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# Newsletter

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# The history and development of the Anisotropic Linear Model: part 2

by Professor Ken Mercer, Australian Centre for Geomechanics

## Introduction

This is the continuing story of the Anisotropic Linear Model (ALM), its ongoing development and usage. In Part 1 of this article published in June 2012 (Mercer, 2012), the history and background to the development of the ALM was described. The article described the principles of the ALM and the typical geological settings in which it is applicable. It then went on to describe how the first two generations of the ALM (ALM1 and ALM2), which were developed by Snowden Mining Industry Consultants (Snowden), have been applied to slope stability analyses using the limit equilibrium method.

Part 2 of this series elaborates further on the geology of anisotropic rocks and how small scale anisotropic waveform formations, such as those commonly found in the iron mines in the Pilbara area of Western Australia (WA), have added further complexity to assessing anisotropic shear strength. The article describes some of the ongoing research that has been undertaken using numerical modelling and presents three key findings from this research. It then goes on to describe how these findings have been used to further develop and refine the ALM approach, and how they can be applied immediately by practitioners in evaluating the stability of all slopes

Figure 1 Quartzite with parallel bedding partings in Bergen Arcs, Norway

Figure 2 Mylonitic migmatitic granite-gneiss, Namibia

mined in anisotropic rocks. Two papers (Mercer, 2013 and Tokimoto and Mercer, 2013) will be presented at the International Symposium on Slope Stability in Open Pit Mining and Civil Engineering which will more fully expound the findings of the research presented in this article.

## Anisotropic rocks

Part 1 of the article briefly describes the anisotropic rock formations of the Pilbara region in WA. The formations in the Pilbara have been particularly well studied due to the presence of the large West Australian iron ore mining industry. However, it is worth noting that anisotropic rock formations are found commonly throughout the world in many different geological settings and rock types. Anisotropic rock can be broadly divided into two categories:

- Banded ironstone formations (BIFs), sandstones and shales are typically characterised by relatively linear, pervasive bedding which have developed from sedimentary formation processes. These are commonly referred to as having bedding or sedimentary anisotropy. Rock such as metamorphic quartzites and slates, which have retained the influence of relic bedding, also fall into this category (Figure 1).
- Rock that have been subject to large strain deformation may also display anisotropic shear strength characteristics. These include protomylonites, mylonites, shear zones and rocks which contain pervasive joint sets that have relatively small spacing and long trace lengths. These rock types are often referred to as having structural anisotropy (Figure 2).

The terms ‘bedding anisotropy’ and ‘structural anisotropy’ are used fairly loosely. Regional metamorphic processes that form meta-sediments may significantly alter the shear strength of anisotropic sedimentary rock. As an example, the anisotropy in phyllite, which is highly fissile, is strongly influenced by fine-grained mica flakes that have developed in a preferred orientation as a result of a regionally imposed stress state. In contrast, the anisotropy of slate is formed by extremely fine clay flakes laid down in the sedimentary environment in which it formed. High-grade metamorphic processes may reduce the magnitude of the shear strength anisotropy by altering pre-existing sedimentary anisotropic formations into foliated or banded isotropic rock such as gneiss. Gneiss is characterised by alternating darker and lighter coloured bands and, depending on the grade of metamorphism, often does not necessarily result in the rocks displaying marked anisotropic shear strength characteristics.

Further complications with anisotropic rocks are as follows:

1. They are occasionally found in semi-continuous curvy-wavy formations also known as waveform formations that have developed due to folding as shown in Figure 3. The presence of these formations can make the assessment of shear strength particularly difficult especially at relatively small scales and low amplitudes.
2. Intact completely weathered tropical residual soils such as saprolite can retain a marked degree of anisotropy due to the retained influence of relic structures and bedding.
3. In slightly and partially weathered anisotropic rocks, weathering may occur preferentially along the planes of weak lamellae, such as shale bands or structures. This may magnify the anisotropic characteristics of the material by preferentially weathering the weaker materials first, thereby reducing the bedding shear strength before significantly reducing the overall rock mass shear strength.

Figure 3 Examples of waveform formations in Pilbara iron formations, Karijini, Western Australia

## Research into anisotropic rock mass behaviour

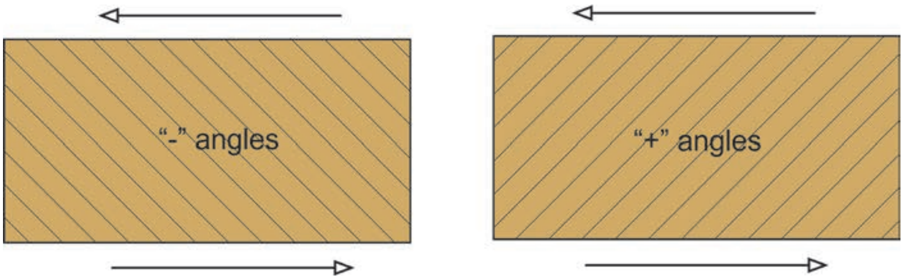
Research into the shear strength of anisotropic rock mass has been complicated by how to address the scale of the problem. Laboratory testing can only accommodate small scale tests which, in themselves can verify anisotropic shear strength characteristics at laboratory scale, but provide little help into directly predicting the shear strength and behaviour of anisotropic rock mass at full scale. As discussed in Part 1 of the article, in the ALM1 and ALM2 models, and the Mohr-Coulomb and Barton Bandis criteria have been used to estimate rock mass and bedding non-linear shear strength relationships. Laboratory testing is only used to provide input parameters into these criterion. In order to simulate the full scale shear strength characteristics of anisotropic rock mass during shear, Snowden and the ACG have therefore turned to numerical modelling.

The approach chosen to model these materials was to develop virtual shear box (VSB) models using UDEC (Itasca, 2013), in which different anisotropic rock mass types can be tested under varying normal stresses, through a range of angles of anisotropy (AoA) and rates of shear. The shear strength determined by the VSB as the AoA is rotated from 0 to 90° is plotted to develop shear strength transition models, as described in Part 1 of the article. These transition models are normalised to a percentage which eliminates the need for absolute values of shear strength and facilitates comparison between different types of materials.

The early transition models developed using planar discontinuities confirmed that the overall shear strength is at a minimum when AoA is 0° (bedding shear strength). As the AoA rotates in either direction, the overall shear strength becomes increasingly influenced by the rock mass shear strength and consequently the overall shear strength rapidly transitions to the maximum rock mass shear strength.

