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Celebrating 20 Years

ACG AUSTRALIAN CENTRE FOR GEOMECHANICS

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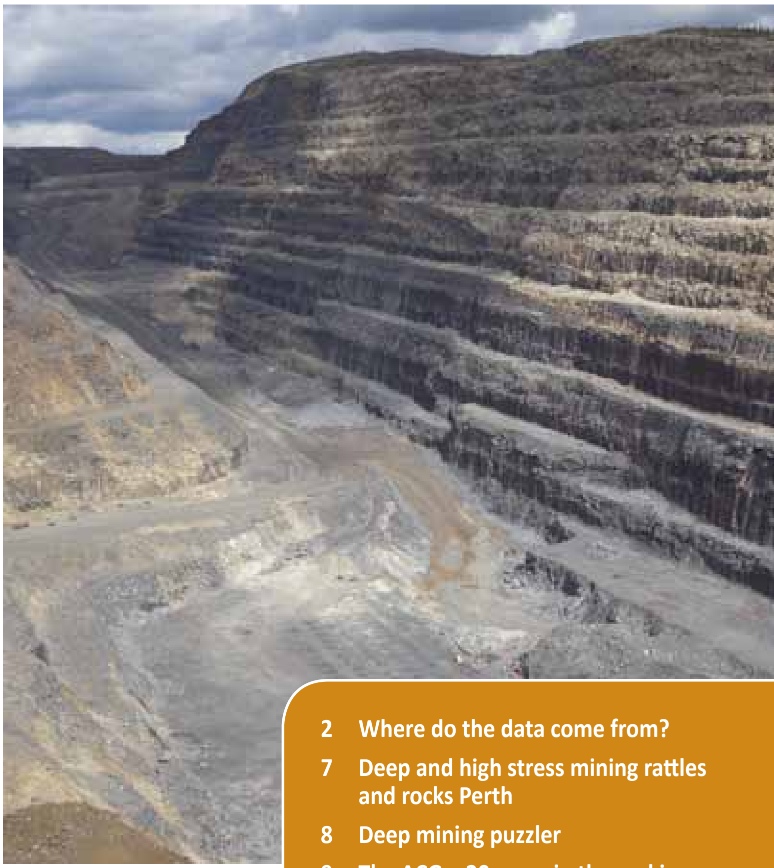
Newsletter



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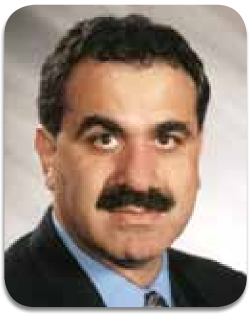


Where do the data come from?

edited from ACG's Sixth International Seminar on Deep and High Stress Mining proceedings keynote paper as written by Professor John Hadjigeorgiou, Lassonde Institute of Mining, University of Toronto, Canada

Introduction

The need for data is neither new nor restricted to mining. An eloquent description for the need for data is provided by Doyle (1892). In the book "A Scandal in Bohemia", the fictional detective Sherlock Holmes advises Dr Watson that:

> *"It is a capital mistake to theorize before one has data. Insensibly one begins to twist facts to suit theories, instead of theories to suit facts."*

In a rock mechanics context the need for geotechnical data was articulated by Hoek (1994). In a letter to the International Society of Rock Mechanics (ISRM) News Journal he provided a sobering comment:

> *"I see almost no research effort being devoted to the generation of the basic input data which we need for our faster and better models and our improved design techniques. These tools are rapidly reaching the point of being severely data limited."*

Although we have made significant strides in certain areas of data collection, the above sentiment is still of pertinence today. In order to be useful, geomechanical data have to be processed and converted into information. In a deep mining context, it may very well be that, depending on the level of detail required, one person's information is another person's data. The thesis of this edited paper is that understanding the limitations of data collection techniques and geomechanical data management are important in the design of all mining excavations. In deep and high stress mining, however, the severity of challenges faced by the mines allows little tolerance for mishandling or misinterpreting geomechanical data.

The need for data in engineering design

A rational approach in the design of mining excavations would require clearly defined engineering objectives. The primary objectives being the economic and safe extraction of ore under difficult ground conditions. It is consequently surprising that, given our improved understanding of the major issues in rock engineering, there has not been more work in formalising the design process.

A notable exception is the work of Bieniawski (1992) who identified the following design principles for rock engineering:

- clarity of design objectives and functional requirements
- minimum uncertainty of geological conditions
- simplicity of design components
- state-of-the-art practice
- optimisation
- constructability.

In his work, Stacey (2004) explored the link between the design process in rock engineering and the code of practice to mitigate rock fall and rockburst accidents and later on, suggested a distinction between defining and executing the design. This was illustrated in "the engineering circle" where the first phase (defining the design) contains four steps and the second (executing the design) six steps (Figure 1).

Irrespective of whether the process is described as minimising uncertainty or otherwise, there is a need for geomechanical data collection. For example, Bieniawski (1988) suggested that:

> *"…..geological and rock mechanics data must be collected in sufficient quantity and of high quality; data interpretation should be performed specifically for purposes of engineering design; and innovative design approaches should be used to bring about improvements in productivity and safety".*

Analysis and design

In a deep mining context, there is a need to construct geological and geomechanical models, employ classification systems, build structural models and assess the necessary input data into a 3D numerical stress analysis model. All these processes have different data requirements. Unless these needs are understood and communicated to the personnel

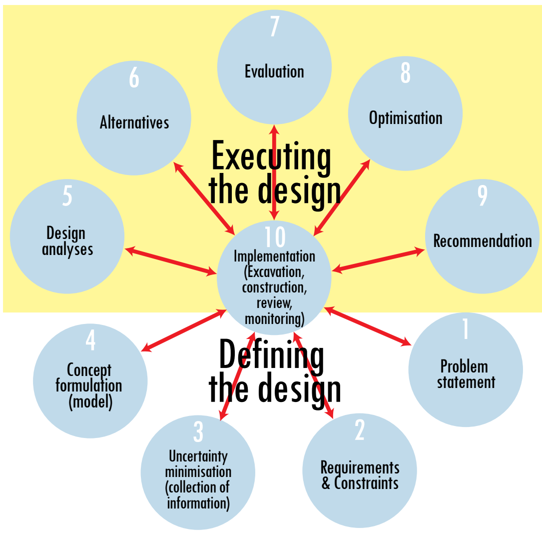


Figure 1 The engineering circle, after Stacey (2009)

responsible for data collection, this information is missed.

In all conceptual design diagrams, data collection precedes analysis and design. This sequential process may be appropriate and applicable in civil engineering projects but it is not necessarily the case in deep mining projects. In a mining context, what is more applicable is a continuous process where several of the steps are either run in parallel or through several iterations, i.e. closing the design loop.

A further issue, sometimes overlooked, is that the engineering design process has become tool driven. Therefore, unless there is a clear understanding, a priori, of the input data needed to apply these tools, the required data will invariably not be collected. As a result, further data collection campaigns may become necessary or, alternatively, the gaps are tentatively filled by extrapolating available data.

Rock mass classification systems

Rock mass classification is one of the only approaches for estimating large-scale rock mass properties. In mining, the Q classification system proposed by Barton et al. (1974) and the rock mass rating (RMR) developed by Bieniawski (1976), form the basis of many empirical design methods. As well, they are often used towards defining failure criteria in numerical modelling programs. Rock mass classification systems have evolved as engineers have attempted to apply them to a wider range of engineering problems.

Invariably, it is not feasible to collect all possible data. On the other hand, if data are collected specifically for one classification system, they may not be adequate for another. In practice it is commonly observed that a mine or a consulting company have a certain affinity or preference for a particular classification system or a version of the system. If the raw characterisation data are used for classification, then the classification ratings become the new data. Depending on the system used, the results can be quite different.

It should be remembered that the basic assumption of the classification systems is that the rock mass contains a sufficient number of "randomly" oriented fractures, so that it can be treated as a homogeneous isotropic mass. Consequently, rock mass classification systems may be inappropriate for rock masses with dominant structural orientation such as foliation.

The LaRonde Mine further provides several examples where the structural anisotropy and inhomogeneity in a rock mass were taken into consideration in data collection and interpretation. Mercier-Langevin and Hadjigeorgiou (2011) demonstrated that structure was arguably the single most important factor to the onset of squeezing at the site (Figure 2). This requires an investment in constructing representative structural models at the site.

Discrete fracture networks

Recent years have seen a concerted effort to the use of Discrete Fracture Modelling (DFM) and Discrete Fracture Networks (DFN) as part of engineering design in underground mines. The success of DFN, however, is dependent on the availability of quality geotechnical data. The generation of DFN intensity data together with fracture orientation and spacing are required to develop a representative DFN model (Figure 3). Golder Associates (2009) has identified the necessary measures of fracture intensity data. This information, however, is rarely included in the standard data collection process and, as such, limits the future application of this type of advanced rock mass modelling technique.

Figure 2 Variations in squeezing severity at locations less than 200 m apart at 2,300 m depth as a function of foliation thickness, after Mercier-Langevin and Hadjigeorgiou (2011)

Stress analysis models

A necessary input for stress analysis models is the strength of the rock mass. This is often derived through laboratory tests on intact rock samples and some form of extrapolation strategy for large scale samples that incorporate the presence of defects. This is often through the use of empirical relationships based on rock mass classifications schemes. Consequently, it is important to keep these requirements in mind when designing a data collection campaign. It follows that it makes sense to collect the information that would be best suited for these empirical relationships.

Classifying geotechnical models according to the level of understanding of their geotechnical environment

It is evident that the quality and quantity of data is defined by the design objectives and functional requirements. In a mining context, this is further qualified by the timeline of the operation from preliminary feasibility, feasibility, development, early production, late production and mine closure. Bullock (2011) provides a series of geotechnical activity definitions from the preliminary to final feasibility stages.

From a geotechnical perspective, the early stages are often characterised with both limited data and large variations on how data are collected and by whom. It is unfortunate that this information is often disjointed, and reporting of geotechnical data is often quite variable even within mining and consulting companies. The usual justifications for these omissions and lack of conformity are the lack of human resources, costs or simply failure to see the pertinence for this work. This, however, is in sharp contrast to reporting of mineral resources and ore reserves where there are clear guidelines, for example, the Canadian and Australian standards of disclosure and reporting mineral reserves, CIM (2005), JORC (2004).

Data collection techniques

Although there are several standards for geomechanical data collection, these are not necessarily applied or enforced at several mining operations. The reasons for this diversity of approach, or non-compliance to site specific standards, are beyond the scope of this edited paper and have to do as much with the inherent material variability, economics and corporate culture. This section highlights some of the data collection techniques illustrating the issues relating to geomechanical data generation.

Core logging

At the early stage of data collection the first set of available information is based on core logging. This is understandable at the feasibility stage but it is somewhat surprising how these original data, often without being updated, form the basis for subsequent rock mass classification ratings. Rock mass assessment, based only on core logging, can easily be off by 50% (Jakubec and Esterhuizen, 2007).

However, the reality is that we do have access to sophisticated tools to determine rock mass quality from boreholes. The use of optical and acoustical geocameras or televiewers provides a valuable tool in obtaining 360°, digital colour images of the walls inside a borehole and of fractures and other defects along the borehole.

Structural mapping

Structural mapping is undertaken to identify pertinent geological structures, rock mass characterisation and generate reliable input data for stability analyses. Hadjigeorgiou et al. (1995) reviewed the various mapping methods and the need for trade-offs between the different techniques as a function of existing field conditions and intended use of data. Most statistical techniques defining the structural fabric of a rock mass are only applicable when a sufficient amount of data is available. In deep and high stress mines there is often a scarcity of quality data due to mapping difficulties such as limited access, coverage of wall exposures with shotcrete or wire-mesh, dust, poor lighting and noise. These adverse conditions are often compounded by the need to comply with strict production constraints.

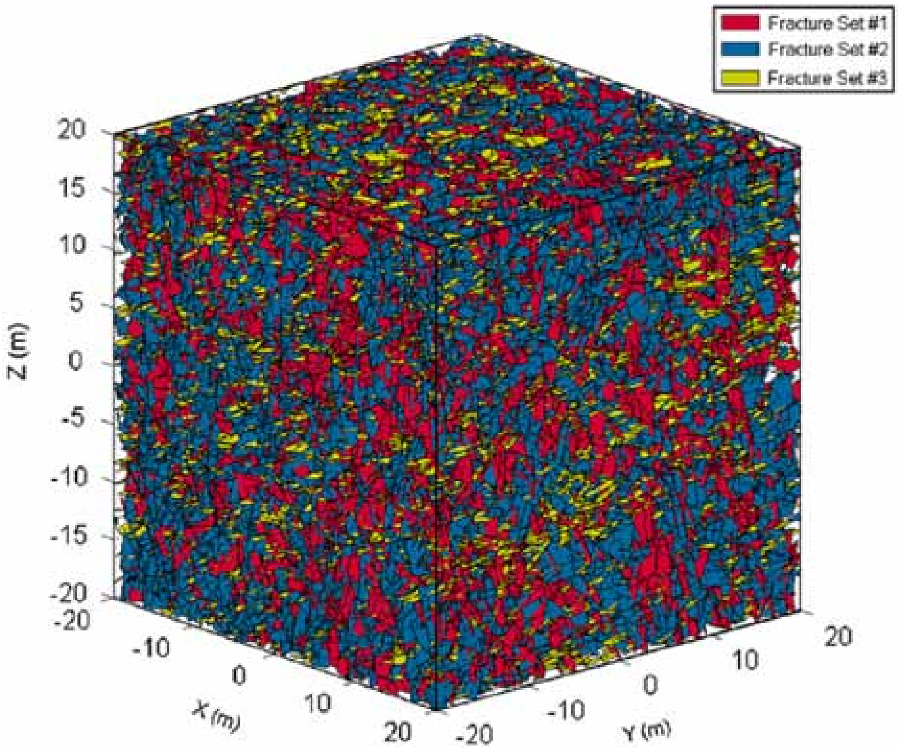


Figure 3 Visualisation of a generated fracture system for Brunswick Mine, after Esmaieli et al. (2010)

In situ stress

In a deep and high stress environment it is desirable to have access to quality stress data. Hudson et al. (2003) proposed a series of incremental steps that can be used in developing knowledge of the rock stress tensor components.

