Newsletter

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Design – a strategic issue

The circle of design reflects the importance of review and monitoring in the two phases of successful design and implementation: defining the design, and executing the design

writes Emeritus Professor T.R. Stacey, School of Mining Engineering, University of the Witwatersrand, South Africa

Introduction

Engineering design usually involves the development of a 'solution' (the design) to a known 'problem'. There is no unique solution, and different engineers will produce different solutions – some solutions will work better than others, but all solutions should work. The reason that solutions are not unique is probably because of the very wide scope of the issues involved in design. In reviewing the engineering design process, Bieniawski (1991, 1992) quotes the definition of engineering design from ABET (1987):

"Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet a stated objective. Among fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing and evaluation. In addition, sociological, economic, aesthetic, legal and ethical considerations need to be included in the design process."

It is unlikely that anyone would dispute that engineering design is a strategic issue. A satisfactory design is fundamental to the expected performance of the engineering structure. The key input to design is required in the early stages of project planning. This is when the key thinking and most important decision-making take place.

The design process and the strategic planning process

Satisfactory engineering design involves a design process. According to Hill (1983), as discussed by Bieniawski (1988), the design process is "a sequence of events within which the design develops logically, and a process that provides a work plan in the planning of a design programme". A defined process can serve as a checklist of activities that must be carried out to ensure that a satisfactory design results.

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The defined process or methodology can be considered as a form of quality control, which ensures that all aspects that should be taken into account in the design are taken into account.

Design principles in rock engineering

Bieniawski (1991, 1992) dealt specifically with engineering design in the rock mechanics field. He defined a series of design principles that encompass a design methodology. Although Bieniawski developed these for rock engineering, they are applicable in principle to any form of engineering or investigation. The design principles defined by Bieniawski follow:

1. Clarity of design objectives and functional requirements.
2. Minimum uncertainty of geological conditions.
3. Simplicity of design components.
4. State of the art practice.
5. Optimisation.
6. Constructibility.

Design methodology or process

The design methodology presented by Bieniawski (1991, 1992), corresponding with the above six design principles, is summarised in the ten steps given below.

Step 1: Statement of the problem (performance objectives) [Design principle 1].

Step 2: Functional requirements and constraints (design variable and design issues) [Design principle 1].

Step 3: Collection of information (site characterisation, rock properties, groundwater, in situ stresses) [Design principle 2].

Step 4: Concept formulation (geotechnical model) [Design principle 3].

Step 5: Analysis of solution components (analytical, numerical, empirical, observational methods) [Design principles 3 and 4].

Step 6: Synthesis and specifications for alternative solutions (shapes, sizes, locations, orientations of excavations) [Design principles 3 and 4].

Step 7: Evaluation (performance assessment) [Design principle 5].

Step 8: Optimisation (performance assessment) [Design principle 5].

Step 9: Recommendation [Design principle 6].

Step 10: Implementation (efficient excavation, and monitoring) [Design principle 6].

This methodology represents a thorough design process and can be used as a checklist to ensure that a robust and defensible design has been carried out.

There is often a misconception that analysis is design, and many sophisticated analyses, with little underlying validity in terms of input data and failure criteria, are often carried out. Analysis is science, whereas design is engineering. It may be observed from the above steps that analysis, which involves analytical (including numerical), empirical and observational methods, occupies only one step of the overall design methodology, and is bridged by design principles 3 and 4. Analysis is only a tool to obtain answers to the problem that has been posed. If the input information is inadequate, and the concept or geotechnical model (including the interpretation of mechanisms of behaviour and choice of appropriate failure or design criteria) is incorrectly formulated, the answers obtained from the analysis may be scientifically correct, but will be wrong with regard to a valid design. That is, the sophisticated analysis has provided results for the wrong problem. This illustrates that the other steps in the design methodology are in fact much more important than the analysis step – they are fundamental to a successful design, whereas the analysis simply follows from these other steps.

Independent review during the design process provides a very important control on the quality of the design being carried out. Such an activity should be a formal one that could take place at various stages, depending on the magnitude of the design project. For a large project, the formal review would typically take place at regular time intervals, such as twice a year; for smaller projects, the review could be done at appropriate stages rather than on a regular time basis. The aim of the review is to ensure, independently, that the design is robust and that the design objectives are being addressed. If any shortcoming is identified in the design, it will be necessary to loop back to an earlier step in the process and reassess the design.

Monitoring is an extremely important aspect of design. It could range from being purely visual to the use of sophisticated instrumentation. One of the main aims of such monitoring should be to check whether the mechanism of behaviour of the designed structure or opening is as expected and whether the design criteria used were appropriate, i.e. to determine that the design is valid. If the behaviour and/or criteria are not as expected, it will be necessary to loop back to an earlier step in the process and reassess the design. It may even be necessary to carry out a completely new design. The sooner that monitoring information or data can be obtained the better, since costly errors and consequences will then have the best chance of being avoided.

Strategic planning process and discussion

Ilbury and Sunter (2005) published, 'Games foxes play – planning for extraordinary times'. In this book they describe a strategic planning process that they term a 'strategic conversation'. They propose the following ten step process in their strategic conversation.

Step 1: Scope of the game.
Step 2: The players.
Step 3: Rules of the game.
Step 4: Key uncertainties.
Step 5: Scenarios.
Step 6: SWOT analysis.
Step 7: Options.
Step 8: Decisions.
Step 9: Measurable outcomes.
Step 10: The meaning of winning.

What is remarkable about this process is its uncanny correspondence with Bieniawski's engineering design process. A comparison of the two processes is summarised in Table 1.

Table 1 Comparison of design and strategic conversation processes

Design Process	Strategic Conversation Process
Statement of the problem	Scope
Requirements and constraints	Players
	Rules of the game
Collection of information (minimisation of uncertainty)	Key uncertainties
Concept formulation	Scenarios
Design analysis	SWOT analysis
Alternatives	Options
Evaluation	Decisions
Optimisation	
Recommendation	Measurable outcomes
Implementation (construction, excavation)	Meaning of winning

Since design is a strategic issue, the correspondence is perhaps not surprising. However, such direct correspondence has not been observed with other strategic planning approaches.

Ilbury and Sunter (2005) consider that 'circles of conversation' are most effective, since they avoid the linear approach commonly adopted in strategic planning sessions in which dominant individuals may drive the process in the direction that they favour – "When the strategic conversation is circular, it flows like a current through the heads of all the people sitting around the table, creating its own field of alignment." Their conversation model is expressed in the form of a circular chart (Figure 1).

After viewing this circular process approach, it is considered that the engineering design process should similarly and logically be represented as a circular process. As indicated above, review and monitoring are important inputs to the

Figure 1 The conversation model (Ilbury & Sunter 2005; Chart 7)

Figure 2 The engineering circle of design

design process, which can result in looping back to an earlier step in the process.

As shown in Figure 1, the strategic conversation process is divided into two phases: defining the game (the real strategic part) and playing the game (the implementation or more tactical part); with five steps of the process in each phase. Similarly, the engineering design process can be divided into two phases: defining the design (the very important front end loading part), and executing the design (the implementation of the design at various levels of detail). In this case, the first phase will contain four steps and the second, six steps, as shown in Figure 2. The first phase, 'defining the design', represents the extremely important front end loading phase of projects.

The strategic conversation approach allows issues for potential action (IPAs) to be noted and addressed at an appropriate time during the process (Ilbury & Sunter 2005). Similarly in engineering design, design IPAs arise, and these can be addressed much more easily if the thinking in the design process is circular, with the review and monitoring function centred at the hub of the circle of design.

Strategic and design considerations for vertical pit mining

As a small scale example of some strategic conversation and design considerations, the unique case of vertical pit mining is considered in this section.

Redford and Terbrugge (2000) describe the mining of a small, shallow orebody at Inyala Mine in Zimbabwe by means of a vertical pit. This project is appropriate to use as an example since it was the first time that this mining method had been used (therefore requiring strategic considerations) and there were critical design aspects involved (therefore requiring the application of a thorough design process).

Vertical pit mining is applicable for the mining of relatively small orebodies with vertical geometries, such as small diamond pipes. It avoids a large amount of waste stripping, and removal of ore and transporting of equipment and materials is by means of a crane or other device – at Inyala Mine a Blondin cable hoist was used.

Redford and Terbrugge (2000) describe the project as follows: "Anglo American Corporation Services Limited (AAC), acting on behalf of Zimbabwe Alloys Limited (Zimalloys), called for tenders for conventional open pit mining by contractors of the Inyala Mine "Airfield Block"… The pit was designed… on geotechnical information available at the time… sidewall slopes adopted were 58° in the… gneiss rock footwall, and 45° in the… siliceous serpentinite conditions elsewhere…

"The pit operations were planned to exploit two chromitite ore lenses, each approximately 30 m long by 9 m wide, with a waste middling of some 10 m, at an apparent dip of 80°. Pit production comprised 155,000 t, with 2,500,000 bcm waste…

"In parallel with the conforming bid preparation, an alternative proposal was developed and priced, adopting the vertical pit principle. Based on the geotechnical information provided, the proposal envisaged an oval shaft, with plan dimensions of 41 and 32 m… such a shaft would recover an estimated 147,000 t of chromitite ore to a mining depth of 95 m, together with a further 25,000 t of low-grade material… Shaft sidewalls would be supported by means of a combination of 300 kN, 10 m long cable anchors, rockbolts, mesh and mesh-reinforced shotcrete… A budget cost … was quoted for the alternative, almost half that of the lowest conventional bid submitted."

Additional drilling was subsequently carried out, which showed poorer rock qualities and a greater orebody footprint. Sidewall support costs increased substantially because of the weaker rock mass conditions. The contractor was appointed and the vertical pit was mined successfully to a depth of 78 m. The reduction in the price of chromitite ore was the reason that the mine did not progress to the planned depth of 95 m.

Table 2 SWOT list

Scenario	Strengths	Weaknesses	Opportunities	Threats
Open pit	Established method. Understood flexibility, e.g. production capacity easily increased, pit design can change	High stripping ratio. Large surface area affected. Limited design options for small pit	Conventional	Slope failure. Waste stripping increase. Increased pit limits. Dilution
Vertical pit	Established in civil engineering (basements). Selective mining. Reduced area, and environmental effects. Perceived lower cost	New mining method. Unproven to depth envisaged. Limited flexibility – no negative wall angles. Limited production capacity	Lower cost. Reduced volume of mining. Use of civil contractor	Wall collapse. Poor quality control. Potential loss of mine
Underground mining	Established approach. Probably no surface effects	Infrastructure requirements – shaft, etc. Small orebody	Limited	N/A
No mining	No risks	No use of asset	N/A	N/A

Strategic conversation approach

In this project, the strategic conversation steps could have been considered, as follows.

Step 1: Scope.

A small asset to be mined using an appropriate mining method. How does this match with the mining company's stated objectives, policies, etc.?

Step 2: Players.

Mining companies, contractor, designer, existing miners/employees and dependants, the local population, the broader population, and the government. These would include players for, against and neutral.

Step 3: Rules of the game.

Safety, environmental acceptability, laws, contracts, economic factors, required return on investment, production and profit targets, etc. These include the normative or moral rules of the game, the descriptive rules and the aspirational rules (Ilbury & Sunter 2005).

Step 4: Key uncertainties.

Orebody definition, chrome price, geotechnical information (particularly in the waste rock), mining method, social, environmental and technical issues, quality control performance, government policies, tax, politics, etc.

Step 5: Scenarios.

The mining scenarios are open pit mining, vertical pit mining, underground mining, and no mining.

Step 6: SWOT analysis.

A SWOT list, as suggested by Ilbury and Sunter (2005) can be prepared as in Table 2. It is probable that many more points could be included in such an analysis.

Step 7: Options.

From the SWOT analysis, one might choose only two options – open pit mining and vertical pit mining. Underground mining was probably never a significant option.

Step 8: Decisions.

The tenders received for conventional open pit mining (Redford & Terbrugge 2000) showed that conventional open pit mining of the deposit was not economic. There were also additional risk factors, indicated as threats in the SWOT analysis, which could have made the conventional pit even less economical. Vertical pit mining was therefore the only possibility. The decision-making process at this stage, on the part of the owner, should normally involve a risk analysis.

Step 9: Measureable outcomes.

Milestones, production targets, costs, profit, meeting defined key performance indicators, and satisfaction.

Step 10: Meaning of winning.

All stakeholders satisfied?

- Owner: return on investment.
- Contractor: technical satisfaction and satisfactory profit.
- Designer: design proven, satisfactory income.
- Employees and dependants: employment, income, living standards.
- Local population: income, environment.
- Government: export earnings, tax income, use of national asset.

Circle of design approach

The design process begins once the decision step of the strategic process has been completed. The steps below deal with the geotechnical aspects.

Step 1: Problem statement.

Vertical pit mine, depth defined, production rate defined.

Step 2: Requirements and constraints.

Walls must be stable – critical to safety, but also, if a failure was to occur, it would probably be uneconomic to continue mining. Quality control of blasting and support installation and monitoring of behaviour are critical to successful mining.

Step 3: Uncertainty minimisation.

Collection of information to enable the following: definition of rock materials present; definition of rock mass properties; definition of rock mass geotechnical zones; definition of strength properties of rock/rock mass.

Step 4: Concept formulation.

Geotechnical model incorporating rock mass zones and their expected strength properties, and the expected behaviour and potential failure mechanisms. Concept of support to ensure stability. Influence of three dimensions. Definition of design criteria, e.g. factors of safety, probabilities of failure, acceptable deformations, acceptable extents of failure, etc. Blasting requirements, timing of support installation, sequencing, etc. Monitoring requirements.

Step 5: Design analyses.

Analyses of the geotechnical model or models developed in Step 4, considering the range of material/rock mass properties and alternative support geometries/quantities. Prediction of behaviour and expected deformations, and identification of corresponding monitoring requirements. Identification of critical areas from the analysis results and corresponding specific monitoring requirements. Use of alternative analysis methods.

Step 6: Alternatives; and Step 7: Evaluation.

Consideration of the alternatives analysed and evaluation of the results. Decision on acceptability of the extent of analyses carried out.

Step 8: Optimisation.

Optimisation of the outputs obtained from the design analyses and ranking of chosen alternatives.

Step 9: Recommendation.

Decision on method and quantity of support, support installation requirements, quality control requirements, stability monitoring requirements, recording and reporting requirements (blasting, construction, inspections, monitoring), etc.

Step 10: Implementation (review, monitoring).

Excavation and production. Monitoring and reporting are critical.

Note that interim review is necessary at all stages, particularly at steps 3, 4, 6, 7 and 9. Highlighted steps are particularly important. If the performance is not as expected from the design analyses, the design must be reviewed at the earliest possible opportunity, since it is not feasible to install additional or different support at higher levels in the pit walls when the pit bottom has progressed downwards.

The activities identified in the ten steps above were essentially what were carried out during the design process for the Inyala Mine vertical pit, and the project proved to be successful, as described by Redford and Terbrugge (2000).

Conclusions

The engineering design process developed by Bieniawski (1991, 1992) has been compared with the strategic planning approach described by Ilbury and Sunter (2005). In the latter, the ten steps in the strategic conversation process show remarkable correlation with Bieniawski's logical design process. This is perhaps not surprising since engineering design is a strategic upfront issue, and front end loading in a project is critical to achieve the expected project performance.

Based on the close correlation between the strategic conversation and engineering design processes, a circular design process, rather than a linear process, is proposed. The circle of design better reflects the importance of review and monitoring in the two phases of successful design and implementation: defining the design, and executing the design.

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Open pit training in Mongolia

by Winthrop Professor Phil Dight, Australian Centre for Geomechanics

Figure 1 Looking north across Pit 3, Boroo Gold Mine. The view is towards the hangingwall. Water seepage at the bottom of the pit is coming from the orebody, which dips at about 15° into the wall

Introduction

The International Mining for Development Centre (IM4DC), in collaboration with the General Agency for Specialized Inspection (GASI) and the German Federal Institute for Geosciences and Natural Resources (BGR), delivered training in Mongolia to government officials on open cut slope stability.