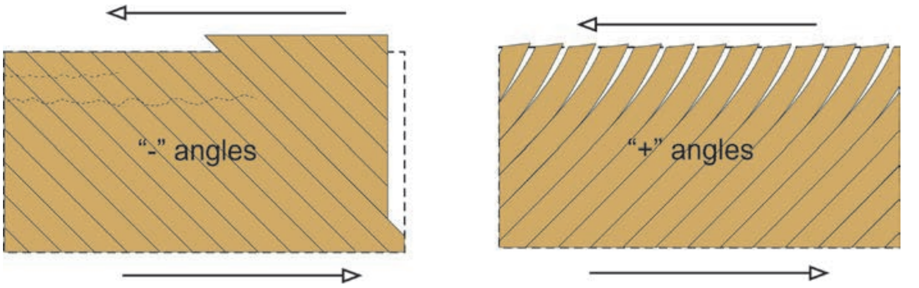
Materials from Pilbara stratigraphic units were selected for evaluation. These included:

- Weathered Dales Gorge (DG) and weathered Mt Newman (MN) banded ironstone formation (BIF), with and without shale bands.
- Weathered Mount McRae Shale from the Hamersley Group and West Angela shale (WA) from the Fortescue Group.




(a) (b)

Figure 4 (a) Downslope (negative) angles of anisotropy; (b) upslope (positive) angles of anisotropy




(a) (b)

Figure 5 (a) Combination of shearing and/or planar sliding on bedding; (b) flexural failure of rock lamellae

All units display ubiquitous bedding. The DG member is an alternating, planar-bedded assemblage of 17 BIF and 16 macrobands. The MN consists of BIF with a number of thick shale bands. Typically, these members are moderately to highly weathered and generally occur with shale bands that are relatively more weathered than the BIF. The VSB models were initially carefully calibrated to bedding and rock mass shear strengths of these units that were determined from laboratory testing.

## Behaviour of anisotropic rocks during shearing

There are a number of important aspects of anisotropic deformation behaviour during shearing that have come apparent as a result of this numerical modelling.

### First key finding

The first key finding was that anisotropic materials display different failure mechanisms when sheared at positive AoAs in comparison with negative AoAs.

For example, while it may be intuitively expected that the shear strength of an anisotropic material is the same at an AoA of +45° as it is with an AoA of -45°, as shown in Figures 4(a) and (b), they are in fact very different. The different failure mechanisms that develop during shearing are illustrated in the corresponding Figures 5(a) and (b). At negative AoA, the failure mechanism is sliding on bedding or lamellae (at low AoAs) that transitions into direct shear through the rock mass. At positive AoA, the failure mechanism is that of flexure of the lamellae leading to dilation and finally flexural failure or plastic/ductile behaviour of the individual lamellae, depending on the type of intact rock material of the lamellae and rate of shear.

### Second key finding

The second key finding was that the different failure modes have a greater impact on the overall shear strength of the rock mass than was originally believed, and confirms that shear strength is dependent not only on the magnitude of the angle of the anisotropy able but the direction of shearing with respect to the rock lamellae. Numerical modelling has identified a zone of shear strength reduction at AoAs between +50 to +85° which reaches a minimum at AoAs between +70 to +75°. This appears to be a result of a flexural failure of the lamellae and has been colloquially termed the zone of ‘upslope shear strength reduction’ (USSR).

Sensitivity studies have shown

that flexural failure of rock lamellae is dependent on the strength of the intact materials as well as the spacing of the bedding partings. Materials with very thin bedding partings such as shale and slate and especially those that are weathered appear to be particularly sensitive to this failure mechanism with the shear strength differential reducing by as much as 90%. Stronger and fresher rocks such as BIF and those that have wider bedding spacing appear to be much less sensitive. In some instances the USSR may not be evident. Comparisons of two selected normalised transition models for weathered shale and BIF that illustrate the USSR are shown in Figure 6.

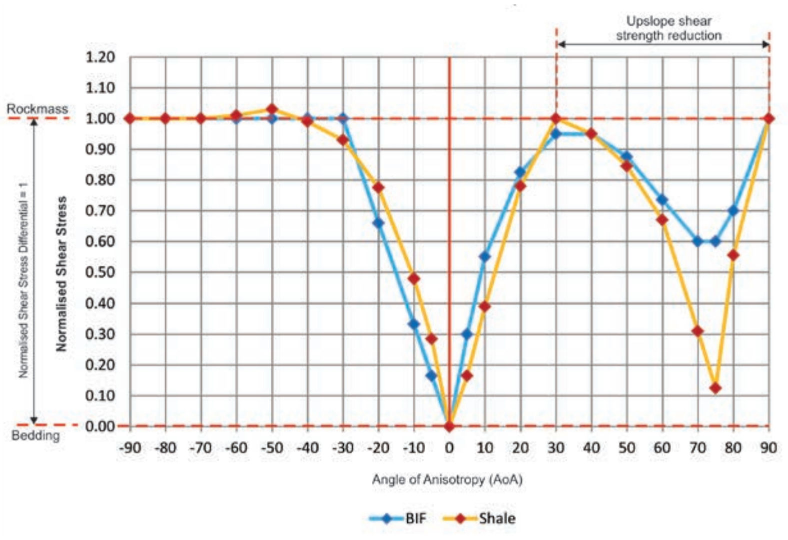



Figure 6 A comparison of the normalised transition models for a selected BIF and shale material

## Other important aspects

There are a number of important aspects evident in Figure 6 that are worth highlighting. These include the following:

1. UDEC modelling continues to strongly support the overall bedding shear strength transition models originally developed.
2. The unsymmetrical nature of the shear strength transitions for both types of materials has become even more apparent.
3. The differences in transitional shear strength characteristics between BIFs and shales have become more pronounced. In general this being a smoother transition to rock mass shear strength for the shales and more abrupt for the BIFs.
4. Failure of the BIF to achieve full rock mass shear strength at positive AoA less than 90°.

## Kink band slumping

It is important to consider whether the USSR has been independently identified and/or investigated in historical case studies and literature. Case studies of failures in slopes with anisotropic rock masses that have high +AoA, relative to the plane of failure, have demonstrated a phenomenon called 'kink band slumping'. The term kink band slumping or kink zone instability (KZI) was first introduced by Kieffer (1998) to describe the primary failure mechanism of rock slopes that have bedding dipping steeply into the slope. In KZI, the lamellae undergo large S-shape deformation suggesting large shear displacements and dilatancy of the lamellae. Kieffer's conceptual model is shown in Figure 7. Zinschinsky (1966) published case studies of slope failures in the Swiss Alps that were also interpreted to have similar overall failure mechanisms. These are illustrated in Figure 8 and show flexural failure at relatively high positive AoAs. They also indicate that these types of failures may exhibit secondary associated failure modes on limited sections of the failure, such as toppling and planar sliding.