- Use pre-existing information on the rock stress state at the site.
- Consider whether the vertical direction is a principal stress direction (from topography, geological evidence and other information).
- Estimate the vertical stress component magnitude (from the rock density and overburden depth).
- Consider indications of the principal stress directions and the ratio of stress differences (from focal plane solutions inversion or seismic shear wave anisotropy).
- Establish the minimum principal stress orientation (whether actual or minimum horizontal stress) from hydraulic or drilling induced fractures and borehole breakout orientations.
- Find components of the stress tensor using indirect methods on borehole core (such as the Kaiser effect and differential strain analysis).

Instrumentation and monitoring

Valuable geomechanical data can be gained from a well-designed and executed instrumentation programme that aims to provide answers to specific questions. A review of all available instrumentation techniques is not within the scope of this edited paper.

In deep and high stress mines under a series of conditions there will be a seismic response to mining activities. Recent years have seen a change in strategy where the objective is to gain an improved understanding through monitoring. This can allow the implementation of proactive measures such as modifying mining sequence and modifying support strategies.

The mining community has recognised the need for collecting seismicity data as a means to characterise if a geological structure is active, as well as monitoring rock mass degradation and fracturing. Rockburst data are extremely useful in assessing the performance of support systems, constructing re-entry protocols, etc.

This is reflected in an increase in the number of installed mine-wide seismic monitoring systems worldwide. In Australia, the number has reached close to 60, and in Canada close to 40.

Filling in the gaps

Irrespective of the quantity of data collected there is always a need to fill in the gaps. This is often when the design tools require input parameters that were either not collected through omission, lack of foresight or simply the needs changed.

Mine design, whether relying on empirical or numerical techniques, will eventually use geomechanical data as input. This is the stage that engineers realise that there are gaps in the type, quality and quantity of data required for their analysis. At this point there are two alternatives: initiating data collection campaigns; or attempting to fill in the gaps of information by extrapolating material from existing data based on experience and conversions. Both options have severe limitations. A new data collection campaign will generally result in time delays, and in certain cases, access may no longer be available or core may no longer be available or potentially mishandled.

Perhaps the greater source of concern is the tendency to rely on software packages, or published databases to provide the necessary geotechnical data. In the most popular packages, the user can identify a rock type and can gain access to laboratory test results, for example, uniaxial or triaxial. Quite often, however, the information is provided as an "average" value with little information on the number of tests, deviations, sample description or observed failure mechanisms. The reality is that there exists a huge variety of rock masses and ground conditions requiring the application of relevant tools that represent the actual rock mass and ground conditions encountered.

Management of geotechnical data

Given the time and effort to collect geomechanical data, it is quite surprising that the process of managing data is not given greater importance. It is desirable that geomechanical data are shareable, transportable and secure. Furthermore, data must be continuously kept up-to-date.

An indication on how well data are managed in a mining operation is when it is possible to trace and document what happens to any geomechanical data. Is it possible to know what transformations and manipulations happened to that data?

The path forward is to establish a priori of the objectives of any geomechanical data collection programme. It is necessary to issue specific guidelines and tasks and ensure that the personnel assigned to these tasks are competent. Following the initial geomechanical data collection programme, the information has to be collated and verified by a quality assurance programme. Once this is in place, a well-established and understood dissemination protocol must be implemented.

Solving data limited problems

The shift to tool driven design has led to a change in mind set and the belief that we can model complex material behaviour. This has been further advanced by gains in computer power and advancements in modelling. In the absence of quality data, this has sometimes resulted in not realistic expectations or blind faith in the results of modelling.

It is important to note that simple models with limited data are still of use. In certain cases, and unless there is an effort to identify and collect the necessary geomechanical information, our most sophisticated models are limited or can be misinterpreted as more "precise" than the input data warrant.

Data integration and visualisation

Geomechanical data are most useful when analysed, processed and represented in 3D space. Increased value is derived when there is a flawless data transfer between geomechanical databases, monitoring data and modelling. This is an area where there has been considerable progress.

The role of human resources in data collection

A major issue, often overlooked, is who collects geotechnical data? The data collection process is dependent on employing and training personnel assigned to these tasks. Unless the people doing the geomechanical data collection realise how important their effort is and how useful it is to the operation, they do not assign the same level of priority as other tasks. It is imperative to establish a strategy on who collects data, how qualified they are, how the information is recorded, what are the quality control measures in place, etc. It is a reality that people are an essential part of an organisation's memory and data management and this emphasises the need for efficient and reliable communication.

How reliable are the collected data

Sources of error for engineering design purposes are often associated with data collection and material testing methods. In cases where data collection uses specific standardised techniques and equipment, it can be relatively easy to quantify the magnitude of error (Hadjigeorgiou and Harrison, 2011).

A recurring question when planning a rock testing programme is how many samples have to be tested for any particular test to adequately describe the mechanical properties of a given rock or rock mass type. Gill et al. (2005) compiled sample sizes as suggested by the ISRM (Table 1).

Gill et al. (2005), however, made a strong case that it is not possible to decide a priori of the number of required tests for a given rock type and a target precision index. Instead they proposed to establish the number of tests based on small-sampling theory. They further demonstrated that for a given rock and test type, the minimal sample size varies from one case to the other. The conclusions by Gill et al. (2005) are in direct agreement with more recent work by Ruffolo and Shakoor (2009). The latter work investigated the number of required tests to estimate the mean unconfined compressive strength of different rock types. It further established a relationship between the minimum number of samples needed, using the confidence interval approach, and the coefficient of variation (Figure 4).

In effect, the higher value of coefficient of variation indicates higher variability and the need for testing a higher number of samples.

Conclusions

Collecting data is not an objective in itself. Unless they can be analysed and summarised, they are of limited use. In order to be useful, data have to be processed and converted into information. In a deep mining context it may very well be that, depending on the level of detail required, one person's information is another person's data. The process is completed when information is transformed into knowledge. This requires education and experience and a clear understanding of the processes.

It should be recognised that the use of rock mass classification systems, although convenient, is not always applicable in rock mass conditions which are neither homogeneous nor anisotropic. Consequently, there is a need to better define discrete features that may control the behaviour of a rock mass at depth.

As the engineering process advances it is necessary to validate the predictions of any employed design model. This is only possible if there are monitoring or performance data. Although the need to close the design loops from data collection, design, implementation, and monitoring has been recognised for some time, there are concerns in its implementation.

Although traditional design methodologies advocate a sequential process of data collection, analysis, and geotechnical model construction followed by analysis and design, this is not really the most applicable approach in deep mining. The case is made that a more optimal approach in data collection takes place, in parallel with design. It is realised that this imposes further constraints in time and personnel and introduces a committment to continuous data collection and modelling. Nevertheless, it is felt that the increased benefits justify such an approach.

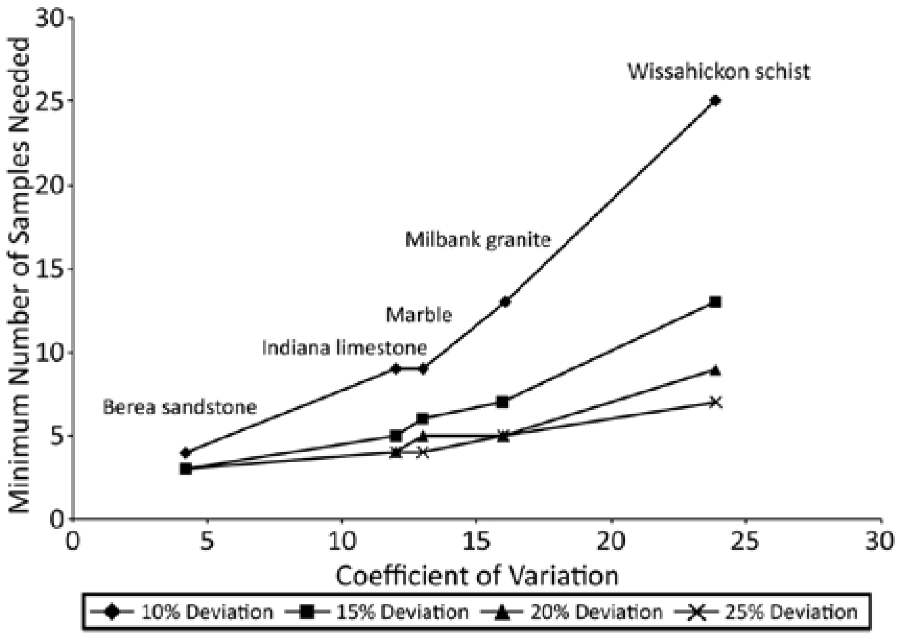


Figure 4 Minimum number of samples needed to estimate the mean unconfined compressive strength based upon the acceptable deviation from the mean and the corresponding coefficient of variation, using the confidence interval approach, after Ruffolo and Shakoor (2009)

Table 1 Sample sizes as suggested by the ISRM, after Gill et al. (2005)

Test Type	Sample Size
Uniaxial compression	Determined from practical consideration but at least five are preferred
Direct and indirect tensile strength	Determined from practical consideration but at least five are preferred
Point load test	At least 10, more if heterogeneous or anisotropic. The two lowest and highest values should be discarded
Triaxial	Determined from practical consideration but at least five are preferred
Shore hardness	A large number
Porosity/density	At least three

Acknowledgements

The author acknowledges the technical input of his colleagues at several mining companies. The continued support of the Natural Science and Engineering Council of Canada is greatly appreciated.

Please contact the ACG for the full, unedited paper.

Deep and high stress mining rattles and rocks Perth

ACG director Yves Potvin with Mark Cutifani, CEO, AngloGold Ashanti Ltd (left), and Emeritus Professor Ted Brown AC (right)

Underground mining continues to progress to deeper levels and industry is extracting mineral reserves at depths that would have been "un-minable" a few decades ago. With the high value of minerals being maintained for a long period of time in this unprecedented mining boom, industry is also in a good position to plan for developing future resources lying even deeper under the Earth's surface. It is envisaged that in Australia this limit will soon be pushed beyond 2 km; in Canada it will be 3 km; and in South Africa it may eventually reach 5 km. This is extraordinary, considering that the industry has managed, in most cases, to maintain and improve its safety record, in an ever-increasing hazardous and difficult environment.

It was very clear at the Sixth International Seminar on Deep and High Stress Mining held in Perth, Western Australia, 28–30 March 2012, that the importance of deep and high stress mining had moved up the agendas of many mining companies; with increased pressure on industry to head the call for improved mine worker safety conditions.

Senior mining practitioners presenting at the seminar said that scrutinising mining practices and technologies in these often highly stressed and hazardous environments, prior to decisions being made about the productivity, is now more common practice.

More than 165 delegates from 14 countries attended the seminar. The three-day technical programme was excellent and the event was well supported by many sponsors, namely: Stratacrete Pty Ltd, Barrick (Australia Pacific) Ltd, Beck Engineering Pty Ltd and Coffey Mining Pty Ltd. Deep and High Stress Mining 2012 follows previous international Deep and High Stress Mining Seminars held in Santiago in 2010, Perth in 2007, Quebec in 2006, Johannesburg in 2004, and Perth in 2002.

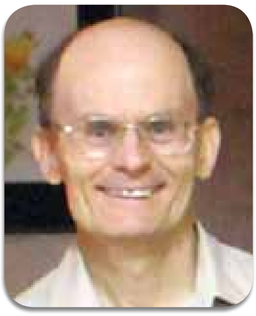
The ACG was thrilled to have Mark Cutifani, CEO, AngloGold Ashanti Ltd, South Africa, open the seminar with an address entitled, "Perspectives on Deep and High Stress Mining in AngloGold Ashanti". AngloGold is already operating at 4 km depth, with mine automation potentially facilitating mining at 5 km. With the unique challenges mining at great depth presents, AngloGold's focus is firmly centred on safety performance, "zero harm", and reducing the influence of high stress and seismicity in the South African region. The company supports new and diverse ideas to mine at depths beyond 5 km such as encouraging breakthroughs in cutting and backfill technologies. Cutifani also noted South Africa's industry "brain-drain" and loss of rock engineering skills. AngloGold Ashanti is committed to improving the educational opportunities for its workforce.

Other highlights included Emeritus Professor Ted Brown reviewing four main deep and high stress mining themes: geomechanics risks, risk assessment and management, rock behaviour under high stress and numerical modelling. The second keynote given by Professor John Hadjigeorgiou, director, Lassonde Institute of Mining, Claudette MacKay-Lassonde Chair in Mineral Engineering, University of Toronto, Canada, explored the critical question for deep mines, "Where do data come from?" The topic of geomechanical data feeding into a mine design is too often conveniently ignored, but several issues were raised and useful advice given in this keynote, concerning the quantity, quality, integrity, storage, manipulation and communication of geomechanical data.

The third keynote was a comprehensive case study of a deep and high stress mine given by Peter Hills, who described the evolution of the mining method and the thorough geotechnical management systems implemented at the Tasmanian Mine.

The seminar was immediately followed by a very successful one day ACG Stress Measurement Workshop facilitated by Winthrop Professor Phil Dight.

"Successful deep and high stress mining requires sound strategic mine planning approaches as well as good processes allowing to react adequately to unforeseen situations."



Deep and high stress mining puzzler

proposed by Dr Peter Mikula, Mikula Geotechnics Pty Ltd

Forget Sudoku and cryptic crosswords. If you really want to exercise the grey matter, try the competition question asked at the Deep Mining 2012 Seminar

Suppose a seismic event occurs and causes damage to the rock mass and the installed support in a dry excavation. Would the damage have been greater or lesser if the excavation had been flooded, i.e. full of water?

Credit for the question goes to Rowland Whiting and Claire Dyson of Lightning Nickel Pty Ltd, where a tradition of hard questions has arisen of late. Credit for the answers goes to the 13 bold respondents whose collective answers are listed below.