In April 2014, ACG Winthrop Professor Phil Dight visited Mongolia to deliver geomechanical theoretical and practical training in open pit mining and provided a basis for GASI geology and mining inspectors and its offices in the provinces (Aimags), the "Inspectorate", to develop an understanding of what to look for when conducting their visits. Almost 30 people attended the course.

Previous visits and workshops held for GASI in Mongolia by IM4DC have identified GASI as a key institutional linkage. Mongolia is going through a rapid mining expansion and GASI development is sought.

The programme was organised through the German-Mongolian Technical Co-operation project, "Environmental Protection in Mining"; which is jointly conducted by the BGR and GASI. The project manager in Mongolia is Dr Thekla Abel.

Professor Dight undertook further education and training in the following areas:

- A general awareness of slope instability and the driving forces involved.
- The approaches used in design and the difficulties experienced in slope design where data is limited.
- Failure mechanisms.
- Influence of physical processes on stability (weathering, alteration, and groundwater).
- Influence of in situ stress on stability.
- Methods for stabilising slopes.
- Methods for slope monitoring.
- Methods for collecting data.

The training course also featured two site visits: Boroo Gold Mine; and Darkhan Metallurgical Plant and Tumurtolgoi iron ore mine.

Boroo Gold is currently rehabilitating previously mined pits. In Pit 3 (Figure 1), the main constraint on further mining is the stripping ratio of the hangingwall. The design of the pit appears to have been based on Russian Code, and has an overall wall of 45° with 10 m bench heights and batter angles of 63°. The walls in Pit 3 show little instability, which from a safety viewpoint is excellent, but by referring to the approach discussed in the training course it is thought that the hangingwall could have been steepened between 5 and 10° above the design adopted, with potential considerable savings in the stripping ratio or potential to release more ore.

The geology of Pit 3 comprises granites and meta-sediments, while Pits 5 and 6 comprise sediments. The orebody formation has a profound impact on the structures controlling pit stability. It was not possible during the course to ascertain the connection with the controlling structures and the pit design. This would be valuable to establish for future pit designs.

The course attendees also viewed Boroo's heap leach pads and tailings dam.

A very instructive visit was made to the Darkhan Metallurgical Plant (DMP). At present, they are only processing scrap steel that is used to make reinforcing bars for the construction industry. The plant uses an electric arc furnace and can be efficiently run when electricity prices are favourable, specifically at night.
A new wet plant for beneficiating the ore from Tumurtolgoi is currently under construction.

This mine is in the early stages of development. There will be clay slopes exposed from at least 16 years based on mining 5 mtpa and a stripping ratio of 4:1 (Figure 2). This is an issue that the inspectorate will need to review regularly.

The mine has a nominal head grade of 53% iron, but mining practices reduce the actual grade delivered to 43% due to dilution and waste in the product.

Figure 2 Clay slopes, right side of the photograph, will be exposed for at least 16 years before rehabilitation. Tumurtolgoi iron ore mine

Figure 3 View of the hangingwall of Tumurtolgoi. In the foreground is evidence of the oversize resulting from drilling and blasting 5 m benches with approximately 2.4 m of stemming

The hangingwall has a similar design to Boroo Gold with 45° overall slope angle and batter angle of 63° (Figure 3). The overall slope height will be approximately 200 m. At this stage, they are experiencing little in the way of instability on the hangingwall. However, there is a need to commence gathering geotechnical/structural data on the wall exposure so that the pit can be optimised. The present 5 m mining height (called a flitch in Australia) is leading to significant fragmentation problems. The oversize resulting from the use of 5.5 m long holes (0.5 sub drill assumed) and 2.4 m of stemming has led to large boulders, which have not been fragmented in the upper 2.5 m of the flitch. This will have a profound effect on the project economics.

A visit was also undertaken to view the dry crushing of the ore into fines and coarse sizes.

Conclusion

The course was very well received by the attendees. The ACG was privileged to undertake geotechnical training in such an evolving and interesting mining landscape and looks forward to visiting this beautiful and growing country again. As noted by Qingfeng Zhang, www.dw.de/is-mongolias-mining-boom-causing-ulan-bator-to-run-out-of-water/a-17910293, "Mongolia's economy has been expanding rapidly. After experiencing a GDP growth rate of 17.5 per cent in 2011, the economy grew by 11.7 per cent in 2013, easing from 12.4 per cent in 2012. The massive development of mineral and coal mining has been largely the driving force behind the swift economic rise of the Central Asian nation. Mongolia – nearly the size of Western Europe – sits on a virtual treasure trove of natural resources estimated at around 1.3 trillion USD."

The ACG appreciates the support of key course collaborators: BGR, IM4DC, GASI, Mongolian University of Science, the Australian Government, The University of Western Australia and The University of Queensland, to host this training course in Mongolia.

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Rock mass variable velocity model for improved accuracy in seismic data processing and analysis

by Ian Pinnock, Dr Dave Collins and Zara Hosseini, ESG Solutions, Australia and Canada

Rock mass velocity

The accuracy of seismic data depends on a variety of factors, one of which is the assumed velocity model. A velocity model that does not match the seismic wave propagation velocity, and the path taken from source to sensors, will result in higher errors. The simplest assumption is to use a single velocity and use blast data to determine the optimal velocity and quantify the absolute location accuracy. More complex geologies, like layered geological units, require a model that can account for the different velocities in different layers. Both of these types of models have been used for decades and generally perform well in mines with homogeneous geological units and relatively few stopes. ESG Solutions' Advanced Analysis Group has developed a variable velocity model that can take into account irregular shaped geology and voids resulting in higher accuracy source locations, source parameters, and source mechanisms than would otherwise be obtained using simpler velocity models.

Case study 1 – a stope mine in Canada

Case study 1 is a Canadian mine that uses the backfill mining method. Blasts taken close to the stopes resulted in higher than average errors (Figure 1(a)). It was suspected that the nearby stopes surrounding the blast resulted in longer ray paths that were affecting the location accuracy when using a single velocity model. The location in Figure 1(b) was improved by excluding sensors where the direct ray path passes through the backfilled stopes. This method is not practical for processing all events or blasts as it is very user intensive and time-consuming. This led to the development of a variable 3D velocity model that takes into account the 3D shapes of the stopes and better estimates the fastest path from source to sensor.

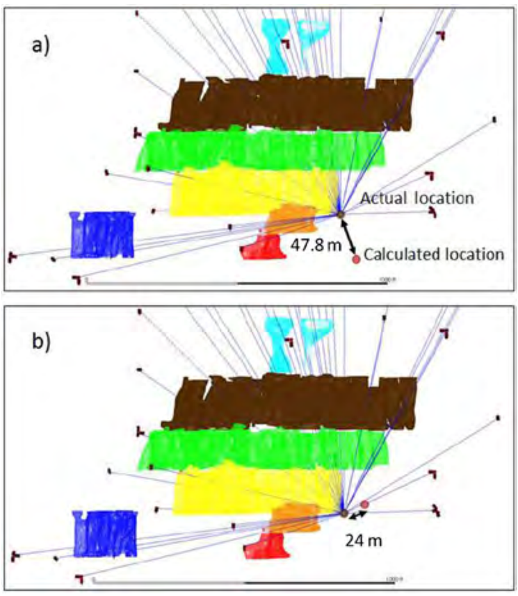

Figure 1 Difference in location accuracy for a single velocity model when (a) all ray traces are used; and (b) when ray traces that pass through stopes are excluded

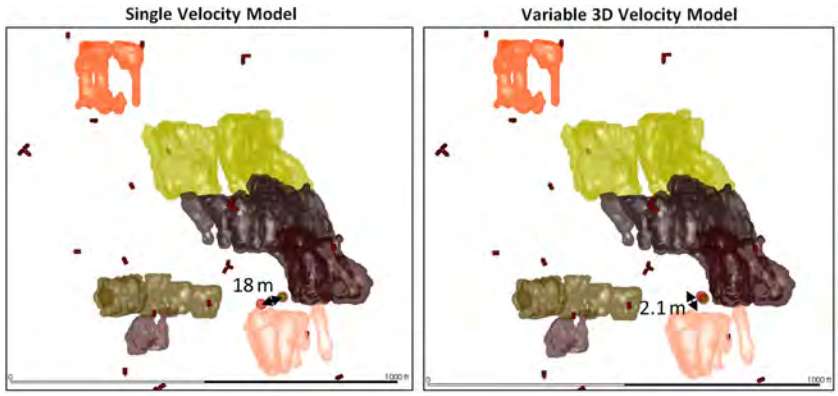

Figure 2 The improvement seen in absolute location error for a blast when using a variable 3D velocity model

The stopes were smoothed to remove unnecessary detail in the velocity model which decreases the processing time with little loss in accuracy. From Figure 2, the location accuracy is improved by approximately nine times with the use of the variable 3D velocity model. Processing of events takes approximately 3-5 times longer than the single velocity model. This equates to a few seconds per event, meaning the model can still be used for real time applications.

Case study 2 – a Canadian block caving operation

Case study 2 is of a caving operation situated in a complex geological system comprised of four irregular 3D units with near vertical boundaries. The cave was incorporated into the velocity model, assuming an air filled void. Figure 3 highlights the difference in travel time for wave propagation through the geological units and around the cave. A single velocity model would be represented by perfect circles propagating outwards. Interestingly, the cave is seen to effect the travel time well beyond the cave profile.

In situations where a single velocity model is assumed, but the seismic wave passes around a void, the residual between the theoretical arrival and actual wave arrival is increased. Figure 4 shows an example of a ray path passing around the cave while Figure 5 highlights the improvement in the residual, as a result of accounting for the cave with a variable 3D velocity model. The red circles in Figure 5 show the theoretical arrival for the same sensor and the same event, comparing a single velocity model and a variable 3D velocity model. A significant improvement in residual is seen in the variable 3D velocity model.

Ten blasts were taken in different locations at the mine. These blasts were used to highlight the difference in absolute location error between the single velocity model and the variable 3D velocity model. A 47% improvement in absolute location error was seen for the ten blasts. It is worth noting that due to access restrictions the blasts could not be placed in a location where the ray paths to the sensors were significantly affected by the cave. As such, the improvement in location accuracy can be mainly attributed to the complex

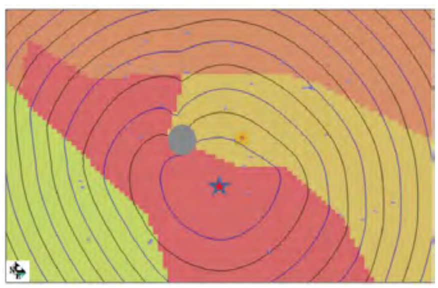

Figure 3 The effect four different geological units have on travel time. The grey circle represents the cave position, the star represents a theoretical event and the iso-lines represent travel time

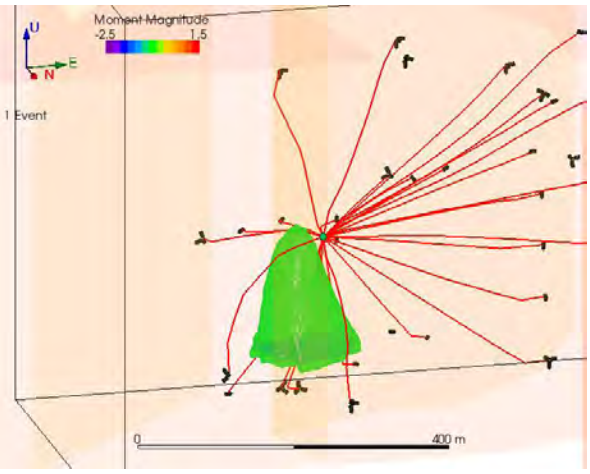

Figure 4 An example of a ray path travelling around the void

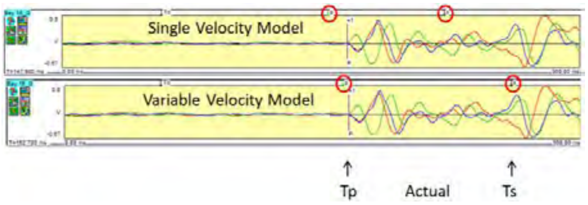

Figure 5 The difference between the residual arrival times for the single and variable 3D velocity model, for the same sensor

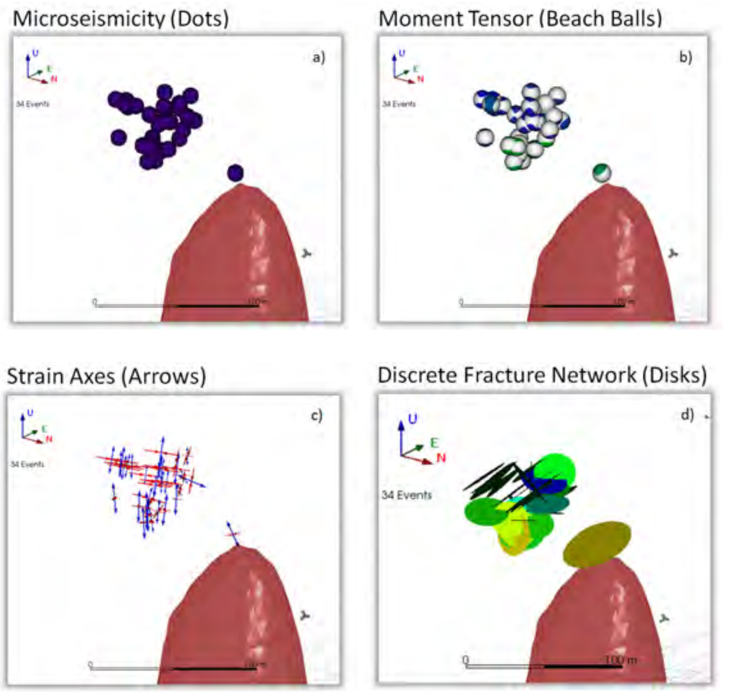

Figure 7 (a) Shows the locations of a seismic event cluster occurring above the cave; (b) represents the mechanism result displayed as beach balls. There are two distinct types of event groups: blue (shear) and green (opening) events; (c) the strain axis for the mechanism solutions; and (d) shows the mechanism results as a discrete fracture network scaled to the event source dimension

geological units. It is expected that for events positioned around the cave, or voids in general, the improvement in location accuracy will be even greater (Figure 2).

Case study 2 – source mechanism analysis

Continuing with case study 2, the variable 3D model was implemented for advanced analyses such as determining source mechanisms. Part of source mechanism determination requires accurately knowing the angle of incidence for the fastest ray path to the sensor. The assumption for the single velocity model is that the fastest ray path goes direct from the event to the sensor; this is not the case where the seismic wave has passed around a void. Figure 6 shows a hypothetical example where the angle of incidence differs by approximately 45° from the straight ray path assumption. This, coupled with the error in location accuracy and source parameters, can have a detrimental impact on the final mechanism result if a single velocity model is used.

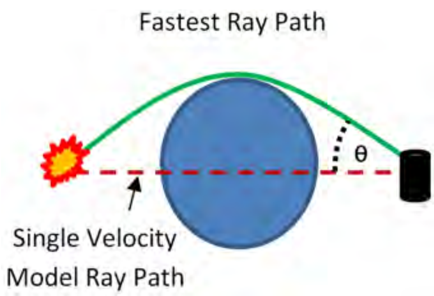

Figure 6 An example of incident angle error when using a single velocity model passing around a void

Figure 7 shows different display options for a cluster of events modelled using the variable 3D velocity model. Figure 7(a) shows event locations. Figure 7(b) overlays the source mechanism determined for each event identifying two distinct clusters of events. The blue cluster represents shear type events, while the green cluster represents tensile type events possibly associated with rockfall into the cave zone. Figure 7(c) shows the strain axes determined in the source mechanism. The strain axes are scaled to the ratio of strain in each direction. The higher shear events generally have similar strain ratios showing equal movements in each direction, as is expected for shearing. The lower cluster has a dominant sub-vertical tensile strain that is expected for opening type events. Figure 7(d) shows the discrete fracture planes of the events. The fracture planes associated with tensile opening are orientated in the dominant sub-vertical strain axis. For shear type events, there are two possible fracture planes. However, for events in a cluster occurring over a short period of time, it can be assumed each event was under similar stress conditions. With this assumption, seismic stress inversion was performed on the source mechanism solutions, which allowed the most likely fracture plane for each event in the cluster to be determined. The majority of the upper shear type events are found to have their dominant axis approximately parallel to the cave profile.

