

International slope stability research

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Clouds shroud Ok Tedi Mine in Papua New Guinea. High rainfall and over 700m high pit walls place this mine among the largest open pits in the World

The never-ending quest to go further, faster and higher not only applies to professional sports and space science, but is also a trend reflected in the mining industry.

As rich, near-surface mineral deposits are depleted and environmental and social awareness grows, mining operators move to greater depths, pit slopes are getting higher, and modern technologies are used to excavate rocks at a much faster pace than ever before.

Similarly, the safety and economic consequences of potential failure are becoming more significant and the demand on design reliability is increasing. It is not enough to defer the solution to the production stage and hope to "fix" the problem on the run.

The Large Open Pit (LOP) project was one of several international research projects that were formed to address the mining industry's need for more reliable design in new, challenging environments. The LOP was spearheaded by CSIRO, an Australian scientific and research organisation, with several sponsors from the mining

industry. The project was supported by leading industry experts and consulting houses, and SRK was proud to participate. As stated by the LOP, the focus was "on the relationships between rock mass strength and deformability. Innovative geomechanics research is examining potential new definitions of rock mass strength criteria, the effects of pore pressures on slope failure mechanisms, and how slope failures may develop and propagate through the jointed rock mass."

After a number of years of international collaboration, the LOP produced **Guidelines for Open Pit Slope Design**, which were formally presented to the mining and geotechnical community at the Slope Stability 2009 Conference in Santiago Chile, and have become an important tool within the modern geotechnical engineer's toolbox.

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Geotechnical characterisation

The geological and geotechnical models are foundations of any mine design. These models could also be the leading sources of technical risks for mining projects. In order to minimise these risks, it is necessary to reduce the uncertainty in understanding the geological context of the deposit.

With ever more sophisticated computer tools, it is possible to tackle more complex tasks in shorter times

than before. However, with advanced computerisation, the mining industry also faces challenges concerning many designs that have been developed “in the office” without appropriate field data to support them and where the interpretation of drilling and mapping programs is poor. Today, project presentations are rich in eye-catching graphics, illustrating in 3D the geological models, stress distribution, etc., and creating the impression of reality and a full understanding of problems. Unfortunately, these impressions can often be misleading; the presented results may lack common geological and geotechnical sense, or are simply wrong.

The significance of using the appropriate geological and structural model is not always appreciated in characterising the geotechnical rock mass, which is often undertaken by engineers, not by geologists. On the other hand, geologists usually have a poor understanding of mine design processes, while engineers often disqualify the data collected at exploration stages at more advanced stages of the project. It is important to make sure that all disciplines, geology, geotechnical and mining engineering, are fully integrated and that both understand the mining method in order to produce reliable characterisations and increase confidence in the geotechnical analyses, numerical modelling and, finally, mine design.

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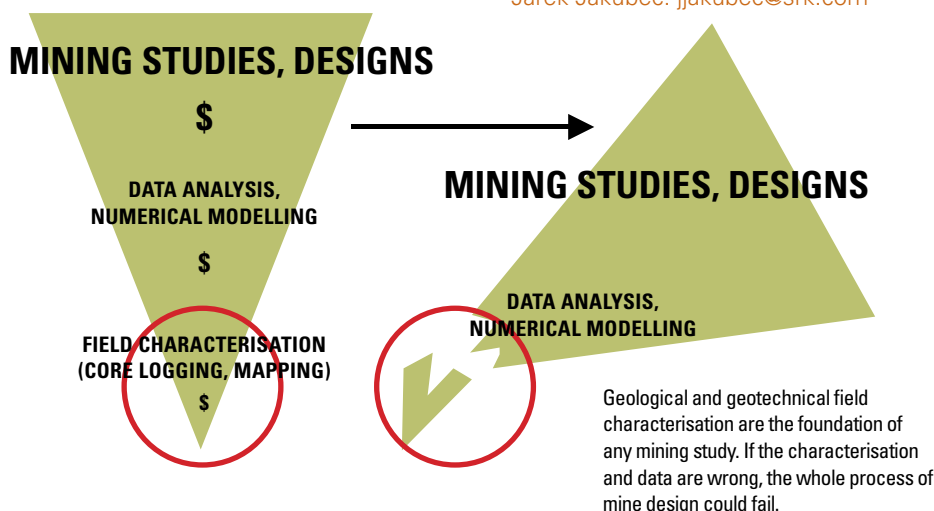


The word “risk” is widely used when people perceive a hazardous event, resulting in widely different perceptions of risk. The technical definition of risk as used in geotechnical engineering is:

Risk = P(event) x Consequences.

Slope design for large open-pit mines presents unique challenges to the engineer that are captured in the oft-quoted maxim that “the objective is to have the slope fail the day after the last truckload of ore leaves the pit rim”. This infers that the maximum benefit has been extracted from the mineral resource. The engineer, however, has to provide a design that is functional and economic at an acceptable risk. The great attraction of the geotechnical discipline is that it relies on different engineering, geological and hydro-geological disciplines to achieve the stated objectives.

Uncertainty and variability of properties within a rock mass provides the first challenge: How much data do we need



Risk aware!!!



to adequately describe the rock mass properties? Codes for data adequacy have been established for the minerals industry to define the geological certainty. SRK has used that same logic and applied it to geotechnical data, since this is also derived from the geological environment. Early in the study program, geotechnical data requirements for different study levels can be defined using logic diagrams to determine the relative importance of different parameters. Effort and cost can then be focused on the more critical parameters, instead of the common "populate the database" procedures.

This approach to geotechnical data collection has provided a rigorous process that allows exploration programs to be rationalised and cost-justified. While experienced judgment, embraced in the definition of the competent person, remains the anchor to success, the process suggested enhances such judgment decisions.

Benchmarking data and processes against practical experience of slope performance is of paramount importance for defining the different levels of confidence, namely, levels that are measured, indicated and inferred. SRK has embarked upon a systematic recording of information quality at different sites onto data templates to improve the estimates of data required for different classes of geological complexity.

These issues lie at the core of the engineer's ethos to produce a design that can be termed functional and economic at an acceptable risk. For this reason, risk valuation in geotechnics must be upgraded to a quantified status as practiced in other engineering disciplines. SRK has adopted this concept of risk engineering, instead of risk assessment that follows after the engineering design.

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OSKAR STEFFEN

Dr Oskar Steffen, a corporate consultant with over 40 years' experience in the international mining industry, is one of the founders of the SRK group. With a PhD in Engineering and a Master's Degree in Civil Engineering, he places special emphasis on geotechnical and mine planning aspects of open pit mines. Oskar has been involved in open pit planning and design; rock and soil slope stability for road and rail cuttings and strip mines, and surface mining geotechnics, including slimes and tailings dam investigation and design. He applies probability techniques in geotechnical engineering to slope failure analysis or strip stability investigations and slope design for coal strip mines and open pit mines internationally.



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3D modelling structurally controlled weak rock masses using blockiness

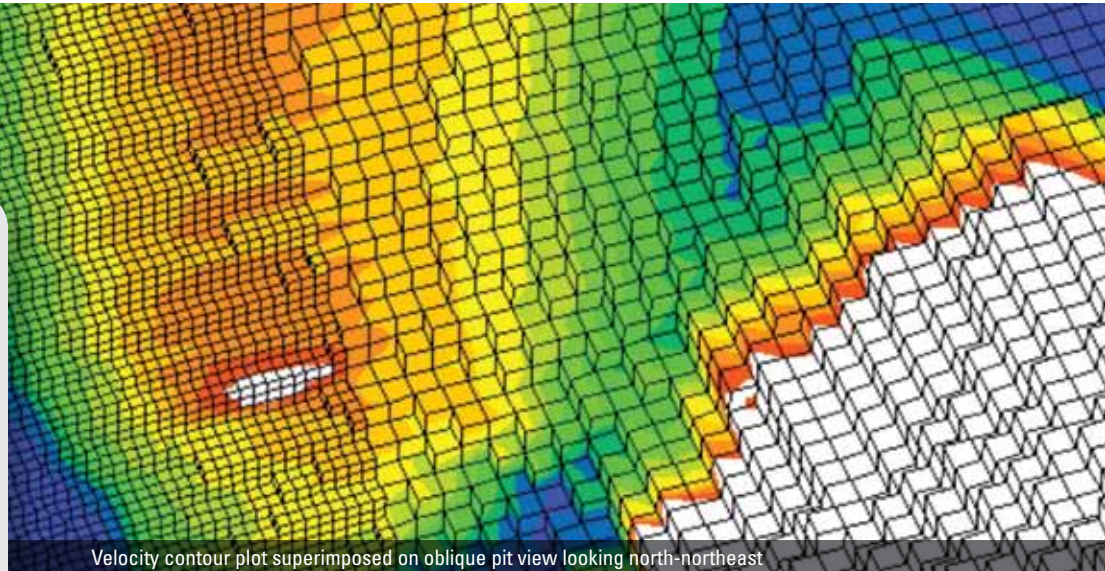
JEFF PRICE

Jeff has over 20 years' experience in civil and mining geological engineering and a PhD in fracture hydromechanics. His expertise includes investigation and



design for open pit mines, tailings storage, and open pit and underground numerical modelling, especially for slope depressurisation and open pit-underground interaction for projects in Australasia, Russia and the former Soviet Union, South America and Africa. He is the Head of the SRK Perth Geotechnical Department, which includes teams covering mining geomechanics, tailings and heap leach engineering and mining hydrology and hydrogeology.

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Velocity contour plot superimposed on oblique pit view looking north-northeast

Design of deep open pits in structurally complex, weak deformable rock masses is a challenge. Recently, SRK in conjunction with HTA Consulting, engaged in assessing the slope stability for such a proposed pit. Experience has shown that incorporation of the Geotechnical Blockiness Index (GBI) within the 3D geotechnical domain model improves our ability to simulate pit design performance.

The digital geotechnical domain model, developed by project staff and HTA, consisted of four classifications: lithology, oxidation state, alteration and GBI. The rock mass was divided into design sectors based on Mohr-Coulomb properties and ubiquitous jointing, extensive laboratory testing and field investigation. The figure at right shows variability in the distribution of different material types.

The numerical codes Slide, Phase² and FLAC3D were used to assess potential instability. This staged approach raised confidence in the controlling instability mechanisms and

the interaction of 3D confinement on slope performance. Applying strength reduction factors (SRF) to the FLAC3D solution also demonstrated the potential development and extent of open pit instability. The figure above indicates zones of velocities with cool colors referring to low, warm colors to moderate, and white color, high velocities.

The FLAC3D runs incorporated rock mass and fabric variability to assess the sensitivity of the slope response. Comparison of the 2D and 3D models allowed a re-evaluation of the expected rock mass performance so that the model results could be applied realistically to the slope design accounting for pit concavity.

Conclusions from the study indicated:

- The application of the GBI improved the quality of the geotechnical data set and enabled better definition of areas of poor rock mass quality
- The use of 3D modelling to assess the critical design criteria, using

Estimating rock mass strength

Estimating rock mass strength (RMS) remains one of the challenges facing rock mechanics practitioners. The infinite variability of geology, weathering and alteration processes, the influence of mining and the inability to test rock mass strength directly, all pose great challenges to making reliable estimates. The experience of the practitioner, therefore, plays a crucial role in such estimates.