Reasons why damage might be greater:

1. Water lubrication of joint and structure surfaces may reduce friction and allow more movement.
2. In permeable materials, the increase in pore water pressure reduces strength (effective strength principle) which may lead to more damage.
3. Water in joints and fractures transmits pressure pulses through the whole fractured zone as there are no isolating air gaps, so that the vibrational damage is more extensive and assists the mobilisation of rock blocks. Hydraulic connection has shown damage from blasting.
4. In the longer term, corrosion of installed support can be detrimental.

Reasons why damage might be lesser:

1. Water being incompressible provides confining pressure against dynamic movements, which acts to assist ground support.
2. The incoming P wave may undergo less reflection at the free rock surface as part of the wave will transmit through water – thus less damage. Does not apply to shear waves as water does not transmit shear.
3. Water acts like a cushion, dampening ejection. The dynamic viscosity of water is much higher than that of air, and dissipates the energy much quicker.
4. Buoyancy of rock in water will reduce effective weight and improve the static case. However, energy and momentum relate to mass, not weight, so buoyancy makes no change to the driving velocity.

A bet each way reasons:

1. Hydraulic fracturing may occur through pressure pulses in water contained in fractures, which may enlarge the fractured zone, but at the same time dissipate more of the energy.
2. Water may make the static case worse which may override any better dynamic performance.
3. Hydraulic pressure acts equally on all sides of a block of rock, thus having no net benefit.

Frivolous reasons:

1. Dry is best. Try and fix it when it is full of water.
2. Have frozen water, which will conclusively result in less damage.
3. Wet is best because then the mine can be more profitable by adding fishing as a byproduct.
4. Wet will encourage development of corrosion resistant underwater rockbolts which will drive research and assist the economy.

The voting was 50/50, some entrants voted both ways, so the competition was no help whatsoever in arriving at a consensus. The competition winner was Kyle Woodward, ACG/UWA Masters Student whose answer canvassed a large proportion of the various reasons in the answer pool. Runners up were: Beth Askew, Aurico Gold, Stawell Gold Mine; Max Lee, AMC Consultants Pty Ltd; and Denis Thibodeau, Vale Base Metals Technology Development, Canada.

The challenge is now thrown open to everyone. If you can convince Peter that you are right, $500 from Mikula Geotechnics could be coming your way. Email Peter before 30 September 2012 at pm@MikulaGeotechnics.com. He is looking for answers that relate the discussions to the type of ground support that ought to be used in dynamic conditions. Dry, of course.

Good luck!

The ACG – 20 years in the making and still going strong

as written by
Winthrop Professor Yves Potvin, director
Australian Centre for Geomechanics

There is a saying that, "from every bad thing comes a good thing!" Well, it is twenty years ago that the Australian Centre for Geomechanics, following an unsuccessful application for a multi-million dollar Collaborative Research Centre, started its activity with a very modest budget, but with the very big ambition to become a world-class geomechanics centre. This original vision of the founding director Professor Richard Jewell, was instrumental in developing a strategy that lead to the future success of the newly formed centre. The new Australian Centre for Geomechanics was an unincorporated Joint Venture (JV) between The University of Western Australia, the CSIRO, The Western Australian School of Mines (WASM), Curtin University and the Department of Minerals and Energy (DME). Seed funding of $243,980 was originally provided by the JV partners.

Despite this humble beginning, Richard Jewell knew how to lay solid foundations and he could not select a better person than Christine Neskudla as the "central pillar" to assist him to build the ACG. During the first five years, Richard and Christine, supported by a Board of Management chaired initially by Dick Carter, and a great number of volunteers from the JV partners, consulting firms and mining houses, established and delivered annually, a comprehensive professional development curriculum for geomechanics practitioners. As early as 1993, the ACG was delivering several further education and training industry courses:

- Geo-Engineering for Pit Wall Stability
- Terrestrial Photogrammetry for Open Pit Mining
- Tailings Management and Rehabilitation
- Design of Underground Excavations in Rock
- Applied Rock Fracture Mechanics
- Underground Mine Design and Ground Control
- Underground Ground Control

In 1993, a major multi-disciplinary research project, "Modelling the Stability of Deep Open Pit Mines", was undertaken through the ACG and supported by the Western Australian Government and China Economic and Technical Research Fund. The project's scope was formulated following a visit to China by Dr Chris Swindells and Professor Jewell.

"Integrated Monitoring Systems for Open Pit Wall Deformation" was the first of what was to become a long and successful succession of Minerals and Energy Research Institute of Western Australia (MERIWA) funded projects at the ACG. This project was led by Dr Xiaoli Ding from Curtin University. The second ACG research project to be supported by MERIWA was developed in 1994 and fostered collaboration between a research team from UWA's Geomechanics Group and the Geological Survey of Western Australia (GSWA). The team worked on the management of tailings in the gold mining industry. The project focussed on the consolidation behaviour of saline and non-saline tailings.

In the first five years of the ACG, oil and gas offshore geomechanics were also part of the centre's brief and Winthrop Professor Mark Randolph, an ACG board member at the time, initiated a MERIWA funded project supported by Woodside and West Australian Petroleum Pty Ltd (WAPET), on an "Integrated Study of Foundation Systems in Calcareous Sediments". Professor Randolph carried on his very successful research work and created in 1996 the Centre for Offshore Foundation Systems at UWA, allowing the ACG to thereafter concentrate on mining geomechanics.

Whilst maintaining a full schedule up to eight annual professional development courses, the ACG expanded its research programme with the continuation of the MERIWA funded project, "Integrated Monitoring Systems for Open Pit Wall Deformation". This project was also supported by Hamersley Iron. By 1995, the third ACG staff position, public relations officer, was created.

In 1996 the ACG struck gold! We received a Centre of Excellence Grant from the Western Australian Government of half a million dollars to enhance our services to industry. The funds were wisely invested to grow the geomechanics capabilities within the three JV partner organisations. A sum of $150K was allocated to Professor Randolph to assist in the purchase of a new drum centrifuge; an essential facility for the development of world-class research in soil geomechanics.

A further $210K was allocated to the Western Australian School of Mines to assist them to create a professorship of mining geomechanics. Professor Ernesto Villaescusa was appointed to this position in 1997. Fifteen years later, after having built an internationally recognised geomechanics research facility in Kalgoorlie, Professor Villaescusa is still leading one of the world's best geomechanics masters' programmes at WASM.

CSIRO was awarded $150K to undertake fundamental research into the time dependency in rock deformation.

It was in 1998 that I joined the ACG as the new research coordinator. Up to this point, the ACG was very active in open pit and mine tailings geomechanics. But at the time, the Western Australian underground mining industry did not have a good track record, and rockburst and rockfall fatalities were common occurrences. My mandate was clear: to help address the urgent safety issues in underground mines through innovative research, training and education in geomechanics. During 1998 and 1999, we organised three courses on mine seismicity which culminated with the creation of the first phase of the research project "Mine Seismicity and Rockburst Risk Management (MSRRM Phase 1), initially lead by Associate Professor Marty Hudyma.

Twelve years later, MSRRM is undertaking its fifth phase with a budget exceeding $1.5M for the next three years. In addition to the software MS-RAP, which is used in mining operations world-wide, the most significant legacy of this long lasting project is the achievement of five graduated PhD and one Masters degree specialists currently working for the benefit of the mining industry. A further two PhD students are currently supported by this project. A spin-off project to MSRRM was also created in 2004 looking at the implementation of seismic monitoring in open pit mines.

The new millennium signalled a year of big change at the ACG. Founding director Richard Jewell retired from his role, but this did not prevent him from continuing to contribute to the centre as a part-time member. Before leaving the command, the wise man had another strike of genius and initiated the first International Seminar on Paste and Thickened Tailings (P&TT). The ACG had never organised an international mining event before, but its phenomenal success opened up a whole new world for the ACG. Twelve years later, and the ACG has just hosted its twentieth international mining event. In addition to the P&TT seminars, the ACG has created several highly successful international event series such as mine closure and deep and high stress mining, which tour the world annually or bi-annually. These initiatives allowed us to establish a strong international reputation via regular presence in South Africa, Canada, Europe and Chile.

The other event that transformed the ACG in 2000 was the employment of Josephine Ruddle who rapidly became the second pillar at the ACG, whilst re-inventing our whole approach to marketing and communication. By 2001, the ACG was running up to 12 short courses as well as one international event annually.

In the meantime, the underground mining industry in Australia was working on what became an incredible step change in its safety performance. This was clearly demonstrated in the project "Towards the Elimination of Rockfall Fatalities", a landmark project of the ACG, where statistics showed that the industry achieved a sustained reduction of 75% in rockfall injuries within two years (between 1997 and 1999). The ACG was very fortunate to have Paul Nedin, a highly experienced mining engineer and former mine manager, join the ACG to work on this research project. This research culminated with the publication of the Minerals Council of Australia's "Industry Guideline for Rockfall Risk Management" in 2003.

To reach our vision to contribute to better geomechanics practices at mine sites, it was readily understood that we needed to not only address the needs of engineers, but also to reach the workers spending days and nights at the mine face. With the wonderful contribution of Dr Phil Dight working with BFP Consultants at the time, the ACG offered "training on demand" at mine sites throughout Australia. This popular programme called "Ground Control at the Mine Face" was gradually complemented by a series of several videos/DVD and one interactive CD, produced by Jack Creswick, Lodestone TV, since 2004, under a wide participation of many mining companies and suppliers' sponsorship.

In 2005, the ACG's environmental geomechanics programme received a gigantic boost with the addition of Winthrop Professor Andy Fourie joining our team on a full time basis for a period of three and a half years. This new position was funded by AngloGold Ashanti, BHP Billiton (previously WMC Resources), Newmont Asia Pacific, and Rio Tinto for three years, each contributing $60k. Andy

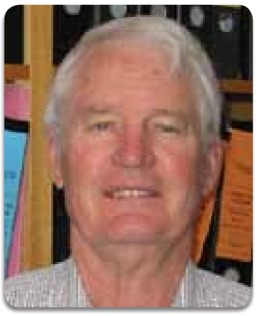
"To reach our vision to contribute to better geomechanics practices at mine sites, it was readily understood that we needed to not only address the needs of engineers, but also workers spending days and nights at the mine face"

already had an excellent involvement with the ACG through his high level of participation at all paste seminars and his co-authorship of the first edition of the book "Paste and Thickened Tailings – A Guide". In his new position, Andy co-authored the second edition of the same book which was published in 2006, as well as the "Handbook on Mine Fill" in 2005. In collaboration with Professor Mark Tibbett, Andy initiated the very successful series of mine closure conferences in 2006 and, completed in 2010, a three year research project entitled, "An Effective Stress Approach to Mine Fill". A continuation of this research through Australian Research Council (ARC) funding is currently underway.

In 2007, the sustainable growth of the ACG continued with the arrival of Dr Johan Wesseloo from SRK, South Africa. Johan completed the work on our open pit seismic monitoring project and has taken over the lead of the fourth and, recently, the fifth phase of the MSRRM project, succeeding Dr Daniel Heal.

In 2008, the ACG had the great fortune of welcoming another long term contributor, Winthrop Professor Phil Dight, as a full time member and leader of our open pit geomechanics programme. During the last four years, Phil has organised several conferences, courses and workshops, and continued his research work on stress measurements and pit slope stability.

There are so many people whom I regrettably did not have the chance to mention in this short article that have made outstanding contributions to the 20 years of success at the ACG. Nevertheless, before closing, I would like to acknowledge the past chairmen of the ACG Board of Management: Dick Carter, Peter Lalor, Ian Burston, Andrew Grubb and the current chair, Ian Suckling, who have all generously provided guidance and lent us their precious time, expertise and wisdom, and taken an active part in the management of this centre.



The early years of the ACG

by Professor Richard Jewell, inaugural director, Australian Centre for Geomechanics

In 1991, the Federal Government initiated a programme of funding Collaborative Research Centres (CRCs). These CRCs were to incorporate collaboration between different research organisations and industry. The Geomechanics Group in the Civil Engineering Department at The University of Western Australia (UWA) developed a proposal for a centre entitled, "Australian Centre for Geomechanics", to provide research and education services to the mining industry. Some 100 plus applications were submitted for the first round of CRCs and our proposal got through to the final 30, but missed out as one of the successful 15. This was a disappointment at the time but proved to be about the best thing that could have happened. To enter into the second round of applications would have involved a new proposal into a completely different line of research, but a meeting of the proposed partners agreed that the direction of the original proposal was what we were best equipped to deliver and, in our opinion, best met the needs of the mining industry at that time.

The industry partner withdrew and the remaining partners written into the initial proposal agreed to provide seed funding to initiate a collaborative joint venture centre, retaining the original objectives. The UWA housed and administered the centre which took on the status of a UWA research centre with external collaborative joint venture partners. A grant from the UWA Engineering Foundation provided the funding required by UWA Civil Engineering to remain in the partnership. We are grateful that the centre became essentially self-funding from year one, and the seed funding was never drawn down - assisted greatly by UWA paying the salary of the director of the centre for the initial years.

The centre retained the name first mooted in the CRC application. Thus, in June 1992, with an industry dominated board chaired by Dick Carter, then president of BHP Iron Ore, the ACG was launched at a function hosted by the DME. Dr Chris Swindells, at that time with the DME, provided considerable support and encouragement to the ACG during the early years.

A very early task was to recruit a secretary and 72 applications were received for the position. To conform to the guidelines of the UWA, an exhaustive process of selection ensued and at each stage one particular application was cast aside as being "too different"– only to be reinstated because it was "promisingly different". Needless to say the applicant finally chosen was a German lass who had married an Australian and moved to Perth after working with a firm in the shipbuilding industry in Hamburg for eight years. She had a lot to learn and a lot to contribute and after being with the ACG now for 20 years, Christine Neskudla could rightly be considered to be the glue that has formed and developed the ACG to what it is today. In what was a busy two person team running the ACG during the formative years, Christine was operating as very much more than a secretary in that she sat in on all meetings; initiated correspondence and effectively "made things happen". In short, she was indispensable and selecting her from the 72 applicants was without question the best staffing appointment I ever made and she is a quality friend and colleague. In the very early days, contacting someone on the phone involved long descriptions of what the ACG stood for and did, but thankfully we progressed beyond that to the stage where the acronym "ACG" is now recognised within the mining industry around the world.

