excavation surface. The selection of cable bolt hardware and installation equipment is rapidly expanding with new innovative products and installation methodologies being developed all the time.

The use of cable bolts and any other geomechanical tools at a mine site should ideally follow the cycle shown in Fig. 2. The cycle can be entered at any stage and each node or circle in the figure contains numerous uncertainties and approximations. With adequate feedback from the cable bolt installation crews and the use of verification techniques, these unknowns are reduced, understanding is increased and design and implementation of the support elements can be optimised. This paper summarises some of the work required in the "verification" node and provides a case history to illustrate the concepts.

An evaluation of cable bolt performance should involve underground observation of the stope boundaries, numerical modelling to determine the mining-induced stress changes and some form of instrumentation. If failure of the excavation or stope occurs, then collecting data regarding the volume and shape of any failure is also very important. With the results of a well-conceived instrumentation programe, it should be possible to understand the reasons for any failure of the cable bolts and to optimise the design of the cable bolt system. The collection of useful data depends upon a well-designed and installed instrumentation programme that takes a number of factors into account, including:

1. The full range of instruments available, including the advantages and disadvantages of each.
2. Definition of the types of measurements and instruments required based on the hypothesised rock mass behaviour.
3. Cable bolt performance.
4. The complexity of the rock mass structure and ore/waste contacts, the available budget and access for installation and data collection.
5. Observation of rock mass and excavation response.

The value of the data collected from the programme hinges upon a timely and accurate evaluation and interpretation of the data. To complete the cycle, the data collected through such a programme must be used to assess and optimise the design of the cable bolt system.

An instrumentation programme conducted at Ansil Mine is used to illustrate a number of the principles outlined in this paper. The design and installation of the instruments are discussed in the context of this case history and some of the data interpretation provided. In conclusion, an alternative cable bolt design for Ansil Mine is suggested, based on the increased understanding of the interaction between the cable bolt and the support elements gained from the results of the instrumentation programme.

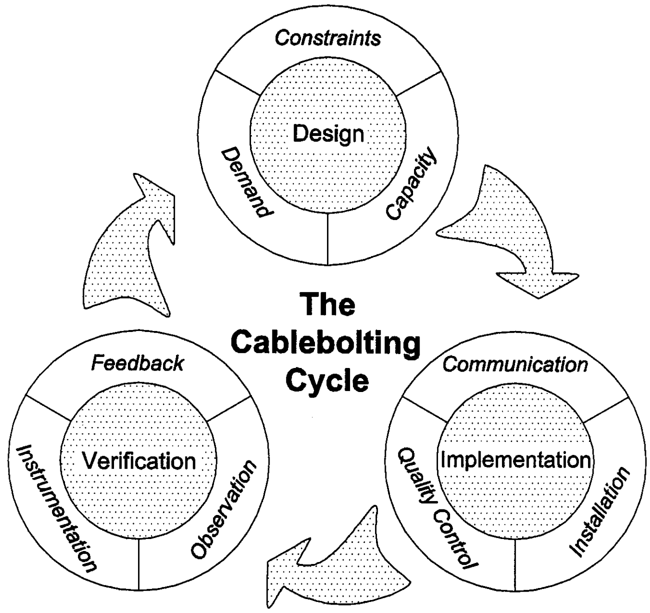


Fig. 2
The cable bolting cycle

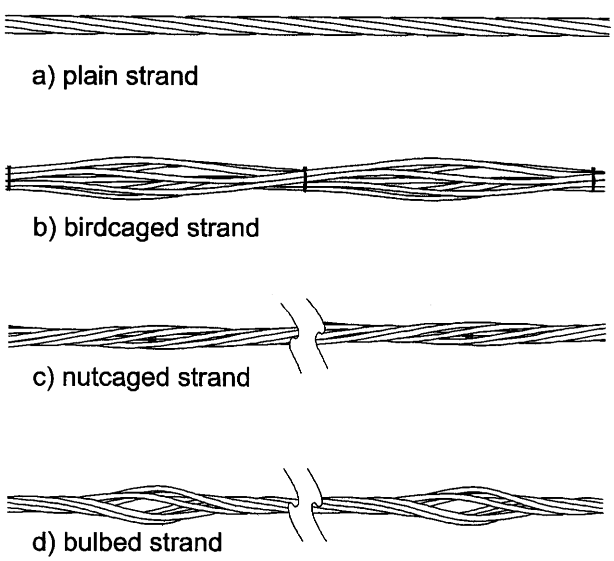


Fig. 1
Plain and modified strand steel cable bolts

Instrument toolbox

Excellent descriptions of the wide variety of instruments available and the use of instruments in mining environments are provided by Dunnicliff (1988) and the Canadian Institute of Mining and Metallurgy (1990) respectively. In this paper, the visual observations that can be made at underground stopes are also included as part of the instrument toolbox. Although visual observations are not normally considered to be part of a conventional instrumentation programme, they can provide invaluable information to aid in the interpretation and understanding of the interaction between the rock mass and the support element.

Rock mass instruments

Extensometers monitor displacement of discrete points within the rock mass (at the position of the extensometer anchors) relative to the position of the head. Extensometers are relatively inexpensive, may have several anchors within each unit at user-specified positions, are easily installed and read and no data reduction is required. The purchase cost and installation difficulties may increase where limited access, or the use of a data logger, necessitate the use of a remote readout head.

Stress cells are often overcored to take individual, discrete stress tensor measurements. Stress cells may also be left in the rock following installation to record stress changes by monitoring the strain in the rock mass over time. Successive strain measurements are reduced to calculate the rock mass stresses and can be used to determine the change in stress in the rock mass. Stress cells are precise instruments which are difficult to install and relatively expensive. Although a great deal of time is required to reduce, plot and interpret the data, they can be vital to understanding the rock mass behaviour and interaction with support.

"Visual" instruments

The borehole camera has been used frequently and with great success in underground rock mechanics investigations in recent years, as discussed by Milne and Gendron (1990). Information about the rock mass structure and response to stress change is easily "seen" by the device as it moves along the borehole, including the type, orientation, dilation and offset of structures and any stress-induced spalling or fracturing around the borehole. Ideally, the camera should be used to log the borehole(s) several times throughout the duration of the instrumentation program, thereby providing a very valuable "visual" record of the changes to the rock mass. The camera units are relatively expensive to buy but can be rented.

A number of mines are now using cavity monitoring devices, which comprise laser scanning devices mounted on specially designed arms which rotate to record the three-dimensional shape of underground excavations; see for example Miller et al. (1991), Anderson and Grebenc (1995) and Dunne and Pakalnis (1996). Combined with commercial drawing and visualisation software, the devices allow the engineer to "see" and to quantify where and how much waste rock or backfill dilution has fallen from the stope walls or where ore has been left behind. Germain et al. (1996) note that data collection from stopes of very complex shape will often require the combination of survey data shot from a number of different vantage points to ensure that all of the corners are seen. The cavity survey information can be used to gain an understanding of how well the cable bolts have supported the rock mass. Such information is also used on a regular basis in some mines to determine the volume of dilution and to provide some of the information required to assess the effectiveness of the blasting pattern and design.

Cable bolt instruments

At least two different types of instruments specifically used on cable bolts are available at this time. External spiral strain gauges, developed by Choquet (1993), are available for use with plain strand cable bolts, while internal strain gauges installed along the king wire of plain or modified strand cable bolts have been developed recently by Hyett and Bawden (1997) and are currently undergoing extensive field trials. Both types of gauges are applied to the cable bolt prior to installation in the borehole and hence instrumented cable bolts can be easily included in the normal cycle of cable bolt installation.

External spiral strain gauges

The external spiral strain gauge records an average strain over the instrumented length of the cable bolt which can be related to an average cable bolt load. Spiral strain gauges are moderately priced and can be placed at any position along the length of a cable bolt. It is recommended that the gauges be positioned on the cable bolt following a borehole camera survey of the hole. If this is not possible, gauge placement should at least be based on an understanding of the orientation and spacing of joints in the rock mass. The purchase of pre-installed gauges is preferable because complete waterproofing of the gauges is essential to their long-term continuing performance.