Numerical modelling of kink band slumping has been undertaken by Preh and Poisel (2004) (Figure 9), and Noël and Archambauldt (2009) using both physical models and UDEC. Both research efforts independently verified this phenomenon. Preh and Poisel's modelling used lamellae with a dip of 35° into the slope with a resulting AoA ranging between +35 and +75°. Noël and Archambauldt investigations reported that KZI develops when primary joints are orientated as low as between +5 to +30°, relative to the major principal stress under confining pressures below 5 MPa. Unfortunately they did not investigate AoA of greater than +40° but confirmed the shear strength increase by varying the AoA between +5 to +35°.

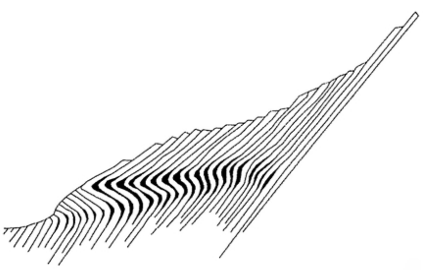


Figure 7 Conceptual model for kink band slumping (after Kieffer, 1998)

The failure mechanism associated with KZI therefore appears in practice to have the potential to influence the shear strength under all positive AoAs. In summary, the conditions under which the USSR particularly affects slope stability are where:

1. The direction of shearing takes place at higher positive AoAs in the range between +40 to +80°, however this needs to be researched further.
2. There must be few or discontinuous cross-cutting joint sets that could enable other types of failure mechanisms to develop.
3. The rock lamellae are relatively thin in comparison to the overall scale of the slope.
4. The intact material is relatively weak or weathered.

It is important that the rock mechanics practitioner considers the potential impact of USSR on the stability of open pit slopes, not only under inward dipping planar pervasive bedding as shown in the examples above, but anywhere where large scale folding may result in sections of

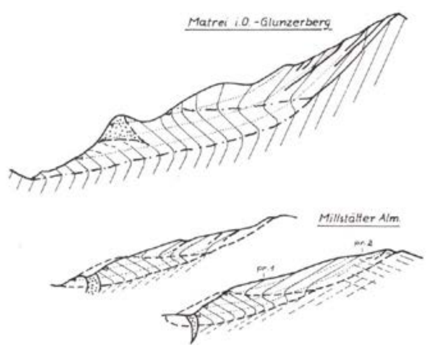



Figure 8 Similar overall failure mechanism to that shown in Figure 7 (Zinschinsky, 1966)

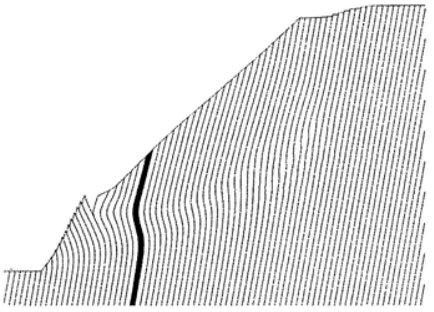


Figure 9 S-shaped deformation of rock lamellae (after Preh and Poisel, 2004)

the critical or failure surface shearing through lamellae with positive AoAs in relation to the direction of shear. In these instances, a down rating of overall shear strength for these domains would be prudent.

The flexibility of accommodating the USSR in the transition model, if required, has provided the motivation for the further development and refinement of the third generational ALM (ALM3). The ALM3 is presented by Mercer (2013).

## Third key finding – shear strength of waveform formations

Anisotropic rock masses found in the Pilbara region of WA can often exhibit intensive folding at all scales. These are commonly referred to as waveform formations. While large scale folding can be relatively easily modelled in limit equilibrium slope stability analyses as individual geotechnical domains, the influence of relatively small scale folding cannot.

There has been no previous studies into how small scale waveform deformation influences the overall shear strength of a rock mass and how the transition from bedding shear strength to rock mass shear strength differs from that of rock mass with planar discontinuities. Once again numerical modelling via the VSB approach has been adopted at the ACG in which the waveform of the bedding is simulated using a sinusoid function with amplitude (A) and wavelength(λ), as shown in Figure 10. By varying the amplitude (A) and wavelength(λ) for all AoA, the overall anisotropic shear strength was investigated and anisotropic waveform transition models developed.

The results of these studies have shown that variations of A and λ have a significant effect on the shear strength transition models over the entire AoA continuum. This effect includes the change in the shape of the shear strength transition models, an increase in the minimum shear strength, as well as a reduction in the maximum shear strength. The changes are dependent on the magnitude of the amplitude and wavelength of the waveform deformation as well as the nature and type of the intact rock.

Generally it was observed that the lower the wavelength the more isotropic in shape the resultant transition model becomes, i.e. the more the shear strength differential reduces. With decreasing wavelength, the effect of the bedding shear strength at an AoA of 0° and the USSR are dimished and the overall average shear strength gradually increases until it reaches approximately 80% of rock mass shear strength for shales and 95% for BIFs. The rock mass is thereafter said to have 'locked up'. A variation in the amplitude parameter of the waveform exhibits a similar reduction in shear strength differential and a more isotropic transition model. However increasing amplitude in shales does not support using overall transition shear strengths greater than 50% of the shear strength differential in shales and 75% in BIFs.

## Conclusions

Ongoing research into the shear strength and deformation behaviour of anisotropic rock masses using VSB numerical modelling has highlighted important new aspects of their shear strength behaviour:

- The first key finding is that deformation and failure mechanisms of an anisotropic rock mass are dependent on the direction of shearing relative to the AoA.
- Secondly, at positive AoAs in particular, numerical studies have identified the potential for flexural failure of the rock lamellae which results in an upslope shear strength reduction particularly between AoAs of +50 to +85° and reach a minimum between +70 to +75°. This phenomenon appears to be collaborated by independent research and case studies.
- The flexibility of incorporating the USSR in the transition model, if required, has provided the motivation for the development and refinement of the third generational ALM (ALM3). The ALM3 is presented by Mercer (2013).
- Practitioners may need to make provision for the reduced shear strength where appropriate.
- Finally, VSBs have confirmed that curvy-wavy anisotropic waveform formations may result in the highly anisotropic rockmass becoming 'locked up' and exhibiting more isotropic shear strength characteristics. Notwithstanding the more isotropic characteristics of the transition model, reduced overall shear strengths should be applied. Further details are presented by Tokimoto and Mercer (2013).

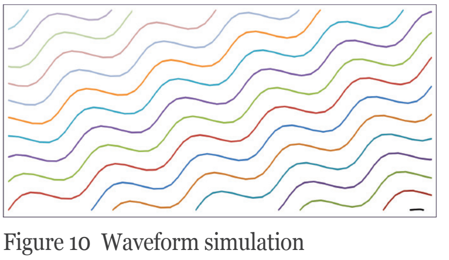


Figure 10 Waveform simulation

The author is actively promoting further research into these topics and therefore the ACG is considering to develop an Anisotropic Research Programme to accelerate the study of the shear strength characteristics over a wide range of anisotropic materials. The intention is to eventually develop Guidelines on Geotechnical Design in Anisotropic Rock Masses. For further details please contact the author.