Although the problem with estimating RMS is not yet solved, in recent years another approach was developed that helps to provide more realistic estimates and generate and evaluate "what if" scenarios. This approach is called synthetic rock mass (SRM) and was pioneered by Itasca Consulting. It involves calibrating small-scale specimen strength, developing digitized detailed models of fracture and other defects called discrete fracture network (DFN) and estimating defect strength.

In close collaboration with Itasca, SRK used this approach on several world-class projects as input for further analysis, such as investigating block cave fragmentation. This approach is crucial, especially in rock masses that contain numerous defects such as microfractures, veinlets and cemented joints. It is encouraging to see that the results of SRM models are compatible with the empirical method of estimating rock block and rock mass strength developed by Dr Dennis Laubscher, author of one of the widely used rock mass classifications systems, in collaboration with SRK in 2000.

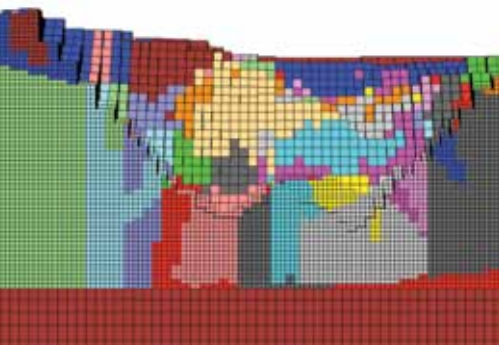
Practical experience gained from SRM analysis on mining operations and projects gives SRK a significant advantage in assessing rock mass strength more realistically than in the past using traditional industry tools.

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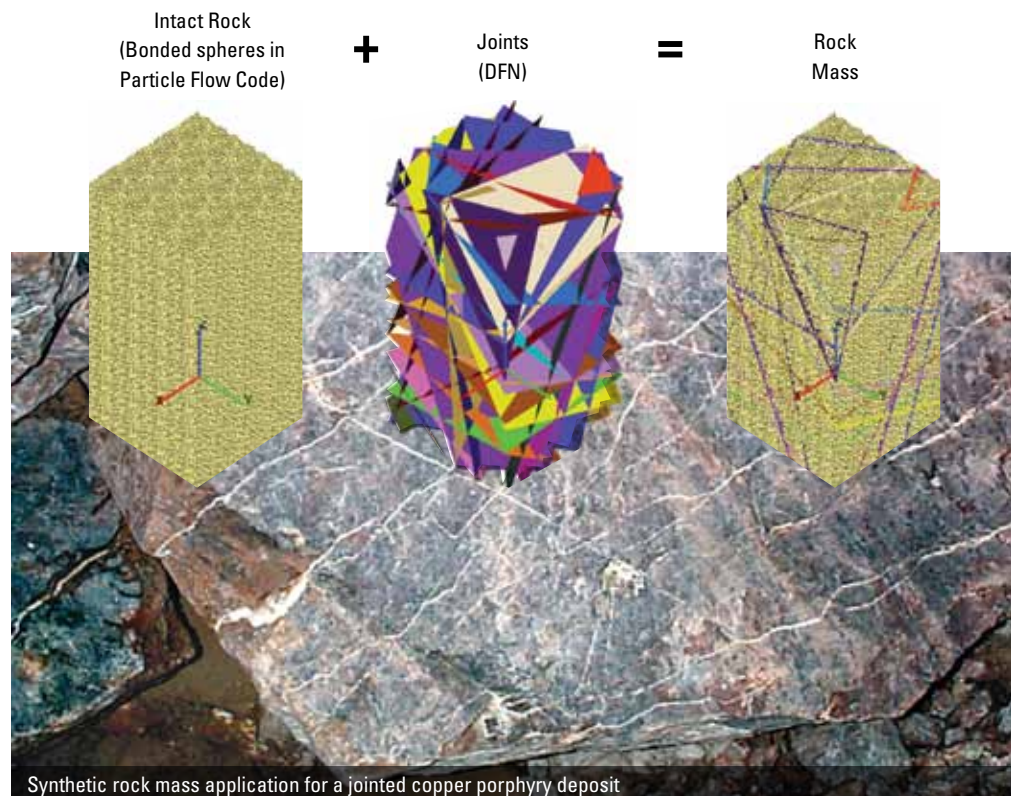
detailed geotechnical and structural domain model, provided a sound basis for a reassessment of the slope design

- 3D and 2D analyses were used to simulate slope performance and provide guidance on pit slope design. 3D analysis show an increase in SRF, compared to the 2D analyses (typically 20 to 30% higher)
- FLAC3D results were used to review the existing 2D slope design parameters resulting in steeper than recommended slope geometry

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FLAC3D model cross-section showing cohesion in kPa, looking west



Synthetic rock mass application for a jointed copper porphyry deposit

Itabirite iron ore bodies: Generic geotechnical models

SRK has recently been involved at the feasibility and pre-feasibility level studies on a number of large-scale iron ore projects in west and central Africa and Brazil. Experience across these locations has highlighted a number of similarities that should be considered when generating a geotechnical model in itabirites.

In the weathered horizon, itabirites are characterised by strong iron bands and weaker silica bands resulting in a significant degree of anisotropy, where

materials react differently to stresses applied in the direction of banding. It is therefore important to determine if this banding is consistent in terms of direction, which can often be seen to run parallel to the footwall contact if this contact is conformable or of a similar nature. By contrast, material that is unweathered or strongly foliated can be very strong and produce massive block sizes, intersected by unfavourable discontinuity sets.

The process of ore formation and depth of leaching can have a significant impact on the state of the silica banding within the itabirites and their subsequent geotechnical behaviour, as well as the behaviour of the surrounding waste rocks. The itabirites can form a boundary protecting the surrounding waste rock from the processes involved in the ore formation. For example, in itabirite deposits in Guinea, there is a strong correlation between the friability of the itabirite and the degradation of the surrounding phyllitic waste rocks.

Due to the massive size of these itabirite ore bodies, and the drilling problems associated with them particularly in tropical regions, it is often difficult to gain the desired degree of structural information. Phyllitic and amphibolitic marker horizons within the itabirites can be seen on geophysical gamma-gamma logs and can be correlated between boreholes which can prove useful in interpreting large-scale macro structure and determining lithological offsets, particularly where there is little surface exposure.

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Rapid development techniques maximise activity at the tunnel face and advance completion rates without compromising safety. Good project planning should prepare for both expected ground conditions and unexpected variations in the rock mass to be excavated. This will reduce delays and mitigate the effect of poor ground conditions, which can slow advance rates by 50%.

It is no surprise that poor ground slows advance rates. For example, the industry-leading development practices at Newcrest's Cadia East operation in New South Wales produced better than average advance rates in the access decline. Rapid development rates of over 8 m/day were achieved using longer drilling rounds and emulsion explosives, but the project still suffered low advance rates of less than 3 m/day as a consequence of poor ground.

Investment in a "rapid development" program is usually justified to realise higher Net Present Value for a project. The risk of not being able to excavate the rock mass as planned can result in inadequate prediction and preparation to deal with the actual ground types encountered.

A Ground Control Management Plan (GCMP) created from site investigation data can mitigate this risk. An active GCMP uses data collected prior to and during excavation. The aim is to predict ground conditions and select design control methods through a structured risk management approach.

Confidence in predictive models increases with geological, structural and geotechnical mapping, and ground behaviour monitoring. Feedback is essential to keep the GCMP "live".

ALICE JACK

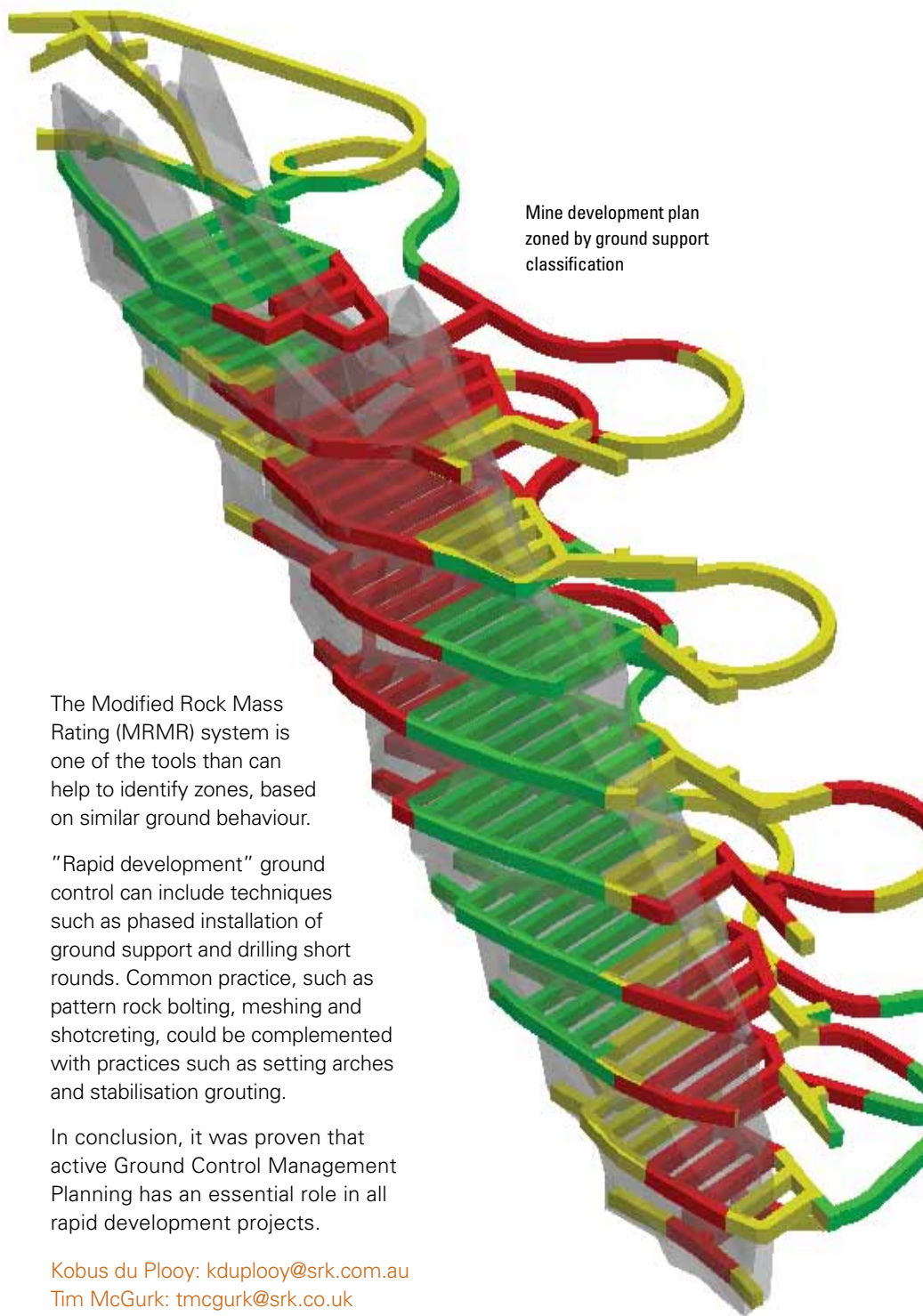
Alice Jack is a Geotechnical Engineer with six years' experience in exploration and mining geotechnics in Europe, Asia and Africa, including civil engineering geotechnics and foundation design experience both abroad and in the glacial and coal measure rocks of South Wales. Her expertise includes limit equilibrium and the analysis and design of finite element slope stability, seismic, structural and kinematic analysis, underground rock mechanics, assessing and conceptualizing rock and soil masses, geological and geotechnical mapping, borehole core logging and geotechnical data collection and interpretation, training of site personnel, site and project management.

