2015

Importance of Monitoring Technologies and In Situ Testing, with Relation to Numerical Analysis for Ground Control Design

Charles Sweeney

Publication Details

Charles Sweeney, Importance of Monitoring Technologies and In Situ Testing, with Relation to Numerical Analysis for Ground Control Design, 15th Coal Operators' Conference, University of Wollongong, The Australasian Institute of Mining and Metallurgy and Mine Managers Association of Australia, 2015, 84-93.

IMPORTANCE OF MONITORING TECHNOLOGIES AND *IN SITU* TESTING, WITH RELATION TO NUMERICAL ANALYSIS FOR GROUND CONTROL DESIGN

Charles Sweeney

ABSTRACT: As Underground (UG) coal mining companies look to reduce costs, whilst attempting to mine through increasingly difficult ground conditions, UG strata monitoring and testing data is becoming more and more important to acquire. The current monitoring technologies have their uses, but with mines getting deeper and entering new areas these laborious technologies are becoming too labour intensive and potentially subjecting personnel to potentially hazardous situations. With certain difficulties surrounding the implementation of electronic remote monitoring systems in UG coal mines, acquiring this data has seen little headway in terms of being able to expand the range of monitoring equipment being used in UG coal mines. There are a number of products on the market today which are effective in remotely monitoring strata deformation, however these can be very specialised and not entirely established or user friendly. Where an experience base of strata deformation is not available for a particular mine site, UG strata sampling and relevant *in situ* testing is able to compensate in the validation of numerical models. The data obtained from this testing can be used to build calibrated numerical models for site-specific ground control issues - to be used in predicting the behaviour of UG strata deformation. The rapid increase in computer power and affordability has seen enormous growth in the development of sophisticated computer codes. This paper discusses a number of limitations surrounding the collection of UG monitoring data and its use in mine design. The relevance of *in situ* data collection is also discussed in relation to the emergence of numerical modelling, as a tool to predict ground behaviour in UG coal mines.

INTRODUCTION

There are many different requirements for monitoring the environment in an Underground (UG) coal mine; from groundwater and gas drainage, to strata movement and seismicity. There currently exists little in the form of cost effective, reliable and user friendly remote monitoring technologies for strata control and its associated hazards. The majority of extensometer and tell tale instrumentation available today require mine site personnel to read the instrumentation directly, with the potential of putting themselves in harm's way. Limitations exist in the practical application of electrical remote monitoring equipment in UG coal mines, especially in explosion risk zones (ERZ0) where these devices are required to have intrinsically safe and explosion proof certification which can be difficult to acquire. With regard to strata monitoring instrumentation, limitations exist not only in terms of the equipment being used but also the ability to capture the changing geological conditions over short distances through extrapolation. With a lack of access and staffing/resources due to recent cut backs and initiatives to run low-cost mines, time intensive reading of UG instrumentation and conducting the appropriate analysis has led to an increasing need for remote monitoring and real time reporting. There are products on the market today which are capable of remote monitoring, however these are mostly in the developmental stage and can be expensive and impracticable. At this point in time, the limitations of using historical monitoring data for use in complex mine design scenarios is taken up through *in situ* testing of support elements in the UG environment as well as laboratory testing of UG samples - to be used to develop applicable predictive numerical models for site-specific UG environments. As mines enter new domains or green/brown field sites, an insufficient experience base exists. The development of predictive models is an alternative to this lack of monitoring data, until it can be readily obtained. The development of a field-based monitoring program is still essential in order to build up an inventory of relevant data and to warn personnel of pending movement during mining activities, as well as to validate numerical models. In terms of support design, most mines will use a

Charles Sweeney, Blackrock Mining Solutions Pty Ltd, Email: csweeney@blackrockmining.net

combination of historical monitoring data (if available), together with calibrated numerical models, in order to design their pillar systems and strata support requirements.

This paper will detail the various monitoring techniques available for strata deformation and design, and discuss the rise in using *in situ* and laboratory test results to build calibrated numerical models for use in complex ground control design scenarios within UG coal mines.

AVAILABLE MONITORING TECHNIQUES

The development of monitoring technologies and techniques, to provide early warnings of hazardous strata conditions, has been underway for many years. The purpose of monitoring the underground environment during mining is to characterise and define the relevant failure mechanisms that are occurring around particular UG excavations. This is in order to provide an understanding of the design requirements and effectiveness of roadway support systems on the stability of the roadway, as well as to warn personnel of pending strata deformation. The following section details the available monitoring devices in UG coal mines today and highlights some emerging technologies in the field of remote monitoring of strata movement.