Conclusion

The variable 3D velocity model is shown to provide a significant improvement in location accuracy for seismic events at stope and cave mine operations. For an individual blast, an improvement of approximately nine times was seen in the location error for case study 1, while an average of ten blasts showed a 47% improvement in location accuracy for case study 2. The variable 3D velocity model takes approximately 1 or 2 seconds to run per event, meaning it can be used in real time applications. The variable 3D velocity model can be implemented for advanced analyses such as source mechanism determination, as was performed for case study 2. A discrete fracture network was used to display the source mechanism results. Two distinct groups of events were seen above the cave, including those associated with opening type cracks and shear type events.

Ian Pinnock,
ESG Solutions,
Australia

Hydraulic conveying: slurry, paste and cake transport by piston pumps

Peter Peschken, Putzmeister Solid Pumps GmbH, Germany, explores how pumping system developments are reducing the amount of water needed for the hydraulic transport of solids

Figure 1 Tailings at Bulyanhulu Gold Mine, Tanzania

Figure 2 A KOS 25100 pump installation for fly and bottom ash (Kogan Creek, Australia)

The traditional way to transport liquids and semi liquid material generally uses a lot of water. But nowadays, where water has become a limited resource, this is no longer acceptable. However, the amount of water needed can be easily reduced by selecting the right kind of pumping system.

In searching for a solution to reduce the amount of water needed for the hydraulic transport of solids, Putzmeister Solid Pumps has developed, in the last couple of decades, a pumping system that needs less water for transportation of any kind of material compared to the traditional way of pumping. For more than 30 years double piston pumps have been operating in various industries. They are proven to transport materials which have previously been described as not pumpable. Today, it is considered state-of-the-art to pump high density slurries, paste and cakes safely, economically and environmentally friendly, which results in improved public acceptance.

Material characteristics

Hydraulic driven piston pumps can handle all materials including slurry, high density slurry, paste and cake.

Slurries, if they are not abrasive and if the delivery pressure is low, can be handled by centrifugal pumps. If multi-stage centrifugal pumps are needed and the material is abrasive, the costs for wear and energy and the downtime due to repairs will influence the economy of the project. The material has to be pumped at high speeds through the pipeline to achieve enough turbulence to avoid sedimentation.

High density slurries are often pumped over distances of 5 to 15 km. Depending on the distance, delivery pressures are between 20 and 100 bar. At the German coal mine Walsum, a high density slurry was pumped over a distance of 11 km. This material was fine grained and it could be pumped with low speed laminar through a high pressure pipeline, reducing the wear on the pipeline.

Pastes normally require positive displacement pumps. Paste is a non-Newtonian plastic material which does not settle. It can be pumped at low speeds through the pipeline. At least 30 per cent ultra fine material smaller than 30 µm is needed in the mix to make the material pumpable and to avoid sedimentation in the pipeline.

Paste will produce no bleed water and the slump is higher than 15 cm and lower than 28 cm. If there is no cement or other active material in the paste, it can stay in the pipeline for a certain time without plugging. Due to the high yield stress of a paste, to restart the high pressure, a positive displacement pump is needed. The pumping distances are up to 5 km and the delivery pressures up to 150 bar.

Cake is a very stiff material. For example, sewage sludge with 35 per cent solid content by weight can only be handled by hydraulic driven piston pumps. This material is fed into the pumps by feeding screws to achieve a good filling efficiency of the delivery cylinders. Due to the stiff material, the pressure loss per metre can go up to 2 bar per metre and due to this the pumping distances are short.

Mining applications

In the mining industry, tailings with or without cement are pumped back into the underground mine for stabilisation and environmental reasons. The pump is normally placed above ground to use the full static energy of the shaft line for transport (Figure 4). This material is normally a cemented paste with a slump value of 15 to 23 cm.

For above ground tailings placement, paste is often delivered from a deep cone thickener with a slump value of 25 to

Figure 3 Fly ash hardens within a short time

Figure 4 Plutonic Gold Mine, Western Australia

28 cm. This allows a self-levelling at the deposit with angles of up to 5° in arid areas.

Another application for high density solids pumps is the high rise pumping of liquid, sandy and very dirty mine water at high pressures. Concrete, mortar and shotcrete material is pumped in mines and tunnels with high density solids pumps as well.

Types of pumps

High density solids pumps are hydrostatically operating machines which displace the medium being pumped and thus create a flow. One piston of a double piston pump sucks the material out of a hopper into one delivery cylinder, while the other piston pushes the material simultaneously into the delivery pipe. The following piston pumps are normally used for conveying slurries, pastes and cakes:

- KOS double piston pump with S-transfer tube for coarse grained slurries, pastes and cakes (Figure 2).
- HSP double piston pumps (seat valves) for fine grained slurries, pastes and cakes.
- KOV double piston pump (ball valves) for fine grained slurries.
- EKO single piston pump for cakes and material which is not pumpable.

These machines are driven by hydraulic power packs. These power packs supply the pressurised oil which is necessary to drive the piston pump and to control the valve system. While one piston sucks the paste into the delivery cylinder from the feed hopper, the other piston pushes the material out of the second delivery cylinder into the pipeline via a valve control system. Depending on the pump type, the control system consists of an S-transfer tube, seat valve, ball valve or a gate valve. The delivery cylinder and the hydraulic cylinder are separated by a water box which cools and flushes the delivery cylinder and guarantees that no material will contaminate the hydraulic oil.

Advantages of pumping

Reduced dust potential: compared with dry placement, paste transport in a pipeline generates less dust. The pipeline is a closed system and if fine grained material is transported on belts or trucks, dust formation can occur. Truck transport creates additional dust and dirt, as well as noise and exhaust emissions.

Figure 5 Zhongzhou Aluminium, China

Flexible transport routes: with pipeline transport the topography does not matter. Materials can be pumped several hundred metres upwards, even vertical if required, without any problems. No roads are necessary and the pipeline transport is clean, safe and does not create any dust, dirt, noise or smell. Going around corners, difficult layouts in buildings are easy to handle too. On the deposit, as a final layer, a surface paste crust can be produced, e.g. with cement or fly ash to prevent dust lift-off.

Less workforce and mechanical equipment: dry material has to be transported and levelled on the deposit with graders and dozers. This creates a lot of wear, costs and downtime for these machines. Also a large workforce is needed at the deposit site. A well prepared paste levels itself (Figure 3).

Almost no free water: in arid areas the paste like medium will dry out due to evaporation. No seepage water goes into the groundwater or into the environment. Fresh, clean water is very valuable and a reduced fresh water take up lessens the costs.

Reduced danger of dam failures: when a media is transported as a paste and then allowed to dry out like at Bulyanhulu, a gold mine in Tanzania, a dam is not necessary (Figure 1).

The material builds up a new landscape and is stable. This helps progressive reclamation and an improved closure of the deposit area. In areas where more rainfall is expected, the paste can be mixed with cement and fly ash to achieve the requested stability. This method is utilised by Zhongzhou Aluminium in China (Figure 5).

Peter Peschken,
Putzmeister Solid Pumps GmbH,
Germany

PASTE 2015

5–7 May 2015
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ACG AUSTRALIAN CENTRE FOR GEOMECHANICS
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This influential and respected annual event continues to provide a valuable forum for international tailings and mine waste practitioners to explore, learn and share advances in paste and thickened tailings and, increasingly important, water conservation and environmental stewardship. www.paste2015.com.

KEYNOTE SPEAKERS

Dr Gordon McPhail
SLR Consulting Australasia Pty Ltd
"The high density thickened discharge tailings storage facility at Osborne Mine – a case history from inception to closure"

Professor Peter J. Scales
The University of Melbourne
"Thickener modelling – from laboratory experiments to full scale prediction of what comes out the bottom, and how fast"

KEY DATES

Sunday | 3 May 2015	Monday | 4 May 2015	Tuesday | 5 May 2015	Wednesday | 6 May 2015	Thursday | 7 May 2015	Friday | 8 May 2015
Rheology Fundamentals for Slurries and Pastes Short Course	An Introduction to the Design of High Density Tailings Disposal Pipelines Short Course	Paste 2015 Seminar			Site Visit: Chinova Resources Pty Ltd Osborne Mine
	Mine Backfill System Design, Operation and Management Short Course				

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Paste and Thickened Tailings – A Guide (Third Edition)

New guide in development!

Following on from the first edition released in 2002 and the second in 2006, the ACG is producing the third edition of "Paste and Thickened Tailings – A Guide". The revised edition will include the significant advances made in the field since 2006 and will include a number of new chapters. For more information and guide sponsorship opportunities email marketing-acg@uwa.edu.au.

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The use of numerical models for ground support systems optimisation: applications, methods and challenges

by Gordon Sweby, Winthrop Professors Phil Dight and Yves Potvin, Australian Centre for Geomechanics

Introduction

Numerical modelling provides an attractive design option for geomechanical engineers as it provides a means to analyse rock mass behaviour and support interaction from engineering 'first-principles', rather than having to rely on precedent, experience and/or empirical methods. This article examines the numerical tools available to engineers, the scenarios in which they are applicable and the critical input parameters required for meaningful analysis.

In order to design a ground support system for an underground mine, (comprising typically rockbolts, mesh and/or fibrecrete), the engineer must first establish the potential failure mechanism, which is dependent on the rock mass and stress conditions. Figure 1 (Potvin 2013) gives an outline of the range of different failure mechanisms which could be encountered. Table 1 lists examples of the range of numerical codes available for ground support design, given a particular mechanism.

Having established an applicable numerical code, the design engineer must determine the input parameters required to simulate the rock mass, loading cycles and ground support systems. These may vary in complexity depending on the code selected, but usually comprise of the following, or subsets thereof:

- Stress state – at the loading stage under consideration.
- Rock mass material model.
- Rock mass fabric.
- Ground support geometrical and mechanical properties.
- Numerical model control parameters.

Case study

To demonstrate the application and variability in outcomes of key input parameters, a simple two-dimensional numerical modelling code, Phase² (Rocscience Inc. 2014), is used as illustration. By examining the rockbolt and liner loads in response to varying key inputs, an appreciation of the variability in potential outcomes can be gained.

A simple example typical of that encountered in Western Australia is shown in Figure 2. Base case input parameters are listed in Table 2.

Material model

The material model selected (Generalised Hoek–Brown) (Hoek et al. 2002) has been adapted in accordance with the methodology described in Diederichs (2007), whereby peak and residual strength parameters are selected such that strain-softening behaviour occurs close to the excavation perimeter whilst under increasing confinement, strain-hardening occurs.

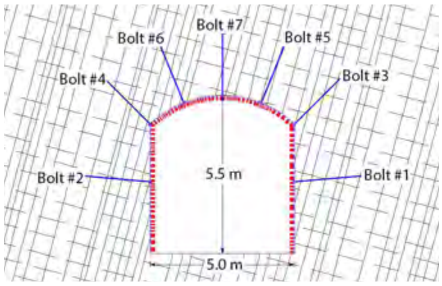

Figure 2 5 x 5.5 m arched tunnel in jointed rock mass, supported by rockbolts (Split-Sets) and liner (shotcrete)

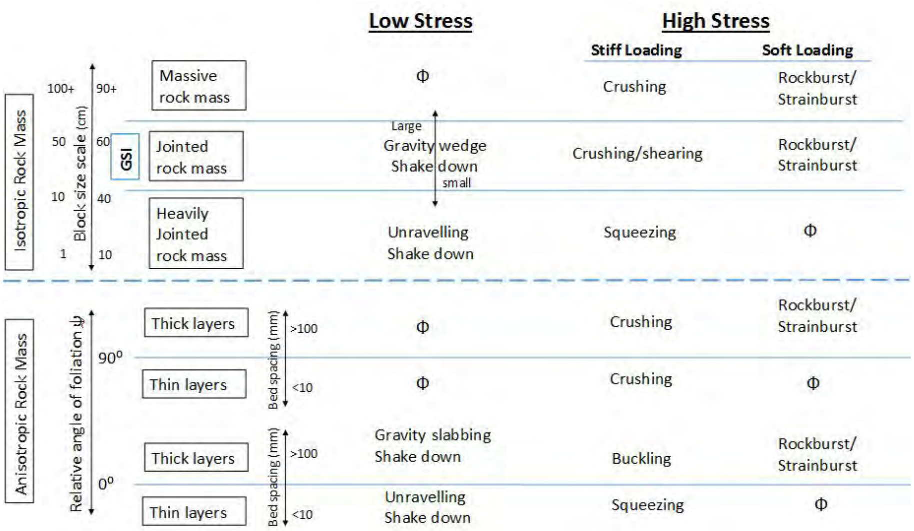

Figure 1 Potential failure mechanisms. The symbol Φ denotes that failure is unlikely

In situ stress

The stress state used in the base case analysis is as follows:

σ_1 – 30 MPa (horizontal).

σ_2 –15 MPa (horizontal, out of plane).

σ_3 – 15 MPa (vertical).

By varying the in situ stress components within realistic bounds (+/- 10%), the model sensitivity in terms of rockbolt and liner load can be determined.

Table 1 Examples of numerical codes applicable per failure mechanism category

		Low Stress	High Stress	
			Stiff Loading	Soft Loading
Isotropic Rock Mass	Massive	N/A	FLAC2D/3D, Phase², ABAQUS	FLAC2D/3D (Dynamic), ABAQUS
	Jointed	UDEC/3DEC, UNWEDGE, Phase², JBLOCK	FLAC2D/3D, Phase², ABAQUS	FLAC2D/3D (Dynamic), ABAQUS
	Heavily Jointed	FLAC2D/3D, Phase², ABAQUS	FLAC2D/3D, Phase², ABAQUS	N/A
Anisotropic Rock Mass	Thick Layers	N/A	UDEC/3DEC, Phase², ABAQUS	FLAC2D/3D (Dynamic), ABAQUS
	Thin Layers	FLAC2D/3D	FLAC2D/3D	N/A

Table 2 Key input parameters

Material Model	**Generalised Hoek–Brown**
Young's modulus	60 GPa
Poisson's ratio	0.3
Density	2.7 t/m^3
Uniaxial compressive strength	95 MPa
Dilation	0.66
Hoek–Brown m (peak)	1
Hoek–Brown m (residual)	6
Hoek–Brown s (peak)	0.033
Hoek–Brown s (residual)	0.0001
Hoek–Brown a (peak)	0.25
Hoek–Brown a (residual)	0.75
Joint model	Barton–Bandis
Joint compressive strength	90 MPa
Joint roughness coefficient	9
Residual friction angle	28
Joint normal stiffness	600,000 MPa
Joint shear stiffness	60,000 MPa
Rockbolt model	Elastic
Rockbolt modulus	200 GPa
Rockbolt shear stiffness	100 MN/m
Rockbolt bond strength	0.17 MN/m
Liner model	Elastic
Liner modulus	30 GPa
Liner Poisson's ratio	0.2
Liner thickness	0.1 m

Elastic properties

The Young's modulus and Poisson's ratio of the intact rock blocks between the joints were varied as follows:

Young's modulus – 55-65 GPa.

Poisson's ratio – 0.27-0.3.

The sensitivity of rockbolt load is shown in Figure 3. The sidewall bolts (1 and 2) show the most variability, +/- 5 t in each instance.

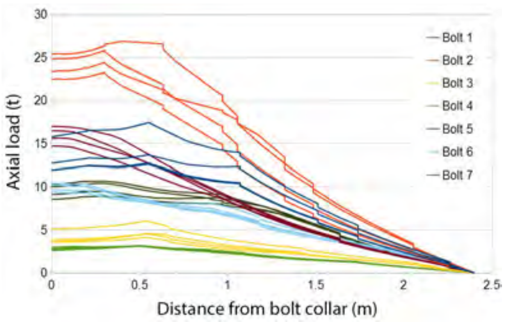

Figure 3 Sensitivity of rockbolt load to varying elastic properties

Intact rock strength

The uniaxial compressive strength of the intact rock blocks varied between 90 and 100 MPa (+/- 5 MPa). With the exception of sidewall bolt 2, the variability is minimal. The variation in bolt 2 is ~6 t.