## Acknowledgements

I would like to acknowledge Snowden for using their in-house research, Shintaro Tokimoto for his research into the shear strength of waveform formations, and Harry Speight and Phil Dight for reviewing this article.

*Contact the ACG for the unedited paper. Please click here for article references.*

Professor Ken Mercer,
Australian Centre for Geomechanics

# Going underground with new technology

International mining group Rio Tinto is developing better ways to mine through its Mine of the Future™ programme

International mining group Rio Tinto is developing better ways to mine through its Mine of the Future™ programme. The next-generation technologies introduced as part of the programme aim to improve efficiency, lower production costs, health, safety and environmental performance, and create more attractive working conditions.

Rio Tinto invests in technologies and the supporting organisational systems that allow for step change improvements in productivity and efficiency. Focusing on three key themes – achieving efficiency in surface mining through autonomy, accessing underground orebodies faster and deeper through tunnelling and improving recovery practices – the Mine of the Future™ programme is aimed at mining safer, better and faster.

Rio Tinto head of innovation John McGagh said “across the industry there is the clear objective to meet growing demand for our products while being more efficient through each stage of mining and metal production. Without technology and new ways of doing things we will not stay ahead of the productivity curve and achieve these targets.

“Through this approach Rio Tinto is changing the face of mining.”

The company is tackling the challenges facing the mining industry head on with key investments and partnerships aimed at identifying, developing and implementing innovations across the business. Improvements in technology can change the way mineral deposits are viewed with ore bodies that would once have been uneconomic becoming viable as a result of new technologies.

With maturing orebodies and deposits becoming deeper and more complex, Rio Tinto forecasts that underground mining will become more common over the next two decades.

For miners it is almost always preferable to keep an existing mine open rather than planning and constructing a new one.

“Rio Tinto is continually searching for ways to extend the operating lives of its mines to maximise potential value from its orebodies, which can mean going underground,” Mr McGagh said.

In April this year, the company opened the new USD 2.2 billion Argyle underground diamond mine in the east Kimberley region of Western Australia. The move from open pit mining to an underground block cave operation will extend the life of Argyle until at least 2020, resulting in production of 20 million carats per year, on average over the life of the block cave.

The longevity of the Argyle open pit and its unique diamonds continues to feed the demand for diamonds in


In April this year, the company opened the new US$2.2 billion Argyle underground diamond mine in the east Kimberley region, Western Australia

established and emerging markets. Since 1983 Argyle has produced around 800 million carats of rough diamonds producing a broad range of sizes, colours and qualities of diamonds including the rarest diamonds in the world, pink diamonds.

The Argyle underground mine is the first of its kind in Western Australia, using the latest block caving technology. The Argyle block cave requires the manipulation of tens of thousands of tonnes of rocks with considerable scientific monitoring and close management. To give an idea of the scale, the operation will extract a block of ore 500 m long, 200 m wide and 250 m high.

The underground mine comprises of around 40 km of tunnels all built to Rio Tinto's high safety standards. There are four main tunnels – two to carry vehicles, one for ventilation and another for transporting the ore 2.2 km to the surface for processing.

Argyle Diamond Mine managing director Kim Truter said "The Argyle Diamond Mine is a world class resource which has been strongly supported by Rio Tinto since exploration began in the 1970s.

"A new chapter begins at Argyle and I am proud to acknowledge the many men and women who have contributed to the discovery and development of the mine and the production of some of the best diamonds the world has ever seen," Mr Truter said.

Block cave underground mining is an immense engineering and geotechnical challenge. The technique involves the controlled collapse of ore from under its own weight into specially-designed chutes for collection. The ore is then brought to the surface for processing.

Block cave mining is safer, more cost-effective and can be done on a much larger scale than traditional underground mining methods. The technique is especially effective for a large low grade orebody like Argyle because it is a high volume mining method, which can match open pit production levels, keeping unit costs low with high levels of efficiency.

Rio Tinto is a world leader in underground block cave mining. Last year, the company opened the world's first training centre dedicated to the specialist underground mining technique of block caving. The USD 13 million Block Caving Knowledge Centre provides a unique programme of skills transfer for Rio Tinto miners and engineers from around the world to develop the technical and operational skills needed to operate future block cave mines.

# Deep mining – bringing mining to a lower level

by Associate Professor Marty Hudyma, Laurentian University, Canada

Of the 12 underground mines in the Sudbury area, six are operating at depths greater than 1,500 m

## Introduction

Extraction of deep orebodies is one of the frontiers of underground mining. The challenges include difficult ground conditions, complex and expensive transportation and material handling systems, and a hostile workplace environment associated with high rock face temperatures. Vale's Creighton Mine has a virgin rock temperature of 48 degrees at 2,400 m (Hardcastle, 2007). Each of these challenges poses technical issues and drives up mining costs.

There is a long history of deep mining in South Africa and Canada. However, deep operations are also underway around the world. In Australia, Glencore Xstrata's Enterprise Mine has development at depths of 1,800 m. St Barbara's new Gwalia gold operation, in Western Australia, is below 1,400 m. In Europe, Zinkgruvan and Kiruna, in Sweden, are mining below 1,000 m, while in Finland, Inmet's Pyhäsalmi operation is Europe's deepest mine with development below 1,400 m.

## How low can we go?

In Canada, cost and efficiency requirements have pushed mining methods towards bulk, open stope mining. This has been successful at depths down to 2,000 m. But can the use of bulk mining methods be extrapolated to depths of 3,000 m? Three mining operations in Canada are leading the way down. Near Sudbury, Vale's Creighton Mine is currently stoping at 2,400 m and going deeper. A few hundred kilometres north, near Timmins, Glencore Xstrata is mining stopes at Kidd Mine at similar depths, with the plan to mine open stopes at 3,000 m below surface. A few hundred kilometres to the east, Agnico-Eagle's LaRonde extension is open stoping at more than 2,500 m, with stopes planned deeper than 3,000 m.

## Research, development and innovation

There are a number of fundamental challenges in deep mines. Research, development and innovation are underway to address a number of these areas. Three topics of particular focus are:

- Managing difficult ground conditions.
- Materials handling.
- Heat management.

To identify and manage difficult ground conditions, efforts are focussing on topics such as:

- Improved mine design through schedule optimisation, improved sequencing and application of innovative technologies such as rockcutting and electronic detonators.
- Ground support and reinforcement systems to withstand extreme deformation and strong ground motions from large seismic events.
- Application of seismic monitoring to identify and manage seismic hazard.