Extensometers

In-house mechanical extensometer devices have been used in parts of the USA for decades (Lannacchione *et al.*, 2005). Extensometers generally comprise of a series of anchors located at set intervals along a borehole, in either the roof or rib (SCT, 2000). Results are interpreted to determine the displacement/strain between anchors with time and face advance/retreat (SCT, 2000). Two types of extensometers are:

1. The sonic probe extensometer - for detailed monitoring and design purposes, and
2. Roadway deformation indicators for routine monitoring – for verification/checking purposes.

These instruments are used to measure deformation around a roadway – roof, floor and rib-sides. For design purposes the height of strata softening into the roof and depth of failure of the roadway sides is critical, but this information only comes with much experience and is available post-mining.

A play on the typical extensometer is the tell-tale (mechanical extensometer), which was first introduced in France in the 1970's (Lannacchione *et al.*, 2005) and is used to warn miners of strata movement. Tell-tales are considered a deflection monitor and are common place in any ground control management plan in most UG Australian coal mines. The definition of a tell-tale is typically a strata extensometer which incorporates a visual indication of strata movement into an excavation and is intended to provide a visible warning of excessive ground deformation (Bigby, *et al.*, 2010). Altounyan, *et al*., (1997) found that uncontrolled falls of ground in British coal mines were reduced from 267 to six between 1990 and 1995, partially due to the use of tell-tales (Lannacchione, *et al.*, 2005). These instruments are currently used to gain widespread coverage of roof deformation throughout the mine, and are very common in Australian UG coal mines due to the low cost and low level of skill required for installation and monitoring. A limitation of these devices however, is that they are only capable of assessing the behaviour of a localised section of the immediate roof – generally within and above the bolted horizon. The geology and geotechnical conditions within any coal mine can change rapidly within a very short distance and therefore coverage around geological structures, for example, tends to necessitate an increase in instrument density. High roofs and stone/coal dust/fines however, can obstruct the view of the visual indicator making it difficult to monitor. In addition, if movement is triggered, the routine reading of these tell-tales, in an area where the roof is readily deforming, can be hazardous to coal mine workers if the appropriate Trigger Action Response Plan (TARP) based actions are not implemented.

An intrinsically safe, remote reading tell-tale monitoring system has been developed which allows a number of tell-tales to be read remotely, along a linear line. This reduces the difficulty in monitoring these devices and allows for up-to-date data analysis and real time alarming of trigger levels, however depending on the density, it still only assesses the localised behaviour in the immediate roof around the tell-tale location. High densities can be costly and impractical, as the system is still in the development stage and only allows a certain number of instruments onto the one 'daisy-chain' link of instruments. A huge benefit of any remote reading system is the ability to monitor the area in question, 24 hours a day/7 days a week, with alarms set to alert on movement triggers. The alarms need to be practical however, and relate to the appropriate mining practice. To date, remote reading systems have been implemented in Tailgates (TG's), installation faces left standing for a long period of time as well as in mine critical infrastructure areas such as belt chambers, however the system was typically designed for the monitoring of the TG during LW retreat and is under development to be used in other parts of the mine as a long term monitoring system.

The GEL-extensometer, which is a 5 anchor tell-tale, has a potentiometer built into the casing to enable the instrument to be read from a distance with a readout box. These instruments are intrinsically safe, however they only have a small excitation of 0.96V. This amount of excitation severely limits its use as a remote monitoring extensometer – where with increasing distance the reduction in voltage and impedance will get too great to register. A further limitation for the potential of the GEL-extensometer to become a remote monitoring device in UG coal mines is the lack of an intrinsically safe data logger and stand-alone transmitting system able to be used in ERZ0 zones of an UG coal mine.

Several intrinsically safe wireless devices, for transmitting sigals, are currently available, however these are typically very expensive and not practical in relation to the variable and extensive network of monitoring instruments to be monitored in the elaborate network of UG coal mines. By utilising wireless devices in the UG environment, data acquisition and analysis time can be minimised significantly. The ability to set alarms of total movement on certain triggers is fundamental to any remote monitoring system. With the extent of UG mines continuing to escalate as mines go deeper and broader, having to read extensometers manually in every part of the mine becomes laborious and the data interpretation can be very time consuming.