Joint properties

Joint properties varied as shown in Table 3. Note that in the case of joint shear stiffness, the parameter varied between 60 GPa, being the software developer's recommendation (Rockscience Inc. 2014) and an upper bound, being the value based on elastic equivalence between normal and shear stiffness, i.e. assuming identical Young's modulus and Poisson's ratio for the joint 'infill'.

Table 3 Joint parameter values used in sensitivity analysis

	Upper Bound	**Lower Bound**
Joint shear stiffness	230 GPa	60 GPa
Joint roughness coefficient (Barton & Choubey 1977)	11	7
Post-peak behaviour	Perfectly plastic	Residual strength

Joint network geometry

The sensitivity of bolt loads on joint network geometry was investigated by re-randomising the base-case, using identical statistical parameters for joint spacing, length and persistence. A variation on the style of jointing was also incorporated by applying a 'cross-jointed' model available in Phase[2].

The impact of varying joint pattern on rockbolt load is shown in Figures 4 and 5, for bolts 2 and 5. The range varies from ~15 t in the case of bolt 2, to ~6 t for bolt 5.

Combined sensitivity

Combining all the analysed parameters into a single sensitivity plot enables a preliminary assessment of the overall range in expected outcomes, in terms of rockbolt load.

The results for rockbolts 2 and 5 (being the bolts showing most variability in the previous analyses) are shown in Figures 6 and 7. The maximum variations in axial load for bolts 2 and 5 are ~12 and 5 t respectively.

Similarly, the combined sensitivity of the liner radial and axial loads is shown in Figure 8. The radial (shear) loads vary between +25 and -25 t, whilst the axial loads range from 0 to 400 t.

Design criteria

In order to assess a ground support design for acceptability, the engineer must decide on some acceptance criteria, for example:

- Factor of Safety.
- Probability of failure.
- Residual support capacity.

This can be problematic when using numerical models, due to the complexity in the failure mechanisms. Global capacity versus demand approaches can be meaningless in instances where bolts in the pattern are loaded differently, depending on their position around the perimeter: which bolt is selected for the capacity versus demand calculation?

Comparisons between different scenarios are often helpful in making broad assessments of ground support effectiveness, but are not really sufficient for engineering design purposes.

Discussion

For the simple example of rockbolt and liner loading chosen, it has been demonstrated that a significant range in potential outcomes are possible, based on the natural variability (known and/or unknown) of the rock materials and discontinuities.

The challenge facing the geotechnical engineer is basing a design on this level of uncertainty. Ideally a full probabilistic analysis or response surface analysis (RSM) would be carried out, varying all of the key parameters and generating a sufficient number of outcomes to be statistically justifiable. However, the time and computational effort required would

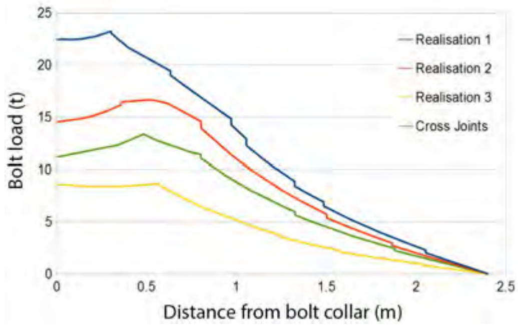

Figure 4 Sensitivity of rockbolt (2) load to variation in joint network geometry

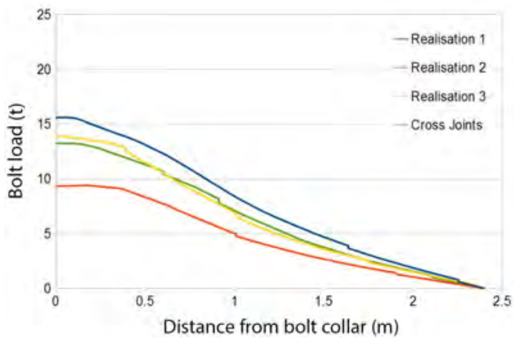

Figure 5 Sensitivity of rockbolt (5) load to variation in joint network geometry

put this approach beyond the means of practitioners.

Simple sensitivity analyses do provide the means for judgment calls, e.g:

- Design for the worst-possible scenario. Base the rockbolt capacity on the maximum load profile generated; or
- Design for an average condition (most probable outcome).

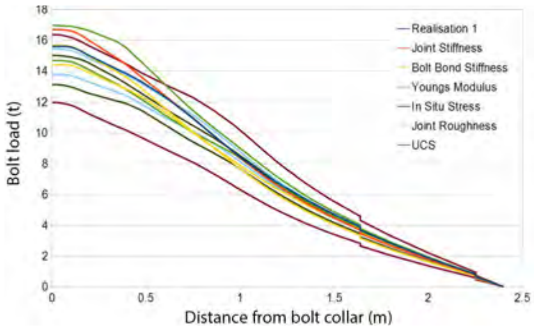

Figure 6 Combined sensitivity for all parameters analysed, but excluding variations in joint geometry – rockbolt 4

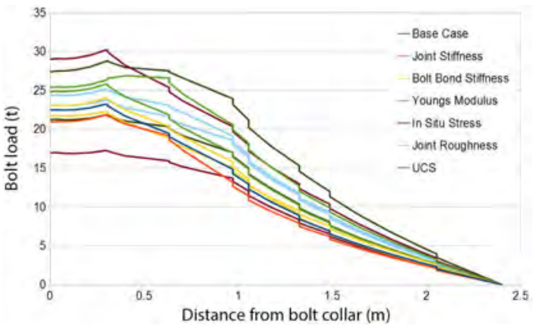

Figure 7 Combined sensitivity for all parameters analysed, but excluding variations in joint geometry – rockbolt 2

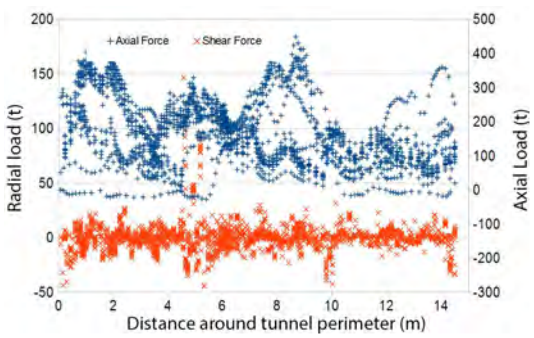

Figure 8 Combined sensitivity of liner axial and radial loads, for all parameters analysed

Table 4 Relative importance of the parameters analysed (listed in order of sensitivity)

	Parameter	Variation	Sensitivity (t)
1	Uniaxial compressive strength	+/- 5%	7.0
2	In situ stress	+/- 10%	13.0
3	Young's modulus	+/- 8%	2.7
4	Joint roughness coefficient	+/- 22%	1.4
5	Rockbolt bond stiffness	+/- 20%	1.8
6	Poisson's ratio	+/- 11%	1.0

When embarking on ground support design using numerical models, it is clear that appropriate effort should be directed towards reducing uncertainty in the input parameters. For the example chosen and parameters analysed, their order of importance is as listed in Table 4.

However, the impact of known unknowns such as joint network and opening geometry may overshadow the importance of other parameters. Thus it is unavoidable that an appropriate number of joint network simulations be carried out.

Conclusions

The challenges in optimising ground support by the application of numerical models are significant, due to the natural variability in the input parameters which greatly affect the outcomes.

Furthermore, numerical models alone do not provide the engineer with an absolute means of assessing the appropriateness of ground support designs in terms of safety and serviceability.

The introduction of probabilistic methods, in combination with numerical modelling, may provide a means to incorporate natural variability in modelling parameters into the design, whilst simultaneously allowing the engineer to make rational decisions on excavation serviceability, based on industry accepted criteria.

Acknowledgements

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- Jennmar Australia
- Fero Strata Systems Pty Ltd
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Please click here for full article and references.

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ACG integrated ground support design project – GSSO

by Gordon Sweby, Australian Centre for Geomechanics

The ACG's Ground Support Systems Optimisation Project (GSSO) has been under way since November 2013. The main deliverable of GSSO is the development of a ground support guide for industry practitioners. Three main sub-project focus areas are: 1) probabilistic approach to ground support systems design; 2) integrated support system design; and 3) benchmarking and case studies.

The integrated support system design sub-project is focussed on numerical modelling and instrumentation, with the main outcome being a section in the guide. The objectives are to develop a methodology based on currently available numerical modelling tools, to design ground support systems, and account for the interaction between the rock mass, reinforcement and surface support. Existing design methods either ignore surface support or look at reinforcement and surface support separately.

The sub-project aims are:

- To implement a comprehensive underground instrumentation experiment at a sponsor mine site where significant deformation is anticipated.
- To model the ground support interaction using several applicable commercial numerical model codes.
- To assess the capability and accuracy of the models.
- To develop a methodology for the use of a commercial numerical model at a mine site for support design.

Work has commenced in preparation for the instrumented trial site implementation to be undertaken in late 2014. Two underground sites have been kindly provided by George Fisher Mine; roughly 1,000 m below surface in a relatively new area of the mine where stoping is at an early stage of development. The locations of the trial sites in relation to the mining voids are shown in Figure 1. Stoping past the instrumentation sites will create a stress front with measurable rock mass deformation which will be recorded by the installed instruments.

Instruments to be used at each

The sustained success of ground support in mitigating rockfalls has generated enormous benefits to the mining industry

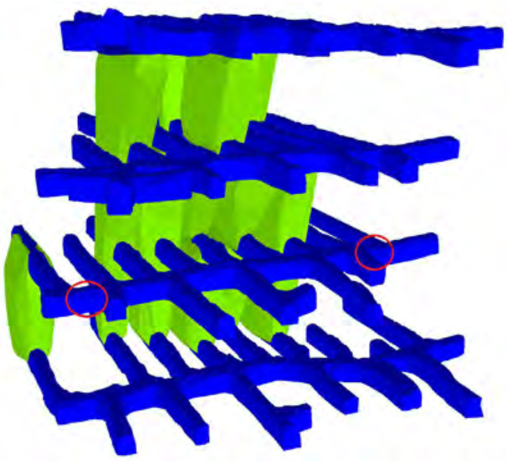

Figure 1 Development and stoping layout showing locations of the two instrumentation sites

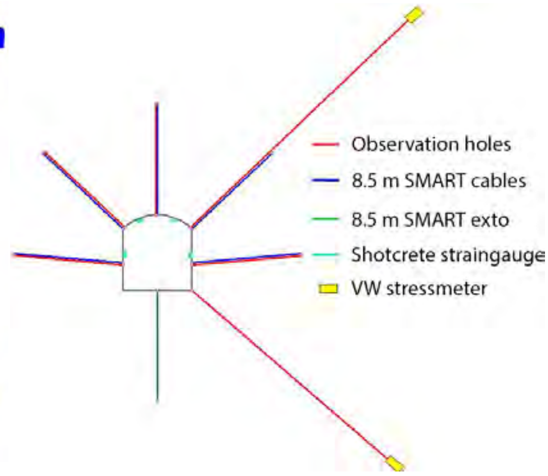

Figure 2 Design schematic showing arrangement of the various instruments

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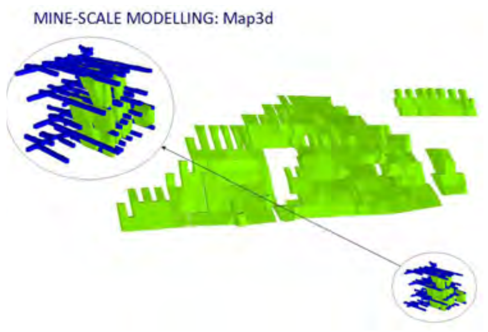

Figure 3 Map3D mine-wide model which includes upper stoping blocks and detailed stoping and development in the trial area

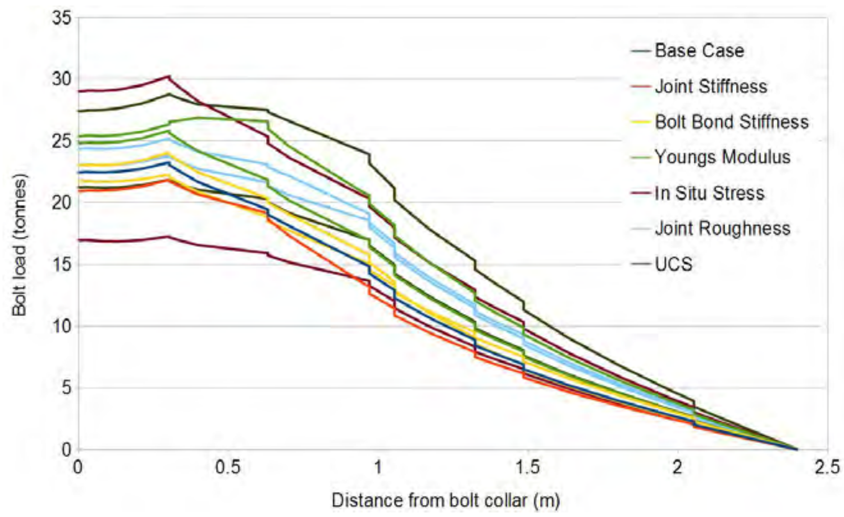

Figure 4 Potential rockbolt load profiles obtained by varying key input parameters within natural ranges of variability

site consist of SMART© cables and extensometers, vibrating wire stress meters, shotcrete strain gauges and closure pins. A tape extensometer will be used to take manual measurements of sidewall closure and a borehole camera will be used to record the depth of fracturing/damage in observation holes. Photogrammetry using the ADAM Technology system will also be employed to develop the full closure profile at each site.

The instrumentation design is shown in Figure 2. The main purpose of the instrumentation is to determine the deformation characteristics of the ground support, which can then be used directly to compare with model predicted loads and deformations, thereby providing the means to calibrate numerical models.

Preliminary assessment of numerical modelling tools has focussed on Phase[2] (Rocscience), FLAC3D (Itasca) and Map3D (Mine Modelling). An example of the Map3D model geometry is given in Figure 3. Sensitivity studies with Phase[2] have shown that there is a wide range of potential outcomes in terms of ground support response, when considering input parameter ranges rather than specific values. An example of the range in rockbolt load is shown in Figure 4.

Once the installations are complete, the sites will be monitored for 12 months while stoping activity takes place. Data will be analysed and processed into a format which can be used for model calibration.

For more information about this project please visit www.gsso.com.au.

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WA Ground Control Group Update

The WAGCG meetings are held as a workshop-style forum for technical exchange, sharing knowledge and experience, mentoring for site geotechnical engineers, and networking. Three meetings are held each year, relying on industry sponsors for venues and catering.

A WAGCG meeting was held in Perth in July 2014. It was attended by about 40 geotechnical professionals from mine sites, mining companies, the Department of Mines and Petroleum (DMP), consultancies, and suppliers. The topic for this meeting was 'Communication and the ground control management plan (GCMP)'. The GCMP outlines the management of geotechnical risks on a mine site. It is a site-specific document, and will typically include information on the geology, the geotechnical model, roles and responsibilities, rock-related hazards, and ground support standards. This is usually owned and updated by the geotechnical department on site. Therefore this 'requirement', in essence, set the theme for the last meeting.

One of the presentations on the day was by the DMP. They discussed the role of the GCMP and the expectations for the content of the document. It dealt with items such as the legal requirements and the use during an investigation following a rock-related incident on site.

In light of the discussions during the day, there was general agreement that the GCMP should:

- Be concise – only include information regarding ground control management and include additional information such as ground support standards and detailed geology as appendices.
- Be accurate – the document should only reflect what is actually being done on site and not aspirations of what wants to be done.
- Reference the site's risk control system.

The final meeting for 2014 was held at The University of Western Australia, 1 December 2014 and was attended by about 50 geotechnical professionals. The workshop topic was, 'Ground support optimisation and rehabilitation'.

WAGCG meetings are open to all members and anyone in the mining industry interested to attend.