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Itabirite outcrop in the Caitite deposit Brazil

Safe and rapid development for major underground mines: Trends for the future



Mine development plan
zoned by ground support
classification

The Modified Rock Mass Rating (MRMR) system is one of the tools that can help to identify zones, based on similar ground behaviour.

"Rapid development" ground control can include techniques such as phased installation of ground support and drilling short rounds. Common practice, such as pattern rock bolting, meshing and shotcreting, could be complemented with practices such as setting arches and stabilisation grouting.

In conclusion, it was proven that active Ground Control Management Planning has an essential role in all rapid development projects.

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KOBUS DU PLOOY

Kobus du Plooy, BSc, GDE, Pr.Sci. Nat, MIEAust is a Senior Geotechnical Engineer with 16 years' experience in the mining industry, combined with geotechnical consulting experience. Kobus started his career in the rock engineering department of AngloGold-Ashanti, where he gained valuable experience in the areas of shallow to deep level hard-rock mining. He started his consulting career with SRK Consulting (South Africa) in 2000 and also worked for Brentley, Lucas and Associates before joining SRK Consulting (Australasia) in 2007. In recent years, Kobus has been involved in projects in Australia, Indonesia, Kazakhstan, Siberia and South Africa.



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TIM MCGURK

Tim McGurk is Principal Mining Engineer with 20 years' experience in underground mine design, production, construction and management. His operational experience includes stope and fill, sub-level caving and room and pillar in zinc, gold, nickel and silica operations. He was responsible for mine production and development, including decline access to around 800 vertical metres at Black Swan Nickel Mine. For Rio Tinto and SRK since 2008, he reviewed and managed scoping and pre-feasibility studies for diamond, copper, gold and industrial minerals.



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BRUCE MURPHY

Bruce Murphy is a Principal Consultant in SRK's Vancouver office with over 20 years' experience in operational and consulting environments, both in open-pit and underground rock engineering. He specialises in establishing the geotechnical and mining context of existing and potential deposits by integrating structural geology, rock mass characterisation and considering hydrogeology, permafrost and existing excavation performance. Bruce has worked on many projects in Canada, the US, South America, Africa, Russia, Kyrgyzstan and Indonesia.



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INTRODUCING SCOTT CARLISLE

Scott Carlisle, M.S., P. Eng., is a Principal Consultant in rock mechanics and mining. He has 18 years' experience in underground mining operations and civil construction and 12 years in consulting. As a rock mechanics practitioner, he has a wide range of experience, including risk assessment, strategic planning, high stress mining, mine method selection and design, stope design and sequencing, crown pillars, rock failure investigations, rock support, instrumentation and modelling. Scott participates in mining and rock mechanics research activities in Canada.



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Mining challenges in permafrost environments



Portal location for the underground exploration decline

The Kumtor gold project is located in the mountainous terrain of the Tien Shan Mountains in the Kyrgyz Republic, at an altitude of around 4000m. The mean annual temperature is minus 8°C.

Locating and designing an exploration decline to access and explore the mineralised horizon below the operating open pit proved to be a challenging experience as a result of poor ground conditions, widespread glaciation and location of the waste dumps. Once the location of decline was chosen, the team faced several engineering design challenges including weather, permafrost and a drop-cut within a glacial moraine with ice lenses.

The mine geology consists of four major thrust slices. The slice hosting the mineralisation is composed of phyllites that are strongly folded and schistose. The footwall contact of this structural segment is the well-developed and weak Kumtor Fault Zone. The adjacent rocks in its hangingwall are strongly affected by shearing and faulting for several hundred meters.

For many reasons, starting the decline near the glacier, within the constricted ore zone was considered the most favorable option, in particular, since it would reach the more competent ground of the hangingwall units more quickly.

An Armtec Multi-Plate® tunnel support was to be installed within the drop-cut and covered with engineered fill to protect the decline access from slope instability, snow falls and possible avalanches. Ice lenses within the moraine could affect the stability of the slopes and the Armtec tunnel foundation, where heated air would be drawn underground. To keep the Armtec foundation frozen, thermosyphons were installed to cool the ground when the ambient air is colder than the subsurface.

The SRK team developed site-specific rock classes based on the GSI and NGI Tunnelling Quality Index (Q) classification systems. The rock mass conditions range from Fair to a Very Poor rating in graphitic phyllite near fault structures. A site specific system was selected to better characterise and differentiate the weaker rock masses. Following a full geotechnical evaluation, four

Shea Creek uranium project



support classes were developed ranging from conventional bolt, screen and shotcrete, to spilling and steel arch (full invert) support. Using the Rocscience software Phase² a squeezing ground assessment was undertaken, with steel set and shotcrete support simulated as a composite liner.

Since the support materials and installation processes needed to function within the initial cold permafrost ground temperatures, choices included an oil-based rebar resin, and a customised shotcrete mixture that used heated aggregate and high water temperatures.

With a moving glacier and waste dump material on the surface, it was extremely difficult to produce a full geotechnical evaluation along the proposed path of the decline. To manage the geotechnical risk, the team developed a comprehensive process of cover and probe drilling and monitoring of excavation and support performance.

SRK, as part of a multi-disciplinary team helped develop this complex design.

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The Shea Creek Project, owned jointly by AREVA Resources Canada Inc. and UEX Corporation, with AREVA acting as project operator, is an advanced uranium project located approximately 700km NNW of Saskatoon and approximately 30km east of the Alberta border, within the western Athabasca Basin of northern Saskatchewan. The property is underlain by two dominant lithologies: metamorphic basement rocks of Archean and Paleoproterozoic granitoid, covered by Proterozoic flat-lying to shallow-dipping, post-metamorphic quartz sandstone.

Uranium mineralisation is of the unconformity-associated uranium deposit type. It occurs 710 to 740 meters below the current surface and beneath the thick sequence of Athabasca Group sandstone. Three styles of mineralisation are encountered, based on their position adjacent to the Athabasca unconformity, and overall morphology. They comprise unconformity-hosted, basement-hosted, and perched uranium mineralisation. Uranium mineralisation is associated with extensive clay alteration, which affects the lower sandstone and extends into the basement rocks.

SRK evaluated and refined an existing structural site model to define the potential risks to a conceptual stage

underground mine design. SRK then incorporated the analysis of drillcore data and photos, 3D geological modelling, whole-rock geochemistry, and geophysics to evaluate the potential structures, which are blind at surface. During the studies four generations of faults were identified, each with individual fill, roughness, strength, and permeability characteristics, including previously unidentified faults that may affect uranium distribution.

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JAMES SIDDORN

James Siddorn, PhD, PGeo, is a Principal Structural Geologist with SRK's Toronto office. He is a specialist in the structural analysis of ore deposits, focused on deciphering the deposit scale controls on ore plunge, geotechnical domains, and hydrogeological pathways. James has extensive underground and surface mapping experience and broad mining experience in conventional and mechanised underground mining. He has spent 15 years in the structural analysis and 3D geological modelling of Au, Ni-Cu-PGE, Ag, U₃O₈, tantalum, and diamond deposits.



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3D fault network with the Athabasca sandstone unconformity, Shea Creek

Integrating structural geology and geotechnics, Los Caracoles Dam

The Los Caracoles is a 140m high hydropower water dam, located in San Juan Province, Argentina, in an arid region of high seismic activity. The spillway system consists of two large parallel tunnels while the gateway structure is formed by two twin boxes, each 30m high, excavated in the upstream slope of the abutment.

Natural stability relies in the continuity of the rock layers along the entire slope and into the foundation levels but this continuity would be altered by the gateway excavation. Design countermeasures were necessary to keep the slope stable.

Soon after the excavation started, fractures appeared on the shotcreted slope surface, the excavation face, and the rock buttress. The job was halted and SRK was called in. The photo below shows the excavation and buttress status at that time.

SRK performed a thorough site inspection and detailed analysis of all conceivable failure modes and determined that, due to the shape of the buttress and lack of lateral confinement, the secondary joints or fractures had been activated so the rock mass slipped along them. The outcome was that secondary joints, other than the bedding planes, had been activated due to the shape of the buttress and lack of lateral confinement. A second reinforcing bolt system (passive,

grouted rockbolts made with rebars) perpendicular to the original one, was designed and installed immediately, and the excavation was continued and completed successfully.

Another challenge was the design of the gateway. The gateway is a critical component of the spillway, and must remain operative after an earthquake. It was feared that the slope would displace further during an earthquake, deform the concrete structure and block the gateway.

When dynamic slope stability analyses were performed to address this concern, SRK found that two large blocks were potentially unstable. For the first block, a step-by-step dynamic Newmark analysis showed that the support system would need to carry 650 MN to assure that its displacement during the shake was compatible with operating the gates. Two large concrete buttresses were built near the rock buttress, both confining it laterally and carrying part of the huge load.

Unfortunately, the 250 MN second block does not contact either the rock or the concrete buttress. Twenty prestressed permanent anchors were designed and installed to reduce displacement. After this design change, the project was completed and works successfully.

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Standing on footwall of open pit coal mine, Colombia

For pit slope design, geotechnical data is typically collected by mapping the benches to supplement data collected from boreholes. Where an open pit has been in operation for some years, bench faces are often difficult to access and, increasingly, access is being restricted to reduce the risk of exposure to rockfall hazards. In order to address these issues, photogrammetry is being used more frequently.

SRK Consulting (UK) Ltd has acquired the expertise to undertake photogrammetric surveys using the Sirovision® system developed by CSIRO Australia. Besides purchasing the data manipulation and analysis software, SRK has invested in the photographic and survey equipment needed to collect the data.

SRK has previously used Sirovision® successfully on a number of open-pit projects. In Colombia, South America,



Upstream face of Los Caracoles and excavation for the spillway tunnels

Use of photogrammetric mapping techniques for slope stability



SRK's brief was to carry out a slope design optimisation study for a cut back of an open-pit coal mine that would increase the height of the highwall from 150m to 250m. As part of this study, during a five-day site visit, Sirovision® was used to:

- Map large-scale geological structures on the existing highwall. For this the camera set up was positioned at the footwall slope crest about 400m from the highwall
- Capture bench scale structural data for use in detailed kinematic analysis from close range (4m-10m)

In conjunction with the large-scale mapping, detailed physical properties of over 1200 individual discontinuity occurrences were obtained from selected bench face locations. These properties included:

- Three dimensional location of features

- Orientation (dip/dip direction)
- Trace lengths/plane area (also used to calculate joint persistence)
- Large-scale joint surface roughness
- Termination indexes (to ascertain feature chronology)
- Fracture set spacing

Sirovision® allowed the rapid collection of a large data set of new structural information, saving the client time and money over more traditional methods of geotechnical data collection. The structural data collected, together with the incorporation of newly measured faults into the geotechnical model, provided for robust and statistically-sound kinematic analysis of the proposed new highwall pit slope design. The 3D positional information of the coal seams and other geological boundaries allowed the geological model to be verified and updated.