The Roof Monitoring Safety System (RMSS) was established by the National Institute for Occupational Safety and Health (NIOSH) in 1999, as a means to remotely read mechanical extensometers. The RMSS is used to monitor the sag, or vertical movement of the roof. The instrument is still required to be read from UG however, reading the resistivity off a multimeter at a distance from the monitoring site, as opposed to monitoring it from the surface.

Emerging remote reading technologies

An emerging monitoring/prediction technique is that of monitoring for microseismicity, which has shown that there is some correlation between measurable rock noise and ground movement. The first evaluation of this technology was in the 1940's by Obert and Duvall, as a means of tracking general stability conditions (Ellenberger and Bajpayee 2007). The technique has recently been used, with varying levels of success, to predict roof falls. Roof falls are generally preceded by a period of elevated microseismic activity, but not all periods of elevated activity result in a roof fall (Ellenberger, 2007).

Performance of UG microseismic monitoring systems depends on a number of inter-related issues, namely; maintaining ever increasing cable runs, preventing component damage from mining activities and avoiding signal degradation due to interference from mining equipment (Bajpayee *et al.*, 2008). A potential solution for this is to use a surface-based monitoring system, where sensors are placed in boreholes above and adjacent to UG mine workings (Bajpayee *et al.*, 2008). Mine-wide microseismic monitoring technology has the capability to collect and analyse a share of the total energy released as localised strata fractures prior to, during, and after rock falls (Ellenberger and Bajpayee, 2007). Despite an advantage of continuous detection and relatively low instrument-to-coverage ratio (geophones cover areas in the range of hundreds of square meters), the use of microseismic monitoring has been limited due to a lack of published data as well as high initial purchase costs (Ellenberger and Bajpayee, 2007). Both NIOSH and CSIRO in the United States are currently undergoing evaluation of this technique as a predictive tool.

A recent research thesis, by Logan, 2008, showed the diverse nature of tiltmeters to measure roof movement in the UG mining environment. Logan went on to explain how wireless tiltmeters, with inbuilt accelerometers, can be used on any surface with a measureable angle. This enables the tiltmeter to record angles of roof alignment change over extended periods of time, where change in readings can infer instabilities in the rock mass. By placing these tiltmeters on the roof mesh, a large area can essentially be monitored.

Acceptance of each monitoring technique is varying within the mining industry as a whole, primarily based on cost and ease of installation/monitoring, as well as intended life-of-mine. As discussed above, most monitoring technologies, especially remote reading monitoring systems, are presently in the development stage and are somewhat being held back by limited interest.

NUMERICAL MODELLING AS A PREDICTIVE TOOL

An accurate understanding of the complex behaviour of rock mass, and jointed rock mass in particular, has always been a difficult task for geotechnical engineers to ascertain. To provide a safe mining operation under complex and difficult conditions, reliable planning and design is of the utmost importance. In order to compensate for the lack of detailed information able to be gained from current strata monitoring techniques, in relation to the prediction and warning of pending strata failure, numerical modelling has emerged as a popular tool to predict strata movement and to assist in proper strata control design and setting of TARP levels in most Australian mines Principal Hazard Management Plans (PHMP) for ground control.

Importance of reliable and accurate input data

Numerical modelling techniques provide for complex geometries and material behaviour, with the models that are generated being heavily dependent on accurate input data. Main sources for this input data are site investigations, and laboratory and field tests (Kumar *et a.l*, 2010).

The testing methods that are used to acquire the input data required, and which are useful in building relevant and accurate numerical models, are as follows:

Stress measurements

Knowledge of *in situ* stress is fundamental to coal mine ground control. Over the last 20 years, it has become clear that horizontal stress is a critical factor affecting roof stability in UG coal mines (Mark *et al.*, 2010). A number of theories have been proposed to explain the presence of horizontal stress, with a major break-through occurring in the 1970's which established the theory of plate tectonics and a dynamic earth crust (Mark *et al.*, 2010). The stress orientation in Australia is considered unique by World Stress Map (WSM) standards, as the stress orientation varies considerably between regions (Figure 1) (Mark *et al.*, 2010). The major stress orientation in the Bowen Basin coalfields in central Queensland is horizontal and orientated at NNE, with the vertical stress being the minor or intermediate principal stress (Mark *et al.*, 2010). In order to get accurate stress magnitude and orientation data, the overcoring method, utilising Strata Control Technologies ANZI 3-dimensional stress cell or the CSIRO cell, is typically used in Australian mines (Figure 2). Stress magnitudes and orientations will vary from site-to-site across Australia, where a general indication of the *in situ* stress field can assist in rock bolting design in virgin ground. Mining induced stress on the other hand, will vary in direction and magnitude depending on the position with respect to previous mine workings (SCT, 2000). Hence increased specific testing of the mining induced stress, when designing roadways around existing goafs etc, will be a key factor for effective rock bolting design. The measuring of stress change around a retreating longwall can also be advantageous, in the effective design of maingate and tailgate support and for chain pillar design for longwall extraction purposes.