For more information please contact Ruth Stephenson, WAGCG secretary, via rstephenson@amcconsultants.com.

WAGCG
Ground Control Group

ISEG-10: a forum for discussion and presentation of research into the geochemical aspects of environmental management and mine closure

writes Associate Professor Ron Watkins, EIGG, Centre for Forensic Science, The University of Western Australia

Figures 1 and 2 Artisanal gold mining in Mali, West Africa

The Tenth International Symposium on Environmental Geochemistry (ISEG-10), will be held in Perth, Western Australia from 19–21 January 2016.

ISEG symposia are organised jointly by the International Association of Geochemistry (IAGC), the International Medical Geology Association (IMGA), and the Society of Environmental Geochemistry and Health (SEGH). They are held every three years and have grown to be the pre-eminent international forum for environmental geochemical research. Previous symposia have been held in Europe – most recently Aviero, Portugal (2012); America – Vail, Colorado 1997; Africa – Cape Town, South Africa 2000; and Asia – Beijing, China 2006. In January 2016, the symposium will take place for the first time in Australasia.

Environmental geochemistry may be defined as the study of the variation in the chemical composition of the Earth's surface that results from natural processes and anthropogenic (human-made) influences

While representing the growing environmental geochemistry discipline, the symposium series is cross-disciplinary, and ISEG-10 will be of interest to a broad spectrum of scientists, professionals and those having an appreciation of the environment or involvement in its day-to-day management. It aims to bring together people with diverse areas of expertise that are integral to an understanding of the complex chemical interactions occurring in the environment. These include, but are not limited to: geochemistry, ecology and biology; atmospheric and environmental science and management; soil and aquatic sciences; and medicine and population health.

Over recent decades, environmental management has moved from being an often peripheral consideration of the mining industry to a core requirement of economical and sustainable mine operation and closure. Accordingly, there is a growing need within the industry for personnel skilled in environmental management. It is also acknowledged that elevating the degree of knowledge of the workings of the environment broadly amongst mining personnel has very beneficial results for the mine site. While effects upon the environment from mining are diverse, e.g. aesthetic, noise, vibration and instability, and particulates, it is the potential to mobilise and release metals and other geochemical substances that is overwhelmingly the most intractable of potential impacts. As in the most evident case of acid mine drainage, inappropriate mining procedures can result in pollution legacies lasting many tens of thousands of years. In the case of metalliferous mining, the aim is the liberation of metals from their ores in which they are robustly held, into their commercially most useful, but environmentally most bioavailable, metallic forms. The copper metal that was obtained by simple burning of copper ores by the first metal miners some 12,000 years ago, exists today in our environment in the form of metal or simple copper compounds accessible to plants and animals and thus influential in human health. Only by understanding the behaviour and fate of such metal substances in the environment – water, soils, atmosphere and biosphere – can we safely prosper in an ever more metal-laden world.

The mining industry, in developing metal resources, is at the forefront of environmental geochemistry. However, experience amongst mining personnel in the subject is often little developed, and there is great scope for increased knowledge both within the industry and amongst regulators and environmental managers and consultants outside, faced

Figure 3 Stream of AMD in the neighbourhood of Sudbury Copper Mine, Ontario

with not only modern mining, but the legacy of hundreds of thousands of old, abandoned mine sites.

As an administrative hub of the mining and petroleum industries, both for WA and offshore in Africa and Asia, Perth provides an excellent opportunity for members of the mining fraternity to take part in ISEG-10. Mining exploration, operation and closure is increasingly governed by environmental regulations. Social acceptance of mining and the sustainability of resource industries requires knowledge of the impacts of individual chemicals on the environment broadly, and human health in particular. There is a need for detailed understanding of the distribution, behaviour and fate of chemical substances at, and around, the mine site. These may include metals and metalloids released from mineralisation, process chemicals, and natural components of the environment mobilised by acidic and alkaline waters.

As the Chairperson of the ISEG-10 Organising Committee, I wish to enthusiastically invite members of the mining industry, mining consultants and regulators to attend the Perth symposium. I am confident that the broad range of scientific presentations will be of interest, and your attendance and contribution will provide a valuable component of the inter-disciplinary nature of the proceedings. A particular theme within the symposium will be the mining environment, from the large scale mining, such as performed in WA, to the widespread problems of small scale, artisanal mining in the developing world.

While a most beautiful city, Perth provides pertinent examples of modern environmental restraints. A doubling of the population in the past two decades and expansion to become one of the world's most extensive urban areas has been driven largely by the mining boom and places stress on natural resources and the environment. Situated on the world's most arid continent, the quality and quantity of Perth's water resources are both critical and sensitive to current climate change. Numerous examples of environmental change, on both geological and historical time-scales are to be seen on the planned field excursions.

ISEG-10 provides opportunity for you to showcase your environmental initiatives, best practices and research, while gaining a broader insight into the potential environmental and health impacts of metals and other chemical substances associated with the mine site.

Ron Watkins,
EIGG, Centre for Forensic Science,
The University of Western Australia, Australia

Deep Mining 2014 Conference report

by Maddie Adams, Australian Centre for Geomechanics

Delegates dined underground amongst the rocks in the Vale Cavern, Science North

The Seventh International Conference on Deep and High Stress Mining (Deep Mining 2014), hosted by the ACG, took place in Sudbury, Canada, 16–18 September 2014. Deep Mining 2014 was the first international geotechnical mining event in Canada hosted by the ACG and was highly successful, with over 300 mining industry professionals attending the conference.

Deep Mining 2014 comprised a three-day focussed technical programme that included 61 presentations and brought together leading visionaries, strategists and experts from local and global industries to discuss and document their experience of deep mining. The objective of this series of international seminars is to promote discussion and documentation of the latest technologies and practices of mining in deep and high stress environments.

Deep Mining 2014 attracted significant international interest and the conference chair for Deep Mining 2014, Associate Professor Marty Hudyma, Laurentian University and the ACG team were pleased to welcome delegates from over 120 companies from countries including: Australia, Belgium, Canada, Chile, Colombia, Finland, Germany, Ireland, Japan, Norway, Poland, P.R. China, South Africa, Sweden, Switzerland, UK and USA.

The ACG has enjoyed a long and proud association with the Canadian mining industry since our inception in 1992, and collaborated with the University of Toronto and the University of the Witwatersrand to host Deep Mining 2014 in Canada. Sudbury was a particularly relevant location for the Deep Mining Conference, with 12 currently active underground mines within 50 km of the conference venue, six of which are operating at depths greater than 1,500 m. Over 50 delegates attended from the city of Greater Sudbury, and over 180 conference attendees were from Canada.

Deep Mining 2014 followed on from previous events held in Perth, 2012; Santiago, 2010; Perth, 2007; Quebec City, 2006; Johannesburg, 2004; and Perth, 2002. The past events often had a strong focus on ground conditions, ground support and mining-induced seismicity, which were discussed at this conference, with the addition of strong technical contributions in the areas of mine productivity, mine planning and ventilation, along with several deep mine case studies.

Deep Mining 2014 opened with an address from Samantha Espley, Vale Canada Ltd., Canada; *Learning from each other*. Following this, David Counter, Glencore Canada Corp., presented the first keynote address; *Kidd Mine – dealing with the issues of deep and high stress mining – past, present, and future*. Keynote presentations opened the second and third days of the conference; Ray Durrheim, University of the Witwatersrand and CSIR, South Africa delivered his address titled, *Has research and development contributed to improvements in safety and profitability of deep South African mines?*; and Stephen Hardcastle, Canmet Natural Resources Canada, Canada, discussed, *The continuing challenges to provide adequate ventilation and a safe environment in deep mines.*

The ACG is appreciative of the support received from the Deep Mining 2014 sponsors, namely the major sponsor ArmorPIPE® Technologies and industry sponsors SRK Consulting (Canada) Inc. and Vale Canada Ltd.

Alongside Deep Mining 2014, delegates had access to a number of associated events prior and post conference. A Practical Rock Mechanics in Underground Mines Course took place from 13–14 September 2014, presented by Drs Will Bawden and Kathy Kalenchuk, Mine Design Engineering, Canada.

An Applications of Seismic Monitoring in Mines Course, also held on the 13 September, was presented by Drs Dmitriy Malovichko and Daryl Rebuli, Institute of Mine Seismology, Australia and South Africa.

Getting the Most from a Seismic System Workshop was presented by Dr Dave Collins, Dr Yuzo Toya, Tony Butler and Alexander Mataseje, ESG Solutions, Canada on 14 September.

The ACG's Ground Support Subjected to Dynamic Loading Workshop was held on 15 September. The workshop was facilitated by Winthrop Professors Yves Potvin and Phil Dight.

Following the conference on 19 September was the Practical Calibration of Numerical Models for Meaningful Predictions of Ground Behaviour Course, presented by Drs Bawden and Kalenchuk.

Two site visits took place on the 19 September 2014: Glencore Company's NiRim South Mine of Sudbury Integrated Nickel Operations, and Creighton Mine, operated by Vale Canada Ltd.

The proceedings of the Seventh International Conference on Deep and High Stress Mining, edited by Professors Marty Hudyma and Yves Potvin, provide documentation on the latest technologies and practices of mining in deep and high stress environments. These proceedings feature 62 technical papers, and are accompanied by a CD of colour figures from the publication. Deep Mining 2014 proceedings and individual papers are available to purchase; visit www.acg.uwa.edu.au/shop.

ACG event schedule*

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

*The ACG event schedule is subject to change.

2015

2D/3D Slope Stability Analysis for Open Pit Mines Short Course	5–6 March 2015 | Perth, Australia
Emerging Technologies in Waste Management Seminar Series	9–13 March 2015 | Perth, Australia
Open Pit Slope Stability and Ground Support Seminar – *metalliferous and coal mining*	14–16 April 2015 | Brisbane, Australia
Rheology Fundamentals for Slurries and Pastes Short Course	3 May 2015 | Cairns, Australia
An Introduction to the Design of High Density Tailings Disposal Pipelines Short Course	4 May 2015 | Cairns, Australia
Mine Backfill System Design, Operation and Management Short Course	4 May 2015 | Cairns, Australia
Paste 2015 Seminar www.paste2015.com	5–7 May 2015 | Cairns, Australia
Using Remote Sensing and Space Borne InSAR to Monitor Mine Sites Seminar	31 May 2015 | Vancouver, Canada
Introduction to Environmental Geochemistry of Mine Site Pollution Short Course	29–30 July 2015 | Perth, Australia
InSAR and Emerging Technologies Workshop	7 September 2015 | Sydney, Australia
Radar and Monitoring Workshop	8 September 2015 | Sydney, Australia
Ninth International Symposium on Field Measurements in Geomechanics www.fmgm2015.com	9–11 September 2015 | Sydney, Australia
International Seminar Design Methods in Underground Mining www.dmug2015.com	17–19 November 2015 | Perth, Australia
Practical Application of Numerical Methods in Underground Mine Design Course	20 November 2015 | Perth, Australia
Basic Principles of Acid Mine Drainage Short Course	30 November 2015 | Perth, Australia
Long Term Mine Waste Landform Management in Regional and Remote Communities Seminar	1–2 December 2015 | Perth, Australia
Advanced Mine Drainage Short Course – *geochemistry, assessment, control and remediation*	3 December 2015 | Perth, Australia

2016

10th International Symposium on Environmental Geochemistry www.iseg10.com	19–21 January 2016 | Perth, Australia
First Asia Pacific Slope Stability in Mining Conference www.apssim2016.com	2016 | Australia

www.acg.uwa.edu.au/events/current

The ACG team wishes you and your family a

Merry Christmas and a Happy New Year

Our office will be closed from Monday, 22 December 2014, reopening on Monday, 5 January 2015.

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Design – A Strategic Issue

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A set of six design principles for rock engineering was developed by Bieniawski: design objectives; minimum uncertainty; simplicity of design components; state of the art practice; optimization; and constructability. These principles translate into a ten step design process. Although this methodology was developed for rock engineering, it is applicable to any design process, feasibility study, etc. Diligent use of such a process will ensure that a defensible design or evaluation has been carried out. Recently a “strategic conversation” process has been identified by Ilbury and Sunter that includes the following ten steps: scope; players; rules of the game; key uncertainties; scenarios; SWOT analysis; options; decisions; measurable outcomes; and meaning of winning. A comparison of these steps with those of the design process shows a remarkable correlation. This is perhaps not surprising since engineering design is a strategic up-front issue, and front end loading in a project is critical to achieve the expected project performance. Based on the close correlation between the strategic conversation and engineering design processes, a circular design process, rather than a linear process, is proposed. The “circle of design” better reflects the importance of review and monitoring in the two phases of successful design and implementation – defining the design, and executing the design.

1 INTRODUCTION

Engineering design usually involves the development of a “solution” (the design) to a known “problem”. There is no unique solution, and different engineers will produce different solutions – some solutions will work better than others, but all solutions should “work”. The reason that solutions are not unique is probably because of the very wide scope of the issues involved in design. In reviewing the engineering design process, Bieniawski (1991, 1992) quotes the definition of engineering design from ABET (1987):

“Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet a stated objective. Among fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing and evaluation. In addition, sociological, economic, aesthetic, legal and ethical considerations need to be included in the design process.”

It is unlikely that anyone would dispute that engineering design is a strategic issue. A satisfactory design is fundamental to the expected performance of the engineering structure. For example, satisfactory design of a mine shaft involves many aspects including siting, shaft pillar if appropriate, rock support, lining, steelwork, hoist design, etc. If any one of these aspects is unsatisfactory, the mine is unlikely to perform to its required production capacity.

The key input to design is required in the early stages of planning a project. This is when the key thinking and most important decision making take place. These provide the groundwork in the definition of the requirements for the design. It is well accepted that front end loading of projects is essential if they are to meet their desired performance objectives. Front end loading, and therefore also design, are part of the strategy.

2 THE DESIGN PROCESS AND THE STRATEGIC PLANNING PROCESS

Satisfactory engineering design involves a design process. According to Hill (1983), as discussed by Bieniawski (1988), the design process is "a sequence of events within which the design develops logically, and a process that provides a work plan in the planning of a design programme". A defined process can serve as a checklist of activities that must be carried out to ensure that a satisfactory design results. The defined process or methodology can be considered as a form of quality control, which ensures that all aspects that *should be* taken into account in the design, *are* taken into account.

According to Ilbury and Sunter (2005) "strategy is about where you are going and tactics is how you get there", and they introduce a process which they term a strategic conversation.

The design and strategic conversation processes will be dealt with in the following sections.

2.1 Design Principles in Rock Engineering

Bieniawski (1991, 1992) dealt specifically with engineering design in the rock mechanics field. He defined a series of design principles that encompass a design methodology. Although Bieniawski developed these for rock engineering, they are applicable in principle to any form of engineering or investigation. The design principles defined by Bieniawski are summarized below.

2.1.1 Design principle 1: Clarity of design objectives and functional requirements

A statement of the "problem" and a statement of the design objectives, taking account of any constraints that are present, to satisfy this problem, is essential to any design process. These statements clarify the design thinking at the outset. If this is not done, different engineers may interpret the problem differently and hence may design solutions for different problems.

2.1.2 Design principle 2: Minimum uncertainty of geological conditions

The rock masses in which mining takes place are very variable, which is true of any natural material. Rock engineering and mine design therefore take place in an environment of considerable uncertainty. In mining, which is almost always tightly cost controlled, there is usually an aversion to spending money on geotechnical investigations, with the result that geological conditions are often unknown or, at best, little known. In many mines, designs are carried out with inadequate knowledge of the in situ stresses, the rock material strengths and deformation properties, and the rock mass behavioural conditions.

The minimization of uncertainty will provide an environment in which more confident design can be carried out, and hence will reduce risk. The remaining uncertainty must be taken into account in the design method, for example, by using a probability of failure approach.