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Xander Gwynn holds a BSc (Hons) in Engineering Geology and Geotechnics (ACSM) and has been studying for a PhD in Earth Resources at the Camborne School of Mines, University of Exeter. He joined SRK in April 2008 and is currently finishing his PhD thesis. Xander previously worked offshore in the oil industry after completing his undergraduate degree. He specialises in the geotechnical characterisation of rock masses using photogrammetric mapping methods. Xander's PhD focuses on the assessment and advancement of digital remote data capture techniques for natural and man-made slopes. He is now applying his PhD expertise for SRK and is able to undertake Sirovision® photogrammetric mapping for various open-pit, end-use applications.



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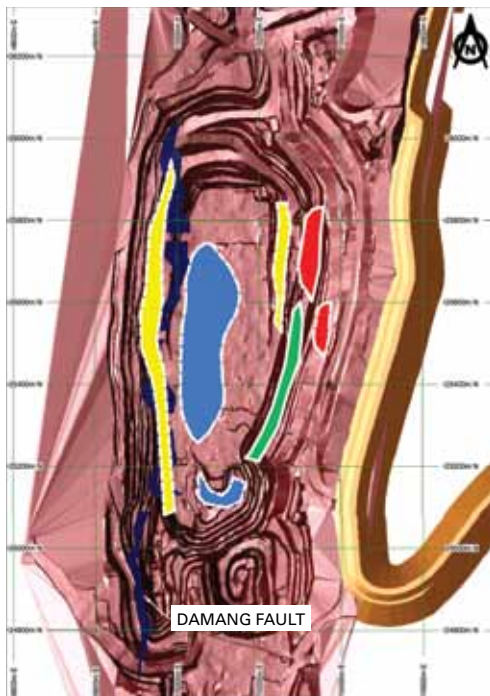
Alejo, Principal Geotechnical Engineer, is managing director for SRK (Argentina). Concurrently, he serves as Professor of Soil Mechanics and Head of the Geomechanics Group



at the University of Buenos Aires. His academic and professional experience is reflected in the many papers he has authored and delivered at conferences worldwide. For SRK, Alejo and his team focus on optimising construction processes, providing expert consultancy in geotechnical engineering, tunnel design, soil-structure interaction and computational geomechanics.

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Assessing geotechnical management using the Ground Blockiness Index (GBI)



Location plan of the Damang pit layout in April 2009

Risk management and risk assessment are important processes, and should be applied to both the development of mining studies and the implementation of designs. SRK has completed a risk assessment as part of the cutback feasibility study and practical design for the Damang pit in Ghana.

For operational risk management, reliable field data needs to be collected. By using the Geotechnical Blockiness Index (GBI) in our field mapping, SRK applied a rapid rock mass characterisation tool to accelerate assessment at Damang.

The GBI concept, developed by Diane Walker and Ian de Bruyn of SRK (Perth) in 2006 classifies the rock mass according to 8 categories of block size and rock mass texture. It has the additional benefit that direct access to the face is not required.

Rock mass domains were derived from field observations, which were related to locations shown in the adjacent site plan. The location plan (left) shows the principal

East and West Wall domains as Good, Fair and Poor in green, yellow and red, respectively. The rock mass conditions were extrapolated where similar conditions were assessed as likely to be encountered. The approximate water level is shown by the light blue colored infill.

The Good rock zone comprises sandstone and, locally, dolerite, where it has been intruded along bedding structures. The domain fabric typically comprises large blocky to massive, very thin, widely-spaced bedding shears with occasional minor wedge or planar failure.

The Fair rock mass zone exposes the steeply dipping Damang Fault. The rock mass quality generally appears similar to the Good domain, although the presence of the fault provides a zone of persistent sub-vertical structural weakness.

The Poor domain corresponds to the zone where bedding shears and faults intersect with reduced block size, variable bedding dip and the flatter westerly dipping joints and shears.

UDEC modelling



View of Damang cutback looking south

The risk assessment incorporated the results of the GBI mapping with the Abosso Goldfields risk-assessment methodology. Geotechnical hazards were considered in terms of the consequences of slope failure. The principal hazards for the Damang Pit relate to the perceived instability of slope elements at decreasing scale (from the whole slope to an individual bench), including whether there was a ramp at risk, and according to slope material (oxide, weathered or unweathered rock).

The Damang cutback is generally situated within strong rock. Blockiness variability within the main pit walls represents an important structural control on bench performance. The approach adopted presents a robust field technique that allowed identification of common geotechnical domains, and categorisation and definition of risk mitigation measures.

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The Universal Distinct Element Code (UDEC), developed by the ITASCA Consulting Group, is a “distinctive element program for discontinuum modelling”. UDEC simulates the response of discontinuous media (different rock types) when they are subjected to either static or dynamic loading. Linear or non-linear force-displacement causes movement in both normal and shear directions.

SRK used UDEC modelling on part of the east pit of a gold mine in western China to gain a better understanding of the mechanical behavior of the rocks in the two main joint sets encountered in the east wall, when the upper pit is excavated sequentially, and to provide a basis for the design of the final pit.

Two cases were modelled:

- Model 1: Includes only one set, 1m continuous
- Model 2: Includes both sets, 1m continuous and 4m discontinuous

It was assumed that the horizontal and vertical stresses are equal and are caused purely by their own weight. A strength reduction technique was used to evaluate the factor of safety (FOS). The material

strength was reduced to a level where the pit becomes unstable and failure develops. Figure 1 shows the point where the slope becomes unstable, providing clues to the likely mechanical behavior of the pit walls as the pit is gradually deepened.

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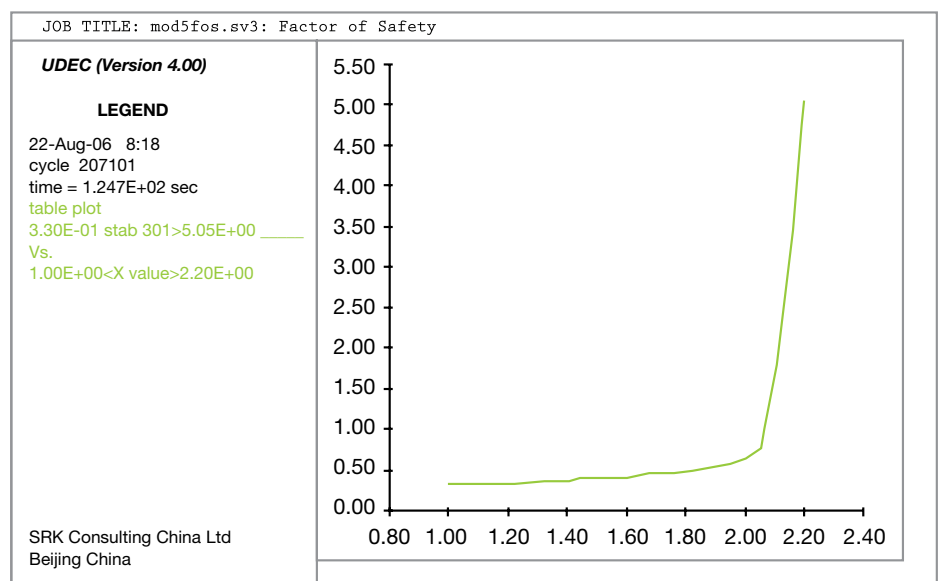
Dr Yonglian Sun is a Principal Consultant with over 20 years' experience in geotechnical engineering, rock mechanics and mining engineering. He has worked in



five countries across four continents. His considerable experience emphasizes site investigation, analysis and modelling of geotechnical issues in open pits, underground mines and tunnels, and evaluating mining projects. Yonglian established the SRK (China) Beijing office in 2005 and 49 full-time employees now provide technical review, exploration management and audits, design, scoping and feasibility studies on mining projects.

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Figure 1: Factor of safety (FOS = 2.05)



Antamina geological modelling, Peru

The Antamina Cu-Zn mine which lies in the high Andes of Peru, 270km north of Lima, is operated by Compañía Minera Antamina S.A., for a consortium of owners including BHP Billiton, Xstrata, Teck Resources, and Mitsubishi Ltd. An expansion of the mine has been recently approved which takes advantage of a 75% increase in reserves; the current extraction rate of 94,000 tonnes/day will be increased

by 38% by 2012, with a corresponding extension of the mine life to 2029. With a rapidly expanding open pit in mountainous terrain, it is imperative to have a good understanding of the structural and lithological architecture, to ensure continuing safe and profitable extraction of the orebody.

Since 2004, SRK has been involved in producing and updating a 3D model of the major structures in the vicinity of the open pit. The current model comprises 60 structures in 6 suites of faults, characterised by their initiation and development history, continuity and geotechnical characteristics. A 3D Leapfrog™ geological model produced from drillhole data shows the distribution of the major rock types encountered during pit development, including intrusive rocks, endoskarn and exoskarn, hornfels, marble and limestone, as illustrated and explained below.

The combined structural and lithological models have been used for a variety of purposes, including geological and geotechnical evaluations and hydrogeological studies. As development of the mine proceeds, updated information will continually be used to revise and refine the structural geological model.

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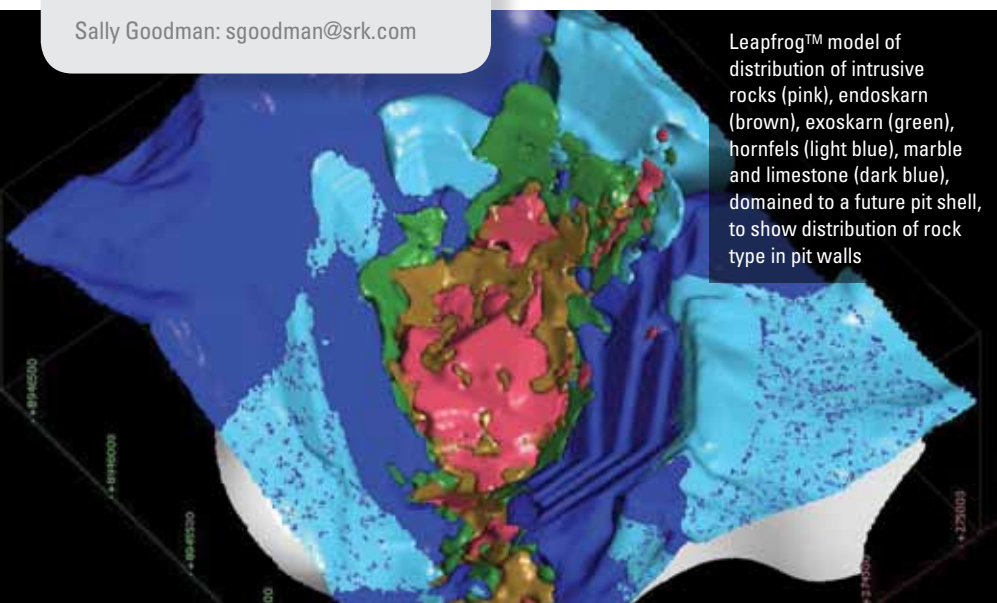
SALLY GOODMAN

Sally Goodman, PhD, PGeo, is a Principal Consultant with SRK's Toronto office. She has over 20 years' experience in the structural analysis of complex areas.