Early sources of income for the centre came from industry short courses, principally in tailings management and engineering geology, and an administration component from small research projects and government grants won as a result of proposals developed by the centre. The research projects promoted by the centre were undertaken by the joint venture partners and funded either directly by the industry, or through funding brokered through bodies such as the Minerals and Energy Research Institute of Western Australia (MERIWA) and AMIRA. The centre has never received any recurrent funding from any source and, while this slowed growth, it has meant that there was never any threat of closure as a result of the termination of any source of funding.

During the 1990s, the staff of the ACG increased gradually through full and part-time appointments until we had generated sufficient funding to underwrite a senior research position which enabled us to approach and recruit Yves Potvin. In this appointment, we were fortunate to be guided by Professor Barry Brady who was at that time the Dean of the Engineering Faculty.

The centre was at this time entering into a phase of expanding the scope of its activities. For example, we commenced planning for a seminar on paste and thickened tailings which was held in Perth in 2000. This was an outstanding success and has developed into an international series held annually in different venues around the world that have become the key event in this field, considerably enhancing the credibility of the ACG. Very importantly, this became the "blueprint" for a series of symposiums/seminars in a range of mining oriented disciplines which the ACG initiated, and now promotes and administers on a regular basis generating income that has contributed towards the ACG developing to where it is today.

The gradual expansion of the ACG through the 1990s required several moves from our initial one room office in the

UWA Engineering building, to houses in Cooper Street, Nedlands, Rokeby Road, Subiaco, and back to the current facility. During that time we were fortunate to have a number of senior mining industry people take on the role as chairman of the ACG Board.

In the year 2000, I handed over the role of director of the centre to Yves Potvin as was envisaged at the time of his appointment some 18 months earlier, and then I retired. I have been fortunate to have been able to continue an involvement with the centre on a part-time role, mainly with the tailings seminars, and am gratified to see the expansion and growing recognition of the ACG over that time.

Ground Control Groups

The Ground Control Group of Western Australia (WAGCG) and the Eastern Australian Ground Control Group (EAGCG) each, separately, hold regular meetings that enable underground and open pit geotechnical engineers to meet, discuss and exchange ideas, techniques and experiences in a technical yet formal setting. The meetings also provide a forum for attendees to discuss ground conditions specific to their own sites and to seek the opinions and recommendations of others.

For EAGCG information please contact the EAGCG secretary via adeveth@amcconsultants.com.au.

For WAGCG information please contact the WAGCG secretary via rstephenson@anglogoldashanti.com.au.

The EAGCG congratulates the ACG on their 20 years of valuable service to the geotechnical community and cheers to the next 20 years.

The WAGCG congratulates the ACG for their 20 year anniversary and continued support of the WAGCG.

writes Ken Mercer
Professor Environmental and Mining Geomechanics,
Australian Centre for Geomechanics

The history and development of the anisotropic linear model: part 1

Background

This is the story of the history of the anisotropic linear model (ALM), its ongoing development and guidelines to its usage.

The ALM was originally developed by the geotechnical division of Snowden Mining Industry Consultants (Snowden) in Perth, Western Australia, specifically for implementation and application in the RocScience program SLIDE. It was developed to undertake limit equilibrium stability analyses of open pits in anisotropic Pilbara geological settings in Western Australia, in a relatively simple but representative way. It can, however, be considered applicable to most anisotropic rock masses. In part 1 of this article, the background to the development of the ALM will be described.

What is a generic anisotropic shear strength model?

An anisotropic strength model is a constitutive model that describes the shear strength of an anisotropic rock mass in relation to the change in the angle between the plane of shear, and either the predominant plane of weakness of the rock fabric or the predominant orientation of major structural weakness. This angle is known as the angle of anisotropy (AoA) (Figure 1). Most commonly, the predominant plane of weakness of materials laid down in sedimentary environments is the bedding itself. This is typical of shales, sandstones and banded ironstone formations (BIF). For the remainder of this article, this will be termed "bedding shear strength" for both ease of reference and the fact that in most situations this predominant plane of weakness is applicable to material bedding planes.

The shear strength model defines the shear strength relationship within a continuum as defined by an AoA that varies between rock mass strength and bedding shear strength, as illustrated in Figure 2. At an AoA of 0°, the angle of shear is parallel to the bedding and the shear strength model reflects the shear strength parallel to this plane of weakness. At an AoA of +90° or -90°, the angle of shear is at right angles to the bedding. At this point the predominant plane of weakness is unlikely to have any influence on the shear strength of the rock mass and hence this is termed "rock mass shear strength". The rock mass shear strength at both +90° and -90° is defined to be equal. On either side of an AoA of 0°, the shear strength transitions from bedding shear strength to rock mass shear strength in both the positive and negative directions, as the angle of anisotropy changes. The difference between the rock mass shear strength and the bedding shear strength is termed the "shear strength differential". Clearly two aspects of the anisotropic strength model are of importance:

1. The manner in which shear strength transitions from bedding to rock mass strength as the AoA changes either in a positive or negative direction from 0°.
2. The magnitude of both the rock mass and the bedding shear strengths.

The ALM defines both of these criteria using a simple, pragmatic approach for use in limit equilibrium stability analyses.

How the ALM came about

Snowden has been working in Pilbara open pits since 1999. The Pilbara region is located in the northwest of Western

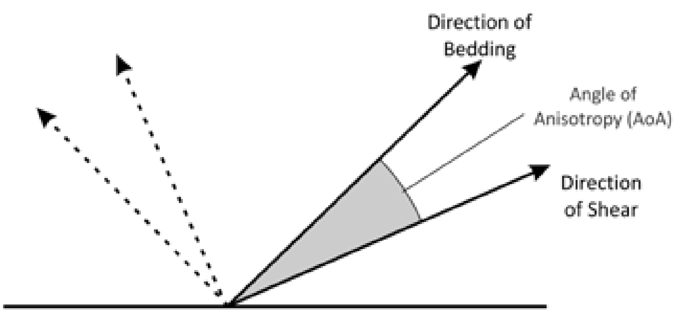


Figure 1 Angle of anisotropy

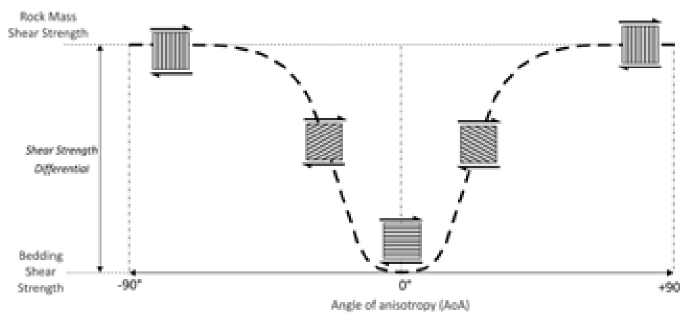


Figure 2 Influence of angle of anisotropy on available shear strength

Australia and contains approximately 80,000 km^2 Hamersley Iron Province. The geology of the Province is characterised by a 2.5 billion year old group of late Archaean and early Proterozoic rock formations known as the "Hamersley Group". The Hamersley Group contains deep, predominantly bedded, BIFs and shales. Many of the commercially important iron ore deposits in the Pilbara were formed by natural enrichment of these materials. The lithological units have, in places, been considerably deformed by geological and tectonic processes, and eroded by weathering to form the extensively deformed geological formations that are seen today. Figure 3 illustrates the extent of the anisotropy typically evident in these formations. The pervasive and intensive nature of the bedding throughout the stratigraphic units of the Hamersley Group has resulted in them being highly anisotropic with regard to the shear strength of the overall rock mass.

In 1999 Snowden recognised that a fast and holistic approach was needed for analysing the stability of open pits using limit equilibrium methods suited to the complex Pilbara structural/geotechnical settings. In particular, the approach needed to model the interaction of both structurally controlled as well as rock mass failure modes. Whilst these models were originally developed for use in the highly anisotropic bedded rock masses of the Pilbara iron ore formations, they are nevertheless applicable to similar geological terrains elsewhere.

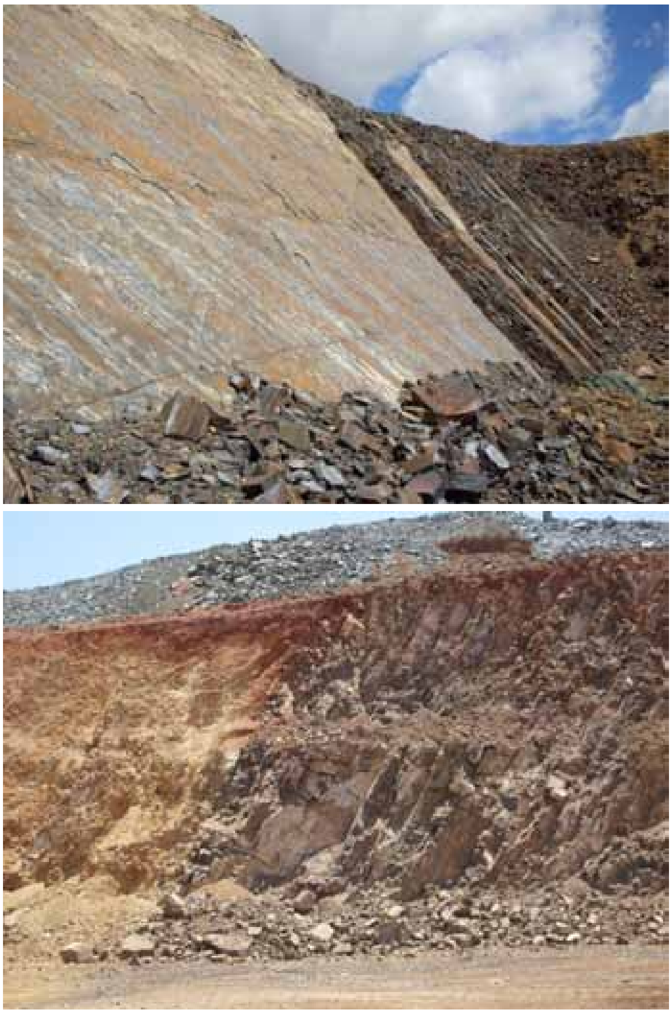


Figure 3 Typical anisotropic rock masses

Other anisotropic models

At the time Snowden developed the first generation of the ALM in 2005, there were two other models that were already available in SLIDE. These were the anisotropic function (later the generalised anisotropic strength model) and the anisotropic strength model). The generalised anisotropic model (Figure 4) enables the shear strength anisotropy to be defined as strengths applied in a series of arcs with a step change strength transition between each arc. Each arc can also be assigned a different shear strength criterion, i.e. Mohr-Coulomb, Hoek-Brown, etc. In a design environment, this model has proven to be slow and impractical to use for all but the simplest slope structural models. Additionally, unless the individual arcs are defined in very narrow increments, the magnitude of the step change can provide unreliable factor of safety (FoS) results.

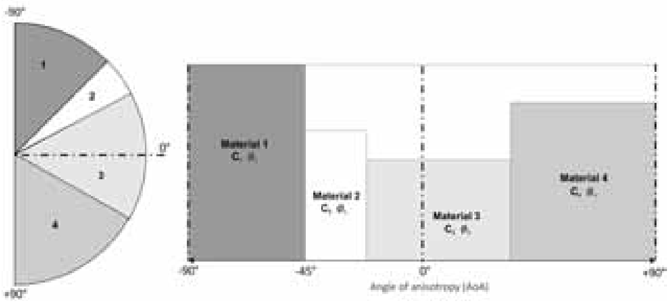


Figure 4 Rocscience anisotropic function

At this time, in addition to the previous model, the anisotropic strength model was also available which defined the cohesion and frictional components of the shear strength as:

$$c = c_1 \cos^2 \alpha + c_2 \sin^2 \alpha$$

$$ø = ø_1 \cos^2 \alpha + ø_2 \sin^2 \alpha$$

Where:

- c_1 and c_2 are bedding and rock mass cohesion respectively.
- $ø_1$ and $ø_2$ are bedding and rock mass friction respectively.
- α = angle of anisotropy.