The cable bolt is effectively debonded from the grout over the length of the spiral gauge, because four of the six inter-wire grooves are filled with plastic-sheathed wire and the anchor ends of the gauges are heavily waterproofed with a smooth PVC tube casing and tape. As with stress change cells, the data must be reduced and interpretation can be complicated in some cases, particularly when the exact distribution and magnitude of deformation within the rock mass is not known. This is due to the fact that the true load applied to the cable bolt depends upon the location and number of joints crossing the hole over the gauge length. For this reason, borehole camera holes should be located close to any spiral strain gauged cable bolts and logged frequently to provide a record of the detailed rock mass movement.

Internal strain gauges

Internal strain gauges recently developed by Hyett et al. (1997) are placed on the cable bolt king wire, allowing them to be used for both plain and modified strand cable bolts. As they are installed on the inside of the cable bolt, these gauges do not interfere with the interaction between the grout-cable bolt interface. De Graaf et al. (1999) note that the instrument is similar to a miniature multipoint extensometer. A low-cost electronic readout head, supplied with the instruments, is easily inserted into a borehole with the instrumented cable bolt. Readings may be taken using either a hand-held unit or a data acquisition unit.

Visual observations

Visual observations made throughout the mining of the stopes under investigation can provide information that is extremely valuable for the interpretation of both the interaction between the rock mass and cable bolts and the response of the stope boundary to the creation of the mining excavation. Underground visits to observe the rock mass and cable bolts should be made as frequently as possible, especially during the final stages of blasting the stope. Visual observations should be supplemented with photographs or video images which create an excellent record of the appearance of the rock mass. When observing the stope boundaries underground, it is important to make note of any evidence of rock mass failure (e.g. new cracks forming, joints opening up, spalling, slabbing or wedge failure) and of the appearance of any exposed cable bolt ends (Fig. 3).

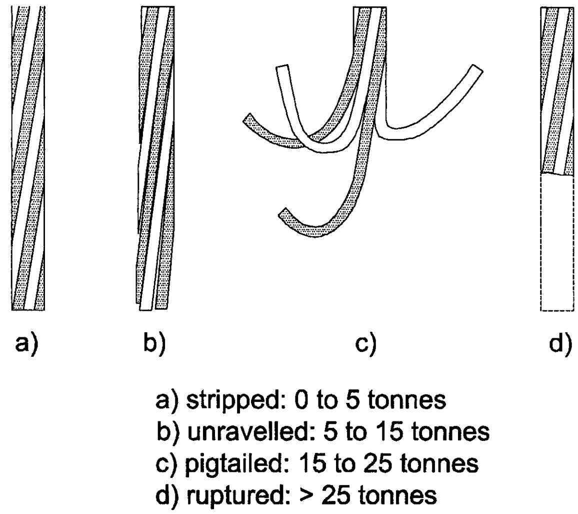


Fig. 3
Visual appearance of failed cable bolts as observed in laboratory tests by MacSporran et al. (1992)

Locating rock mass instruments

An understanding of the potential rock mass failure mode and its likely extent is an important starting point for the design of an instrumentation programme, as it is for the design of cable bolt or other support systems. Predictions should be made of the possible failure mechanism, the volume of rock affected and the displacement and stress changes in the rock mass. These factors will help to determine the number, type, length and accuracy of the instruments that should be used in the programme.

Rock mass failure can result from two or more inclined structures combining to form a wedge, excavation parallel structures liberating slabs of rock in a peeling failure, or blocks of rock progressively unravelling from the surface of the excavation (Fig. 4). Failure could also result from a combination of two or more of these modes, or could be initiated by other factors such as dynamic loading or stress-induced failure of the rock mass.

Initial predictions of the response of a rock mass to mining are generally based on a combination of approaches, including:

1. Precedent experience in similar rock mass conditions summarised into empirical design charts (Potvin and Milne 1992; Diederichs et al., 1999).
2. Observations of the performance of other excavations on the same mine site.
3. Mechanistic models such as analysis of wedge stability or voussoir beam stability (Diederichs and Kaiser 1999a,b).
4. Numerical modelling to assess mining-induced stress levels and changes (Hoek et al. 1995).

This paper examines the influence of structure on the failure mode and the instrumentation data collected at Ansil Mine. The effect of mining-induced stress levels and stress changes on rock mass and support behaviour are also important for this case history and are discussed elsewhere, by Hutchinson and Grabinsky (1992), Kaiser et al. (1992) and Grabinsky et al. (1997).

Consideration of the three failure modes shown in Fig. 4 results in the hypothetical predictions of rock mass failure shown in Figs. 5, 6 and 7 for wedge, peeling and unravelling failures respectively. In these plots, the response of several instruments to the rock mass movement and

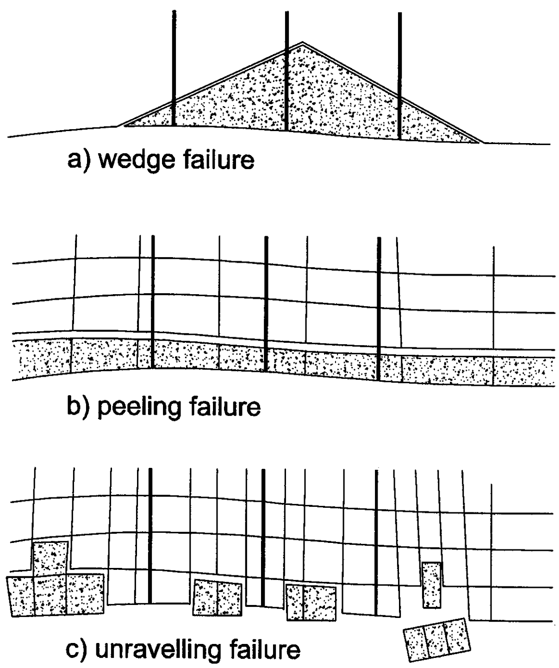


Fig. 4
Possible rock mass failure modes

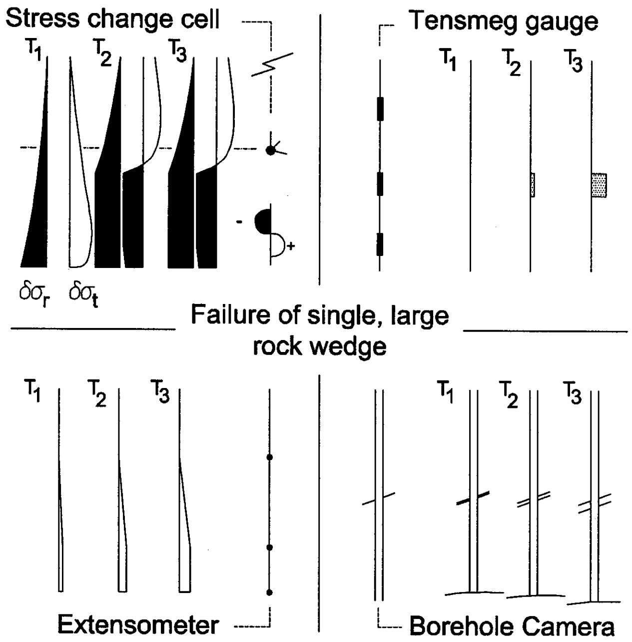


Fig. 5
Hypothetical data recorded by rock mass and cable bolt instruments during wedge failure