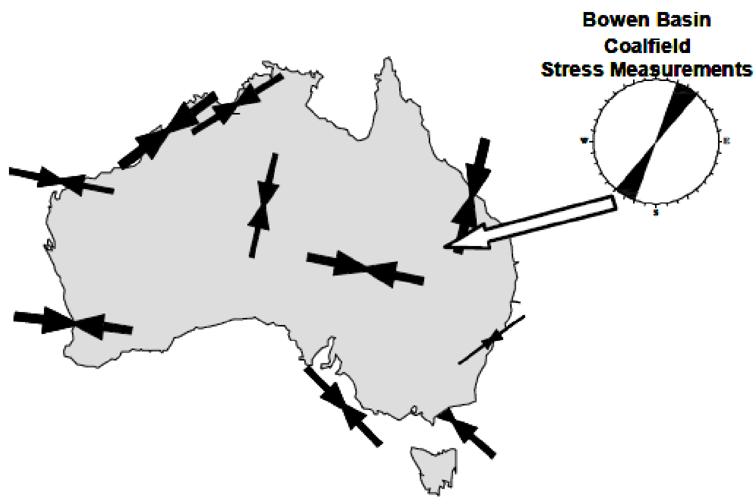

Figure 1: World Stress Map of Australia, compared with stress orientations determined from Bowen Basin coalfield stress measurements (Map after Hillis *et al*., 1999; Stress measurements after Nemcik *et al.*, 2005)

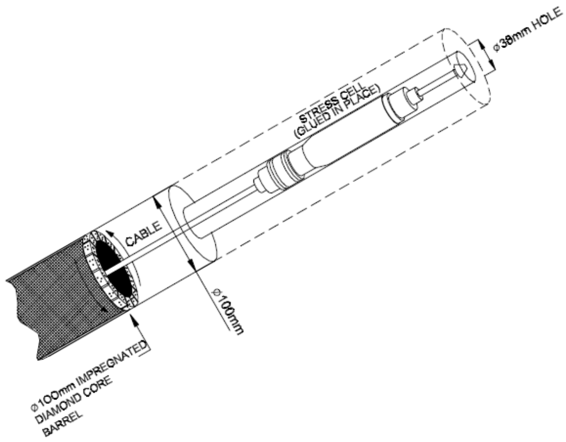

Figure 2: Overcore method for CSIRO HI 3-dimensional stress cell (SCT, 2000)

Key properties of coal and rock

Accurate coal and rock input data is paramount in building representative numerical models. There are multiple methods for predicting the *in situ* strength of coal/rock throughout UG coal mines. Sonic velocity is one of these methods, which is cheap, fast and easy to produce (Butel *et al.*, 2014). *In situ* testing of coal and rock samples collected from the UG mining environment is essential in correlating UCS with geophysical characteristics, to allow extrapolation of rock strength data about the proposed mining areas and also to assist in calibrating the applicable numerical models.

Rocks have a number of properties that determine their behaviour in the UG mining environment. An example of the variation of rock properties for different coal measure strata can be seen in Figure 3. In order to gain detailed knowledge of the key rock properties from any proposed mining area, a detailed testing program is required. The following key rock properties should be determined for proper design and modelling purposes (SCT, 2000):

- Unconfined compressive strength (UCS)
- Confined compressive strength properties of intact and failed rock (triaxial strength)
- Bedding plane properties
- Rock modulus properties
- Moisture content
- Tensile strength (if appropriate)
- Moisture sensitivity and mineralogical analysis of clay-rich strata (if present)