These equations produced the shape of the function as shown in Figure 5. This is more simple and practical to use than the anisotropic function model and enabled rapid, holistic stability analysis. However, the main concern with the model is that it returns unrealistically low FoS for existing, very stable slopes. These low FoS were attributed to a very conservative strength transition, particular in the lower range of the AoA from ±0° to ±30°. Designs using this strength model are therefore based on

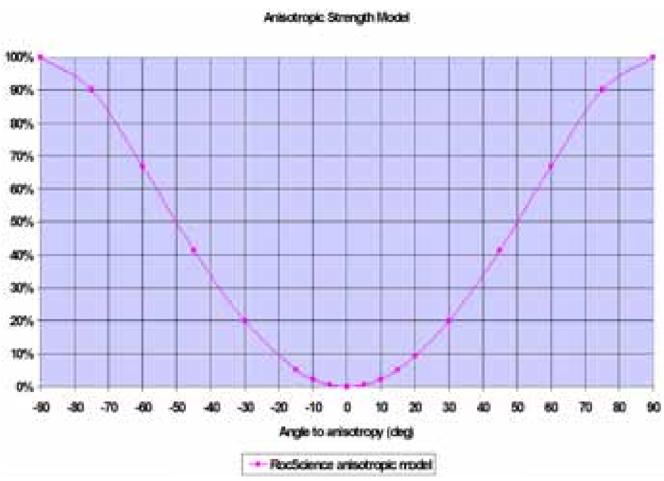


Figure 5 Rocscience anisotropic strength model

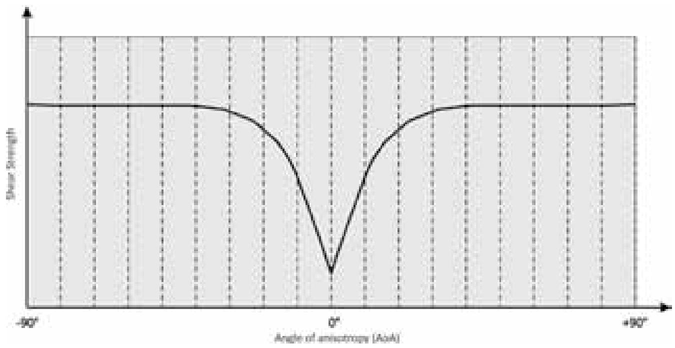


Figure 6 Numerical simulation of the effect of rock mass bedding anisotropy and its unique influence on shear strength

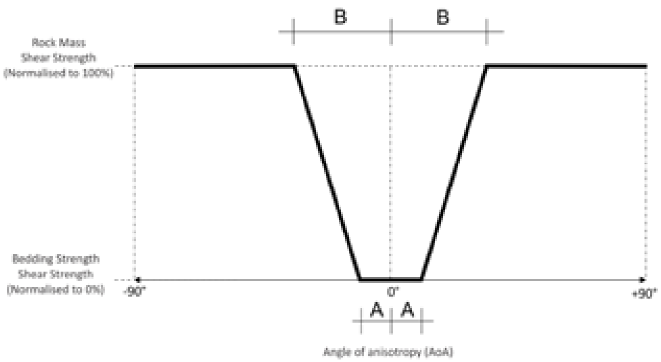


Figure 7 First generation anistropic linear model

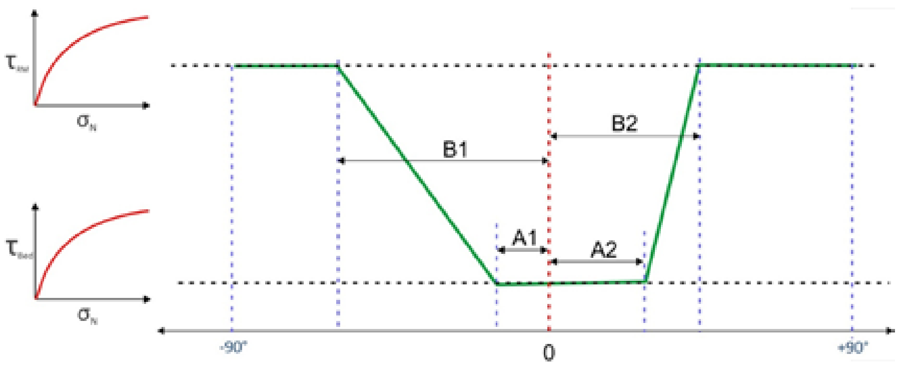


Figure 8 Second generation anisotropic linear model

a relatively low, non-industry standard FoS of 1.2 for overall slopes to allow for the inherent conservatism.

First generation ALM

In 2005, Snowden undertook an in-house investigation using numerical modelling to define the nature of the shear strength transition between rock mass and bedding parting strength. The basis of this model was a very large scale virtual shear box in which bedding planes were modelled discretely and the angle between bedding and the shear plane was varied. The results of this initial investigation showed that the shear strength remained at a rock mass strength from an AoA of +90° or -90° down to a range of ±30° to ±40°, either side of 0°. Thereafter the shear strength reduced in a roughly symmetrical quasi-linear transition down to a bedding shear strength at an AoA of 0°. The generic shape of this transition is illustrated in Figure 6.

Based on this work, at Snowden's request, this model was implemented by Rocscience in SLIDE in 2007 as the ALM. Rocscience simplified the model, as shown in Figure 7, and defined the parameters A and B which enable the user to easily define a linear symmetrical transition from bedding plane strength to rock mass strength, with respect to shear plane orientation. The "A" value is not strictly a material parameter but is used to allow for uncertainty in structural models.

As with the existing anisotropic strength model, the bedding and rock mass shear strengths of the first generation ALM were defined in terms of the Mohr-Coulomb parameters of cohesion and friction angle. The anisotropic linear model (Figure 7) expresses the model in these absolute terms, i.e. with bedding and rock mass. As the AoA is varied between A and B, there is a linear increase in strength until the rock mass strength is achieved.

As implemented in SLIDE, rather than being expressed in absolute terms, the ALM transition is normalised to a percentage. At 0%, the material's bedding shear strength is applied. Higher percentages indicate the proportion of the shear strength contributed by rock mass strength. At 100%, rock mass shear strength contributes all the shear strength. This normalised ALM is therefore independent of the shear strength magnitude, and hence curves of different materials can be simulated and compared.

Then as now, Snowden uses Hoek-Brown and Barton-Bandis strength criteria to estimate rock mass and bedding shear strengths for the Pilbara stratigraphic units. The Mohr-Coulomb parameters used in the first generation ALM simulate these underlying non-linear criteria over normal stress ranges likely to be experienced on sliding surfaces in the Pilbara mine slopes.

Implementation

Following implementation in SLIDE, Snowden carried out benchmark studies for selected existing Pilbara slopes to check the validity of the ALM. These results confirmed that estimated FoS were in accordance with stability demonstrated by each slope. Following this, the ALM was implemented in the stability analyses of Pilbara slopes. A default "B" material parameter of 30°, as suggested by the 2005 modelling, has generally been used for feasibility studies. Generally, during much of the period the ALM has been in use, the reliability of project structural models has been uncertain and typically an "A" of 5° has been used in feasibility studies to model this uncertainty. Alternative "A" and "B" values have since been applied in troubleshooting studies.

The ALM is specifically used with SLIDE's non-circular critical surface searching, analysis and optimisation functions. In use, it has become evident that the identification of critical surfaces and the consequent minimum FoS is very sensitive to the particular non-circular analysis functions used and the rigour of the analysis. Thus, the ALM is relatively simple to implement but requires usage experience.

Further, the use of Mohr-Coulomb shear strength parameters in the first generation ALM, the use of which was largely driven by computational speed of analysis, has proved to be generally inaccurate. Snowden's experience in the use of the ALM highlighted the need to directly replicate the underlying non-linear Hoek-Brown and Barton-Bandis strengths which the applied first generation Mohr-Coulomb parameters approximate.

It is this experience that led Snowden to undertake further development of the ALM leading to the second generation ALM, which was recently implemented in SLIDE.

Second generation ALM

Since 2009, Snowden has been undertaking further research and development of the ALM. This has provided increased confidence that the gradual transition (rather than instantaneous as has been suggested by others) between bedding and rock mass strength is real, and that the rate and shape of the transition depends on the bedding to rock mass strength ratio as well as the normal stress. Furthermore, it is apparent that the strength transition either side of an AoA of 0° is in fact not symmetrical.

At Snowden's request, the non-symmetry of the ALM transition and the ability to model the non-linear criteria with negligible decrease in computational speed were implemented in Rocscience's version 6.0 of SLIDE in 2011. This new model of the ALM is called the Snowden modified anisotropic linear model (SMALM) and is shown in Figure 8.

As shown, the parameters "A1", "A2", "B1" and "B2" enable the non-symmetrical shape of the shear strength transition to be modelled directly. Both the rock mass and bedding shear strengths are now modelled non-linearly in terms of the normal stress directly from the Hoek-Brown and Barton-Bandis criteria.

In part 2 of this article, the results of ongoing research into the ALM will be presented, in particular the shape of the ALM in regard to different material types and the third generation ALM will be introduced.

Acknowledgements

The author acknowledges the Snowden geotechnical team and thanks them for their ongoing contributions to the development of the ALM and, in particular, Harry Speight for reviewing this article.

Article references are available on request.

New Professor Environmental and Mining Geomechanics Ken Mercer joins ACG

The ACG is delighted to announce the appointment of Ken Mercer to the professorial position in environmental and mining geomechanics.

In welcoming Ken to the ACG team, ACG director Yves Potvin said that this position highlighted the importance of environmental and mining geomechanics to the local and global mining industries.

"The ACG has enjoyed a mutually-rewarding and successful relationship with industry, primarily through the delivery of world-class research, and Dr Mercer's appointment will enhance our research and continuing education and training platform. The ACG looks forward to further developing our environmental technical arm; following on from the pioneering efforts of former ACG director Professor Richard Jewell, and Winthrop Professor of Mining, Andy Fourie, The University of Western Australia in the key area of mine waste," Dr Potvin said.

"Ken brings extensive mining sector consulting and business management experience to the ACG. His professional career includes a leadership role as divisional manager, Snowden Mining Industry Consultants", Dr Potvin added.

"Ken is recognised as a leading geotechnical practitioner in many areas, including surface mining and open pit rock mechanics, tailings dams, waste dumps, water dams, and the evaluation of risk. Ken has provided geotechnical engineering advice on projects throughout Australia, Africa, South America, Europe and Asia", Dr Potvin said.

Speaking about his appointment, Dr Mercer said that he was attracted to the ACG by their strong focus on geotechnical excellence and the importance of mine safety, the high level of research and technical expertise, and their reputation for delivering world-class geotechnical knowledge and information via their relevant and accessible mining events, publications and training products. As the ACG's environmental mining geomechanics principal, Ken will be responsible for developing and leading the environmental geomechanics programme and will also have a strong involvement with slope stability research.

Planning for mined land rehabilitation in an Australian context

written by Professor Mark Tibbett, Department of Environmental Science and Technology, Cranfield University, UK

Australian mining and rehabilitation

Australia has an abundance and diversity of mineral resources. Consequently, its economy is heavily dependent on exploiting its resource wealth. Australia has more than one third of the world's known economic uranium resources, very large coal (black and brown) resources, that underpin exports and low-cost domestic electricity production, and substantial metalliferous geological resources. This globally significant resource base puts Australia near the top of the world's mining economies, where its production and export earnings are highly ranked (Table 1). As a result of the importance of mining to Australia, it has developed a system of bonded regulation for environmental protection, a major part of which involves rehabilitation and closure planning. In order to achieve success in rehabilitation it has become apparent that considerable research effort is required to underpin rehabilitation practice so that the rehabilitation can be shown to be effective and sustainable, to ultimately achieve mine lease relinquishment (Gardner and Bell, 2008; Grant, 2008).

The case for active rehabilitation

In Australia many mine sites are located in remote areas and exist on relatively undisturbed natural ecosystems. So the question may be asked, "when mining finishes, why not let nature take its course?" Natural communities of flora and fauna are perfectly adapted to their climate and substrates and, once established, possess great ecological resilience. However, human timescales (bound up with legal and financial consequences), and offsite impacts usually dictate that such a lack of intervention is impossible.

Human needs may require any one of the numerous potential land uses from the post-mining landscape, e.g. the return of a natural ecosystem or farmland, or the creation of industrial or recreational land, and these require intervention on human timescales in ecosystems that have been effectively obliterated. Surface mining may be viewed as an extreme landscape disturbance that obliterates the pre-existing ecosystem. The level of disturbance is so severe that equivalent natural events might include glaciations, volcanism and meteorite impacts. So to recover from this level might take decades at best (Dale et al., 2005), and therefore requires intervention and active rehabilitation.

General principles for success

In order for mine site rehabilitation to be successful it needs to address certain criteria that require planning and forethought. In particular, mining and rehabilitation practices need to be integrated and not seen as two separate activities.

There are five basic components that are needed for rehabilitation success. These are framed here in the context of the rehabilitation of a natural or semi-natural self-sustaining ecosystem, as is commonly required in Australia. Firstly, the final land use needs to be defined and this will set the agenda for all that follows. Without this fundamental component of planning, all subsequent stages are based in ambiguity and lack certainty. Secondly, the nature and properties of the post-mining materials need to be assessed. Thirdly, the desired vegetation type needs to be understood. Fourthly, the functioning of the proposed ecosystem needs to be considered (from pollinators to hydrology), and finally, the criteria for rehabilitation success need to be defined.

Table 1 Australia's major mining outputs and values 2008–2009

Ore Type	Production Volume	Export Value ($A)	World Rank
Iron Ore	353 Mt	34.2	First
Metalmergical Coal	125 Mt	36.8	First
Alumina	19 Mt	6.0	First
Thermal Coal	136 Mt	17.9	Second
Zinc	1.4 Mt	1.9	Second
Copper	890 kt	5.9	Third
Lead	569 kt	1.6	Third

Final land use

Planning for this component of rehabilitation is often poorly defined and considered too late in the process of mining. Defining a clear goal for the landscape after mining not only informs decisions concerning rehabilitation but may also impact on how mining proceeds, and how and where waste materials are stored. Where mines have a clear outcome for the post-mining system, the chance of successful rehabilitation is far greater. Good examples of this exist in the bauxite mining industry in Australia where high biodiversity forests are resorted after mining with a reasonable measure of success (Figure 1) (Hinz, 1992; Koch and Hobbs, 2007; Spain et al., 2006, 2010; Tibbett, 2010).

Nature and properties of materials

Understanding the materials the mining process liberates is essential for planning rehabilitation processes and waste handling. Variability of post-mining materials can be very high and they can be chemically and physically extreme in undesirable factors such as salinity or slaking.

The first source of information is typically available through geological surveys prior to mining and rock assessments during mining. Considerable useful data can be found in the catalogued geological stratigraphy of the mine. Inevitably more detailed analysis will be needed and these might include various tests for erosivity, nutrient supply, acid generating potential, salinity and sodicity, amongst others. Once preliminary characterisation is complete, materials can be classified into positive, negative and inert in terms of their use in post-mining landforms.

Some regolith materials can make very good potential soil materials but care must be taken to ensure that the full suite of essential plant nutrients are provided by the selected material and, where necessary, that the missing nutrients are supplemented by judicious fertilisation. Essential nutrient elements are necessary for plant growth to progress normally, with each element having a particular role in the physiological functioning of plants (Table 2). Given the number of elements needed it is surprising that nutritional deficits are not more commonly reported.

Some basic principles apply when handling and placing materials in post-mining landforms. A golden rule is to select stable non-erosive materials for surfaces and to confine potential acid forming materials to dry or anoxic zones as far as possible. For soil covers, it is best to select materials with appropriate physiochemical properties to capture and supply fertility, and retain suitable plant available water content. This will also require that covers are deep enough to meet the requirements of the selected vegetation, an aspect that is often overlooked at great cost by geotechnical plans when considering many (deep rooted) Australian native plant species that might be used in rehabilitation of a tailings storage facility (TSF) and waste rock dump (WRD).