Her key skill is integrating the structural framework with diverse data sets to reconstruct the spatial and temporal development of mineralising systems. She applies this skill to ranking project targets, optimising drill-testing, resource estimation, grade control and geotechnical studies in Europe, North and South America. Sally has taught geology at McGill and Concordia Universities, Montreal.

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The Koidu Kimberlite Project is situated in the Kono District of Sierra Leone, approximately 330 km east of the capital city, Freetown. The mining lease area is 4km² and comprises two kimberlite pipes, four dyke zones and a number of blows off the dykes. In 2003, Koidu Holdings established operations on the property and began dewatering and removing silt from the existing 30m excavation of the No.1 Pipe. While the original planning for the pipes included conventional open pit operations, mitigating factors such as the proximity of the town, the presence of houses close to the perimeter of the pit, the size of the kimberlite pipe and the planned open pit depth, combined with relevant stripping ratios and uncertainties on the grades concerning an underground operation, lent themselves to the vertical pit concept. A diagram showing the comparison of a conventional pit and vertical pit is included as Figure 1.

Koidu vertical pit, Sierra Leone

PETER TERBRUGGE

Peter Terbrugge, a Principal Engineering Geologist, has over 40 years' experience in engineering geology, rock slope stability, site investigations and tunnelling. His expertise includes open pit slope design for large copper mines, diamond mines, gold mines and iron ore mines; feasibility studies; the design of remedial measures to maintain access in critical areas, civil engineering projects.



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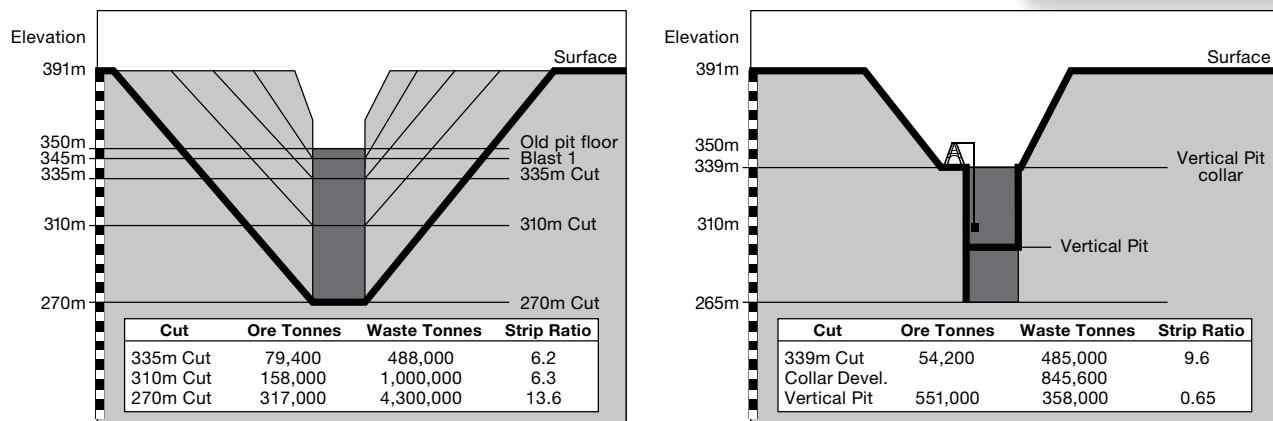


Figure 1: Comparison of the open pit and vertical pit scenarios

The vertical pit was established using an A-frame headgear for the hoisting arrangement, with sidewall support comprising a combination of cable anchors 20m and 40m long, rock bolts, wire mesh and pneumatically applied concrete. The pit reached steady state production in January 2007 and produced some 26,000 tonnes of head feed per month until August 2007, when

mining reached a depth of 74m below the pit collar (approximately 126m below surface). Mining was suspended following a sidewall failure that disrupted operations. Now that the grades in No.1 Pipe have been validated, the focus has switched to an underground operation taking account of both No. 1 Pipe and No. 2 Pipe.

While the mining costs for the vertical pit have been higher than for a conventional open pit, the concept did circumvent the social implications, the issue of grade consistency and diamond value at depth; it also provided the time to carry out a full underground mining study.

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IAN DE BRUYN

Ian de Bruyn has 15 years experience in the geotechnical engineering field, over a wide range of projects in both the mining and civil engineering sectors. He has strong



expertise in geotechnical assessment and in providing design parameters for open pit mining operations. He has worked on projects involving very large pits in challenging rock mass conditions. He is well versed in rock mass characterisation and domain modelling for input into fragmentation analysis, the selection of mining method and support design for underground mines. Ian's projects have involved site investigation, characterisation, analysis, evaluation, design, risk assessment and reporting at all levels – from conceptual through pre-feasibility, feasibility and working design.

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JIM CREMEENS

Jim Cremeens has over 20 years' experience in geotechnical engineering, primarily related to the mining industry. He has managed



large multi-disciplinary projects, both domestically and internationally. His areas of expertise include surface rock mechanics, heap leach facility design, and mine reclamation. Jim is a registered professional engineer in Colorado and New York, and is a registered professional geologist in Wyoming.

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Numerical analyses for evaluating pit wall and underground stability at Ok Tedi



The southeast pit wall at Ok Tedi

A staged numerical analysis program was conducted for the final pit and proposed underground mining excavations at Ok Tedi Mine in Papua, New Guinea. The analyses were conducted to evaluate the performance of the final east and west pit walls, and the stability of the underground mining excavations beneath these walls, as mining progresses. These evaluations were intended to facilitate the design and to assist with decision-making concerning the viability of the underground mining project.

The mine is situated in a complex geological setting including faulted and highly altered rock in an area that is seismically active and that is subject to very high rainfall. Detailed geotechnical characterisation and hydrogeological modelling was therefore carried out to provide accurate input for the numerical analyses.

The numerical analyses were performed while the most suitable mining methods were still being assessed, and therefore the analysis had to be flexible in method and application. The initial method selected was two-dimensional distinct element analysis using UDEC software for evaluating pit wall stability throughout the underground mining sequences. However, it became evident that certain mining geometries were not amenable to satisfactory analysis in two dimensions. Therefore, SRK performed three-dimensional finite difference analyses using FLAC3D to investigate pit wall and rock mass stability and the effectiveness of prospective stabilisation measures. In addition, SRK performed boundary element modelling to rapidly assess the likely extent and magnitude of stress concentrations within the rock mass.

Blasting program optimises pit slope performance



An Open Benching mining method was originally considered, with the remainder of the ore then to be mined out by these underground methods: Sub Level Caving beneath the east and southwest pit walls, and Block Caving beneath the central west pit wall. Subsequent to the first phase of numerical analyses, it was decided that only underground mining methods would be used.

Conclusions were reached concerning the risk and scale of slope failure resulting from the underground / pit wall stress interactions. SRK assessed measures to mitigate the failure of slopes and underground excavations, including using rock-fill to minimise underground voids, and leaving stabilising pillars within the orebody.

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Barton Mines, a garnet mining operation in upstate New York, contracted SRK to conduct a slope stability evaluation of the active Ruby Mountain pit. Three geotechnical coreholes were planned, along with cell mapping of the pit exposures to provide data for the slope stability analyses. During our site investigation, it became apparent that rock mass characteristics would not limit the slope design. The rock was relatively uniform lithology, and of relatively high strength. SRK recommended against drilling the third geotechnical corehole, because the uniformity of the rock mass observed in the first two coreholes indicated that collecting more data would not significantly affect design recommendations.

SRK also observed that the slope instability in the Ruby Mountain pit was due primarily to failure of the blocks of rock created by a more or less randomly-oriented fracture system, characteristic of blast induced damage. The instability was not necessarily consistent with the tectonic rock structures observed. Based on these observations and given the high rock strength and favorable orientation of structures, SRK recommended that a full-scale pit slope

evaluation was not warranted. Instead, a review of the blasting design was considered.

SRK made several recommendations regarding blast procedures. These included decreasing the production hole burden, using bottom-up detonation on the pre-split row, and changing to zero subgrade on the pre-split row. As a result of implementing these recommendations, there was very little blast damage to the pit walls, allowing a near vertical pit face to develop in the high strength rock. Oversized rock had previously created the need for secondary blasting and handling. The SRK blast recommendations significantly reduced the amount of oversized rock and the associated cost of secondary handling and blasting.

The reduction in the drilling program, and the resolution of pit stability issues with a low-cost blasting plan, compared to a full-scale pit slope evaluation, demonstrated SRK's commitment to providing the most efficient solution to our clients' complex problems.

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Recent photo of Barton Pit

Economic success in underground soft rock mining

The economic success of industrial mineral projects, such as potash, often depends on recovering high tonnages at low cost. These deposits are often tabular and, are subjected to the full weight of the overburden, are of relatively low strength, which makes underground high extraction problematic. Most of the tools and techniques available to the mining and rock mechanics engineer are based on the experiences of practitioners in hard rock mining. While a good starting point, these experiences often do not account for the unusual physical properties of soft rock that lead to adopting a conservative design.

The normal stresses of mining can exceed the uniaxial compressive strength of soft rock even at shallow depths, and excavations based on criteria accepted in hard rock mining inevitably fail. Instead, such excavations must be modified to allow the controlled yielding and displacement available with alternative mining methods.

The time dependent behaviour of many soft rocks can be taken advantage of by allowing creep deformation of the rock with minimal loss of strength. Pillars can be allowed to yield to maintain the safety and integrity of excavations long enough to allow the mineral to be extracted. The mining method chosen must accommodate the large displacements of the rock around an excavation when yielding pillars are used. It is essential to consider the stability of the larger rock

mass located at a distance from the mine excavations, particularly where even minor inflows of water – easily managed in hard rock mining – can result in the loss of a mine.

In concept, the techniques applied to the design of excavations in soft and weak rock are very similar to hard rock design techniques. However, the datasets used to develop the design tools are smaller and, combined with sedimentary rocks' variability, must be used with care. Empirical and numerical design tools developed for excavation design are based mainly on experience gained in coal and potash mining operations and research in nuclear waste disposal. SRK has experience in classifying soft and weak rocks to set the parameters for these tools. Two- and three-dimensional numerical assessments of large deposits can be conducted rapidly using displacement discontinuity methods in the Map3D boundary element code, while more detailed assessments use the FLAC and FLAC3D finite difference codes.

Working within the constraints that the low strength of the intact rock places on mine design, soft rock miners use an approach that will interest traditional hard rock miners as they target resources at greater depths. This is where the economic challenge of excavation design will be critical to success.