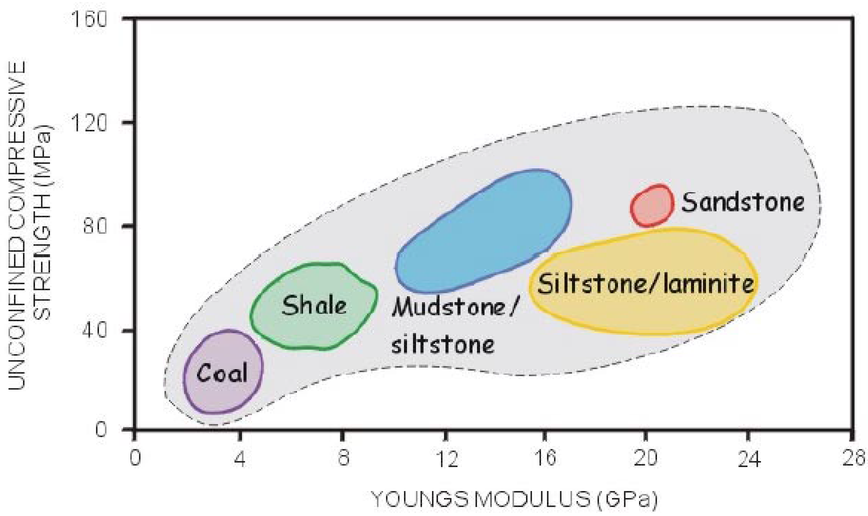

Figure 3: Examples of variation of rock properties for different coal measure strata (SCT, 2000)

Core sampling is the typical method of collecting samples appropriate for laboratory testing. The location and number of sampling sites would normally be determined following an evaluation of the existing data and a consideration of the likely variation in geological conditions within the proposed mining area (SCT, 2000). An example of the method of coring can be seen in Figure 4, whereby core is taken from both the floor and roof horizons. The boreholes are drilled with specific orientations to sample rock strength and bedding planes.

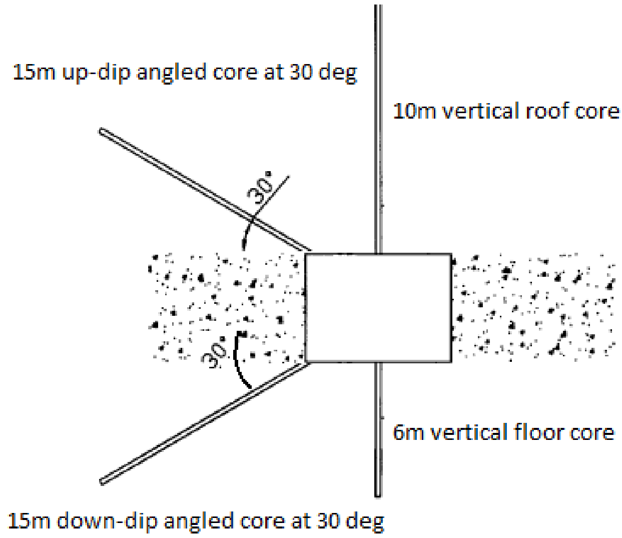

Figure 4: Typical coring requirements for rock property determination about the immediate roadway zone (SCT, 2000)

When testing samples in the laboratory, a number of things need to be taken into account to accurately represent the natural environment. Sample size and moisture content are two examples of this. Moisture content can significantly affect the rock properties of a wide range of rock types (SCT, 2000), therefore in order to obtain representative results the natural moisture content should be maintained prior to testing (SCT, 2000). Sample size is also known to have an effect on many rock experiments, where smaller sample sizes of a particular rock can exhibit much higher strengths than that of the *in situ* rock. The effect of sample size on specimens of coal can be seen in Figure 5, where the tested strength is required to be corrected i.e. reduced, compared with that of the *in situ* strength (SCT, 2000).