2.1.3 Design principle 3: Simplicity of design components

Designers often rush into the carrying out of complicated analyses using sophisticated analysis methods. These methods often require input data, knowledge of which is very uncertain. There is therefore a mismatch between the sophistication of the method of analysis and the lack of sophistication of the input data available. The use of sophisticated analysis methods often leads to the false confidence that a good design analysis has been carried out. Bieniawski indicates that, in terms of the Simplicity Principle, a design should be broken down into a series of simpler components. It is suggested here that the principle should be viewed in addition in its broadest context – simpler designs, design methods and design analyses are easier to understand and therefore likely to be more robust. Where there is a simple way, it is to be preferred to a complex or sophisticated way, provided that it addresses the design requirements.

An important step in rock engineering design is to develop a geotechnical model. This may be conceptual, but it is important to be able to describe the likely behaviour of the rock mass and the possible mechanisms of deformation and failure. Only once this has been done can appropriate design (failure) criteria be decided on, design limits be defined, required factors of safety or probabilities of failure be defined, a design model (or models) be developed, and appropriate design analysis methods be decided upon. It is to be noted that these steps are carried out before any analyses are conducted. This will ensure that the design is appropriate, and as simple as possible.

2.1.4 Design principle 4: State of the art practice

The implication of this principle is that up to date concepts, analyses and methods must be used whenever they are appropriate.

2.1.5 Design principle 5: Optimization

Risk integrally involves numerous factors including safety, cost, productivity, seismicity, water, labour, etc. Therefore, to minimize risk, designs must be optimized. In addition, since conditions in which mining is taking place (economic, political, mineral price, depth, seismicity, geology, etc) change over time, it is likely that designs will need to be optimized again when conditions change. An optimized design will result from the evaluation of the output from alternative designs. Monitoring during the progress of mining will provide data that may facilitate design optimization.

2.1.6 *Design principle 6: Constructibility*

If the design cannot be implemented safely and efficiently it does not satisfy this principle and therefore is also not optimized. It will be necessary to review the design and repeat, either partially or completely, the design methodology.

2.2 Design Methodology or Process

The design methodology presented by Bieniawski (1991, 1992), corresponding with the above six design principles, is summarized in the ten steps given below.

Step 1: Statement of the problem (performance objectives) [Design principle 1]

Step 2: Functional requirements and constraints (design variable and design issues) [Design principle 1]

Step 3: Collection of information (site characterization, rock properties, groundwater, in situ stresses) [Design principle 2]

Step 4: Concept formulation (geotechnical model) [Design principle 3]

Step 5: Analysis of solution components (analytical, numerical, empirical, observational methods) [Design principles 3 and 4]

Step 6: Synthesis and specifications for alternative solutions (shapes, sizes, locations, orientations of excavations) [Design principles 3 and 4]

Step 7: Evaluation (performance assessment) [Design principle 5]

Step 8: Optimization (performance assessment) [Design principle 5]

Step 9: Recommendation [Design principle 6]

Step 10: Implementation (efficient excavation, and monitoring) [Design principle 6]

This methodology represents a thorough design process and can be used as a checklist to ensure that a robust and defensible design has been carried out.

There is often a misconception that analysis is design, and many sophisticated analyses, with little underlying validity in terms of input data and failure criteria, are often carried out. Analysis is science, whereas design is engineering. It may be observed from the above steps that “analysis”, which involves analytical (including numerical), empirical and observational methods, occupies only one step of the overall design methodology, and is bridged by Design principles 3 and 4. Analysis is only a tool to obtain answers to the problem that has been posed. If the input information is inadequate, and the concept or geotechnical model (including the interpretation of mechanisms of behaviour and choice of appropriate failure or design criteria) is incorrectly formulated, the answers obtained from the analysis may be scientifically correct, but will be wrong with regard to a valid design. That is, the sophisticated analysis has provided results for the wrong problem. This illustrates that the other steps in the design methodology are in fact much more important than the analysis step – they are fundamental to a successful design, whereas the analysis simply follows from these other steps.

Independent review during the design process provides a very important control on the quality of the design being carried out. Such an activity should be a formal one that could take place at various stages, depending on the magnitude of the design project. For a large project, the formal review would typically take place at regular time intervals, such as twice a year; for smaller projects, the review could be done at appropriate stages rather than on a regular time basis. The aim of the review is to ensure, independently, that the design is robust and that the design objectives are being addressed. If any shortcoming is identified in the design, it will be necessary to loop back to an earlier step in the process and reassess the design.

Monitoring is an extremely important aspect of design. It could range from being purely visual to the use of sophisticated instrumentation. One of the main aims of such monitoring should be to check whether the mechanism of behaviour of the designed structure or opening is as expected and whether the design criteria used were appropriate, ie to determine that the design is valid. If the behaviour and/or criteria are not as expected then it will be necessary to loop back to an earlier step in the process and reassess the design. It may even be necessary to carry out a completely new design. The sooner that monitoring information or data can be obtained the better, since costly errors and consequences will then have the best chance of being avoided.

2.3 Strategic Planning Process and Discussion

Ilbury and Sunter (2005) have recently published a book on strategic planning “Games foxes play – planning for extraordinary times”. In this book they describe a strategic planning process that they term a “strategic conversation”. They propose the following ten step process in their “strategic conversation”.

Step 1: Scope of the game

Step 2: The players

Step 3: Rules of the game

Step 4: Key uncertainties

Step 5: Scenarios

Step 6: SWOT analysis

Step 7: Options

Step 8: Decisions

Step 9: Measurable outcomes

Step 10: The meaning of winning

What is remarkable about this process is its uncanny correspondence with Bieniawski's engineering design process. A comparison of the two processes is summarized in Table 1 below.

Table 1 Comparison of design and strategic conversation processes

Design Process	**Strategic conversation process**
Statement of the problem	Scope
Requirements and constraints	Players Rules of the game
Collection of information (minimization of uncertainty)	Key uncertainties
Concept formulation	Scenarios
Design analysis	SWOT analysis
Alternatives	Options
Evaluation Optimisation	Decisions
Recommendation	Measurable outcomes
Implementation (construction, excavation)	Meaning of winning

Since design is a strategic issue, the correspondence is perhaps not surprising. However, such direct correspondence has not been observed with other strategic planning approaches.

Ilbury and Sunter (2005) consider that "circles of conversation" are most effective, since they avoid the linear approach commonly adopted in strategic planning sessions in which dominant individuals may drive the process in the direction that they favour - "When the strategic conversation is circular, it flows like a current through the heads of all the people sitting around the table, creating its own field of alignment." Their conversation model is expressed in the form of a circular chart, shown in Figure 1 below.

Figure 1 The conversation model (Ilbury and Sunter, 2005; Chart 7)

After viewing this circular process approach, it is considered that the engineering design process should similarly and logically be represented as a circular process. As indicated above, review and monitoring are important inputs to the design process, which can result in looping back to an earlier step in the process – this looping back would form the "spokes" of the wheel in a circular process. Again, the similarity with the strategic conversation process is remarkable - Ilbury and Sunter (2005) state, "… the direction of the process is circular, i.e. a conclusion reached later on in the conversation can lead to a review of earlier material". Therefore, the final step of the engineering design process, which is the implementation (excavation and construction) step and includes review and monitoring, should be logically positioned at the centre of the "circle of design".

As shown in Figure 1, the strategic conversation process is divided into two phases: **defining the game** (the real strategic part) and **playing the game** (the implementation or more tactical part), with five steps of the process in each phase. Similarly, the engineering design process can be divided into two phases: **defining the design** (the very important front end loading part), and **executing the design** (the implementation of the design at various levels of detail). In this case, the first phase will contain four steps and the second six steps, as shown in Figure 2. The first phase, "defining the design", represents the extremely important front end loading phase of projects. Front end loading determines, to a very great extent, whether a project will be successful or not in returning the performance expected, on time and budget.

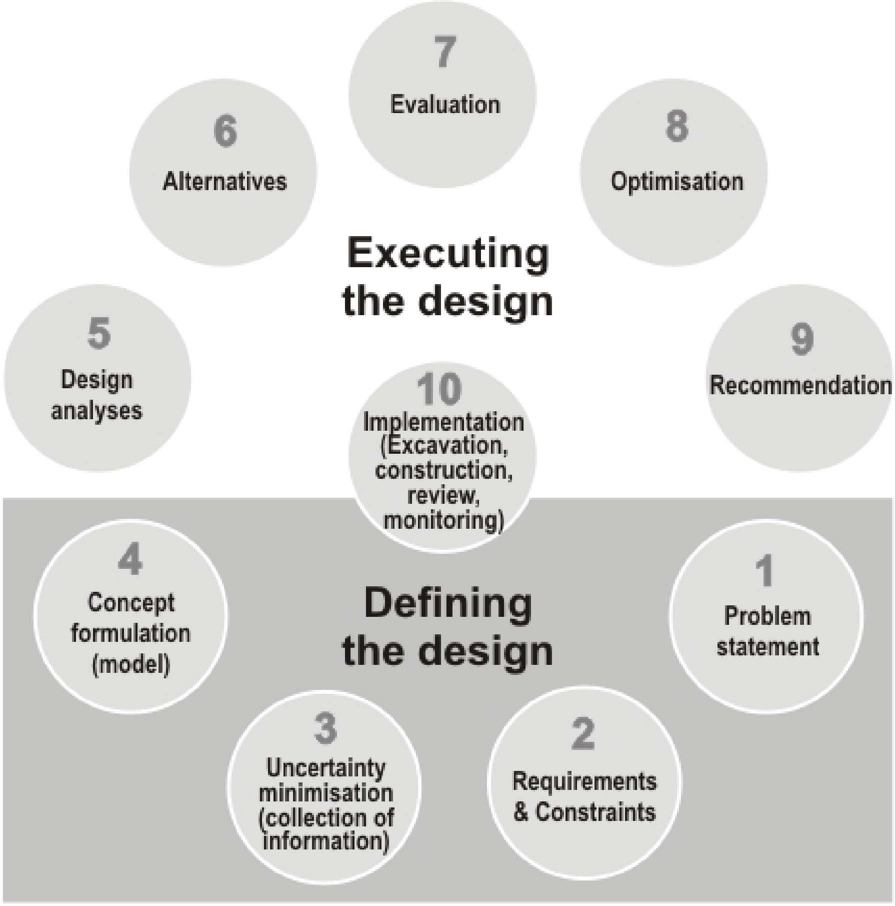

Figure 2 The engineering circle of design

The strategic conversation approach allows issues for potential action (IPA's) to be noted and addressed at an appropriate time during the process (Ilbury and Sunter, 2005). Similarly in engineering design, design IPA's arise, and these can be addressed much more easily if the thinking in the design process is circular, with the review and monitoring function centred at the hub of the circle of design.

3 STRATEGIC AND DESIGN CONSIDERATIONS FOR VERTICAL PIT MINING

As a small scale example of some strategic conversation and design considerations, the unique case of vertical pit mining is considered in this section.

Redford and Terbrugge (2000) describe the mining of a small, shallow orebody at Inyala Mine in Zimbabwe by means of a vertical pit. This project is appropriate to use as an example in this paper since it was the first time that this mining method had been used (therefore requiring strategic considerations) and there were critical design aspects involved (therefore requiring the application of a thorough design process).

Vertical pit mining is applicable for the mining of relatively small orebodies with vertical geometries, such as small diamond pipes. It avoids a large amount of waste stripping, and removal of ore and transporting of equipment and materials is by means of a crane or other device – at Inyala Mine a Blondin cable hoist was used.

Redford and Terbrugge (2000) describe the project as follows: "Anglo American Corporation Services Limited (AAC), acting on behalf of Zimbabwe Alloys Limited (Zimalloys), called for tenders for conventional open pit mining by contractors of the Inyala Mine "Airfield Block" ……. The pit was designed … on geotechnical information available at the time …. sidewall slopes adopted were 58^o in the …. gneiss rock footwall, and 45^o in the …. siliceous serpentinite conditions elsewhere. ….

"The pit operations were planned to exploit two chromitite ore lenses, each approximately 30m long by 9m wide, with a waste middling of some 10m, at an apparent dip of 80^o. Pit production comprised 155 000t, with 2 500 000 bcm waste …

"In parallel with the conforming bid preparation, an alternative proposal was developed and priced, adopting the vertical pit principle. Based on the geotechnical information provided, the proposal envisaged an oval shaft, with plan dimensions of 41m and 32m…. such a shaft would recover an estimated 147 000t of chromitite ore to a mining depth of 95m, together with a further 25 000t of low-grade material… Shaft sidewalls would be supported by means of a combination of 300kN, 10m long cable anchors, rockbolts, mesh and mesh-reinforced shotcrete….. A budget cost of …$4.8 million was quoted for the alternative, almost half that of the lowest conventional bid submitted."

Additional drilling was subsequently carried out, which showed poorer rock qualities and a greater orebody footprint. Sidewall support costs increased substantially because of the weaker rock mass conditions. The contractor was appointed and the vertical pit was mined successfully to a depth of 78m. The reduction in the price of chromitite ore was the reason that the mine did not progress to the planned depth of 95m.

3.1 Strategic Conversation Approach

In this project, the strategic conversation steps could have been considered as follows.

Step 1: Scope

A small asset to be mined using an appropriate mining method. How does this match with the mining company's stated objectives, policies, etc?

Step 2: Players

Mining companies, contractor, designer, existing miners/employees and dependants, the local population, the broader population, the government. These would include players for, against and neutral.

Step 3: Rules of the game

Safety, environmental acceptability, laws, contracts, economic factors, required return on investment, production and profit targets, etc. These include the normative or moral rules of the game, the descriptive rules and the aspirational rules (Ilbury and Sunter, 2005).

Step 4: Key uncertainties

Orebody definition, chrome price, geotechnical information (particularly in the waste rock), mining method, social, environmental and technical issues, quality control performance, government policies, tax, politics, etc.

Step 5: Scenarios

The mining scenarios are open pit mining, vertical pit mining, underground mining, and no mining.

Step 6: SWOT analysis

A SWOT list, as suggested by Ilbury and Sunter (2005) can be prepared as in the table below. It is probable that many more points could be included in such an analysis.

Table 2 SWOT list

Scenario	**Strengths**	**Weaknesses**	**Opportunities**	**Threats**
Open pit	Established method Understood Flexibility – e.g., production capacity easily increased, pit design can change	High stripping ratio Large surface area affected Limited design options for small pit	"Conventional"	Slope failure Waste stripping increase Increased pit limits Dilution
Vertical pit	Established in civil engineering (basements) Selective mining Reduced area, and environmental effects Perceived lower cost	New mining method Unproven to depth envisaged Limited flexibility – no negative wall angles Limited production capacity	Lower cost Reduced volume of mining Use of civil contractor	Wall collapse Poor quality control Potential loss of mine
Underground mining	Established approach Probably no surface effects	Infrastructure requirements – shaft etc Small orebody	Limited	N/A
No mining	No risks	No use of asset	N/A	N/A

Step 7: Options

From the SWOT analysis, one might choose only two options – open pit mining and vertical pit mining. Underground mining was probably never a significant option.

Step 8: Decisions

The tenders received for conventional open pit mining (Redford and Terbrugge, 2000) showed that conventional open pit mining of the deposit was not economic. There were also additional risk factors, indicated as threats in the SWOT analysis, which could have made the conventional pit even less economic. Vertical pit mining was therefore the only possibility. The decision making process at this stage, on the part of the owner, should normally involve a risk analysis.

Step 9: Measureable outcomes

Milestones, production targets, costs, profit, meeting defined key performance indicators, “satisfaction”.

Step 10: Meaning of winning

All stakeholders satisfied?

Owner: return on investment.

Contractor: technical satisfaction and satisfactory profit.

Designer: design proven, satisfactory income.

Employees and dependants: employment, income, living standards.

Local population: income, environment.

Government: export earnings, tax income, use of national asset.

3.2 Circle of Design Approach

The design process begins once the decision step of the strategic process has been completed. The steps below deal with the geotechnical aspects. There would be similar processes for other aspects such as mining, environmental, etc.

Step 1: Problem statement

Vertical pit mine, depth defined, production rate defined.

Step 2: Requirements and constraints

Walls *must* be stable – critical to safety, but also, if a failure was to occur, it would probably be uneconomic to continue mining. Quality control of blasting and support installation and monitoring of behaviour are critical to successful mining.