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The Jwaneng Mine is situated in the Republic of Botswana, approximately 160 km west of Gaborone. The open pit has a general NNE-SSW orientation, with waste dumps located to the west and the process plant area to the east. The excavation of the Cut 8 pit will remove part of the plant area. The current pit has a depth of 330m while the planned pit will have a depth of 645m. SRK carried out a detailed probabilistic stability analysis of the east slope to optimise the design of Cut 8 and ensure adequate performance of the slope and integrity of the plant installations in its vicinity. The analysis also provided data for a quantitative risk evaluation which will incorporate the impacts of slope failure.

The Jwaneng open pit cuts through Paleoproterozoic-aged sedimentary rocks dipping between 10° and 40° towards the NW. The main rock types are laminated shales, carbonaceous shales and quartzitic shales occurring



Abandoned potash production panel entry, Boulby Mine, UK

Probabilistic stability analysis for pit slope optimisation at Jwaneng diamond mine, Botswana



General view of the east wall of the Jwaneng Mine as it is today with plant installations at the top of the slope

in a complex assemblage of tilted and displaced blocks, with dolomites at the base of the slope. The relatively unfavorable attitude of the strata in the east wall is the overriding geological factor governing the stability of the slopes. For this reason SRK used an anisotropic rock mass model for the stability analysis of the interramp and overall slopes, with welded joint strength in the direction of foliation and rock mass strength in other directions.

The rock mass strength parameters were estimated based on the geotechnical borehole logs and on the results of the laboratory testing program. A comprehensive database with this information was used to characterise the rock mass. Groundwater conditions were estimated from the data collected in piezometers considering different dewatering scenarios. The estimated properties were calibrated with analysis of the current slope geometry.

The slope stability analyses were performed on representative sections of the slope with the Rocscience program Slide. Factors of safety (FoS) were calculated using average Mohr-Coulomb parameters. The analysis of probability of failure (PoF) was done using the "Response-Surface" methodology, considering the rock parameters UCS and GSI as uncertain variables for the probabilistic calculation.

As a result of the study, SRK confirmed the low likelihood of overall failures and low potential of economic impact from these events. The critical areas of interramp stability were identified and flagged for a detailed risk consequence analysis. Finally, key design aspects that need to be re-assessed and upgraded on a regular basis as the mining progresses were identified.

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LUIS-FERNANDO CONTRERAS

Luis-Fernando Contreras is a Civil Engineer with a MSc. in Engineering Geology and over 30 years' experience in projects in South America, the Caribbean and Africa, such as hydroelectric developments, open pit mining, foundations and tunnels. His work covers project development from conceptual and prefeasibility studies, through to detailed design and analysis and risk evaluation studies. He joined SRK in 2000 and was a Partner in the Chilean office until July 2007. Currently Luis-Fernando is a Principal Geotechnical Engineer in the Johannesburg office.



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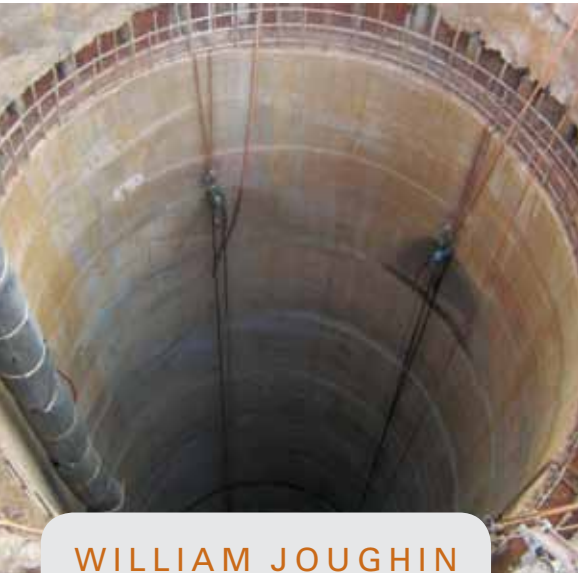
TIM COLEMAN

Tim Coleman has over 15 years' experience in the mining industry, particularly in high tonnage underground mining. He specialises in soft and weak rock; the practical application, selection, testing and design of ground support and reinforcement; geotechnical instrumentation; numerical modelling; the geotechnical aspects of underground mine design, and review, feasibility, risk assessment, and hazard management. His experiences with the challenging ground conditions at the world's deepest potash mine have qualified him to provide practical mining solutions in soft rock.



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Geotechnical design considerations for mine shafts



WILLIAM JOUGHIN

William Joughin is a Principal Mining Engineer with 19 years' experience in mining and rock engineering. He specialises in the design of underground mining excavations and support systems, with a special interest in deep, high stress mining. His expertise includes geotechnical investigation, numerical modelling, seismic analysis, rockburst and rockfall risk analysis. He joined SRK in 1998 and is a Partner in the South African office. William has worked in Africa, North America, Australia and Asia and has 33 publications concerning rock engineering.



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The design, development and operation of a shaft system is a critically important element in mining, and needs specialised technical input.

Experience has shown that the consequences of damage to shaft systems caused by geotechnical factors are serious and costly.

Control of ground conditions is a key factor in the design and sinking of shafts, as these conditions may vary considerably throughout the length of a shaft and require specific technologies to ensure safety and functionality.

Close to the surface, weathered rock and residual soils are common; these materials generally are too weak to carry the high foundation loads exerted by large headgear structures, winder houses and other surface infrastructure. SRK has designed concrete piles to carry surface loads exerted by the shaft headgear. In swelling soils, an innovative double pile system has been used to carry loads and also to prevent soil pressure from damaging the infrastructure.

Ground water often affects upper areas of the shaft and must be controlled by grouting to prevent water from entering the shaft, or by drainage systems built into the lining structure.

Natural breaks in the rock, such as joints and faults, affect the behaviour of the rock mass at shallow and intermediate depths (down to 1,000m below surface). Dolerite sills encountered near surface pose their own problems; they tend to break up into small blocks. Often, around 1000m below surface, the stresses that exist naturally in the ground become large enough to begin to induce additional fractures in the rock mass.

Simple support systems – like rock bolts or split sets, wire mesh and shotcrete – are adequate to protect the workforce involved in sinking the shaft under these conditions. A monolithic concrete lining, usually 300-500mm thick, gives permanent support and carries the fastening systems for buntons, pipework and electrical cable bundles. It also seals the rock and prevents weathering and deterioration over the planned operating life.

Geotechnical investigation for Kwatebala copper open pit, DRC



Concrete piles in residual soil to carry the headgear foundation load and provide support during sinking
Left: Mini piles in soils above concrete lining

Certain weak geotechnical zones exhibit time dependant behaviour and can deform excessively (squeezing) when the shaft experiences stress changes during its life. This squeezing can cause severe failure of the lining. SRK has designed and implemented a support system which can accommodate large deformations in the shaft barrel and maintain serviceability of the shaft.

SRK has developed a systematic design process during the sinking of several shafts, which incorporates experience gained from rehabilitating existing shafts. The design process comprises gathering data from borehole cores and mapping of exposed rock; analysing this data to assess the rock mass response to excavations; assessing the possible modes of failure; analysing excavation and support designs, through to monitoring the implementation of the design.

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Kwatebala is located 12km west-northwest of Fungurume in the Katanga Province of the Democratic Republic of Congo. The topography of the area is characterised by gently rolling hills with pronounced ridges which are frequently associated with copper mineralisation. These ridges have areas of open grassland, known as copper clearances, but are mostly covered with moderately dense bush. Kwatebala is a 1900m long east-west trending ridge that rises from the surrounding valleys to an altitude of 1503m. Before mining began, the hill was covered in grassland with some surface exposure and trial pits, trenches and adits from previous exploration.

Extensive development now includes the construction of the plant, tailings storage facility, storm water dams, waste rock dumps, stockpiles and a mine slope consisting of three exposed benches.

The anticlinal ore body is mined using a Vermeer continuous miner and leaving a central waste portion as high walls; the waste rock is drilled and blasted. The ore material supplied to the plant is sufficiently well fragmented while reducing the disturbance to the rock mass.

The parameters of rock mass strength used in the stability analysis were derived from laboratory tests of representative samples of core taken from selected boreholes during the exploration drilling program. This data is continually updated as samples are collected and tested in ongoing quarterly audits.

The stability of the slopes were characterised “Dry” and “Wet” based on piezometric data gathered from the 2007 groundwater study.

The slope stability analyses were performed on representative sections of the slope with the Rocscience program Slide and Phase². Factors of safety (FoS) were calculated using average Mohr-Coulomb parameters. The analysis yielded acceptable FoS and slopes with a low Probability of Failure. Kinematic analysis indicated that stability would be governed by structures rather than material strengths.

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NOEL SMITH

Noel Smith graduated from the Nelson Mandela Metropolitan University in 2001 with a BSc (Hon) in geology. He worked as an offshore geologist onboard the MV Zacharias diamond exploration vessel off the coast of Namibia before joining Baker Hughes Inteq as a surface logging specialist. Noel began his Rock Engineering/Geotechnical Engineering career with AngloGold Ashanti in 2004. After three years, he joined SRK Consulting's Johannesburg office on the “Rocks” team, involved with feasibility studies, core logging, due diligence studies and support auditing.



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Kwatebala open pit with benches exposed in central waste portion

Auditing the ground control management plan

SRK has developed an audit procedure for Ground Control Management Plans (GCMP) designed for open pit and underground operations. The audit procedure is based on guidelines provided by the Western Australian Department of Minerals and Petroleum (DMP), published in 1997 and 1999, relating to geotechnical considerations for both open pit and underground operations. The original intent of the guidelines was to “provide examples of good geotechnical engineering practice and assist mining operators in achieving compliance with the Mines Safety and Inspection Regulations 1995 (MISR 1995).”

This procedure was developed as a service to clients who require their GCMP documentation and implementation process be audited to ensure compliance to industry standards. The procedure is designed to evaluate and benchmark the GCMP plan consistently and satisfy legal requirements.

The DMP department recognises that mining experience and professional judgment in geotechnical engineering are not easily quantified, but can contribute significantly to formulating various solutions to a particular mining problem. Management is required to recognise, identify and address the geotechnical issues that are unique to their mine, using current geotechnical knowledge and tools.

This approach provides a methodology, checklist and assessment process that auditors can follow when evaluating a client’s GCMP. Since operations can have unique geotechnical issues, certain aspects on the audit form may not apply; auditors use their judgment to include any additional geotechnical aspects identified on the specific operation.

Auditors can use this checklist to ensure that all aspects required are addressed consistently.

The aims of the GCMP Audit are to:

- Provide the client with a systematic evaluation of the current effectiveness of their GCMP and level of compliance
- Provide an action plan or recommendations to address any gaps or deficiencies

The audit process covers:

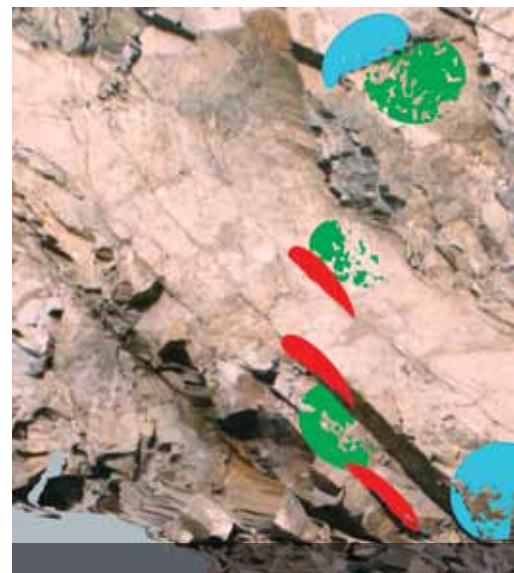
- Life of mine planning
- Geological structure and rock mass parameters
- Blasting considerations
- Excavation or pit design and controls
- Ground support reinforcement
- Hydrogeological considerations
- Monitoring
- Risk management
- Personnel responsibilities

The auditor rates specific questions in each section for compliance and notes any comments and supporting evidence needed or provided by the mine site. Each section is rated according to standard definitions.