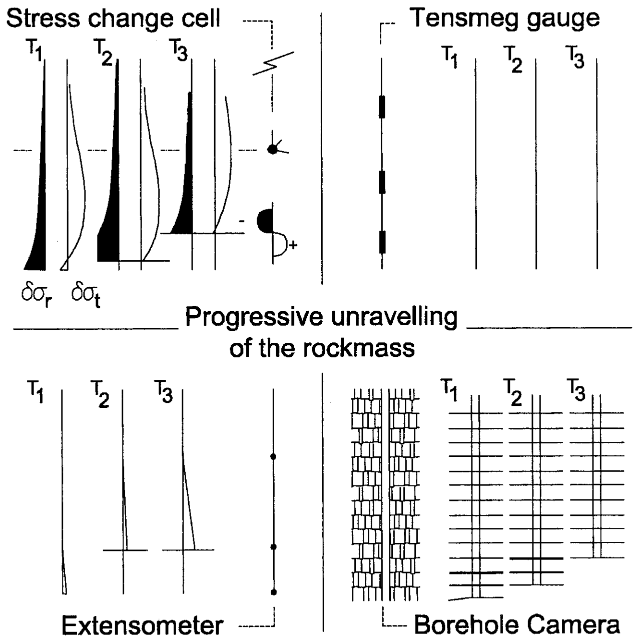


Fig. 7
Hypothetical data from rock mass and cable bolt instruments as rock mass fails by unravelling

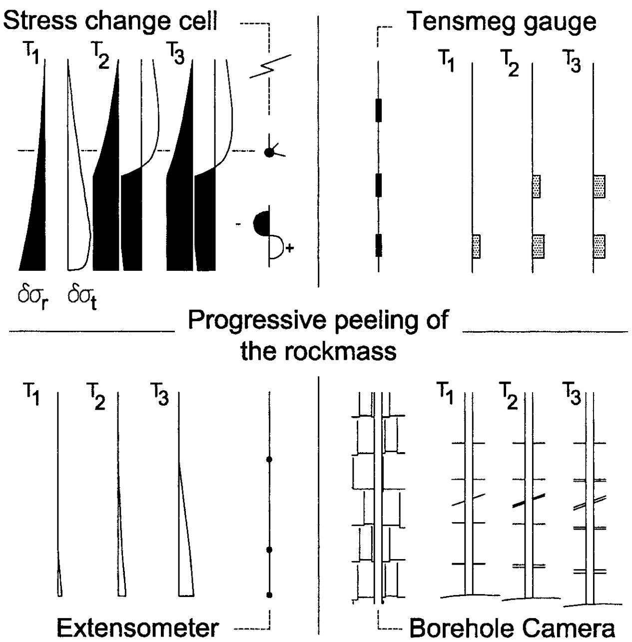


Fig. 6
Hypothetical data recorded by rock mass and cable bolt instruments during peeling failure

failure is suggested. The magnitude of the readings taken by the extensometer and cable bolt gauges is indicated by the offset of the rectangular bars and the type of visual observations made by a borehole camera are shown. For the stress change cells, the tangential stress change, t, is oriented parallel to the excavation boundary, while r, the radial stress change, is perpendicular to the excavation boundary. A black, filled zone indicates a negative stress change while a white zone indicates a positive stress change. During a perfect wedge failure, a single discontinuity will open up at some distance away from the excavation surface (Fig. 5). Over time, as the discontinuity opens further and the wedge is separated from the rock mass, ultimately the instruments will read:

1. A drop in stress equal to the original stress within the wedge (stress change cells).
2. Constant displacement at all points below the open joint (extensometers).
3. Concentrated load at one point on the cable bolt (spiral strain gauges).
4. Increasingly greater displacements on the joint (borehole camera).

Predictions of the instrument responses for peeling and unravelling failures are shown in Figs. 6 and 7 respectively.

When locating rock mass instruments for a study, it is important to predict where movement and failure might occur, based on such hypothesised rock mass failure modes. Once this understanding is gained it should be possible to more effectively locate the instruments for the programme and collect useful data for interpreting the interaction between the rock mass and support elements.

Locating cable bolt instruments

As with the rock mass instruments, it is important to locate cable bolt instruments where they will collect the most useful information. The response of the cable bolt to the creation of an excavation will be related to the rock mass response as these support elements respond to deformation of the rock mass. As a consequence, cable bolt support should be installed and instrumented where excessive deformation or stress change is predicted from the hypothesis of rock mass behaviour.

Models that predict plain strand cable bolt behaviour have been developed by Yazici and Kaiser (1992) and Hyett et al. (1995). These models have been incorporated into computer programs such as CABLEBOND by Diederichs et al. (1992) and CABLE by Bawden et al. (1995) which have been calibrated using extensive suites of cable bolt pull test data. Both models will predict the capacity of a plain strand cable bolt for specific input data, including the borehole diameter, grout quality (water:cement ratio), rock mass strength and stress change. CABLE also predicts the distribution of load along the length of a cable bolt for specific input parameters, including joint spacing.

Figure 8 shows the effect of stress change on bond strength for a cable bolt grouted with w:c = 0.375. For example, for a rock modulus of 10 GPa, a stress change of –10 MPa results in a decrease in ultimate support bond strength of approximately 50%. Figure 9 gives an example of the influence of stress change on predicted pullout load for w:c = 0.4 and $E_{rockmass}$ of 13 GPa (Diederichs et al. 1993). With these tools it is possible to gain an increased understanding of the field cable bolt performance by comparing the predicted cable bolt capacity to the instrumentation data. Useful data for comparison include rock mass deformation and stress change as well as the cable bolt strains and loads.

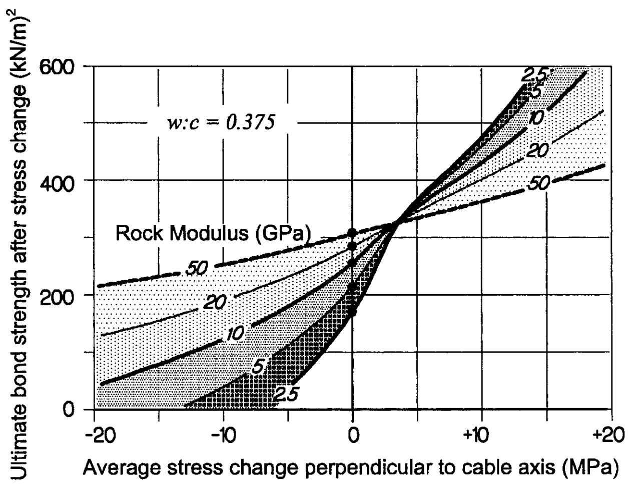


Fig. 8
Effect of stress change and borehole confinement on cable bolt bond strength predicted by the CABLEBOND model

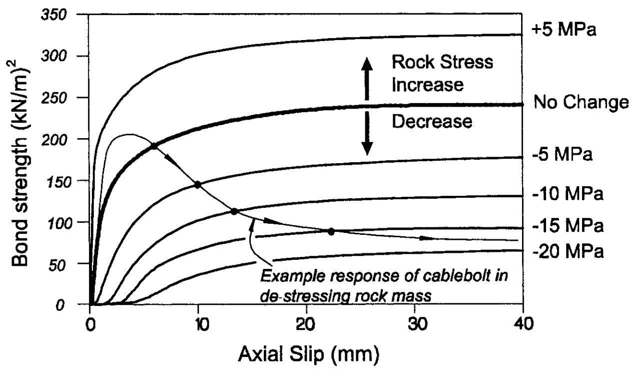


Fig. 9
Example of influence of stress change on predicted pull out load by Diederichs et al. (1993), where rock deformation is causing rock relaxation

Instrumentation programme design

A number of factors should be considered in the design of an instrumentation programme for evaluating the support–rock mass interaction. A discussion of the various factors that should be considered during instrumentation programme design is given by Dunnicliff (1988), Franklin and Dusseault (1989) and Hutchinson and Diederichs (1996). The factors found to be of greatest importance during the Ansil Mine case history are listed below and discussed in the following sections.

A well-designed instrumentation programme must include a variety of instruments and be directed at answering a specific question. For example, instrumentation can be used to determine the deformation of the rock mass, assess the load in a support element or give insight into the more complex rock–reinforcement interaction. The instrumentation programme should be designed to provide as much information about the question as possible, bearing in mind that a percentage of the instruments installed will not provide useful data due to problems with the installation process or subsequent damage to the instruments and that the access for installation of the instruments is likely to be limited. As a consequence, some redundancy should be built into the programme – budget permitting – both in terms of the number and type of instruments installed, in order to improve the likelihood that useful data will be collected. In addition, as noted above, the expected rock mass and support response to the formation of the excavation must be considered when selecting and locating the instruments.