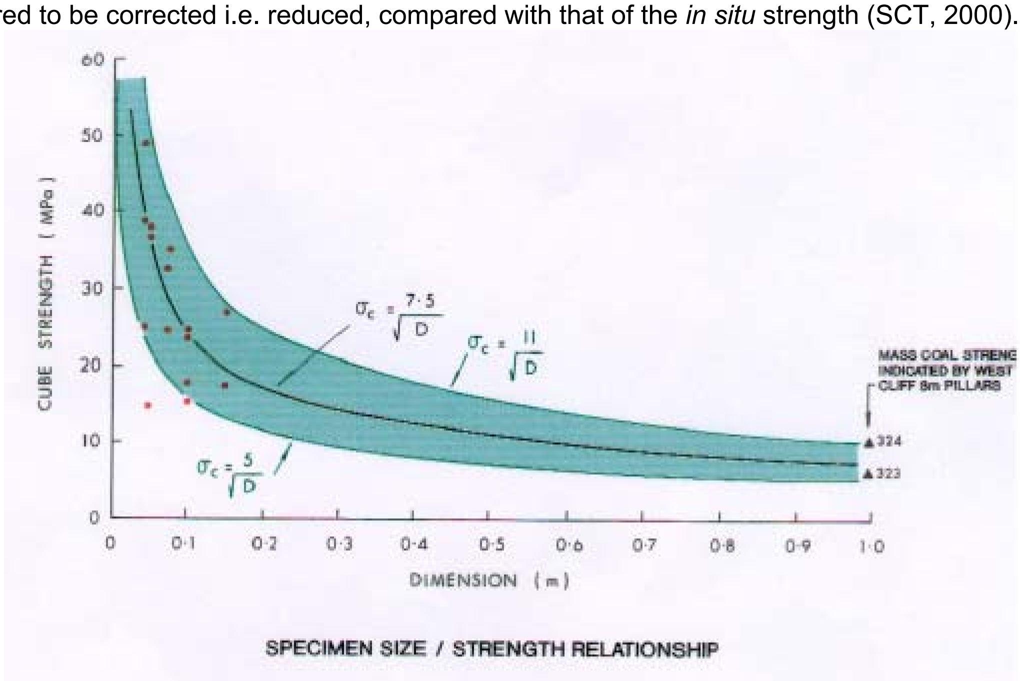

Figure 5: Sample size versus strength relationship for coal (SCT, 2000)

Any investigation program should also provide a detailed understanding of the immediate roof and floor lithology's, as this is an important component of rock bolting design and will give you an understanding of how the strata is likely to behave around any UG excavation in a coal seam.

Rock reinforcement performance characteristics

An assessment of load transfer and system stiffness is an integral component of effective reinforcement design. To assess the bolting system characteristics, a typical test is the Short Encapsulation Pull Test (SEPT).

The SEPT is an internationally recognised method of measuring the resin anchorage or bond properties of fully bonded roof bolts. The bond strength of a resin bonded roof bolt is a fundamental parameter determining its effectiveness. The stronger the bond, and the length of anchorage applied to the bolt, determines the resistance zone over which the full bolt strength is available to resist roof movement. With the modern high-strength, high-stiffness, polyester resins that are in use today, it has been found through numerous tests that a bond length of 300mm is appropriate for determining the resin bond for a standard roof bolt. In terms of system stiffness, in weak roof materials the resin-rock interface controls the failure mechanism whereas in stronger rock material the bond failure may occur on the resin-bolt interface. In order to measure the bond strength, it is necessary to shear the bond on the bolt-resin or resin-rock interface.

A schematic of the typical SEPT test can be seen in Figure 6 below. The data obtained from the SEPT test provides vital information on the shear stress capacity of the system. In correlation with laboratory test results, this provides a rational approach for the selection of consumables to suit specific reinforcement requirements.