Following the audit, the client receives a report highlighting the level of compliance of their GCMP plan and the effectiveness of the controls; and an action plan with priorities addressing areas requiring action.

The intent of this audit procedure is to provide transparency and identify any deficiencies or vulnerabilities in the current GCMP. In the long term, this process will encourage self-management and auditing of ground control-related risks, which typically improve performance.

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Following a multi-bench structural instability along the primary haul road for an operating open-pit copper mine, SRK was tasked with rapidly evaluating geologic structure in the area and subsequently assessing pit slope stability. It was important to determine whether significant pit slope design modifications were necessary for further mining and whether safe transport through the area would be possible.

Given the critical time frame and high risk associated with field mapping near the area of instability, SRK employed remote data collection techniques to characterise geologic structure from a safe distance. Pit walls were scanned using an I-Site 4400CR laser (LiDAR) scanner, automatically integrating high-resolution digital images with detailed 3-dimensional point clouds. Approximately 50,000m² of pit wall were scanned from three primary setups covering four mining bench levels.. The total time required to complete the scanning, including data post-processing, was approximately 8 hours.

Rapid characterisation of slope instability using LiDAR



Typical 3-dimensional bench face model obtained using LiDAR. Digitised structures

Using the Vulcan Geotechnical Module, details of rock structure were digitised directly into an electronic database exported for analysis. The parameters collected in the customised geotechnical database for each of the approximately 400 discontinuities digitised included discontinuity type, coordinates (easting, northing and elevation), orientation (dip and dip direction), length, spacing and termination (single, double or none). The use of these techniques also allowed accurate modelling of several major (pit wall scale) structures. Structural characterisations based on the LiDAR scanning were ultimately confirmed with field reconnaissance.

A sufficiently large sample of the discontinuity population acquired from the LiDAR scans enabled SRK to develop a representative geotechnical model. Statistical datasets were analysed using stochastic simulations of discontinuity orientation, strength and persistence to determine the probability of similar instabilities occurring within the existing bench design and wall orientation as

excavation progressed. Approximately 3 days were necessary to digitise discontinuities and analyse datasets.

Given the variability in geologic structure, SRK determined that bench scale stability could be significantly improved by implementing relatively minor changes to the pit design. Specifically, rather than continuing with a curved wall, which oriented a significant portion of the wall in the newly identified adverse direction (relative to rock structure), the design was modified to include two linear walls with an obtuse “corner,” effectively eliminating the portion of the wall oriented in the adverse direction and, consequentially, reducing the likelihood for reoccurrence of the same mode of instability. Mining of the remaining pit wall has been completed without further such instances of instability.

In this application, LiDAR provided several advantages over conventional field sampling techniques including the ability to acquire comparatively

MICHAEL LEVY

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experience in civil and mining geotechnical projects. Experienced in soil and rock mechanics engineering, he specialises in the analysis and design of open pit slopes including statistical characterisation of geotechnical data and probabilistic modelling. He has managed and supported geotechnical projects throughout the U.S., Canada and Mexico, as well as Central and South America.

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large and accurate data sets quickly and with limited exposure of personnel in areas that would otherwise be unsafe and inaccessible. Directly digitising the data into electronic format also eliminated data input steps and their potential source of error. Above all, LiDAR proved a useful and efficient tool for collecting objective rock mass information which can supplement the subjective observations and assessments of the geotechnical engineer.

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GRAHAM HOWELL

Graham Howell is a Principal Geotechnical Engineer with over 35 years of experience in civil, structural, mining and slope engineering. He specialises in soil/rock structure interaction.



Graham holds a PhD in numerical methods with research interests in applying statistical and probabilistic methods in engineering. His recent projects include planning numerous mining shafts in soft unconsolidated soils, solving slope/earth retaining problems. Since joining SRK in 1985, he has worked from the Johannesburg office on projects in Africa, North America, Europe and Australia.

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Slope stability – fundamental concepts



The remnants of a failed gabion wall

RYAN CAMPBELL

Ryan is an Engineering Geologist in SRK Vancouver's Mining and Geology Division. Since joining SRK in 2004, Ryan has concentrated on geotechnical investigations for open-pit and underground mine development and decommissioning.



His technical strengths are in rockmass characterisation and structural geology for open-pit optimisation and underground mass mining studies, especially in block cave and sub-level cave mining, with experience in technical and project management roles in both greenfield and active mine sites in China, Africa, Australia, Central and South America, and Canada's north.

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Despite the widespread availability of software programs using sophisticated numerical methods, the physical principles of slope engineering should not be forgotten. Simple, well considered engineering judgment based on fundamental principles, which identify all potential mechanisms of failure and account for the stability of each mechanism in the design, are critical.

Recently, SRK was involved in reviewing the design of a 15m high gabion structure that collapsed. The gabion had supported a crusher terrace for the mine. The potential failure mechanisms included toppling/rotation, sliding, deep seated slip circle, bearing and wedge failure. The designers had used software that only considered horizontal sliding, and circular slip failure. The wall was built on rock and the lower section was doveled, making slip failure unlikely, while bearing failure and horizontal sliding were within the bounds of acceptability, but the wall still collapsed. The reason SRK identified was that the software interpreted the gabion structure as an infinitely strong 'monolith' which did not allow internal diagonal

failure. But the planar wedge failure mechanism was "plane" to see on site. This is a clear example of using software that was inappropriate for the task. Simple hand calculations identified the potential flaw immediately. Subsequent numerical analyses using Slide and Phase² confirmed the failure mechanism.

Whenever slope stability is being assessed, the concept of demand versus capacity of the structure must be continually considered. Demand is the loading action applied by gravity through the mass of the material being retained and includes the water, dynamic and seismic effects. Capacity is the internal strength of the material or structure to resist those loads. Both the concept of Factor of Safety and Probability of Failure are derived directly from these terms. The factor of safety is the simple ratio between capacity and demand calculated for defined values. Since the 17th century, engineers have calculated the strength (capacity) of material with given or defined properties, and assessed the load (demand) imposed, to make sure the capacity exceeded demand so the

Weathered rock masses



structure was deemed acceptable.

The probability of failure is a far more powerful concept based on the difference between the fundamental statistical variability of capacity and demand that strives to answer the question: what is the probability that demand will exceed capacity from all possible values of the intrinsic variables?

Closely allied is the concept of risk. Increasingly, clients want to know the risk of their structure failing, including the concepts of voluntary and involuntary risk. Involuntary risk applies to civil structures used by the public, while voluntary risk applies to mining operations. Risk and probability techniques investigate and assess these consequences.

Employing fundamental concepts of probability of failure, factor of safety and risk are obligatory in design. SRK personnel are proficient in all these concepts and regularly bring them to bear on our projects.

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SRK's rock mechanics engineers have recently undertaken open-pit design studies for rock masses hosted within saprolites and highly weathered bedrock. One such example is Oromin Explorations Ltd. Sabodala gold project in Senegal. Since 2006, SRK has designed a series of field programs to satisfy geotechnical, structural and hydrogeological objectives for scoping, pre-feasibility, and feasibility studies.

Geologically, the project is characterised by steeply dipping, shear-hosted gold veins set within Precambrian greenstones. During early study stages, a vertical zonation of material properties was identified within the weathered profile. The degree of weathering was found to decrease systematically near surface from completely weathered soil through a transitional zone into a thin fracture-controlled weathered horizon above fresh rock. This zonation, separated into unique geotechnical 3D domains, has been determined to affect the behavior of the rock mass. Accurate characterisation of the weathered rock mass is vital not only for slope stability, but also for trafficability and metallurgical requirements.

The SRK structural understanding indicates that most brittle features occur along reactivated structures associated with earlier ductile shear zones. In these areas, the weathered profile (i.e. saprolite and saprock) often extends beyond 75m in depth; much deeper than typical background conditions distal to the shear zones.

In-situ sampling using clear plastic liners, as well as more traditional Shelby tubes, has provided the best means of obtaining relatively undisturbed samples of the weathered horizons.

Reverse circulation (RC) drilling has been used to complement geotechnical information gained through in-situ sampling, mapping and diamond drilling. The RC option has proven to be a rapid, cost-effective approach for characterising the weathered profile along proposed pit walls where existing core drilling intercepts are sparse. RC results have been used to calibrate adjacent diamond drillholes from the pre-feasibility geotechnical program. This correlation has improved the confidence of the various geotechnical domains within the weathered profile.

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Geotechnical drilling through saprolite at Oromin's Sabodala project

Slope design in challenging conditions at El Teniente, Chile

The El Teniente mine complex, owned and operated by the National Copper Corporation of Chile (CODELCO), is located about 80 km south of Santiago, Chile in the Andes Mountains, at 2,500 meters above sea level. The complex includes a series of underground operations that use block caving and panel caving to extract copper.

To provide flexibility in production rates and for strategic planning purposes, CODELCO is currently evaluating the Rajo Sur project at a pre-feasibility engineering level. This project involves developing and operating an open pit near the southern border of the subsidence crater. The close proximity to the subsidence crater makes Rajo Sur a challenging project, and a clear example of open-pit mining in difficult ground conditions.

To evaluate the mechanical stability of the open-pit walls, SRK studied approaches involving bench-berm design, and slope stability, at bench, inter-ramp and global scales, based on limit equilibrium models and finite difference elasto-plastic continuum models. SRK developed a complex three-dimensional mechanical model to assess the influence of subsidence cracks and abrupt topography on the stability of the planned open-pit walls, particularly in the southern boundary of the crater.

Since subsidence due to underground caving is a dynamic process, and the crater boundary location would have a pronounced effect on the stability of the planned pit walls, SRK has recommended studies which include different scenarios of underground development.

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ESTEBAN HORMAZABAL

Esteban Hormazabal is a Mining Engineer with a Master's degree, specialising in applied hydrogeology; he is head of Mining Geotechnics for SRK (Chile). With



14 years' experience in geotechnical engineering and rock mechanics, he analyzes and designs underground and surface excavations, using 2D and 3D modelling, stability analysis and slope design for open-pit slopes, waste dumps and heap leach pads. He has worked on geomechanical assessments and technical reviews of numerous projects across Latin America.