Step 3: Uncertainty minimization

Collection of information to enable the following: definition of rock materials present; definition of rock mass properties; definition of rock mass geotechnical zones; definition of strength properties of rock/rock mass.

Step 4: Concept formulation

Geotechnical model incorporating rock mass zones and their expected strength properties, and the expected behaviour and potential failure mechanisms. Concept of support to ensure stability. Influence of three dimensions. Definition of design criteria, e.g. factors of safety, probabilities of failure, acceptable deformations, acceptable extents of failure, etc. Blasting requirements, timing of support installation, sequencing, etc. Monitoring requirements.

Step 5: Design analyses

Analyses of the geotechnical model or models developed in Step 4, considering the range of material/rock mass properties and alternative support geometries/quantities. Prediction of behaviour and expected deformations, and identification of corresponding monitoring requirements. Identification of critical areas from the analysis results and corresponding specific monitoring requirements. Use of alternative analysis methods.

Step 6: Alternatives; and Step 7: Evaluation

Consideration of the alternatives analysed and evaluation of the results. Decision on acceptability of the extent of analyses carried out.

Step 8: Optimisation

Optimisation of the outputs obtained from the design analyses and ranking of chosen alternatives.

Step 9: Recommendation

Decision on method and quantity of support, support installation requirements, quality control requirements, stability monitoring requirements, recording and reporting requirements (blasting, construction, inspections, monitoring) etc.

Step 10: Implementation (review, monitoring)

Excavation and production. Monitoring and reporting are critical.

Note that interim review is necessary at all stages, particularly at steps 3, **4**, 6 and 7, and **9**. Highlighted steps are particularly important. If the performance is not as expected from the design analyses, the design must be reviewed at the earliest possible opportunity, since it is not feasible to install additional or different support at higher levels in the pit walls when the pit bottom has progressed downwards.

The activities identified in the ten steps above were essentially what were carried out during the design process for the Inyala Mine vertical pit, and the project proved to be successful, as described by Redford and Terbrugge (2000).

4 CONCLUSIONS

In this paper the engineering design process developed by Bieniawski (1991, 1992) has been compared with the strategic planning approach described by Ilbury and Sunter (2005). In the latter, the ten steps in the strategic conversation process show remarkable correlation with Bieniawski's logical design process. This is perhaps not surprising since engineering design is a strategic up-front issue, and front end loading in a project is critical to achieve the expected project performance.

Based on the close correlation between the strategic conversation and engineering design processes, a circular design process, rather than a linear process, is proposed. The "circle of design" better reflects the importance of review and monitoring in the two phases of successful design and implementation – defining the design, and executing the design.

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The use of numerical models for Ground Support Systems Optimisation: Applications, Methods and Challenges

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ABSTRACT: One of the main challenges facing geomechanics practitioners is the technical and financial justification of ground support systems at their mines, in order to satisfy management and legislative requirements. Numerical modelling provides an attractive option for support design, due to the highly technical and 'engineered' solutions they provide. This paper examines the various numerical methods available to practitioners, reviews the types of geomechanical environments in which they are applicable and comments on potential pitfalls, risks and variability in outcomes. A case study of the application ground support design in a jointed hard-rock environment, using DFN methodology, is used as illustration.

1. INTRODUCTION

Numerical modelling provides an attractive design option for geomechanical engineers as it provides a means to analyse rock mass behaviour and support interaction from engineering 'first-principles', rather than having to rely on precedent, experience and/or empirical methods. This paper examines the numerical tools available to engineers, the scenarios in which they are applicable and the critical input parameters required for meaningful analysis.

In order to design a ground support system for an underground mining scenario (comprising typically rockbolts, mesh and/or fibrecrete), the engineer must first establish the potential failure mechanism, which is dependent on the rockmass and stress conditions. Figure 1 [1] gives an outline of the range of different failure mechanisms which could be encountered in an underground mining scenario. Table 1 lists examples of the range of numerical codes available for ground support design given a particular mechanism.

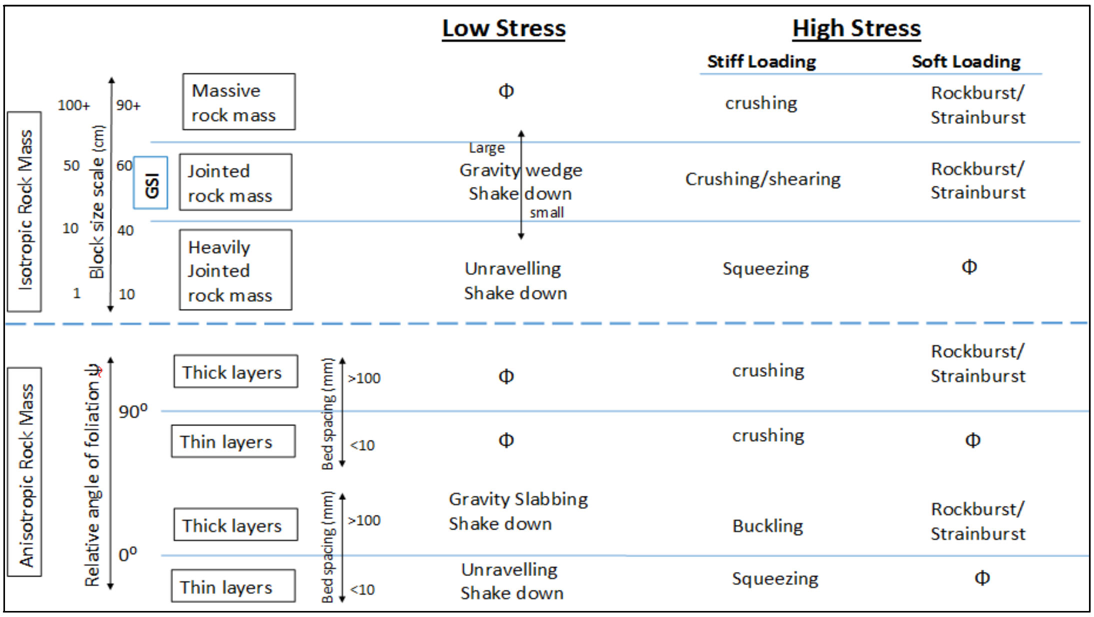

Figure 1. Potential failure mechanisms. The symbol Φ denotes that failure is unlikely.

Table 1. Examples of numerical codes applicable per failure mechanism category

		Low Stress	High Stress	
			Stiff Loading	**Soft Loading**
Isotropic Rockmass	**Massive**	N/A	FLAC2D/3D, PHASE2, ABAQUS	FLAC2D/3D (Dynamic), ABAQUS
	Jointed	UDEC/3DEC, UNWEDGE, PHASE2, JBLOCK	FLAC2D/3D, PHASE2, ABAQUS	FLAC2D/3D (Dynamic), ABAQUS
	Heavily Jointed	FLAC2D/3D, PHASE2, ABAQUS	FLAC2D/3D, PHASE2, ABAQUS	N/A
Anisotropic Rockmass	**Thick Layers**	N/A	UDEC/3DEC, PHASE2, ABAQUS	FLAC2D/3D (Dynamic), ABAQUS
	Thin Layers	FLAC2D/3D	FLAC2D/3D	N/A

Having established an applicable numerical code, the design engineer must determine the input parameters required to simulate the rockmass, loading cycles and ground support systems. These may vary in complexity depending on the code selected, but usually comprises the following, or subsets thereof;

- Stress State – at the loading stage under consideration
- Rockmass material model
- Rockmass fabric
- Ground Support geometrical and mechanical properties
- Numerical model control parameters

2. CASE STUDY

To demonstrate the application and variability in outcomes, of key input parameters, a simple two-dimensional numerical modelling code: Phase2 [2] will be used as illustration. By examining the rockbolt and liner loads in response to varying key inputs, an appreciation of the variability in potential outcomes can be gained.

A simple example typical of that encountered in Western Australia is shown in Figure 2. Base case input parameters are listed in Table 2.

3. Material Model

The material model selected (Generalised Hoek-Brown)[3] has been adapted in accordance with the methodology described in Diederichs [4],whereby peak and residual strength parameters are selected such that strain-softening behaviour occurs close to the excavation perimeter whilst under increasing confinement (i.e. further from the excavation perimeter), strain-hardening occurs.

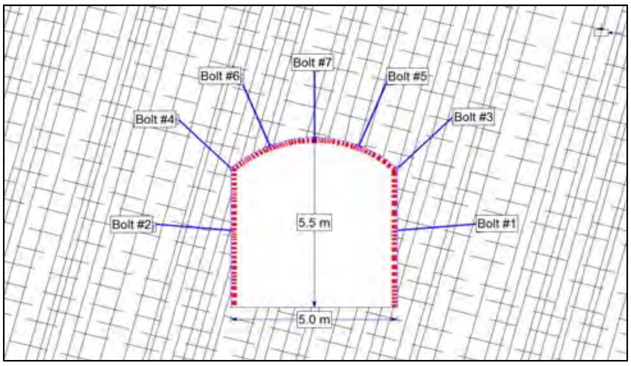

Figure 2. 5 x 5.5m arched tunnel in jointed rockmass, supported by rockbolts (Split-Sets) and liner (shotcrete).

The parameters used are as given in Table 2.

4. In situ Stress

The stress state used in the base case analysis is as follows;

σ1 - 30MPa (horizontal)
σ2 - 15MPa (horizontal, out of plane)
σ3 - 15MPa (vertical)

By varying the in situ stress components within realistic bounds (+/-10%) the model sensitivity in terms of rockbolt and liner load can be determined, as shown in Figure 3. For each bolt, an upper and lower bound is shown.

The largest range in variability occurs in sidewall bolt 2: ~12 tonnes. Bolt 5 in the back of the excavation indicates a variation of ~5 tonnes.

Table 2. Key Input Parameters

Material Model	:	Generalised Hoek-Brown
Young's Modulus	:	60GPa
Poisson's ratio	:	0.3
Density	:	2.7 t/m3
Uniaxial Compressive Strength	:	95MPa
Dilation	:	0.66
Hoek-Brown m (peak)	:	1
Hoek-Brown m (residual)	:	6
Hoek-Brown s (peak)	:	0.033
Hoek-Brown s (residual)	:	0.0001
Hoek-Brown a (peak)	:	0.25
Hoek-Brown a (residual)	:	0.75
Joint Model	**:**	**Barton-Bandis**
Joint Compressive Strength	:	90MPa
Joint Roughness Coefficient	:	9
Residual Friction Angle	:	28
Joint Normal Stiffness	:	600000MPa
Joint Shear Stiffness	:	60000MPa
Rockbolt Model	**:**	**Elastic**
Rockbolt Modulus	:	200GPa
Rockbolt Shear Stiffness	:	100MN/m
Rockbolt Bond Strength	:	0.17MN/m
Liner Model	**:**	**Elastic**
Liner Modulus	:	30GPa
Liner Poisson's ratio	:	0.2
Liner thickness	:	0.1m

5. *Elastic Properties*

The Young's Modulus and Poisson's ratio of the intact rock blocks between the joints were varied as follows:

Young's Modulus - 55 – 65 GPa
Poisson's Ratio - 0.27 – 0.3

The sensitivity of rockbolt load is shown in Figure 4. The sidewall bolts (1 and 2) show the most variability, +/- 5 tonnes in each instance.

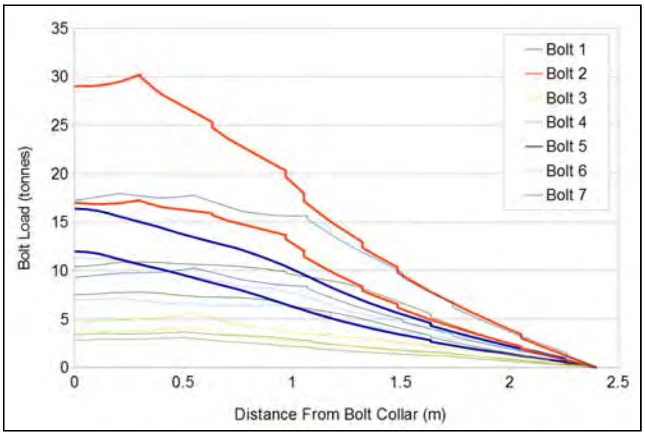

Figure 3. Sensitivity of rockbolt load to varying in situ stress condition.

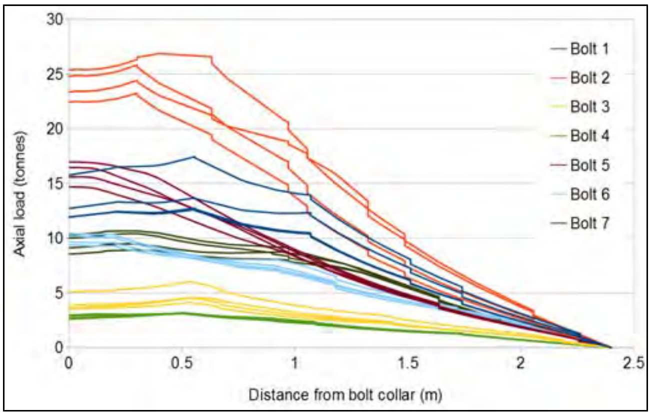

Figure 4. Sensitivity of rockbolt load to varying elastic properties.

6. *Intact Rock Strength*

The uniaxial compressive strength of the intact rock blocks was varied between 90 and 100 MPa (+/- 5MPa) and the impact on rockbolt load is shown in Figure 5. With the exception of sidewall bolt 2, the variability is minimal. The variation in bolt 2 is ~6 tonnes.

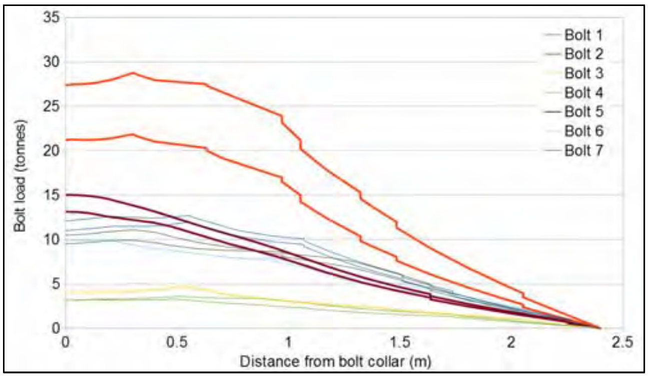

Figure 5. Sensitivity of rockbolt load to uniaxial compressive strength.

7. *Joint Properties*

Joint properties were varied as shown in Table 3. Note that in the case of joint shear stiffness, the parameter was varied between 60GPa, being the software developer's recommendation [2] and an upper bound, being the value based on elastic equivalence between normal and shear stiffness (i.e. assuming identical Young's modulus and poisson's ratio for the joint 'infill')

Table 3. Joint parameter values used in sensitivity analysis

	Upper bound	Lower Bound
Joint Shear Stiffness	230 GPa	60 GPa
Joint Roughness Coefficient [5]	11	7
Post-Peak Behaviour	Perfectly Plastic	Residual Strength

With reference to Figure 6, bolts 2 (~4 tonnes) and 5 (~3 tonnes) show the greatest sensitivity to variation in the given inputs.

8. Joint Network Geometry

The sensitivity of bolt loads on joint network geometry was investigated by re-randomising the base-case, using identical statistical parameters for joint spacing, length and persistence. A variation on the style of jointing was also incorporated by applying a 'cross-jointed' model available in Phase2.

The joint patterns generated are shown in Figure 7. The impact of varying joint pattern on rockbolt load is shown in Figures 8 and 9, for bolts 2 and 5. The range varies from ~15 tonnes in the case of bolt 2, to ~6 tonnes for bolt 5.

9. Combined Sensitivity

Combining all the analysed parameters into a single sensitivity plot enables a preliminary assessment of the overall range in expected outcomes, in terms of rockbolt load (Note: this is not a probabilistic analysis).

The results for rockbolts 2 and 5 (being the bolts showing most variability in the previous analyses) are shown in Figures 10 and 11 respectively. The maximum variations in axial load for bolts 2 and 5 are ~12 tonne and 5 tonne respectively.

(Note: the variations due to changes in joint network geometry are not included in these figures).