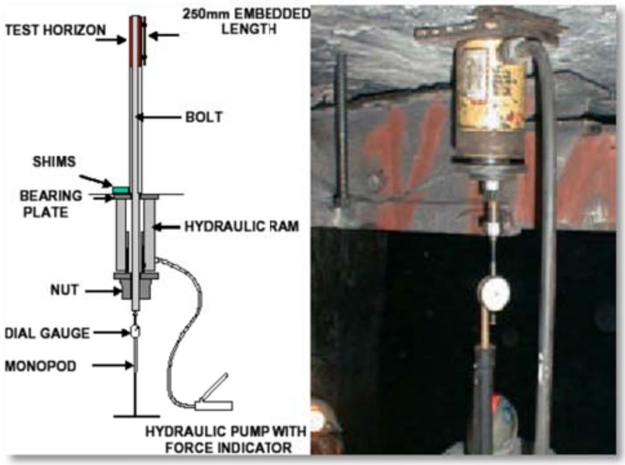

Figure 6: Schematic of typical SEPT set up

Applications of Numerical Modelling Technologies

One of the major problems that engineers are faced with in the geotechnical design of underground coal mines is the change in the displacement field around the coal seam and surrounding rock after extraction (Oraee *et al.*, 2013). Effective mine design has long been recognised as an essential element in establishing safe and productive mining operations (Karabin and Evanto, 1999). Numerous empirical and analytical methods have been developed over the years to analyse pillar stability and support design, with the work of Holland and Gaddy (1964), Obert and Duvall (1967), and Bieniawski (1984), to name a few (Karabin and Evanto, 1999). With the introduction of longwall mining, new methodologies were developed to address design considerations for that technology i.e. ALTS, ARMPS, (Larson and Whyatt, 2009). Each of these technologies can provide a reasonable estimate of pillar strength and stability in certain conditions and simple mining geometries, and have unique underlying assumptions (Karabin and Evanto, 1999). In practice though, the geology of the mine can change dramatically and situations may arise that justify a complex mixture of pillar configurations with varying entry and crosscut widths, spacings, and orientations (Karabin and Evanto, 1999). To validate any model, the input properties should be calibrated to site-specific conditions and observations (Larsonand whyatt, 2009).

Numerical modelling is a tool to obtain detailed predictions of stresses and deformations around UG excavations (Suchowerska *et al.*, 2014). Typically, two categories of numerical modelling approaches exist – these are Continuum and Discontinuum.

Continuum

- Finite Difference Method (FDM) e.g.FLAC
- Finite Element Method (FEM) e.g. Phase2
- Boundary Element Method (BEM) e.g. LaMODEL, MAP 3D

Discontinuum

- Discrete Element Method (DEM) e.g. UDEC, 3DEC

A high level of detail is generally required for any particular scenario which warrants the use of a numerical model, but with rapid growth in computer power and affordability since the 1970's this has led to significant developments in numerical modelling computer codes. Sophisticated material behaviour, such as yielding of the rock mass strata, strain softening and non-associated plastic flow rules are now able to be modelled with a certain degree of accuracy. As mentioned previously however, confidence in numerical modelling as a predictive tool, especially relating to stress, is dependent on accurate field data.

The appropriateness of a numerical modelling methodology depends on the approach adopted and the ability to estimate the relevant key rock parameters. Site-specific information must be used to calibrate and assess the appropriateness of each methodology – for instance LaMODEL does not consider tectonic stress and therefore it might be a poor choice if high horizontal stresses are present (Larsonand whyatt , 2009). Field observations confirm that high horizontal stresses can cause instability to mine roadways. This being a 3-dimensional problem, a full 3-dimensional analysis is needed to capture the details of these damaging effects. Table 1 indicates the applicable pillar design methodologies for certain areas of the mine. Once an understanding of the likely strata failure mechanism is gained, with associated hazards, this will inevitably enable the engineer to design an effective strata support system to suit.

Table 1: Pillar design methodologies (Gale and Hebblewhite, 2005)

Pillar Type	Design issue	Applicable Methodologies
Subsidence protection	Load-bearing stability	experiential
		numerical
		empirical-mechanistic
		hybrid
Barrier pillars	Load-bearing stability	experiential
		numerical
		empirical-mechanistic
		hybrid
	Abutment stress protection	experiential
		numerical
		empirical-statistical
	Partition pillars	experiential
		numerical
Main development	Load-bearing stability	experiential
		empirical-mechanistic
		numerical
		hybrid
Chain pillars	Load-bearing stability	experiential
		numerical
		empirical-mechanistic
		hybrid
	Abutment stress protection	experiential
		numerical
		empirical-statistical
Bord & pillar (production)	Load-bearing stability	experiential
		numerical
		empirical-mechanistic
		hybrid
Fenders	Load-bearing stability	experiential
		numerical
		empirical-mechanistic
		hybrid
	Abutment stress protection	experiential
		numerical
Yield pillars	Load-bearing stability/yield	experiential
		numerical
		empirical-mechanistic
		hybrid
Highwall web pillars	Load-bearing stability	experiential
		numerical
		empirical-mechanistic
		hybrid

In choosing a methodology appropriate to the issue, the geotechnical engineer should work within the limitation of this methodology and understand the significance of the applied parameters. No one methodology should be used in isolation and therefore the numerical model that is generated should be calibrated against an appropriate empirical or analytical method and site-specific conditions.

CONCLUSIONS

With a lack of recent developments in the field of UG monitoring technology, particularly as mines venture into "unchartered territory" and mining through complex geological environments, the use of calibrated numerical models is becoming increasingly important. Numerical models need to be built with reliable and accurate input data, which is only achievable from sampling and testing in the UG environment and laboratory. Field monitoring during development also plays an enormous role in validating these models, as monitoring of the UG environment helps build a site-specific experience base. This field monitoring data is typically used for empirical and analytical design for simple mine geometries. With the increase in powerful 3-dimensional (3D) codes available today, which allow for complex 3D problems to be solved, multiple failure modes can be modelled around discrete block behaviour. Validation and correlation of these models to actual mining environments is critical to their effectiveness as a predictive tool. Numerical modelling is a vital tool in the prediction of ground behaviour in UG coal mines and to obtain a detailed extrapolation of stresses and deformations for complex mining geometries.