Plants and vegetation

Several important aspects of the plants used in rehabilitation need to be considered for success. Seedling establishment is critical to know, in order to calculate seeding rate, when seeds are sown directly into the rehabilitation (Worthington et al., 2006). Many plants will also require microbial symbionts, such as frankia, rhizobia and/or mycorrhizas, in order to establish successfully. These are plant-microbe (actinomycete, bacterial and fungal, respectively) symbioses that are often beneficial to the host plant, particularly in challenging conditions. Post-mining landscapes are one of the few where such microbial inoculations may be effective or even necessary.

The nutrient requirements of the plant species may be generally known but this needs to be understood in the context of individual species. Each plant species has a different response to each nutrient and these may appear to be deficient, sufficient or toxic when placed on a response curve (Figure 2). Therefore knowing the nutritional requirements and tolerances to toxicities of plants is essential where post-mining materials may have very high or low concentration of some elements. For example, many Australian native plants can have phosphorus toxicities that have been reported to affect plant densities in the rehabilitated Jarrah forest of Western Australia (George et al., 2006). The water relations of plants also need to be known, particularly if they are to survive summers in their early years of establishment. Appropriate planning might then require irrigation for a number of years.

Figure 1 From land preparation (year zero) to developing a biodiverse Eucalyptus forest (year 20) at Rio Tinto's Gove Bauxite Mine site in Northern Territory. The success of this rehabilitation is partly based on establishing its final land use before mining commenced (photo courtesy of Alister Spain)

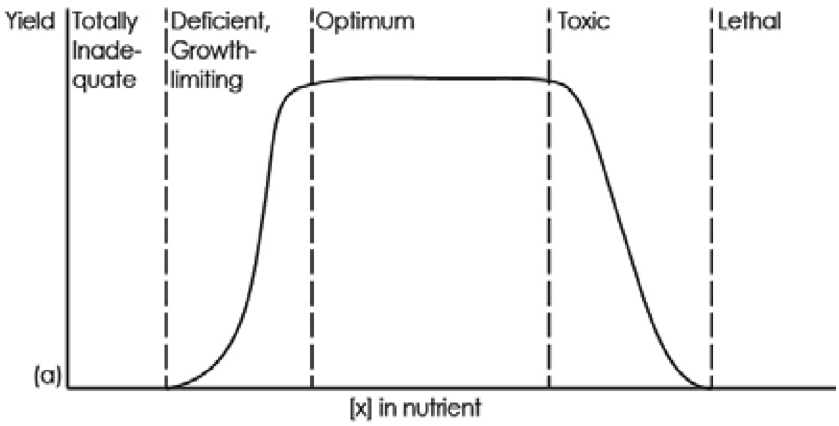


Figure 2 Plant yield as a function of concentration of nutrient element X. If X is a non-essential element, concentrations below the toxic limit will have no effect on yield

Finally, susceptibility of the vegetation to pathogen needs to be understood. Sowing species which may quickly succumb to a local pest may be a waste of time, so such knowledge is essential in sound planning decisions for rehabilitation to be made.

Ecosystem level considerations

When rehabilitating a post-mining landscape, a number of ecosystem level processes will need to be considered and will inevitably impact on that landscape. Firstly, there are a number of factors that are essential for sustainability that need to be understood. These include eclectic factors such as hydrology, essential for ensuring sufficient plant water availability and minimising off-site water flows; and pollinators, essential for vegetation fecundity. Other ecosystem level factors include: climate; invertebrate colonisers (Spain et al., 2010); herbivores; exotic (or native) weeds; and successional sequences and processes (Tibbett, 2010).

The post-mining landscape itself will also evolve as an ecosystem. This is inevitable fate of material left in nature, and geotechnical parameters from which landscape designs were originally conceived and planned may change considerably with time (Fourie and Tibbett, 2007). What should be considered in the future is not engineering a post-mining landscape but "engineering a biological system" as this (the biology) is ultimately going to be responsible for much of the future development of the new landscape, its ecology and stability, often leading to the development of what may be termed a "novel ecosystem" (Hobbs et al., 2009; Harris, 2012).

Criteria for rehabilitation success

Success criteria for rehabilitation success need to be holistic and establish whether the rehabilitation is going to be sustainable. These should address economic and social targets as well as environmental targets. Nonetheless, for natural ecosystem rehabilitation the success is defined primarily on ecological grounds and has all too often relied on the simple observations of the presence or absence of particular flora and fauna. Success criteria are now being developed that move beyond these simplistic measures. Success criteria should be based on definitive and implied measures of ecosystem functions (Grant, 2007; Tongway and Ludwig, 2006). Where possible they should include aspects of ecosystem trajectory and an understanding of belowground as well as aboveground components.

Concluding remarks

Planning for successful mine site rehabilitation requires a wide range of skills and considerable forethought and planning. For natural and many managed post-mining land uses, the key question is, "how successfully can we reconstruct a functioning, sustainable ecosystem?"

One fundamental facet of successful mine site rehabilitation is in its integration with mining practice, and this requires a recognition by the mining operation that the two processes are inevitably interlinked. Materials characterisation: the basic chemical, physical and biological properties of the post-mining materials is always essential to success, as is understanding the other components of the developing ecosystem. While the ultimate proof of success will be in the decades and centuries ahead, we need to understand more about how to assess the success of ecosystem reconstruction today, to be effectively predictive and corrective, where necessary.

Article references are available on request.

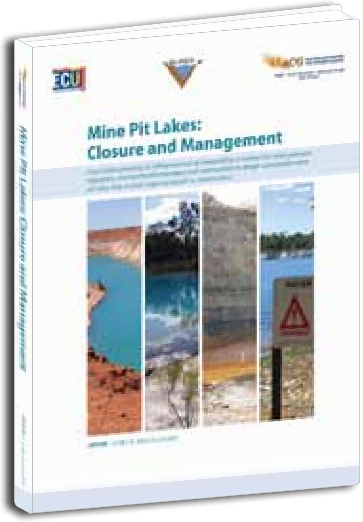
Table 2 Nutrient elements that must be provided by post-mining materials and their functions in plants

Name	Chemical Symbol	Function in Plant
Nitrogen	N	Proteins, amino acids
Phosphorus	P	Nucleic acids, ATP
Potassium	K	Catalyst, ion transport
Calcium	Ca	Cell wall component
Magnesium	Mg	Part of chlorophyll
Sulphur	S	Amino acids
Iron	Fe	Chlorophyll synthesis
Copper	Cu	Component of enzymes
Manganese	Mn	Activates enzymes
Zinc	Zn	Activates enzymes
Boron	B	Cell wall component
Molybdenum	Mo	Involved in N fixation
Chlorine	Cl	Photosynthesis reactions

Book review

Mine Pit Lakes: Closure and Management

writes Robert L. Kleinmann, Mine Water and the Environment, USA



"Mine Pit Lakes: Closure and Management", compiled by Dr Clint McCullough, senior lecturer (aquatic ecotoxicologist), Edith Cowan University, and published by the Australian Centre for Geomechanics, provides an excellent overview of an important topic. The book is written with the practitioner in mind and the authors of the various chapters have done a fantastic job of summarising how to plan, develop, and manage pit lakes. It is quite readable, without a lot of jargon, and will be useful to engineers and managers at mine sites who are involved in designing pit lakes and developing or implementing mine closure plans, as well as regulators who oversee pit lake development and stakeholders who wish to be well informed. It incorporates case studies from around the world and uses them to illustrate many key aspects of pit lake planning and management.

Planning for mine closure is a central theme and is illustrated not only by technical considerations, such as planning lake design features (e.g. slope aspects, bathymetry, and water balance), littoral zone development, and biology, but also aspects that are not normally addressed in more technical books, such as various ways to incorporate stakeholder involvement, and the hows and whys of water quality monitoring. Another nice aspect is that, in addition to pit lakes at coal and hard rock mines, pit lakes that will be formed as a result of oil sands development, which is beginning to be a hot issue in North America, have been incorporated.

It is worth noting that another book on pit lakes is scheduled to be published by Springer in 2012. Since I have had the opportunity to read (and edit) the draft version of that yet-to-be-published book, I can report that there is surprisingly little overlap, since that one is much broader in scope, is focussed more on the science than on the planning and management (engineering) aspects, and has a more academic orientation. Anyone who wishes to be completely up-to-date should, of course, read both.

Mine Pit Lakes: Closure and Management is broken down into three sections: Design, Development, and Closure (entailing 6, 4, and 3 chapters, respectively), but, since planning for mine closure is a central theme, pit lakes as a closure technique is addressed, to some extent, throughout the book. Each of the three sections is a compilation of fairly short chapters that can be read without reference to the chapters that precede it.

The Design section represents nearly half of the book. The first chapter is a summary of things to consider before deciding whether and how best to backfill mine waste and tailings into a mine pit that will subsequently be filled with water, including material consolidation and using liners to protect groundwater. The second chapter in the Design section summarises virtually all of the other aspects of planning a pit lake into 14 pages, using a "lessons learned" approach.

The next two chapters both address aspects of stakeholder involvement, which may be a little too much of a good thing; the second of these two chapters, which reports on the regional aspects of stakeholder involvement, is an overly detailed accounting of a specific case study that had barely begun.

An excellent introduction to designing pit lakes based on engineering considerations follows; it successfully makes the point that pit lakes must be designed for long-term success, and illustrates how key aspects of natural lakes can, and should, be considered when designing a mine pit lake.

This is followed by a chapter on how water quality models are used to design and assess pit lakes. It is a well-written overview, and includes an interesting case study based on a model developed for oil sands pit lakes that incorporates, by

The book is written with the practitioner in mind and the authors of the various chapters have done a fantastic job of summarising how to plan, develop, and manage pit lakes.

necessity, chemical reactions not normally considered in such models. Given the importance of water quality modelling to pit lake planning and design, I personally would have liked to have seen modelling covered to an even greater degree, but I suppose that given how fast models are evolving, a more detailed approach would become dated fairly quickly.

The Development section consists of four chapters; three that address biological aspects and one that addresses ways to fill the pit lakes. The first of these chapters focusses on developing a sustainable ecosystem in pit lakes based on lessons learned by studying natural lakes, despite the significant inherent differences between the two. This is followed by a very nice discussion on the importance of pit lake margins to sustainable pit lakes and how important riparian vegetation is to bank stability, biodiversity, lake aesthetics, wave action, and other important aspects.

The next chapter discusses how to fill mine pits with water and is based on the well-established premise that it is almost always better to fill a mine pit rapidly, when that is an option, and uses examples, mostly from German lignite mines, on how that can be accomplished.

The Development section concludes with a chapter on developing a bacteria-based sulfate-reducing ecosystem within a pit lake and how doing so can improve water quality in pit lakes that are acidic and metal laden. It is interesting to see how this topic, which was quite controversial a decade ago, is now accepted as a valid approach to water quality remediation.

The book concludes with three chapters on how pit lakes can be rationally incorporated into mine closure as long as they are planned for. The Closure section starts appropriately with a chapter on the way regulations and policy guidelines affect pit lake development around the world. This chapter concludes by making the point that regulatory compliance, though necessary, is not the sole goal. Instead, pit lakes should play a key role in a mining company's overall sustainability strategy.

The next chapter addresses the important topic of monitoring water quality. This chapter could have been placed just as easily in the other two sections since baseline monitoring has to start before mining even begins and continues throughout the mining and closure process, but the authors of this chapter have focussed on how monitoring is necessary to manage pit lake water quality, and address practical aspects, such as where and how to sample, and what to measure. Their case study is the infamous Berkeley Pit, which has been filling with very acidic water since mining ceased in 1982; monitoring there will determine when chemical treatment of the lake system will begin, but is also being used to optimise an ongoing copper extraction process.

Finally, the section's last chapter deals with risk management as it relates to health and safety issues, such as avoiding deaths by drowning and illnesses caused by chronic exposure to water contaminants.

Overall, this book is an excellent investment for anyone interested in pit lake design and development. It is a concise, well-conceived, and generally well-written volume. Anyone who deals with pit lakes will find much to learn from it and will want to have it on their bookshelf, as they will find many opportunities to consult it again and again.

Visit www.acg.uwa.edu.au/shop to purchase the book.

Recent advances of high precision radar for monitoring slopes in large open pit mines

Authored by: P. Farina, L. Leoni, F. Babboni, F. Coppi, P. Ricci, IDS Ingegneria Dei Sistemi SpA, Italy; G. Spencer, IDS Australasia, Australia

Introduction

Slope monitoring radars have been widely employed in the last ten years as an active tool for monitoring movements in natural and engineered slopes. With respect to conventional monitoring systems, radar technology presents the advantages of high accuracy measurements, long range capabilities, limited impact of atmospheric effects on measurement performances, and the possibility to quickly acquire the response over a large number of points. Slope monitoring radars are based on the radar interferometry; a technology originally developed for satellite applications in order to retrieve ground displacements related to natural hazards (Rosen et al., 2000). However, there was a limitation related to satellite platform arising from the low revisiting times of the available satellites and consequent temporal de-correlation of the radar signal and unwrapping problems and geometrical distortions induced by the almost vertical line of sight, for example, to overcome these limitations, the same technology has been implemented using ground-based systems. Ground-based radar interferometry has been used for slope monitoring of natural slopes (Antonello et al., 2004; Corsini et al., 2006; Bozzano et al., 2008) and open pit mines (Noon, 2003; Harries et al., 2006). The use of slope monitoring radars in open pit mines is becoming a standard practice for active monitoring of the pit walls. Radar units are effectively used to gain a better understanding of the spatial distribution of slope movements, and for the provision of alerts in the event of progressive movements that can potentially lead to slope failure, thus aimed at an early warning to enable evacuation to ensure the safety of workers, equipment and to increase mine productivity.