Other factors to be considered in the design of an instrumentation programme include:

1. Objective(s) of the instrumentation programme.
2. Cost and applicability of the instruments.
3. Geometry of the ore body.
4. Access for instrument installation and data collection.

Objective

The objective of the instrumentation programme should be stated clearly before the design is undertaken. In the case of Ansil Mine, the objective was to develop a better understanding of the rock mass–cable bolt interaction, in order to improve the cable bolt design process. The instrumentation of both the rock mass and the cable bolts was therefore essential. If this is the aim of the instrumentation programme, individual groups or clusters of the gauges and anchors of the various instruments should be positioned close to one another in the rock mass for comparison.

At Ansil Mine the instruments were installed in a diamond pattern in each of the test stopes (Fig. 10), with gauges and anchors installed at similar elevations in an attempt to collect data which would be comparable to that recorded by adjacent instruments. The diamond pattern consisted of an extensometer (E), borehole camera hole (B) and stress change cell(s) (SC) in the centre, surrounded by an array of three or four spiral gauge instrumented cable bolts (T). Several stopes at Ansil Mine were instrumented using this pattern: details of the locations of the instruments and a discussion of the problems with the installation are presented in Hutchinson and Falmagne (1991) and Hutchinson (1992).

Cost and applicability of instruments

The relative value of the data recorded by each instrument considered for a programme should be assessed, based on precedent experience. If an instrument is very difficult to install, or the data very difficult to interpret, then the perception of the usefulness of that particular instrument at the mine site will be reduced, independent of the purchase cost of the instrument. A ranking of instruments, with respect to the purchase cost, the ease of installation and the time required for monitoring, reducing and interpreting the data, can be a very useful tool during the design of the instrumentation programme to aid in instrument selection.

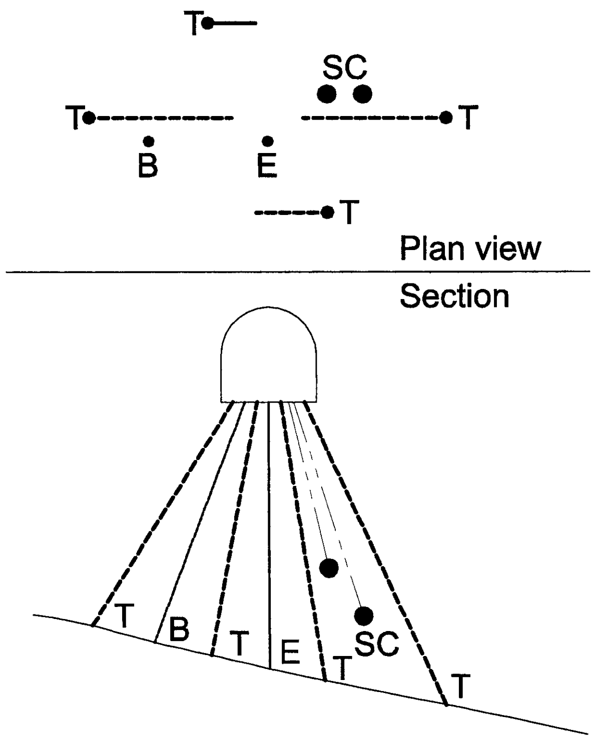


Fig. 10
Basic diamond instrumentation programme used in rock mass at Ansil Mine. *T* Tensmeg instrumented cable bolt; *E* extensometer; *SC* stress change cell; *B* borehole camera hole

The purchase of a data logging device should be evaluated. While the initial purchase cost may be high, the use of a data logger makes the data recording much more simple and reliable. Some of the purchase cost might be offset by the substantial reduction in time spent by personnel collecting data underground and inputting data into spreadsheets. In addition, the frequency of data collection can be set at any level with a data logger: at the time of a blast data should be taken at very short time intervals, while at other times it can be set at longer time intervals. The data logger also continues to collect data at times when personnel may be barred from being near the instrumentation site, such as during blasts.

In the early stages of an instrumentation programme at a mine site, numerous inexpensive instruments should be used, if they will provide the information required. The use of additional, more expensive instruments should be considered when a very specific question arising from the previous instrumentation programme can be answered only by using such instruments.

Geometry of the ore body

The overall geometry of the ore body should be considered in the design of the instrumentation programme. If the boundary of the ore body and the structure of the rock mass are fairly regular, then the data recorded by a particular instrument are likely to be representative of the behaviour of the adjacent rock mass. As a result, the data can be easily compared with data collected by nearby instruments which monitor some other aspect of the behaviour, as was found by Maloney et al. (1992). However, where the geometry of the ore body is very irregular and three-dimensional, such as at Ansil Mine (Fig. 11), then the data recorded at a point in space are not easily comparable to those recorded by a nearby instrument. In this case, more instruments are required over a smaller area to develop a reasonably confident understanding of the rock mass behaviour. A number of clusters of instruments were installed above the upper stopes at Ansil Mine; see the simplified version as shown in Fig. 10. Again, the amount of detailed instrumentation data required will depend upon the type of question that is being investigated.

Access for instrument installation and data collection

The design of the instrumentation programme must also consider the position of the available access drifts with respect to the zone of the rock mass to be instrumented. Safe access to the instruments must be provided throughout the expected life of the instrumentation programme: personnel may have to access the area to take

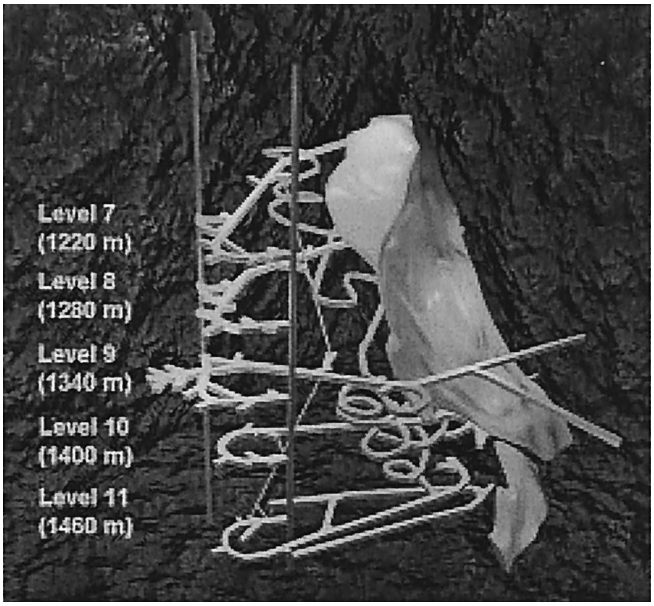


Fig. 11
Ansil Mine orebody visualisation by Grabinsky et al. (1997)