Many mines have deepened over time, going from shallow to deep mines over a period of years or decades. This results often in complex and expensive material handling systems. Innovative work to address these issues include:

- Rail-Veyor™ technology.
- Automation and control systems.
- Improved hoist-rope technology.
- Energy reduction and improved energy management.

Management of heat is being

The sustainability of the mining industry demands innovation and excellence in deep mining practices

The Deep Mining 2014 Conference will be held in Sudbury in September 2014. Delegates will be awed by the spectacular colours of a Canadian autumn

addressed through topics such as:

- Ventilation on demand.
- Understanding of heat stress.
- Improved clothing for hot work environments.
- Increased use of tele-remote equipment.

**"deep and high stress mining is where the future of the mining industry lies"**

Deep mining research and innovation is underway through a number of organisations around the world, including: the Council for Scientific and Industrial Research (South Africa), Deep Mining Research Consortium (Canada), the Centre of Excellence in Mining Innovation (Canada), and Innovative Technologies and Concepts for the Intelligent Deep Mine of the Future (Sweden and Poland).

## Deep and High Stress Mining 2014

In September 2014, the Seventh International Conference on Deep and High Stress Mining will be held in Sudbury, Canada. This is a particularly fitting location for the conference as deep mining challenges are routine problems for many of Sudbury's mines. Today, there are 12 active underground mines in the Sudbury area. Six of these mines are currently operating at depths greater than 1,500 m. In addition, there are five more orebodies undergoing some level of feasibility study, with three of these projects at depths greater than 2,000 m. The future of mining in Sudbury is deep.

If your mining operation is faced with deep mining issues, Deep and High Stress Mining 2014 provides an opportunity to see and hear how mining companies, suppliers and researchers from around the world are developing solutions. Conference themes include:

- Geomechanics risks.
- Energy issues in deep mining.
- Occupational health and safety in deep mines.
- Financial risks.
- Case studies.
- Numerical modelling.
- Rock behaviour under high stress.
- Rockburst and seismicity monitoring.
- Ground support.
- Risk assessment and management.
- Ventilation.
- Blasting.

More than 200 delegates are expected from around the world. The event will be supplemented with a pre-conference workshop and mine tours, and a trade show of some of the leading suppliers of goods and services to the mining industry.

Welcome to Sudbury. You will be overwhelmed by northern hospitality. You will be awed by the spectacular colours of a Canadian autumn, in a city that has more than 300 lakes. You will be delighted by the industry and technical contacts.

*Article reference available on request.*

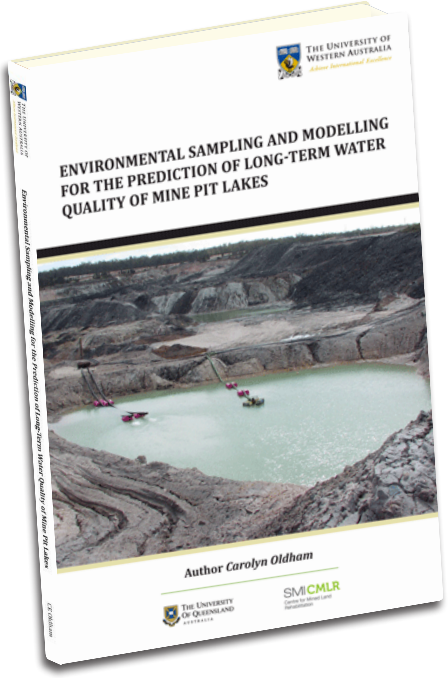
Associate Professor Marty Hudyma, Deep Mining 2014 Conference Chair

# The evolution of pit void science – a new mine pit lakes book

A newly released book, "Environmental Sampling and Modelling for the Prediction of Long-Term Water Quality of Mine Pit Lakes" by Winthrop Professor C.E. Oldham (UWA) summarises the experiences and learnings over the past 10 years with respect to developing water and chemical mass balances and conceptual models for mine pit lakes.

A mine pit lake is a water body that forms in an open cut mine after the mine has ceased operating. Water quality in mine pit lakes can vary from being suitable for drinking water to very poor. Regulators, communities and the minerals industry are becoming increasingly aware of the legacies and potential beneficial end-uses of mine pit lakes, and are placing an increasing reliance on predictive modelling of pit lake water quality to understand the long-term implications of selected closure strategies.

Ten years ago, the Western Australian Centre of Excellence for Sustainable Mine Lakes was established, along with collaborative funding from a number of mining companies and the Australian Research Council. One of the aims of the Centre of Excellence was to improve our ability to predict the long-term water quality of future mine pit lakes. Over the last decade, it became increasingly obvious that one of our largest challenges was to establish water and chemical mass balances for those pit lakes with significant groundwater – surface water interactions. Much research effort focuses on these interactions and their impacts on long-term water and chemical mass balance. However, comprehensive field data sets required for model input and validation are frequently not available. This new book aims to facilitate such data collection, and initially provides an overview of the development of pit lake conceptual




models and finishes with a detailing of the data required to validate the conceptual models, the mass balances and ultimately the more complex numerical models. These aims place this book apart from most other books on mine pit lakes that typically focus on detailed process understanding, for example of hydrogeology, geochemistry or limnology. While the book summarises research outcomes, it has been written for a broad readership, for both the mine manager and the researcher.

Content includes:

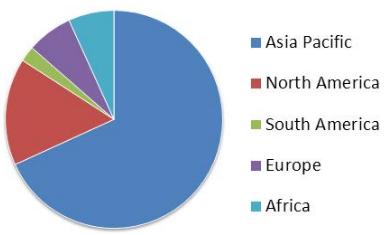
- Development of site-specific conceptual models.
- Water quality prediction.
- Data collection.
- Variables to be measured or modelled.

Winthrop Professor Carolyn Oldham,
School of Environmental Systems Engineering,
The University of Western Australia

*Order your copy via sales-acg@uwa.edu.au.*

# Mine Closure Conference Series – an analysis

Last month the Australian Centre for Geomechanics conducted a survey on the topic of the ACG International Mine Closure Conference Series, including all seven conferences that have taken place from 2006–2012, past delegates were asked which of the seven conferences they had attended, their home region, and more.



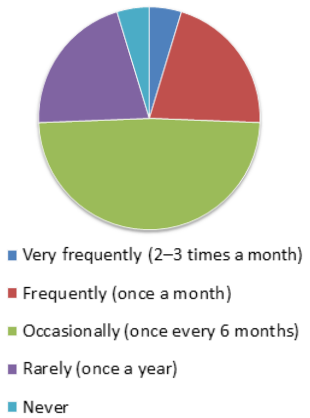

Question results: Where is your home region?

Of the results collected, 46.7% had attended the 2012 Mine Closure Conference, and responses showed that of the mine closure conferences to date survey participants have attended from 2006 to 2011 ranged from 22.2–37.8%.