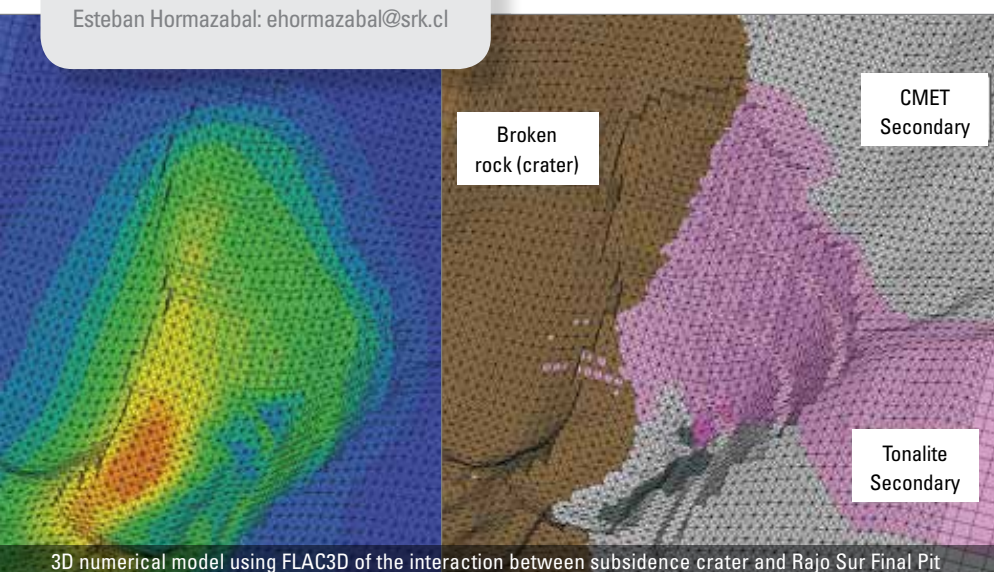
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At the Venetia diamond mine in northern South Africa, owned by De Beers, the country rock structural geology has been under investigation since before the mine was opened in 1994. This includes academic research alliances to better understand the complex structural deformation history of the mine area. These alliances are with the University of Johannesburg, Tect Consulting and more recently the University of Pretoria.

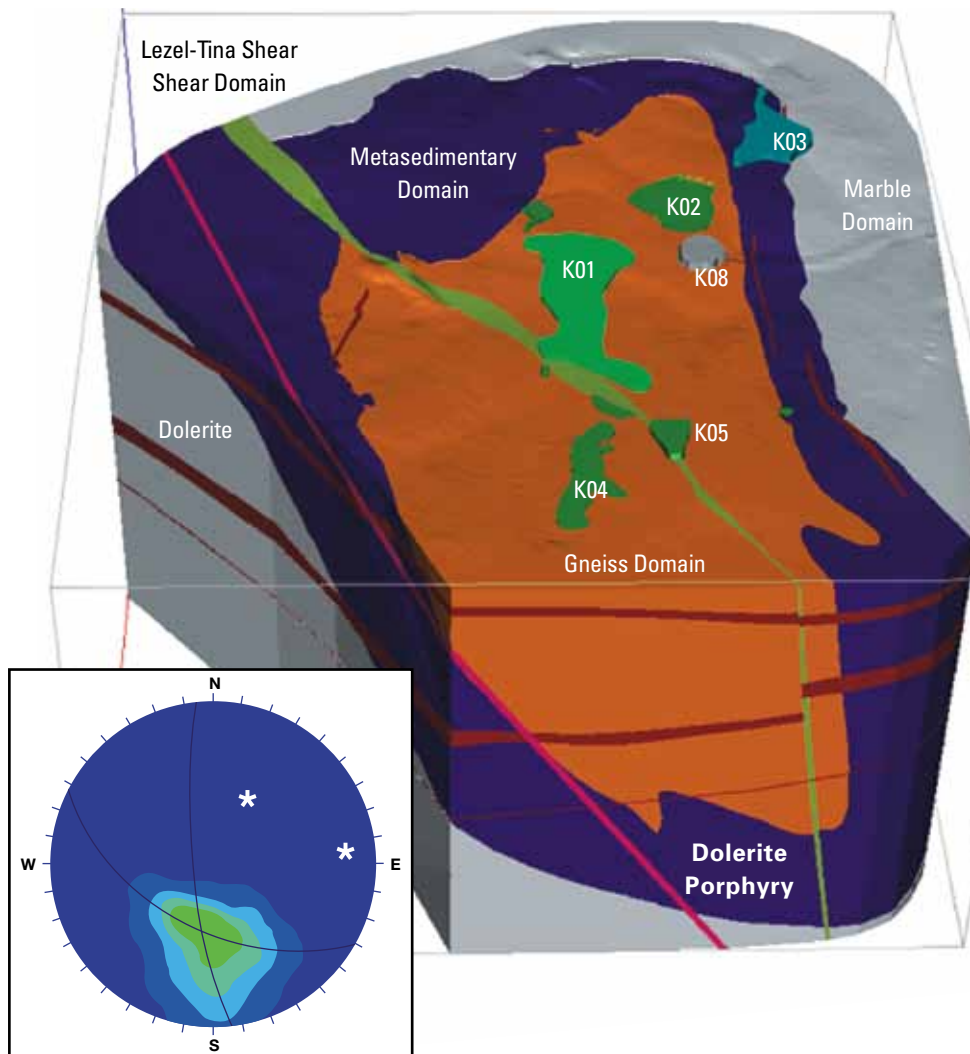
It is located within the Central Zone of the Limpopo Belt, which is a multiply-deformed orogenic zone between the Kaapvaal and Zimbabwean cratons, formed during the Archean and Paleoproterozoic. At least four phases of ductile deformation and an unconstrained number of brittle deformation events are now recognised. The dominant S_2 foliation in the gneissic rocks has been the focus of structural investigations because of its strong influence on the anisotropic strength characteristics of the rock mass within the open pit and the effect of this on the slope stability and slope angles.

The S_2 foliation is deformed by two phases of folding that complicate interpretation (see stereonet inset). The most obvious structural geometry is an eastward plunging synform, the southern limb of which dips between 35° and 55° towards the north. The southern open pit slope design is heavily dependent on the dip angle and projected dip behind the slope, and has been the subject of advanced analyses in probabilistic risk analysis by De Beers and SRK Consulting (South Africa).

More recently, the focus has shifted to underground mine design and the objective of trying to interpolate structural geometries, including foliations and lithological domain contacts, to depths of 1 km. A database



Integrating structural geology and geotechnics at Venetia diamond mine



of over 950 drill holes, with at least 108 orientated cores, currently exist that aid the construction of three-dimensional computer models representing structure and lithologically controlled geotechnical domains.

De Beers logging standards include detailed structural data, with mineral lineations. Comprehensive pit mapping by Tect Consulting combined with drill hole data has allowed De Beers and SRK to construct a 3D model that predicts the dominant structural geometries at depths below the pit.

In particular, a 3D representation of the lineation trends and plunges maps out the dominant fold geometries or foliation patterns that need to be considered in geotechnical design and numerical strain models. SRK continues to be involved in open pit and underground design, and in developing the structural understanding of the country rock in order to reduce geotechnical risk.

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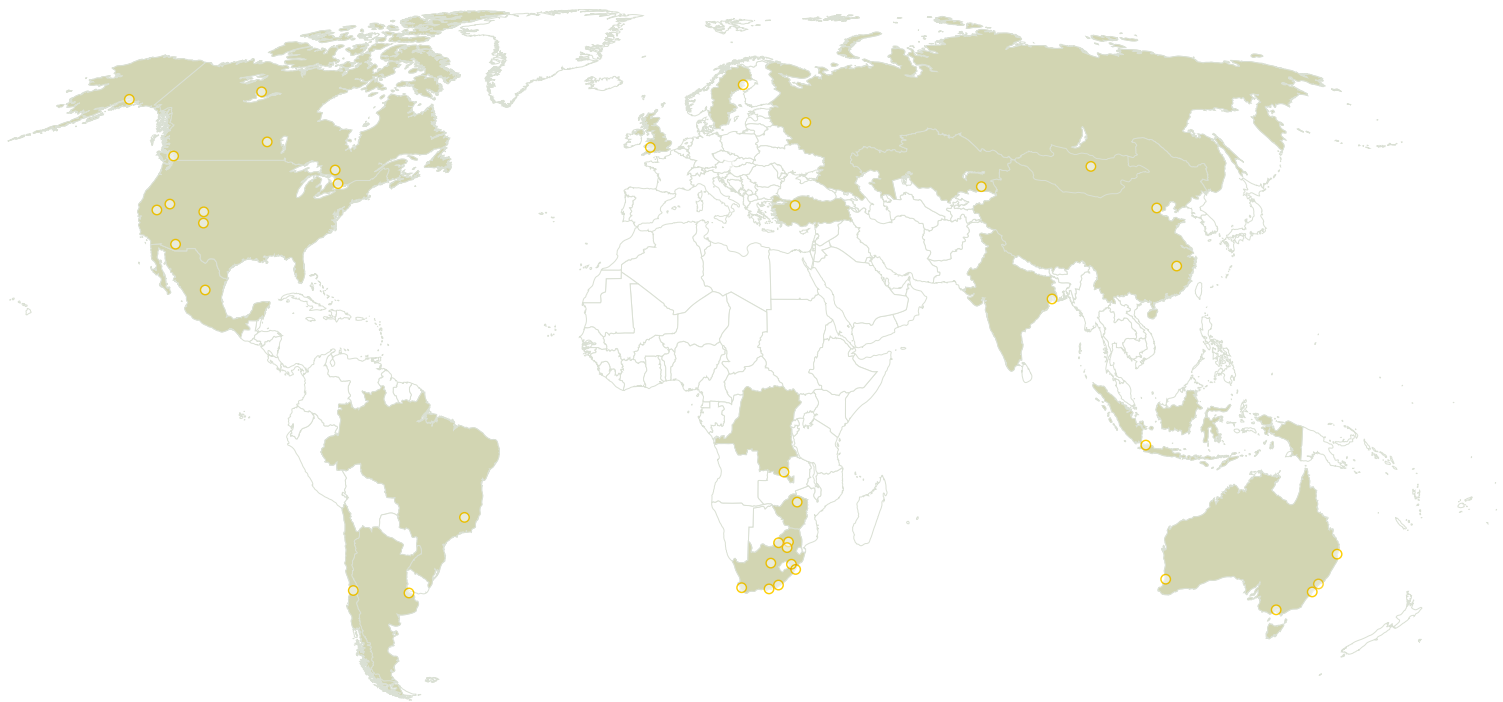
Wayne Barnett, PhD, based in SRK's Vancouver office, has 13 years of experience in the mining and exploration industry. He was employed for 8 years as a mining operations geotechnical engineer and applied structural geologist. Subsequently, he performed the role of consulting structural geology specialist in mining and exploration, including providing review and recommendations on mine geological and geotechnical data collection practices. He is a geological modelling expert, and uses a variety of specialist software for geological interpretation, modelling and analysis. Wayne has significant experience in geotechnical and structural drill core logging and open pit and underground mapping, including geological data management, data QA/QC and statistical analysis of structural data. He is experienced in integrating structural, lithological and geotechnical data to define practical rock mass domains for mine design purposes.



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Above: 3D Isometric view eastwards showing the simplified Venetia lithological domains, the boundaries of which are strongly determined by structural geometries.

Stereonet inset shows contoured poles to all S_2 foliation, with two dominant lineation trends indicated with an asterisk.



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