REFERENCES

Altounyan, P F R, Bigby, D N, Hurt, K G and Peake, H V. 1997, Instrumentation and procedures for routine monitoring of reinforced mine roadways to prevent falls of ground. In Proceedings, *27th Intern. Conf. of Safety in Mines Research Inst,1997, New Delhi, India,* pp 759-766.

Bajpayee, T S, Lannacchione, A T and Schilling, S R. 2008, Detecting strata fracturing and roof failures from a borehole based microseismic system, *27th International Conference on Ground Control in Mining*.

Bigby, D, MacAndrew, K and Hurt, K. 2010, Innovations in Mine roadway stability monitoring using dual height and remote reading electronic tell tales, *UG Coal Operator's Conference, The AusIMM Illawara Branch, University of Wollongong,* pp 146–160.

Butel, N, Hossack, A and Kizil, M. 2014, Prediction of *in situ* rock strength using sonic velocity, *UG Coal Operator's Conference, The AusIMM Illawara Branch, University of Wollongong,* pp 89-102.

Ellenberger, J L and Bajpayee, T S. 2007, An evaluation of microseismic activity associated with major roof falls in a limestone mine: A case study*, 2007 SME Annual Meeting and Exhibit, Denver, Colorado, preprint 07-103*, pp 1-5.

Gale, W J and Hebblewhite, B K. 2005, Systems approach to pillar design; Module 1 – pillar design procedures, *Final report, Volume 1 (of 3) – ACARP Project C9108, 68p*.

Hillis, R R, Enever, J R and Reynolds, S D. 1999, In situ stress field of eastern Australia, *Australian Journal of Erath Sciences,* Vol. 46, pp 813-825.

Karabin, G J and Evanto M A.1999, Experience with the boundary-element method of numerical modelling to resolve complex ground control problems, *Proceedings, 2nd International Workshop on Coal Pillar Mechanics and Design, NIOSH IC*, Vol. 9448.

Kumar, B R, Deb, D, Prasad, V N S and Siva Sanker, U. 2010, Numerical modelling – an effective tool for strata control in coal mines, *National Seminar on Underground Coal Mining*.

Lannacchione, A, Bajpayee, T and Edwards, J. 2005, Forecasting roof falls with monitoring technologies, *Proceedings, 24th International Conference on Ground Control in Mining, West Virginia University*, Morgantown, WV, Aug. 2-4, 2005, pp. 44-51.

Larson, M K and Whyatt, J K. 2009, Deep coal longwall panel design for strong strata: The influence of software choice on results, *Pages 75–87 of: Proceedings of the International Workshop of Numerical Modelling for Underground Mine Excavation Design*, Vol. IC 9512. Pittsburgh, PA: National Institute for Occupational Safety and Health.

Logan, K S. 2008, Analysis of wireless tiltmeters for ground stability monitoring, MSc thesis, Virginia Polytechnic Institute and State University.

Mark C.1991, Horizontal stress and its effects on longwall ground control, *Mining Engineering*, pp 1356-1360.

Mark, C and Gadde, M. 2010, Global trends in coal mine horizontal stress measurements, *10th UG Coal Operator's Conference, University of Wollongong & the Australian Institute of Mining and Metallurgy,* pp 21-39.

Nemcik, J, Gale, W and Mills, K. 2005, Statistical analysis of underground stress measurements in Australian Coal Mines, *in Proceedings of the Bowen Basin Symposium,* pp 117-122.

Oraee, B, Zandi, S and Oraee, K. 2013. A comparison of numerical methods and analytical methods in determination of tunnel walls displacement–A case study, *32nd International Conference on Ground Control in Mining http://icgcm.conferenceacademy.com/*.

SCT Operations Ltd, 2000. Coal Mine Rock Properties – Training Manual.

Suchowerska, A M, Carter, J P, Merifield, R S. 2014, Horizontal stress under supercritical longwall panels, *International Journal of Rock Mechanics & Mining Sciences*, Vol 70, pp 240-251.