Based upon the results of the 2013 survey, it is clear that Asia Pacific dominates the delegate's home region, with 68.2% of attendees coming from that region. Almost 16% were from North America, followed by Europe (6.8%), Africa (6.8%), and South America (2.3%). Of these results, 57.8% of delegates have travelled from their country of origin to other countries in order to attend these conferences.

Attending the mine closure conference series has shown to improve participants' knowledge of mine closure and reclamation matters through different methods. Gaining knowledge directly from presentations was shown to be most successful with 88.1% of respondents selecting this option, followed by one on one interaction with attendees (73.8%), reading and referencing the proceedings after the conference (61.9%), and being able to contact peers and colleagues after the conference with 42.9%.

In regards to how often survey participants refer to the physical proceedings as a guide after the conference, the most common answer was once every six months (48.8%). Following this, 20.9% refer to the proceedings at least once a month or once a year, and only 4.7% of participants said that they very frequently (2–3 times a month) or never refer to the physical proceedings.



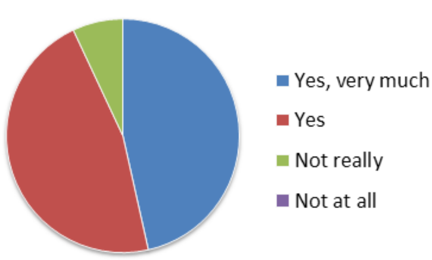

Question results: How often do you refer to the physical proceedings as a guide after the conference?

The conference series is changing and improving mine closure knowledge and responses showed that it was doing so most effectively through overall mine closure planning, landform (design, construction and stability) and ecosystem restoration.

Nearly 52% of participants reference and acknowledge other authors or papers from previous proceedings in their papers and work, followed by 30.2% rarely (once a year) do so, 11.6% said that they never do, 4.7% very frequently (2–3 times a month), and 2.3% answered frequently (once a month).

The conference series was deemed adequate to very successful, by the majority of participants, in changing and improving the process of informing mining industry colleagues of the advance of mine closure knowledge, informing the wider mining industry of good mine closure practice, improving understanding in the wider community and non government organisations that good mine closure practice can be achieved, improving the benchmark standards for mine closure, informing regulators in such a way as to improve current and potential legislation and bringing the different disciplines in mine closure practice together.

The conference maintains a panel of peers to peer review papers for editing, improvement and selection (or rejection) prior to publication; a rigorous process. Results confirmed that 93% of participants value the quality of the papers which result from that process, with the remaining percentage commenting 'not really'.




Question results: The conference maintains a panel of peers to peer review papers for editing, improvement and selection (or rejection) prior to publication, a rigorous process. Do you value the quality of the papers which result from that process?

Overall, the survey showed the Mine Closure Conference Series to be very successful in most aspects, and much positive feedback regarding the conference series was received.

## Acknowledgement

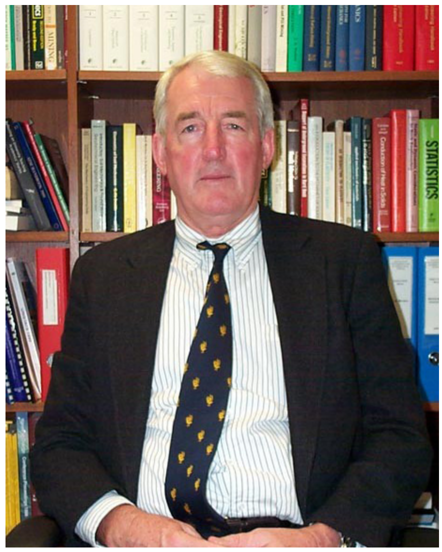
The ACG thanks Harley Lacy, Outback Ecology – MWH Global, for his contribution to this survey.

# Ground Support 2013 Symposium report

The Seventh International Symposium on Ground Support in Mining and Underground Construction was held in May 2013 in Perth, Australia. Followed on from previous symposia held in Sweden, 1983; Canada, 1992; Norway, 1997; Australia, 1999; Australia, 2004; and South Africa, 2008; Ground Support 2013 provided an opportunity for local and international mining and civil engineering professionals to exchange experiences and lessons learnt in the area of rock support and reinforcement, including mining and civil engineering applications.

Ground Support 2013 received a great industry response, with a significant international presence at the symposium and presentations from ten countries, including Australia, Canada, Chile, Czech Republic, Ireland, Japan, South Africa, Sweden, Switzerland and USA.

The 47 symposium presentations focussed on a range of areas within programme sessions topics including squeezing ground, ground support testing, dynamic support, support design and practices, corrosion, numerical modelling, shotcrete and instrumentation.



Ground Support 2013 Symposium Chair, Professor Barry Brady

The symposium ran for three days, bringing together academics, operators and technology developers to share information regarding innovative ground support strategies, processes and products to help maintain a competitive advantage.

Prior to the Ground Support 2013 Symposium, the ACG hosted two associated events. Associate Professor Marty Hudyma, Laurentian University, Canada, facilitated an Advanced Application of Seismology in Mines Short Course, which ran for four days and was attended by more than 20 delegates. The short course provided a background to the topic of seismicity in mines using a blend of theoretical lectures, practical examples and case studies of mine seismology and applied rock mechanics.

The ACG's MS-RAP software (the Mine Seismicity Risk Analysis Program) was used to investigate seismic data, evaluate seismic hazard and seismic source mechanisms in mines.

The short course was followed by a one-day Shotcrete Design and Performance Workshop facilitated by Winthrop Professor Phil Dight from the ACG. The workshop was aimed at site personnel involved in the design, implementation and quality assurance of shotcrete/fibrecrete in mining and attracted over 40 attendees.

The shotcrete workshop presenters included Gary Boon, Matthew Clements, Tony Cooper, Daniela Ciancio, Chris Langille, Charles Lilley, Ian Hulls, Des Vlietstra, Matt Calderwood, Eric Goransson and Uday Singh, and addressed areas such as the use of shotcrete in design, the application, monitoring/control of thickness and testing for quality assurance.

Following the Ground Support 2013 Symposium, the Ground Support Technology – a WASM/CRC Mining Workshop took place over the course of two days. Professor Ernesto Villaescusa, Dr Alan Thompson, Chris Windsor and Dr John Player from the WA School of Mines presented the workshop to over 30 delegates.

Throughout the Ground Support 2013 Symposium, delegates had the opportunity to network with other delegates and to visit the trade exhibition area to learn more from the event sponsors, namely the principal sponsor Stratacrete and major sponsors Beck Engineering, DSI and Fero.