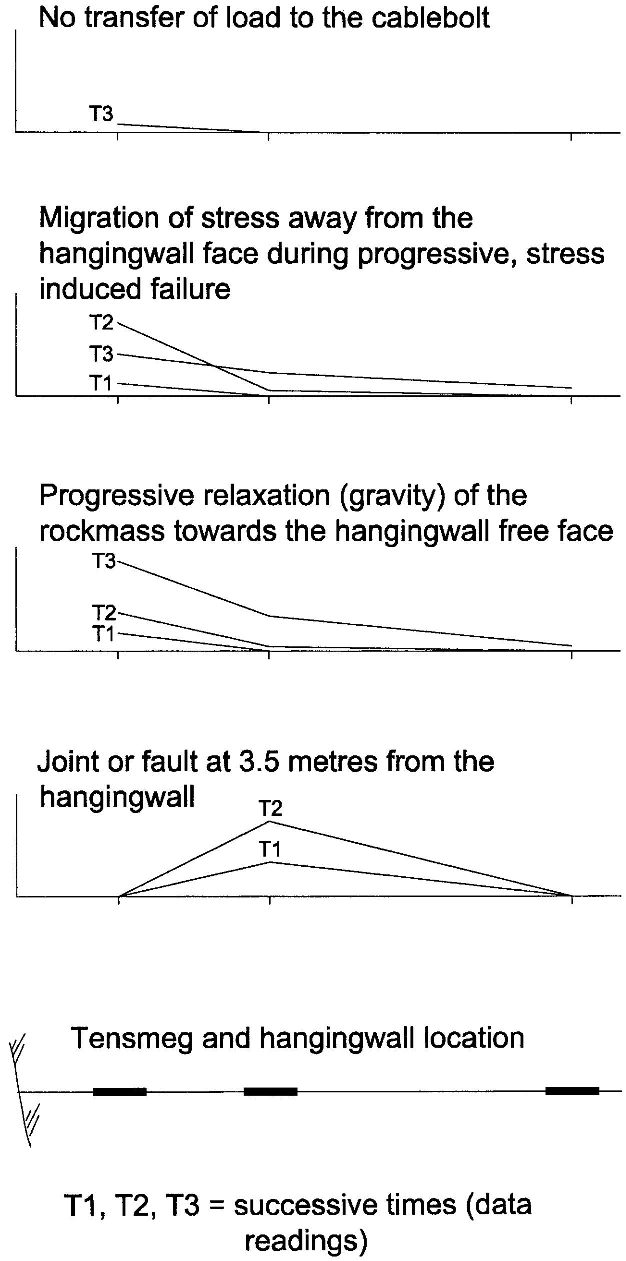


Fig. 12
Evaluation of potential rock mass failure mechanism from distribution of load over length of cable bolts and/or distribution of deformation over length of extensometers

readings and retrieve data as well as to install and maintain the equipment. If safe access is provided, then it is also more likely that the instruments will survive the duration of the monitoring programme as they are less likely to be damaged by such events as falling rock or moving equipment. The longevity and value of the data that can be recorded from an instrumentation programme are greatly improved by building in some form of protection for the instruments.

Interpretation

The interpretation of data from an instrumentation programme can be a time-consuming process, requiring experience, complete familiarity with all of the data, frequent observation of the excavation during mining and an evolving understanding of the impact of mining on the instrumented rock mass. If the programme has been well designed and the data quality has not been compromised by too many unforeseen events, it should be possible to relate the rock mass behaviour to cable bolt performance and efficiency.

The interpretation of extensometers, borehole camera logs, stress change cells and cable bolt gauges is discussed with illustrative examples taken from the data collected at Ansil Mine. In general, however, the changes in the extensometer data with time will indicate if the hanging wall rock mass is moving excessively/rapidly and the approximate source of the displacements. An example of the kind of interpretation that can be made from extensometer data alone is shown in Fig. 12. Borehole camera logs will provide immediate visual evidence of joint displacement and shear, as well as borehole spalling in high stress conditions. As experience with the cable bolt instruments and the stress change cells at a site is gained, these instruments will indicate the approximate magnitude of the cable bolt load and the approximate stress change in the rock mass. The most difficult component of the analysis of the instrumentation data is the visualisation and understanding of the large volumes of diverse data collected. The geometry of the ore body and the location of the instruments at a particular site may render the visualisation fairly simple. However, the compilation of the data recorded at Ansil Mine proved to be a difficult task, due to the three-dimen-

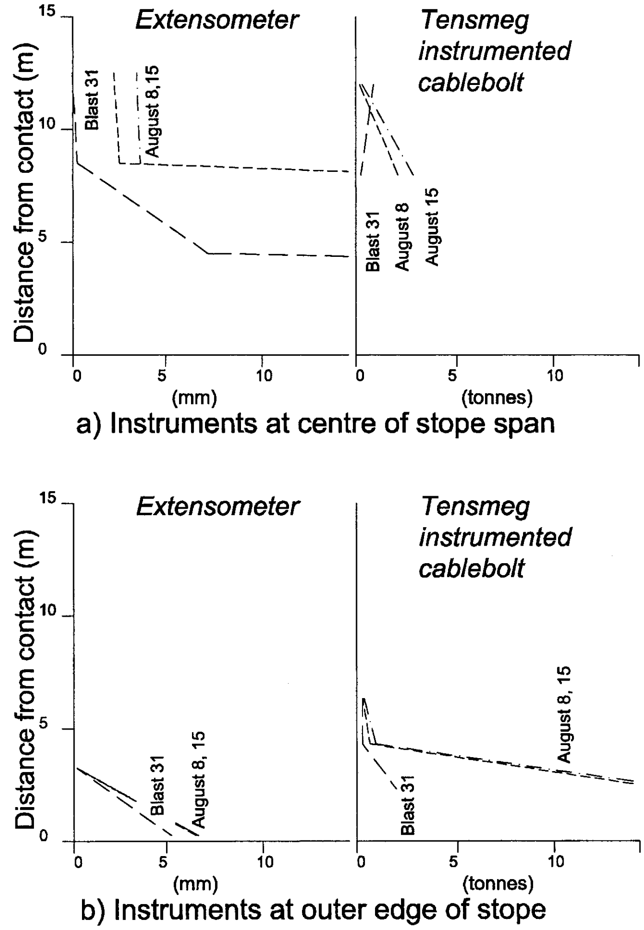


Fig. 13
Instrumentation data collected from stope 7B-5

sional shape of the hanging wall and the vast number of instruments. Several attempts were made to visualise the data effectively. The best methods developed for Ansil Mine are shown in Figs. 13 and 14. These diagrams were produced for all events of significance during the life of the instrumentation programme at Ansil Mine and provided an excellent basis for tracking the changes in the behaviour of the rock mass and cable bolts.

Verification feedback to the cable bolting cycle

Table 1 summarises the feedback for the cable bolt design which may result from the increased understanding of the rock mass and cable bolt behaviour gained from a successful instrumentation programme. Verification feedback is a very necessary – and often ignored – component of the cable bolting cycle. Only through an improved understanding of the interaction between the rock mass and support elements can the support be better designed to both minimise its cost and optimise its effectiveness.