The first type of slope monitoring radar introduced into the mining market was based on parabolic dish-antenna radars (real aperture radar (RAR)); exploiting a fine radar beam that illuminates the target over a series of small area footprints. Various generations of ground-based RARs have been developed in the last few years for the monitoring of slope movements. In more recent times, slope monitoring radar for mining applications has undergone further technological development in the areas of spatial resolution, longer working distances, faster acquisition time, lower power consumption and automatic atmospheric correction techniques (Farina et al., 2011). In this regard, ground-based interferometric synthetic aperture radar (GBInSAR) is helping drive improvements in slope stability monitoring.

Ground-Based Interferometric Synthetic Aperture Radar

History

Development of GBInSAR started in the late 1990s in Italy, including research undertaken at the Electronic Engineering Department, The University of Firenze. The first R&D projects were originally aimed at developing GBInSAR for the accurate measurement of displacement connected to landslides. After 5–6 years of research, prototyping and validation, the first generation of commercial products was released. At that time the goal was to design robust, reliable and user-friendly interferometric radars in two different configurations:

- structural applications, bridge static and dynamic testing, tower and building monitoring, etc.
- landslide monitoring.

In the latter part of the last decade, the GBInSAR approach was tested in the mining industry through a series of field trials in open pit mines in Europe and Australia to gauge its suitability, then fine-tune the technology to the specific needs of the mining industry. Since these trials, there are over 50 GBInSAR systems deployed in open pit mines located in 15 countries.

Technical configuration

A typical GBInSAR system features the following items:

- radar unit; consisting of linear scanner, radar sensor and power supply module
- rugged laptop with Controller software managing the acquisition parameters and system diagnostics housed inside the power supply module.

The overall system operation is managed by Console software for data processing and output visualisation. This software provides the real time processing of radar data with automatic atmospheric corrections, and it is able to provide fully geo-referenced outputs, in terms of displacement maps and velocity maps with 3D interactive data handling (Figure 1). The software generates alarms based on the velocity data with user-defined levels and multiple alarm criteria on user-defined zones (Farina et al., 2011). All the outputs of the software can be exported to the main common mine planning and GIS/CAD software.

GBInSAR technology development

The main technical differences between the GBInSAR system and the dish-antenna based RAR systems used in mining are related to the type of employed radar technology and processing of the radar data.

The areas of slope stability monitoring that are benefitting from GBInSAR technology development are spatial resolution, working distances, acquisition time, power consumption and atmospheric correction techniques.

The GBInSAR system uses an alternative solution to get very high spatial resolution displacement data in the form of images. The system is based on two small horn antennas with a wide beam (usually 80° on the horizontal plane by 55° on the vertical plane) and is designed to exploit the movement of the physical antenna along a straight trajectory (linear scanner), to get a high resolution radar image of the observed scenario. Thus simulating an acquisition with a physical antenna of the double dimension of the length of the synthetic aperture. By observing the same area from slightly different angles, and then combining the backscattered signal coming from the different points along the path by means of digital processing, the SAR system can obtain high resolution image based data. The cross-range or angular resolution provided by the SAR is then combined with the range resolution, a function of the width of the used frequency band, to achieve a small area resolution cell (high spatial resolution range - 0.5 m x cross-range - 4.3 at distance of 1 km).

Typically, the systems operate in a different frequency band when compared to other slope stability radar technologies such as parabolic dish RAR. The GBInSAR system is configured with the Ku band (17 GHz, corresponding to a wave length of 2 cm), rather than the X-band (9 GHz corresponding to a wave length of 3 cm). The shorter wavelength of the Ku band over X-band provides high spatial resolution and high sensitivity and, as a consequence, accuracy in the displacement measurement (Farina et al., 2011).

The limited moving parts of GBInSAR result in a high reliability mechanical robustness and, when combined with the use of small antennas, very low power consumption. The low power consumption reduces the use of the diesel generator and allows it to rely mainly on solar power supply with the generator generally used as a backup power source. The use of small antennas also eliminates the risk of wind-induced vibrations.

The images acquired by the sensor are automatically processed in real time to remove atmospheric effects using algorithms developed from satellite radar interferometry. The employed algorithms enable the selection of a grid of high quality pixels, namely persistent scatterers (PS), used to remove the atmospheric effects from the interferometric signal. Such an approach is based on the exploitation of the different spectral behaviour, through a time-space joint analysis, of the signal components related to displacements from the one related to the atmospheric effects. Phase effects generated by changes in the refraction index of the air (function of temperature, humidity and pressure) can be interpreted as false movements if they are not well addressed. Conventional atmospheric correction used for either optical system, such as robotic total stations and dish radar systems, is based on the selection of identified and assumed stable points located at different distances from the radar. These points are used to estimate and remove atmospheric effects from all the pixels. This method is not as reliable over long ranges and is subject to strong atmospherics. This is a result of the complexity of the spatial distribution of these effects and the consequent difficulties in modelling them with linear solutions. There are times when the selected stable points may become unstable (e.g. in soft rock operations) and invalid for use, thus

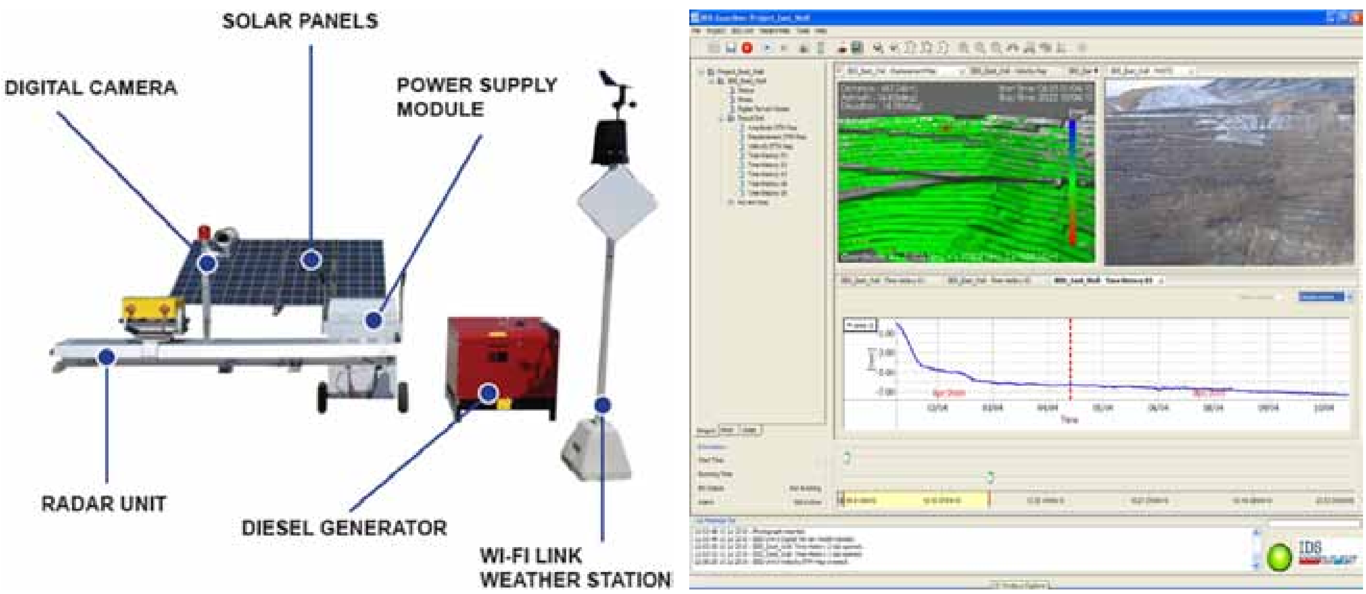


Figure 1 Main GBInSAR system components (left) and a typical output of the Console software (right)

causing errors in the estimation of atmospheric effects. The algorithms developed for GBInSAR are based on the automatic estimation of the atmospheric effects over all the stable points contained in the radar image, they are identified through an automatic and iteratively updated classification to achieve a close and complex model of these effects and remove them from the phase signal. Such a processing strategy does not need any atmospheric region selection to be undertaken by the user. The processing chain extends the operating range of the radar to distances up to 4 km, making it possible to install the radar in very large pits, leaving the radar unit installed permanently in the same position and obtaining a wide area coverage at the same time (Farina et al., 2011).

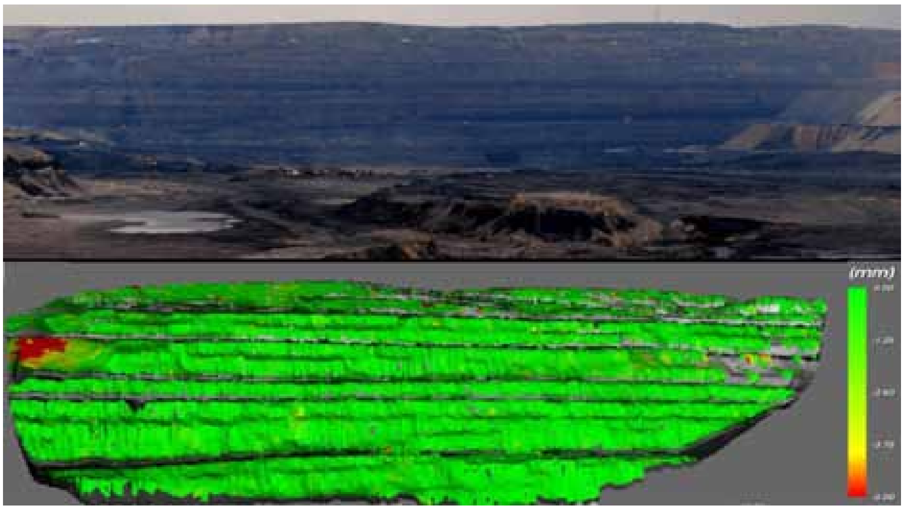


Figure 2 Example of a coal mine GBInSAR installation, at a 2.4 km of maximum distance, and a displacement map draped on a DTM of the mine. The second type of use for radar is critical monitoring, namely alarm generation for progressive movements based on the displacement/velocity measurement. The radar becomes a tool to be combined with other sources of information, that aids risk minimisation by identifying risk conditions and supporting the decision-making process

Application to mining

Using radar in open pit mines provides capability for the detection and management of potential large scale instabilities in the overall slope, multiple inter-ramp slope segments, and localised bench scale monitoring detection at the same time.

The principle reason to use radar within open pits is to get the near real-time monitoring of wall movements. Early recognition of both large scale and bench scale instability over almost all the pit walls, without the need of a prior knowledge of the moving areas (as it may happen with short range radar), allows an increase in the knowledge of the slope behaviour. Covering wide segments of the pit from a single position and providing high accuracy, even at very long ranges on a very fine grid of points, makes it possible for the radar to map displacements potentially as precursors of slope failures.

Finally, the long term monitoring (months, years) of slope movements over very large portions of the pit allows the geotechnical staff to gain a better understanding of the mechanism of large scale instabilities, and knowledge of the rock mass strength and deformation properties via calibration of the movement.

This use of the radar, mainly aimed at developing effective remedial plans, is also facilitated by the possibility to integrate the geo-referenced displacement maps generated by the radar with other geological/geotechnical layers and importing them into mine planning software and GIS. Since the standard 3D view employed in the Console software is represented by displacement or velocity maps draped over a digital terrain model (DTM) of the pit, basic geomorphological analysis can be carried out. In addition, detailed monitoring, from both spatial and temporal points of view, is a critical source of information for the reliable calibration and validation of stability analysis models – to identify the mode of failure and the triggering mechanisms, and to assess the performances of the implemented slope design.

Multi-bench scale failures and inter-ramp scale failures can be measured by both dish based RAR and GBInSAR. The long range capabilities, wide spatial coverage, and the ability to install the radar systems far from the mine highwalls, e.g. on the opposite side of the pit, allows radar to deal with overall slope failures, particularly when dealing with ranges of 2–3 km.

The GBInSAR method provides wide spatial area coverage with relatively high spatial resolution, enabling the radar system to cover a range of spatial scales for the typical slope instabilities within a pit in a relatively short acquisition cycle. The high resolution in range direction (50 cm independently from the distance to the slope) enables the identification within a single bench of several pixels, allowing the detection of benchscale failures at long range (up to 4 km).

GBInSAR's and dish RAR's capability for measuring fast movements from mm/day to few tens of cm/day; which is the typical deformation rates of interest for critical monitoring. GBInSAR can also be

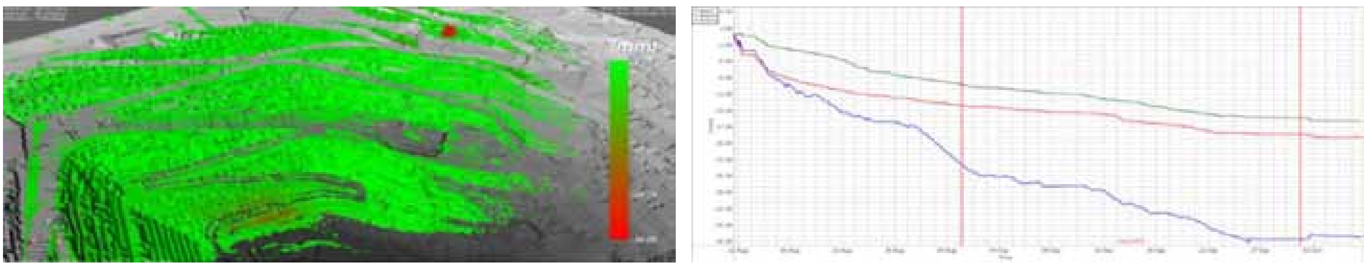


Figure 3 Geo-referenced cumulative displacement map (55 days) from an installation at Minera Escondida, Chile at a 2.5 km of maximum distance and time series of displacements (data courtesy of Minera Escondida Ltd)

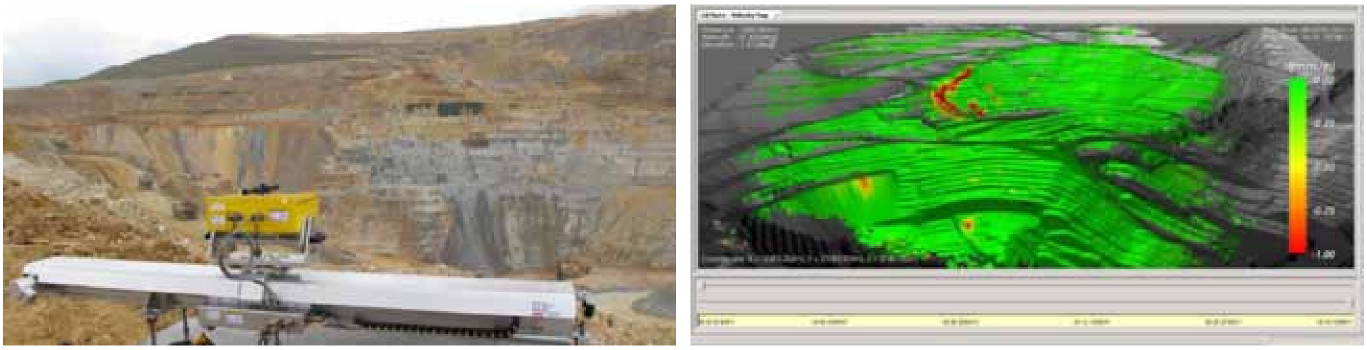


Figure 4 Installation at Minera Yanacocha, Peru (left) and an example of geo-referenced velocity map draped on a DTM of the mine (data courtesy of Minera Yanacocha)

configured to monitor very slow movements (from mm/month to mm/year). Slow movement monitoring can be achieved by using long term installations or repositioning of the radar unit. Through the combination of two specific processing approaches undertaken on different time scales, it is possible to track simultaneously fast and slow slope movements.