**Ground Support 2013 was well received, with over 200 delegates attending**

The Ground Support 2013 Symposium Chair was Professor Barry Brady, Emeritus Professor at The University of Western Australia, who presented the Ground Support 2013 welcome and opening comments. Barry's opening address was followed by Professor Peter Kaiser, Rock Mechanics and Ground Control, Laurentian University, Canada who presented a keynote address on critical review of design principles for rock support in burst-prone ground – time to rethink!

Keynote speaker Professor Erling Nordlund, Luleå University of Technology, Sweden, then presented his paper on deep hard rock mining and rock mechanics challenges.

David Finn, Newcrest Mining Ltd, presented the keynote address on the second day with his paper 'Applying a ground support and reinforcement design methodology'.

Day three of the symposium opened with a keynote address from Dr Loren Lorig, Itasca Consulting Group Inc., USA on guidelines for numerical modelling of rock support for mines.

The Eighth International Symposium on Ground Support in Mining and Underground Construction will be held in Sweden in 2015.

For more than 20 years the ACG has been a leading provider of geomechanics education, training and research. The continued high attendance at ACG events illustrates that many mining companies and organisations find our event content and quality and interactive format to be high calibre, relevant and of real value and benefit. The ACG is delighted to present host the following Ground Support further training and education events in 2014.

**Are Your Ground Support Costs Too High Workshop?** | 23 March 2014 | Adelaide, South Australia

**Practical Rock Mechanics Seminar** | 28–29 July 2014 | Perth, Western Australia

**Ground Support in Open Pit and Underground Mines (Basic) Seminar** | 30 July–1 August 2014 Perth, Western Australia

**Ground Support Subjected to Dynamic Loading Workshop** | 15 September 2014 | Sudbury, Canada


## Paste takes hold in Brazil

The 16th International Seminar on Paste and Thickened Tailings was held in Belo Horizonte, Brazil, 17–20 June 2013. More than 380 delegates from 22 countries attended Paste 2013. Key topics were: hydraulically placed dry-stacks, filter-pressed dry-stacks, paste and thickened tailings, environmental considerations and polymer-amended tailings.

Purchase your set of the Paste 2013 proceedings from ***www.acg.uwa.edu.au/shop.***

**Abstracts due 5 November 2013**

Paste 2014 will be held in Vancouver, a major hub for mining in North America and a home to many mining companies that focus much of their activity on the development of sustainable tailings management practices at their operations.

**www.paste2014.com**

paste2014

17th International Seminar on Paste and Thickened Tailings

June 9-12, 2014 | Vancouver, Canada

# Advancing rockburst risk mitigation techniques in mines research project

by Dr Johan Wesseloo, Australian Centre for Geomechanics

As the mining industry exploits deeper deposits, mining induced seismicity and rockbursts are becoming more prevalent and the effective management of rockburst risk becomes increasingly important. This is one of the main drivers behind the ACG's Mine Seismicity and Rockburst Risk Management (MSRRM) Project. Phase 4 of the project was successfully completed at the end of January 2012 which also marked the beginning of Phase 5.

The overall goal of the project is to improve the methods for managing the risk that mining induced seismicity poses to personnel safety and to company economics in three broad topic areas, namely:

- Seismic hazard assessment.
- Understanding the rock mass response to mining, using seismic data.
- Ground support.

During Phase 5, specific emphasis is given to improving the seismic hazard assessment through the use of Probabilistic Seismic Hazard Assessment methods, quantifying the rock mass response to blasting and its associated hazards, and improving our understanding of the ground support capacity under dynamic loading.

## Development of mXrap

Undoubtedly, one of the major project benefits to project sponsors is the software, mXrap. The software was originally developed in the first phases of the project to fill a need in the industry at the time. It has proven a valuable technology transfer tool as it enables the sponsor sites to implement the results of the research. For this reason the continued development of the software to incorporate the research progress forms an important part of the project.

Dr Johan Wesseloo, Project Leader, Australian Centre for Geomechanics

Paul Harris, mXrap Software Developer, Australian Centre for Geomechanics

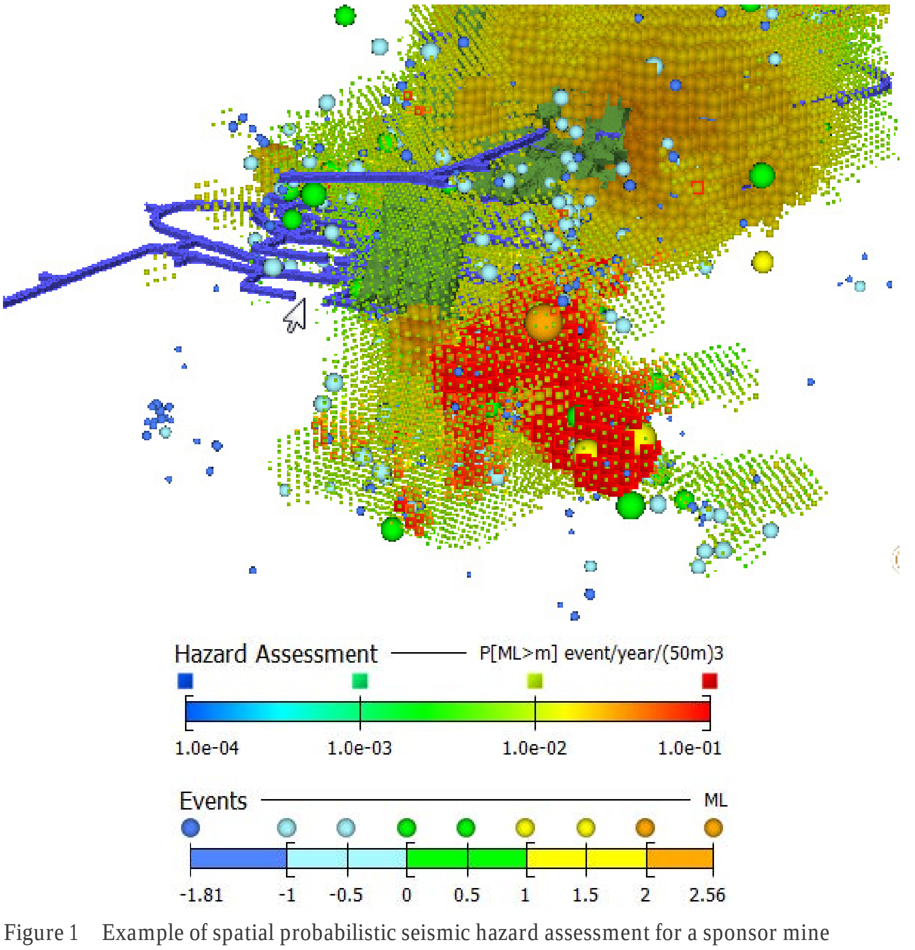
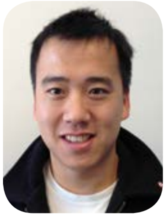