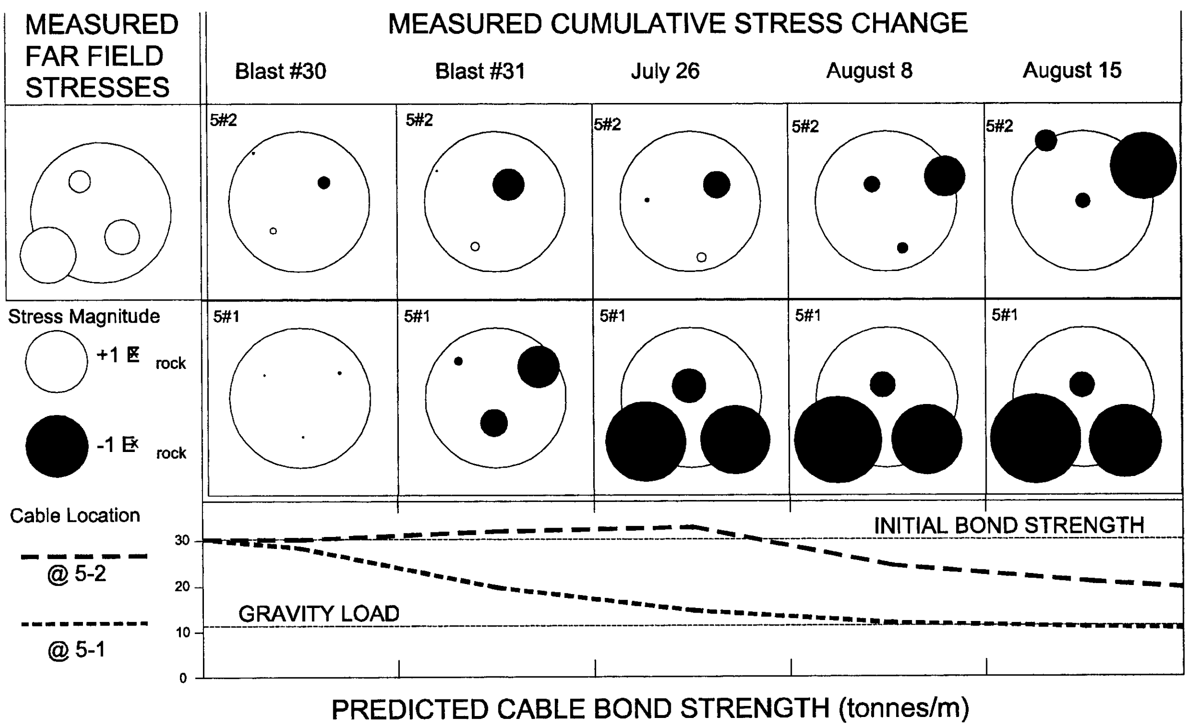


Fig. 14
Stress change cell data from stope 7B-5. Data shown are from cells 5#1 (7 m from hanging wall) and 5#2 (9 m from hanging wall) at centre of span of stope 7B-5. Magnitude of the stress change is represented by diameter of *circle*, and trend and plunge of stress change are plotted on a lower hemisphere stereonet. *Open circle* indicates stress increase, *filled circle* denotes stress decrease

Ansil Mine instrumentation case history

In an attempt to more fully understand the interaction between cable bolts and the rock mass, an instrumentation programme was undertaken at Ansil Mine where cable bolts were used to reinforce portions of the boundaries of open stope excavations. Ansil Mine is situated north of Rouyn-Noranda, Québec, Canada. It had pre-production reserves of 1,517,000 (grading 7.2% copper, 0.8% zinc, 1.7 g/t gold and 25.9 g/t silver) and produced 1200 t/day (Desrosiers 1991). The test stopes were located in the larger, bulbous top section of the ore body, between 1200 and 1280 m below surface, beneath which was a lower tabular section between 1280 and 1500 m below surface (Fig. 11).

There were a number of reasons for the selection of the particular test stopes, including the fact that these stopes were exploited early in the mining sequence; hence there would be time to incorporate any changes to support design arising from the research project in the later stopes. In addition, an access drift, driven above the uppermost level of the stopes to provide access for cable bolting, provided excellent access for installation and protection of some of the instrumentation. Finally, instrumentation could be installed into a number of different stope boundary rock masses which were located close to one another but were expected to experience substantially different stress changes, modes of structural failure and levels of blasting-induced rock damage.

Instruments were selected and installed to monitor the deformation and stress change in the rock mass and the average load carried by the cable bolts. In addition, the changes in the fabric of the rock mass through time were tracked using a borehole camera. The basic pattern of instruments used at Ansil Mine is presented in Fig. 10.

The upper portion of the ore body was divided into eleven stopes (Fig. 15) which were mined in a sequence progressing from the south-east corner towards the north-west corner of the ore body, following placement of cemented rock fill into the adjacent stopes. Geological mapping of core and rock exposures throughout the upper drifts provided the information required to divide this area into four distinct geological domains (Fig. 16) with very different orientations and numbers of joint sets. When the structural information was transposed onto a section through the ore body (Fig. 17), it was possible to predict that wedge failure would be likely to occur from the stope boundaries in geological domains 2A and 3, while blocky, peeling failure could be anticipated from the fault-bounded stope walls excavated in geological domain 1B (Fig. 18). This is indeed what was observed at the mine site. Figure 18 also shows the caved zone of rock above the top of the stopes which failed as a result of the development of mining-induced shear stresses within this zone. Further discussion of this type of failure is given by Hutchinson and Grabinsky (1992) and Grabinsky et al. (1997).

The data recorded at Ansil Mine were compared to the models of rock mass response given in Figs. 5, 6 and 7 in

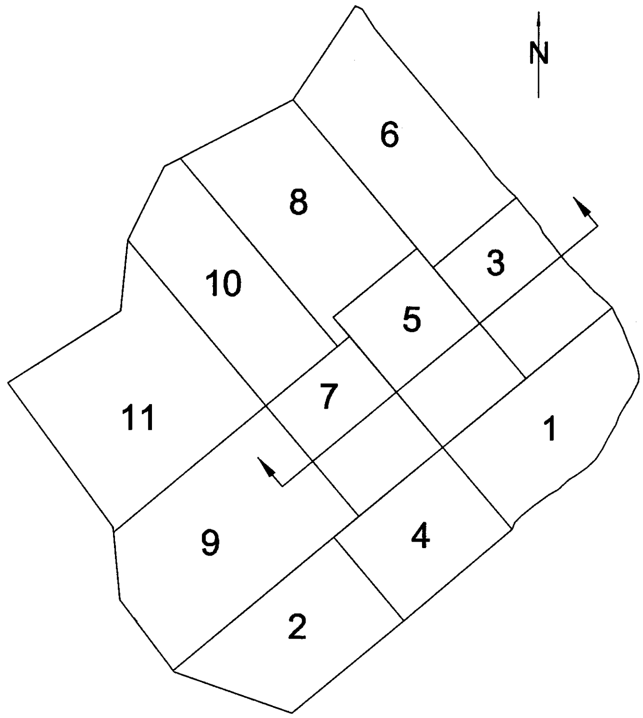


Fig. 15
Plan view of upper horizon stopes at Ansil Mine, including stope numbering and sequence, as well as a section line showing orientation of section in Figs. 17 and 18

Table 1
Cable bolt design feedback

Observation	Data interpretation and conclusion
Rock mass failure and broken cable bolts	Cable bolts loaded beyond their capacity, so more cable bolts are needed. Less stiff cable bolts are required to allow more rock mass deformation
Rock mass failure and stripped cable bolts	Installation quality control must be improved, because problems have lead to cable bolts of reduced capacity Conditions of stress decrease necessitate use of modified cable bolt geometry
Limited rock mass deformation	Cable bolt pattern is too dense, and therefore is unnecessarily expensive. Cable bolt pattern is adequate Cable bolts are not required at all

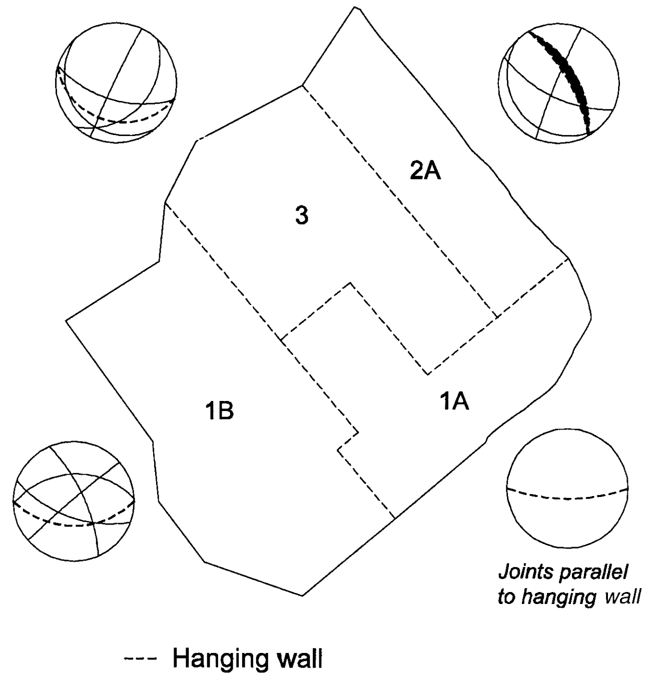


Fig. 16
Geological domains identified for upper horizon stopes at Ansil Mine

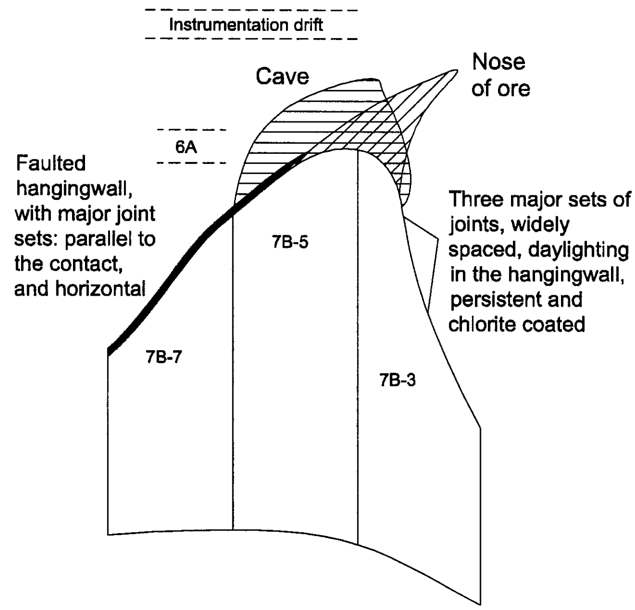


Fig. 17
Section through stopes 7B-3, 7B-5 and 7B-7 showing a description of the geology