GBInSAR's long range monitoring of large open pit mines potentially can remove some of the need for mobile systems in open pit mines in some situations. The GBInSAR mobile configuration can provide higher spatial resolution, at the equivalent distance, to mobile RAR dish systems. In the range direction, it can measure displacement on bench faces as more samples are spatially acquired within the bench height.

Conclusions

Slope monitoring radar represents standard practice for the near real-time monitoring of slope displacements in open pit mines. The development slope monitoring radars based on the InSAR technique recently marked a step forward in improving radar technology for monitoring capability. By covering all the scales of slope potential instabilities, from bench scale in open pit mines to overall slope instability, GBInSAR can be used for both active and background long term monitoring (Farina et al., 2011).

The advances of GBInSAR are related to the improvement of spatial resolution, the working distance from the slope, acquisition time, atmospheric correction, less moving parts and lower power consumption. Improvement of these features enable users to better cover all the typical scales of slope instabilities, from bench scale to overall slope failures and to extend the range of monitored deformation rates to include slow movements (Farina et al., 2011).

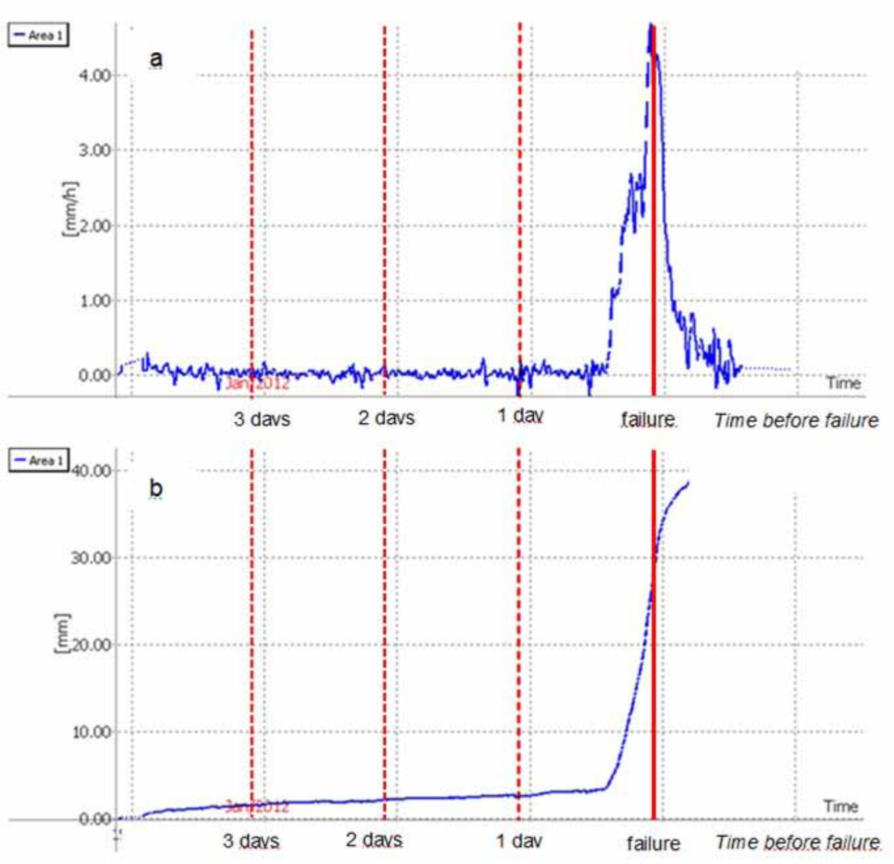


Figure 5 Example of displacement/velocity plots measured before a slope collapse

Future developments of radar will move towards providing full pit monitoring between integrated systems, including mobile systems, providing 360° coverage of the pit walls.

The improvements in acquisition characteristics and fidelity in slope stability monitoring using GBInSAR is also helping drive improvements in all slope stability radar systems. The healthy competition in slope stability radar technology development will ultimately provide benefits to users of open pit slope radar monitoring systems.

The ACG is delighted to welcome IDS Australasia onboard as our new Corporate Affiliate Member.

Article references are available on request.

Messages from some of our Corporate Affiliate Members

AMC CONSULTANTS

AMC Consultants congratulates the ACG on the 20th anniversary of its foundation.

AMC has supported the ACG through participation in workshops and conferences, peer review of papers, and as co-authors in many of the ACG's publications.

Our backfill, geotechnical and mining engineers have skills and experience that complement the specialist skills in the ACG and we are pleased to have been able to add to the technical value of the ACG's activities. We wish them continuing success in conducting research, and delivering education and training in geotechnical engineering to support the resources sector.

Since its inception the ACG has developed a rich and colourful history through its thirst for knowledge, dissemination of knowledge and creation of knowledge.

Quenching thirst There is no doubt that the ACG teams that we have worked with (past, present and certainly future) have had a keen interest in all things geotechnical and as such they continuously strive to be on top of the latest technology and engineering thinking.

Pass it along The seminars, workshops and courses that ACG presents on a regular basis are testament to the organisation's commitment to providing knowledge-share environments. It has been successful in providing for all technical skill and experience levels within the geotechnical engineering fraternity.

Abracadabra Although not pure 'creation' in every aspect, ACG's involvement in industry-funded research projects, such as MERIWA M406 where the software MS-RAP was created, has made a significant contribution to the field. Tools like this allow practitioners to view data in new and innovative ways, helping them make informed decisions and taking the magic black box out of the equation.

AngloGold Ashanti Australia Ltd wishes the ACG the very best in these three aspects of knowledge over its next 20 rich and colourful years.

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SPECIALIST KNOWLEDGE
EXTRAORDINARY OUTCOMES

Coffey would like to congratulate the Australian Centre for Geomechanics on the milestone of their platinum anniversary.

Since joining almost 10 years ago, we have been closely aligned with the centre. We have been enriched by the collaboration, sharing of knowledge and encouraging the highest safety standards for the industry.

At Coffey we pride ourselves in nurturing the next generation of specialists. Our younger members have benefited greatly from engaging with the centre to stay abreast of the complex issues facing the unique environments in which we work.

Similarly, we are very proud of the contribution made by Coffey's senior principals and seasoned practitioners – many of whom have gained experience with some of the world's most challenging ground conditions throughout their careers with us.

In these respects, the Australian Centre for Geomechnics aligns well with Coffey: their safety focus, innovative approach and keeping at the forefront of leading technology are common values we pursue. We too have a deep history and knowledge based in Western Australia but which we have applied to benefit many parts of the globe.

Coffey are proud of our long affiliation with the centre and wish them all the best for the next 20 years and beyond.

Congratulations to the ACG on your 20 years of support to the mining industry. ACG has provided excellent engagement with the mining industry, allowing the industry to keep up to speed on rapidly developing technologies, trends and methodologies from academic and research organisations. It has also successfully facilitated and provided industry important access to education and training events from highly skilled professionals within industry, academia and research, enabling the Australia mining industry to stay at the forefront of managing mine safety and productivity. As a corporate affiliate member, IDS Australasia is keen to continue working and consolidating its relationship with ACG into the future.

IDS
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Newmont has been a Corporate Affiliate Member of the ACG since 1999. Over that time, many Newmont employees have had the benefit of attending training courses, seminars and symposia organised by the ACG. These events are always of a high quality and relevant to our industry. In addition, Newmont is proud to have been a sponsor of several highly regarded training DVDs and research projects. The ACG has made a significant contribution to the field of geomechanics within Australia and globally over the last 20 years and we look forward to continuing our relationship with the ACG into the future.

Snowden Geotechnical Group congratulates the ACG on 20 years of outstanding service to the mining industry.

In particular, the ACG has contributed significantly to the dissemination of geotechnical knowledge and training in Australia and internationally.

We would like to wish the ACG ongoing success for the future.

ACG Corporate Affiliate Membership

The ACG's charter is to support the mining industry by way of applied geomechanics research projects having a direct practical application to industry and through the provision of state-of-the-art training and education.

We seek to provide:

- Direct instructional material being taught thus improving job knowledge and hence safety at work.
- Sharing of knowledge between academic and research institutions and practitioners, and between practitioners themselves.
- Optimisation of the processes at the workface with an inevitable lifting of skills.

To effectively achieve these objectives, the ACG needs guidance from industry as to the direction its research, education and training goals should take.

Our affiliate members support the ACG to play a crucial role in identifying and developing research initiatives, training materials and professional education, particularly as industry moves towards increasing the number of larger open pit mines and deeper underground mining operations.

The ACG team is very appreciative of the support and encouragement of our 2012 corporate affiliates. For information about this programme please visit www.acg.uwa.edu.au/corp_affiliates.

2012 Corporate Affiliate Members

AS OF JULY 2012

AMC Consultants Pty Ltd	Coffey Mining Pty Ltd	Newmont Asia Pacific
AngloGold Ashanti Australia Ltd	Fero Group Pty Ltd	pitt&sherry
ATC Williams Pty Ltd	GHD Pty Ltd	Rio Tinto Iron Ore
Barrick (Australia Pacific) Ltd	Golder Associates Pty Ltd	Sika Australia Pty Ltd
BHP Billiton Cannington	IDS Australasia Pty Ltd	Snowden Group
BHP Billiton Iron Ore	Kalgoorlie Consolidated Gold Mines Pty Ltd	SRK Consulting Australia
BHP Billiton Nickel West		

ACG event schedule*

2012

Practical Rock Mechanics Short Course (Introduction)	20–21 August 2012 | Hotel Ibis, Perth, WA
Ground Support in Mining Short Course (Introduction)	22–24 August 2012 | Hotel Ibis, Perth, WA
Prevention is Better than Cure: the Causes, Consequences and Control of Soil Erosion in Mine Rehabilitation Workshop	22 September 2012 | Sofitel Brisbane Central Hotel, Brisbane, QLD
Sustainable Mining Now and Landform Design Workshop	22 September 2012 | Sofitel Brisbane Central Hotel, Brisbane, QLD
Use of Geochemical Data in Addressing Environmental Problems in the Mining Industry Workshop	23 September 2012 | Sofitel Brisbane Central Hotel, Brisbane, QLD
Working with Communities Facing Mine Closure Workshop	23 September 2012 | Sofitel Brisbane Central Hotel, Brisbane, QLD
Delivering Effective Rehabilitation: Monitoring and Manipulating the Soil Biota for Success Workshop	24 September 2012 | Sofitel Brisbane Central Hotel, Brisbane, QLD
Designing for Closure: Appropriate Design Criteria and Methods of Analysis Workshop	24 September 2012 | Sofitel Brisbane Central Hotel, Brisbane, QLD
Seventh International Conference on Mine Closure	25–27 September 2012 | Sofitel Brisbane Central Hotel, Brisbane, QLD
ACG-ANCOLD Design of Tailings Storage Facilities for Seismic Loading Conditions: Operational and Long Term (Post Closure) Considerations Workshop	24 October 2012 | Burswood Entertainment Complex, Perth, WA
Blasting for Stable Slopes Short Course	5–7 November 2012 | Novotel Perth Langley Hotel, Perth, WA

*The ACG event schedule is subject to change. For event updates visit www.acg.uwa.edu.au/current_events_and_courses

2013

Advanced Application of Seismology in Mines Short Course	7–10 May 2013 | Pan Pacific Hotel, Perth, WA
Shotcrete Design and Performance Workshop	12 May 2013 | Pan Pacific Hotel, Perth, WA
Seventh International Symposium on Ground Support in Mining and Underground Construction	13–15 May 2013 | Pan Pacific Hotel, Perth, WA
Ground Support Technology – a WASM/CRC Mining Workshop	16–17 May 2013 | Pan Pacific Hotel, Perth, WA
Instrumentation and Slope Monitoring Workshop	23 September 2013 | Sofitel Brisbane Central Hotel, Brisbane, Qld
Civil Engineering Applications Workshop	23 September 2013 | Sofitel Brisbane Central Hotel, Brisbane, Qld
Slope Analysis and Design in Anisotropic Materials (Coal Mines) Workshop	24 September 2013 | Sofitel Brisbane Central Hotel, Brisbane, Qld
International Symposium on Slope Stability in Open Pit Mining and Civil Engineering	25–27 September 2013 | Sofitel Brisbane Central Hotel, Brisbane, Qld
The Business Case for Risk-based Slope Stability Design Workshop	28 September 2013 | Sofitel Brisbane Central Hotel, Brisbane, Qld

2014

11th International Symposium on Mining with Backfill Perth, Western Australia, 2014

2015

Ninth International Symposium on Field Measurements in Geomechanics New South Wales, Australia, 2015

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