Figure 1 Example of spatial probabilistic seismic hazard assessment for a sponsor mine

## The human capital

The development of human capital is one of the ways industry benefits from the project.  Many postgraduate and undergraduate students formed part of the MSRRM project team at one time or another.  Currently four PhD students are on the project team; their topics are listed below:

Daniel Cumming-Potvin
Using indirect monitoring methods to quantitatively assess rock mass quality in operating block caving mines



Wei Duan
Evaluation of support design methodologies in rockburst prone ground

Juan Jarufe Troncoso
Quantifying seismic response of major discontinuities in response to mining using numerical modelling

Kyle Woodward
Evaluation and quantification of mine induced seismic response after blasting

# Featured ACG, UWA PhD candidate

Ariel Hsieh
The University of Western Australia

The ACG's key resource, the one that truly sets us apart, is our people with the total commitment and the capability to match. With our academic staff and key industry contacts, the ACG actively contributes to the undergraduate and postgraduate experience in the mining geomechanics discipline at UWA. This issue overviews Phd candidate Ariel Hsieh's thesis.

Ariel's supervisors are Winthrop Professor Phil Dight, ACG, and Winthrop Professor Arcady Dyskin, UWA School of Civil and Resource Engineering.

### In situ stress reconstruction using rock memory

Knowledge of in situ stress for underground construction or excavations is important for design. With an input of in situ stress magnitude/orientations, one can predict the potential failure, improve the efficiency of ground support and/or provide the parameters for numerical modelling/planning to make the design cost-effective. At the ACG we have been investigating two alternative in situ stress measurement methods based on using existing oriented rock core, namely the Acoustic Emission (AE) method and the Deformation Rate Analysis (DRA) method. We firstly reviewed the phenomenon that Kaiser found in 1950 using AE and the use of the Kaiser effect for determining the in situ stress measurement, and then we performed a series of tests in samples with different conditions in the sample end.

For the DRA method, we started with the investigation on the change in tangent modulus under uniaxial load. We proposed a mechanism of DRA under low stress – the frictional sliding over the pre-existing crack, interfaces, and/or grain boundaries. A basic rheological model was developed to simulate the rock specimen with a large number of interfaces. We also studied the effect of sample bending caused by the imperfections of the loading frame and/or sample preparation, and the influence of stress applied earlier than the (assumed) pre-stress, and the influence of in situ stress/previous laboratory applied stress on the DRA stress reconstruction.

The results of this work are presented in Ariel's PhD thesis which was recently submitted.

Some of the observations of the last 3.5 years of testing conducted at the ACG can be summarised as:

- AE can be recorded in samples tested well below the crack initiation threshold, indicating that the mechanism may involve more than the generation of new cracks.
- In situ stress recovery using DRA can be obtained from examination of the axial strain difference or the lateral strain difference. The latter confirms that the mechanism is independent of crack initiation. This response is only applicable to the in situ stress recovery as repeated axial loading of a sample cannot be recovered using the lateral strain.
- Many published test results using AE appear to have been influenced by issues associated with end preparation and probably do not reflect the in situ stress component, but do explain why in laboratory tests the previous maximum axial load can be recovered.
- It appears that the in situ stress memory can be ascribed to the grain structure. This has been confirmed by testing material in which the grain structure does not exist. Such material cannot remember the applied stress even in laboratory testing.
- The age of the in situ stress that is recovered is apparently up to 10,000 years ago. So stress decrease at the sample site cannot be recovered if it has occurred more recently, but stress increases can be recovered.
- The in situ stress can be recovered from block samples recovered from existing development provided the block has been oriented.

So it appears that rock has memory – be careful the next time you kick one it might kick back (actually Newton's Third Law).

AUSTRALIAN CENTRE FOR GEOMECHANICS
CSIRO | Curtin University | The University of Western Australia Joint Venture

# ACG event schedule*

## 2013

| | |
|---|---|
| Instrumentation and Slope Monitoring Workshop | 23 September 2013 \| Sofitel Brisbane Central Hotel, QLD |
| Slope Analysis and Design in Anisotropic Materials Workshop | 24 September 2013 \| Sofitel Brisbane Central Hotel, QLD |
| International Symposium on Slope Stability in Open Pit Mining and Civil Engineering – www.slopestability2013.com | 25–27 September 2013 \| Sofitel Brisbane Central Hotel, QLD |
| The Business Case for Risk-based Slope Stability Design Workshop | 28 September 2013 \| Sofitel Brisbane Central Hotel, QLD |
| Blasting for Stable Slopes Short Course | 4–6 November 2013 \| Novotel Perth Langley, Perth, WA |
| Soil Mechanics in Mining Seminar Series (TBC) | 3–5 December 2013 \| Perth, WA |

## 2014

| | |
|---|---|
| Introduction to Environmental Geochemistry of Mine Site Pollution Short Course | 26–27 March 2014 \| Perth, WA |
| Are Your Ground Support Costs Too High Workshop? | 23 March 2014 \| Adelaide, SA |
| Best Practices in Mine Backfill Technologies Workshop | 19 May 2014 \| Perth, WA |
| 11th International Symposium on Mining with Backfill – www.minefill2014.com | 20–22 May 2014 \| Perth, WA |
| Practical Rock Mechanics (Introduction) Short Course | 28–29 July 2014 \| Perth, WA |
| Ground Support in Open Pit and Underground Mines (Basic) Short Course | 30 July–1 August 2014 \| Perth, WA |
| Open Pit Geotechnical Analysis and Design Training Course | 26–28 August 2014 \| Perth, WA |
| Ground Support Subjected to Dynamic Loading Workshop | 15 September 2014 \| Sudbury, Canada |
| Seventh International Conference on Deep and High Stress Mining www.deepmining2014.com | 16–18 September 2014 \| Sudbury, Canada |
| Unsaturated Soil Mechanics for Mining Seminar (TBC) | 18–19 September 2014 \| Johannesburg, South Africa |
| Open Pit Slope Stability Seminar | 22–24 September 2014 \| Johannesburg, South Africa |
| Blasting for Stable Slopes Short Course (TBC) | 5–6 November 2014 \| Perth, WA |
| Mine Rehabilitation and Tailings Management Seminar Series | 2–5 December 2014 \| Perth, WA |

## 2015

| | |
|---|---|
| Ninth International Symposium on Field Measurements in Geomechanics www.fmgm2015.com | 2015, NSW |

*The ACG event schedule is subject to change. For event updates visit www.acg.uwa.edu.au/events_courses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# The history and development of the Anisotropic Linear Model: part 2

by Professor Ken Mercer *Australian Centre for Geomechanics*

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