an attempt to determine the failure processes in the rock mass. An excellent example of the peeling failure mechanism shown in Fig. 6 was found in the instrumentation data collected for stope 7B-5 (Figs. 13 and 14). During hypothetical peeling failure, the borehole camera and extensometer anchors would show progressively larger displacements on joints near the excavation surface, as well as evidence of joint movement at increasing distances up into the rock mass. In this case as well, the cable bolts would take some load as the rock deformed and moved down the cable bolt. Finally, as the rock layers detached from the mass, they would carry less and less tangential stress and would be cut off from radial stresses. The peeling layers would slide off the bottom of the cable bolt when the demand of the rock dead weight exceeded the cable bolt capacity for the specific embedded length. Again, the cable bolt capacity depends upon the tangential stress change, the grout quality, the type of cable bolt, the rock mass properties and the borehole diameter.

The failure of the rock mass in the hanging wall of stope 7B-5 at Ansil Mine commenced after the last blast (#31) in that stope. The failure continued for several weeks after this blast as blocks of waste rock fell from the hanging wall into the open stope below, resulting in about 8 m of failure at the centre of the hanging wall span. The data collected from the instrumented cable bolts and the extensometers at the centre of the span are shown in Fig. 13a and at the edge of the failure, near the unmined stope boundary in Fig. 13b. The stress change data are summarised in Fig. 14.

In all of these drawings it can be seen that the last blast in the stope (# 31 on 24 July) had a huge influence on the rock mass in the centre of the stope span. Stress cell 5#1 (7 m from the hanging wall) recorded large stress decreases immediately after the blast. This indicates that the rock mass in the vicinity of the cell was totally destressed. The anchors on the extensometers and the spiral strain gauged cable bolts nearest the hanging wall indicated significant displacements and some load transfer to the cable bolts.

With time, as the rock mass continued to fall from the hanging wall (e.g. on 8 and 15 August) the instruments recorded a redistribution of stress within the rock mass and a large caved zone was formed (dark shaded area in the centre section of Fig. 18). The stress changes monitored by stress change cell 5#2 (9 m from the hanging wall) continued to deviate (one increasing and three decreasing) until rock mass failure was reached on 15 August. Later deformations recorded by the extensometers originated from higher in the hanging wall rock mass where the cable bolts were also taking more load.

In contrast to the instruments at the centre of the stope, the deformation of the rock mass at the stope boundary (Fig. 13b) was only significant in the region nearest the drift back. This is due to the fact that the surrounding, as yet unmined, ore and waste rock was still providing a substantial amount of support and confinement to the hanging wall rock mass. It can be seen from the cable bolt strain gauge results that the cable bolts near the drift back in this area were loaded significantly.

The difference in the loads recorded by the instrumented cable bolts at the stope centre span and at the stope boundary can be explained by the effect of stress change on the capacity of a cable bolt. The stress change cells at the stope centre span indicated a reduction in stress, while

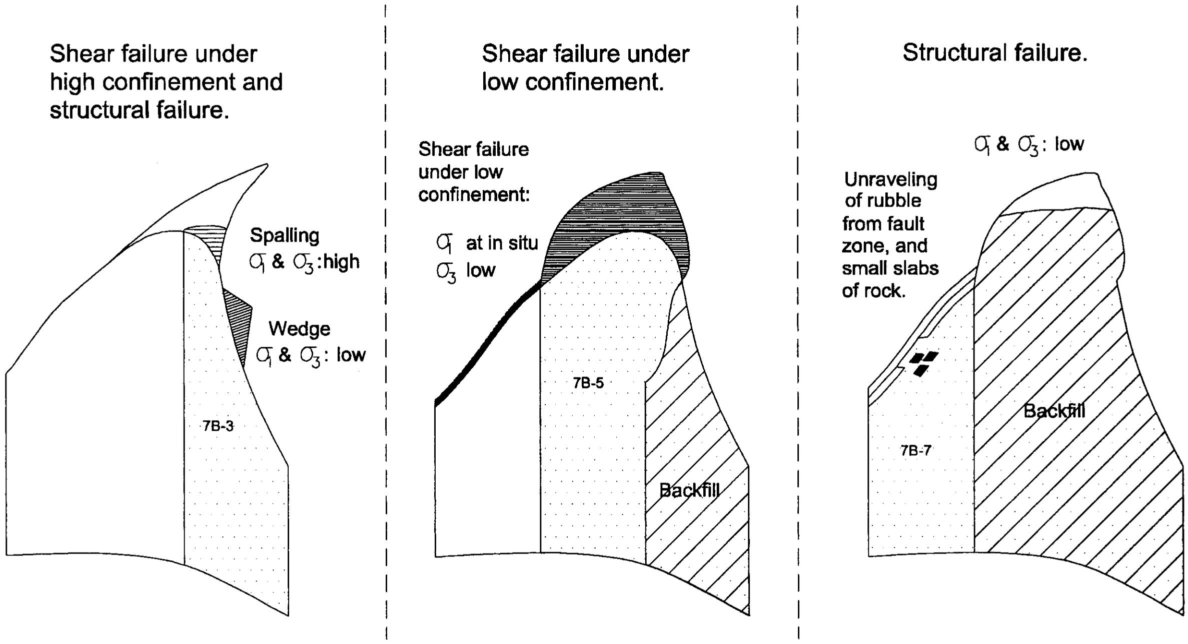


Fig. 18
Failure modes at Ansil Mine observed and predicted from considerations of structural geology and stress change modelling

three-dimensional elastic numerical modelling (reported by Hutchinson and Grabinsky 1992 and more recently revisited by Grabinsky et al. 1997) suggested that the stope boundary rock mass would be under high stress during the mining of this stope, due to the geometry. With subsequent mining and the exploitation of a much larger volume of the ore body, the stresses would be pushed farther away into the hanging wall rock mass, leading to de-stressing of these stope boundary cable bolts, with a resulting loss of bolt bond strength and support capacity.
The strength of a cable bolt-grout system is dependent in part on any stress change that occurs after the installation of the cable bolt (Figs. 8 and 9). CABLEBOND was used to calculate the change in the cable bolt capacity induced by the stress changes recorded above stope 7B-5, as shown in Fig. 14. Also shown in this figure is a gravity load line calculated from the cable bolt spacing and the density of the rock mass. If the cable bolt bond capacity dropped below this critical value, the rock would slide off the end of the bolts. In Fig. 14 it is evident that the stress change allowed the cable bolt capacity to drop to the level of the gravity load demand, leading to failure of the rock mass in the vicinity of stress cell 5#1. Stress cell 5#2, located 9 m away from the original position of the hanging wall, remained in place following the stress change but was very close to the failed back of the stope. It was expected that over time, as adjacent stopes were mined and stresses shed further into the hanging wall rock mass, the cable bolts in the vicinity of stress cell 5#2 would lose capacity due to stress loss and would allow additional rock mass failure to occur. This was indeed observed as large blocks of rock fell from the stope back onto the backfill during mining of the adjacent stopes.
In the case of stope 7B-5, the cable bolts could have been more effectively designed to reinforce the peeling failure mechanism by preventing the failed blocks of rock from sliding off the end of the cable bolts. If these blocks could have been held by the cable bolt support system, the dilution of the waste rock in the stope would have been reduced. Retention of the surface blocks could be achieved by plating the exposed ends of cable bolts installed up into the hanging wall rock mass from the drifts. In addition, using a modified strand cable bolt in the up-holes drilled from the drifts and in the down-holes drilled from the instrumentation drift would reduce the effects of stress decrease on the cable bolt capacity. For example, birdcages could be formed at the end of the cable bolts nearest the stope hanging wall boundary as shown in Fig. 19. The birdcage forms a larger anchor on the end of the cable bolt, preventing the grout column from sliding past the cable bolt steel as easily, potentially improving the capacity of the cable bolt by up to 225% and reducing the sensitivity to stress change. Alternatively, other diameter enlargement modifications, such as nutcage or bulbed anchors, could be used.
Windsor (1992) and Hutchinson and Diederichs (1996) provide further discussion of the modifications that can be made to cable bolts. It is important to match the hypothesised and observed rock mass behaviour to the types of cable bolts available (Fig. 20).