Similarly, the combined sensitivity of the liner radial and axial loads is shown in Figure 12. The radial (shear) loads vary between +25 tonne and -25 tonne, whilst the axial loads range from 0 to 400 tonne.

10. Design Criteria

In order to assess a ground support design for acceptability, the engineer must decide on some acceptance criteria, for example;

- Factor of safety
- Probability of failure
- Residual support capacity

This can be problematic when using numerical models, due to the complexity in the failure mechanisms. Global capacity vs demand approaches can be meaningless in instances where, as in this example, bolts in the pattern are loaded differently depending on their position around the perimeter: which bolt is selected for the capacity v demand calculation?

Comparisons between different scenarios is often helpful in making broad assessments of ground support effectiveness but are not really sufficient for engineering design purposes. For example, in Figures 13 and 14 the yielded zones and displacements around the tunnel are compared, for an unsupported vs supported case. Less yield and displacement is clearly evident in the supported case, however the engineer still needs to make an assessment of whether the supported case is actually adequate to provide a serviceable excavation.

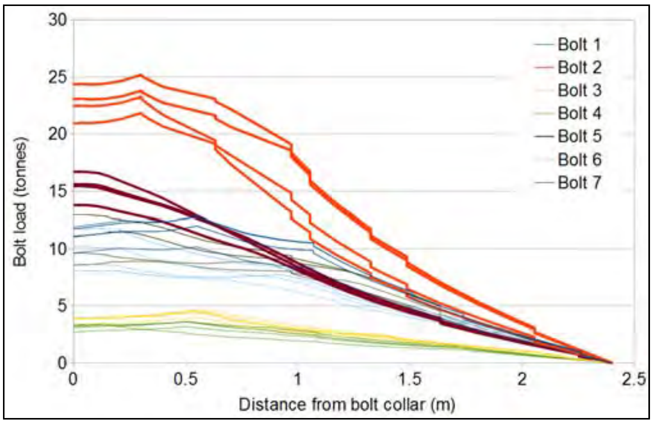

Figure 6. Sensitivity of rockbolt load to joint properties (shear stiffness, roughness and residual strength).

Similarly a comparison between a bolts-only case and a liner-only case (Figures 15 and 16) can provide insight as to which option is more effective (in this case, the liner) but cannot provide the engineer with quantitative guidance on excavation serviceability.

11. DISCUSSION

For the simple example of rockbolt and liner loading chosen, it has been demonstrated that a significant range in potential outcomes are possible, based on the natural variability (known and/or unknown) of the rock materials and discontinuities.

The challenge facing the geotechnical engineer is basing a design on this level of uncertainty. Ideally a full probabilistic analysis or response surface analysis (RSM) would be carried out, varying all of the key parameters and generating a sufficient number of outcomes to be statistically justifiable. However, the time and computational effort required would put this approach beyond the means of practitioners.

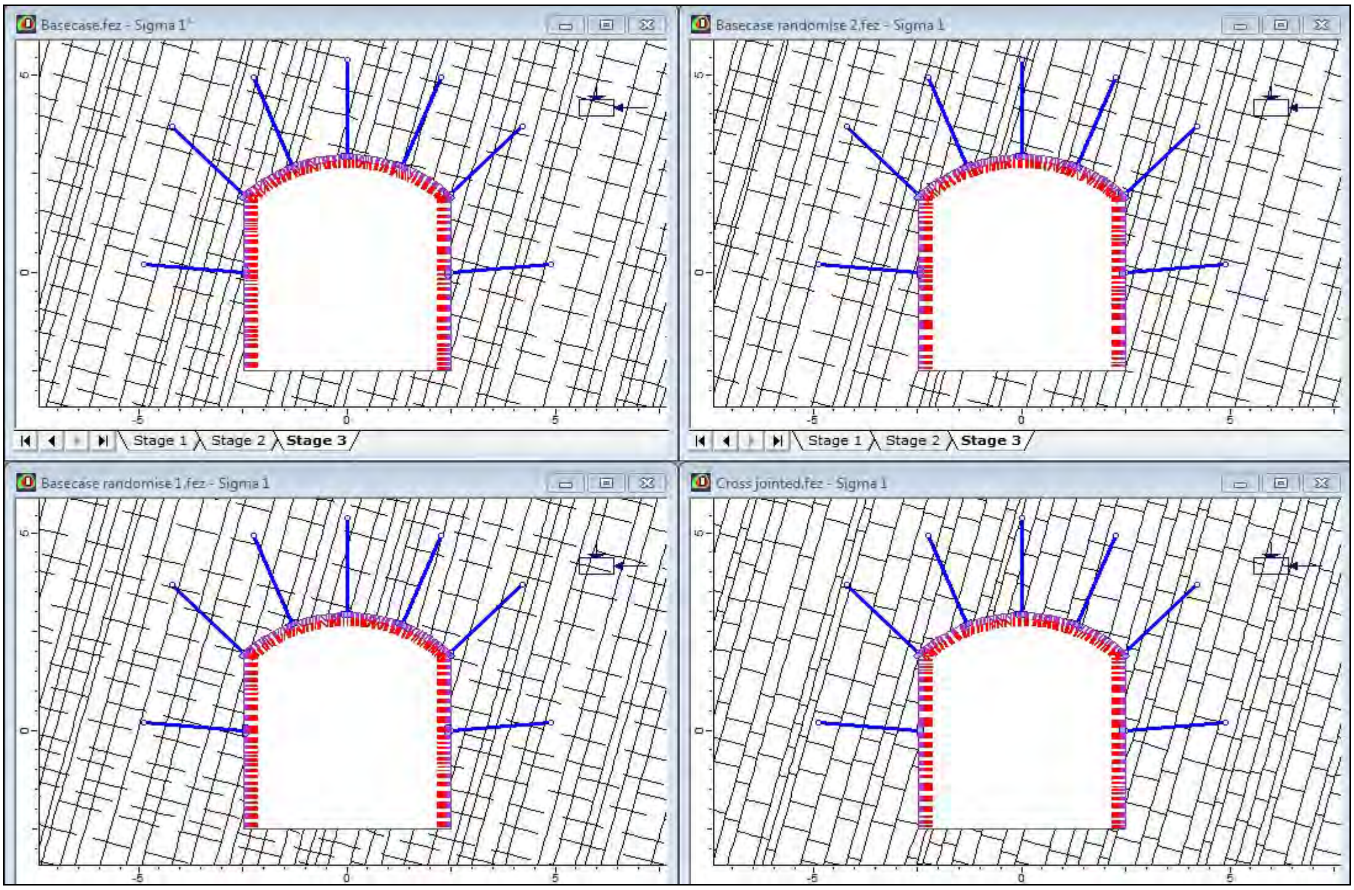

Figure 7. Variations in joint pattern produced by re-randomising statistical distributions of key parameters (spacing, persistence and length). A cross-jointed model is also shown.

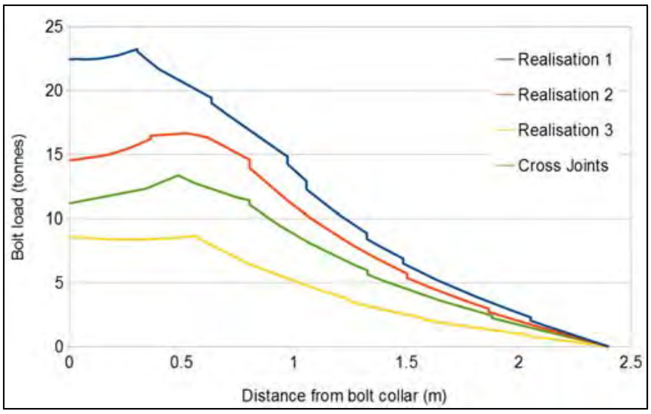

Figure 8: Sensitivity of rockbolt (2) load to variation in joint network geometry.

Simple sensitivity analyses such as demonstrated above however, do provide the means for judgment calls, e.g;

- Design for the 'worst-possible' scenario: base the rockbolt capacity on the maximum load profile generated, or;
- Design for an 'average' condition (most probable outcome).

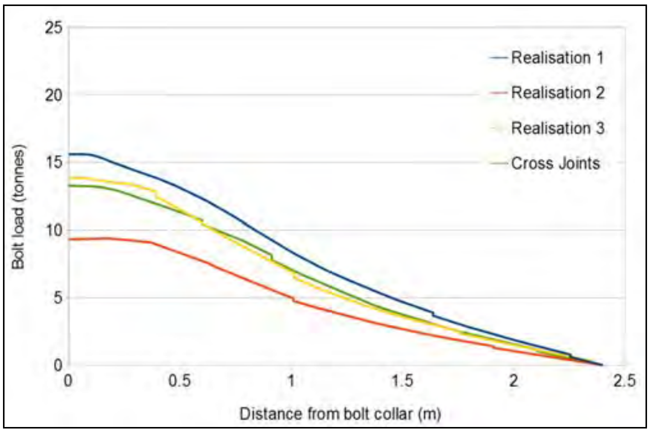

Figure 9: Sensitivity of rockbolt (5) load to variation in joint network geometry.

When embarking on ground support design using numerical models, it is clear that appropriate effort should be directed towards reducing uncertainty in the input parameters. For the example chosen and parameters analysed, their order of importance is as listed in Table 4.

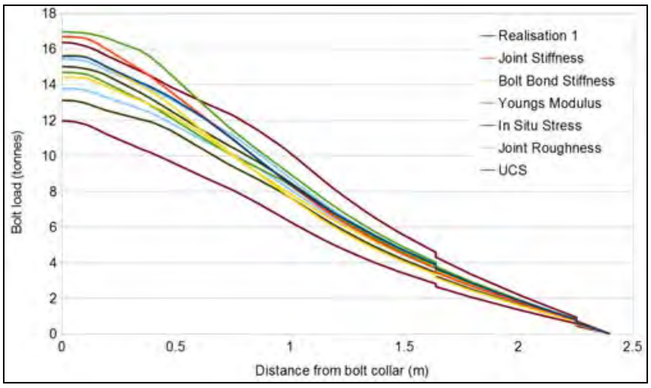

Figure 10. Combined sensitivity for all parameters analysed (but excluding variations in joint geometry) – rockbolt 4.

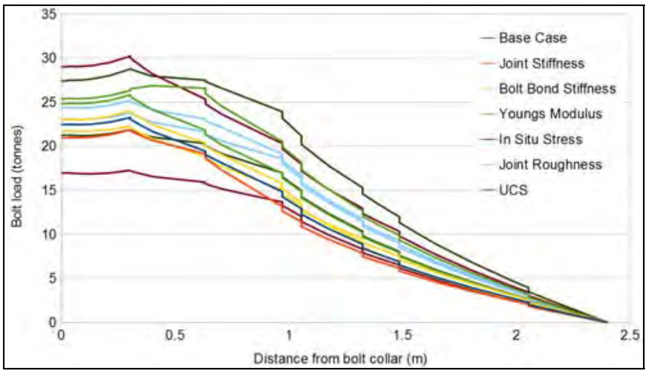

Figure 11. Combined sensitivity for all parameters analysed (but excluding variations in joint geometry) – rockbolt 2.

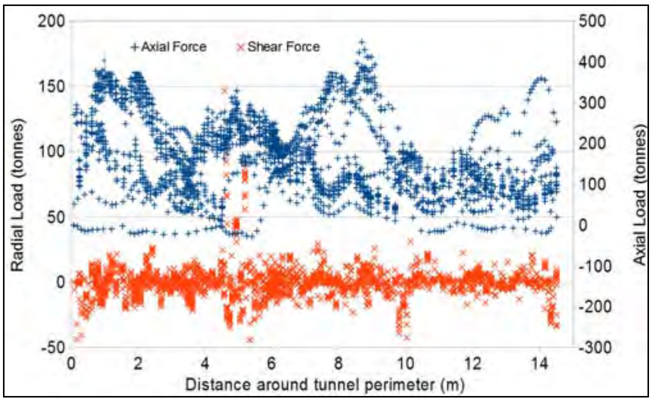

Figure 12. Combined sensitivity of liner axial and radial loads, for all parameters analysed.

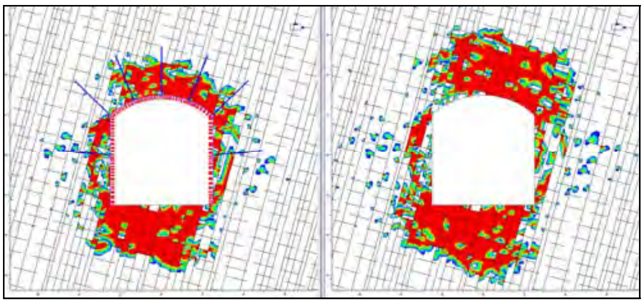

Figure 13. Comparison between the base case (supported) and an unsupported case (decrease in size of the yielded zone).

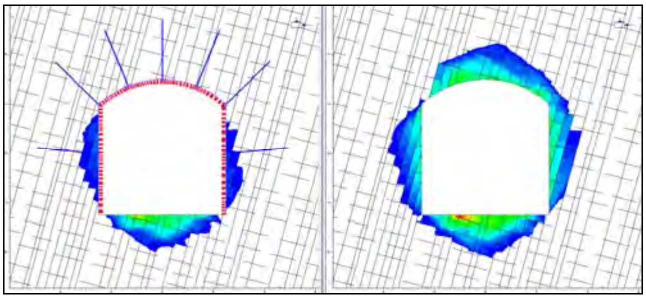

Figure 14. Comparison between the base case (supported) and an unsupported case, showing a decrease in the displacements surrounding the tunnel.

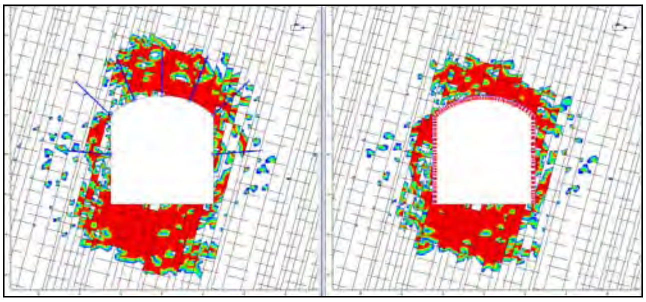

Figure 15, Bolts only vs liner only - yielded zones.

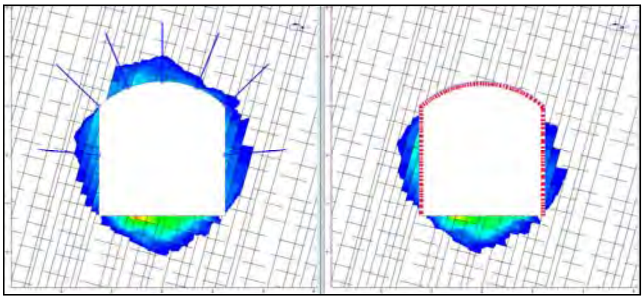

Figure 16. Bolts only vs liner only – displacement.

Table 4: Relative importance of the parameters analysed (listed in order of sensitivity)

Parameter	Variation	Sensitivity (tonnes)
1. Uniaxial Compressive Strength	+/- 5%	7.0
2. In Situ Stress	+/- 10%	13.0
3. Young's Modulus	+/- 8%	2.7
4. Joint Roughness Coefficient	+/- 22%	1.4
5. Rockbolt Bond Stiffness	+/- 20%	1.8
6. Poisson's ratio	+/- 11%	1.0

However the impact of “known unknowns” such as joint network and opening geometry may overshadow the importance of other parameters. Thus it is unavoidable that an appropriate number of joint network simulations be carried out.

12. CONCLUSIONS

The challenges in optimising ground support by the application of numerical models are significant, due to the natural variability in the input parameters which greatly affect the outcomes.

Furthermore, numerical models alone do not provide the engineer with an absolute means of assessing the appropriateness of ground support designs in terms of safety and serviceability.

The introduction of probabilistic methods, in combination with numerical modelling, may provide a means to incorporate natural variability in modelling parameters into the design, whilst simultaneously allowing the engineer to make rational decisions on excavation serviceability, based on industry accepted criteria.

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