Conclusions

As a result of the pronounced three-dimensional nature of the Ansil ore body and the differing geological conditions

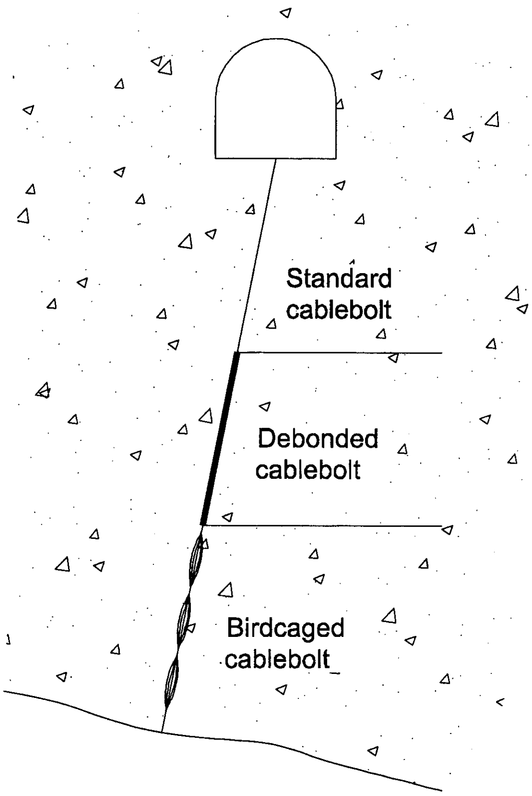


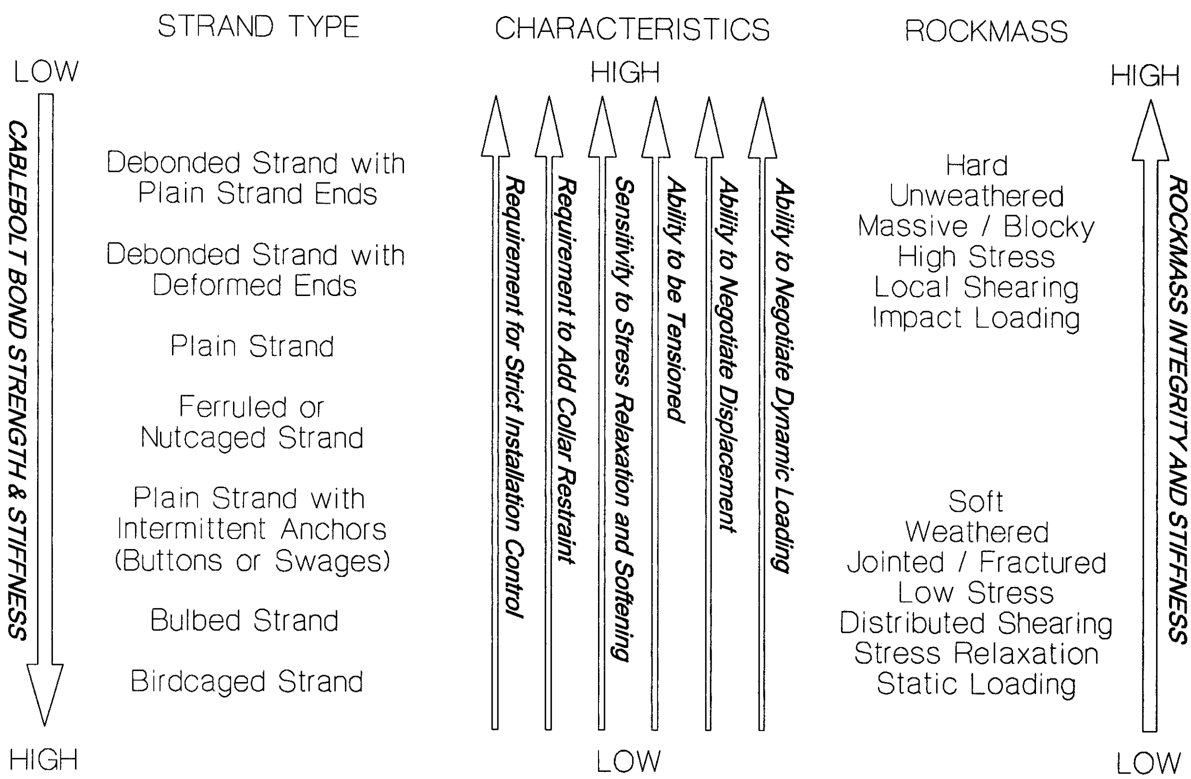
Fig. 19
Suggested modified cable bolt geometry for support of Ansil Mine upper horizon stopes

of the instrumented zones as well as the loss of a number of the instruments for various reasons, it was not possible to acquire all the data required for a complete comparative analysis of the cable bolt performance in all of the stopes. Nevertheless, the information collected did provide a general picture of the failure processes occurring in the boundary rock mass and allowed a redesign of the cable bolt support patterns and elements.

The design of an instrumentation programme aimed at assessing the performance of cable bolts in a rock mass should include consideration of the following items:

1. What is the expected rock mass failure mechanism and which instruments will provide information to confirm this hypothesis?
2. Is there sufficient redundancy built into the instrumentation programme, both in the variety of instruments and the number of each kind of instrument? If some instruments are lost, is it likely that useful information will still be collected by the remaining instruments? The number of instruments required will depend upon the geology of the ore body and the spatial extent of the study area.
3. Some instruments are more difficult to install (stress cells) and to interpret (stress cells and spiral strain gauge instrumented cable bolts) than others. These instruments should only be used when the more basic coverage of the rock mass behaviour is already assured

Fig. 20
Selection of modified strand for expected rock mass quality and stiffness



with the simpler instruments and when the budget allows for more extensive instrumentation.

4. Can the expense of the purchase or rental of a data logger be justified? A data logger makes the collection of the data very efficient and easy, much improving the quality of the data.

Immediate returns may be obtained from the data for the prediction of stability or impending failure, but the full interpretation of a large volume of data and a complete understanding of the rock mass behaviour will take more time.

The instrumentation results can be used to back-analyse and hypothesise the rock mass failure that is occurring and the performance of the cable bolts in the rock mass. Once the failure modes are better understood as a result of the back-analysis, forward prediction of the stope performance is possible.

Stress changes in the rock mass can significantly affect the cable bolt capacity. The influence of stress changes can be calculated using specialized computer programs. The results of the assessment of the performance of the cable bolts in the rock mass are likely to indicate where modifications to the cable bolt design would improve the interaction between the cable bolts and the surrounding grout, particularly where stress change is expected to or has occurred. In the case of Ansil Mine, it was concluded that the use of modified geometry cable bolts as well as plates on the exposed ends of cable bolts installed up into the stope boundary rock mass would have greatly improved the support performance and prevented a substantial volume of rock failure.

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