

## Fruta del Norte: integrated rock mass characterisation

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**The Fruta del Norte project is an undeveloped, underground high-grade gold epithermal deposit in the southeast of Ecuador.**

The deposit will be accessed via twin declines, and ore will be recovered using a combination of transverse open stoping with paste-fill, and drift and fill with cemented rock-fill, catering to the variable ground conditions and geometry of the orebody. SRK has been involved with the project in various capacities since 2009, and in 2015 assisted Lundin Gold with structural and alteration geology, rock mechanics, hydrogeology, and geochemistry aspects for their Feasibility

Study. SRK was given the opportunity to review historic work, and guide the collection and quality control of parameters from drill core. One of the more critical aspects of the data collection from drill core logging was related to alteration geology: time dependent degradation of a dominant sedimentary package, and identification of damage zones related to structure and geomechanically adverse alteration.

*...continued*

## Fruta del Norte (*continued*)

During the 2015 field investigations, SRK completed an extensive alteration

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Bruce, MSc. Eng., P.Eng, FSAIMM, is a Principal Consultant with over 25 years of experience, specialising in mining rock mechanics; he leads the Vancouver mining rock mechanics group. Bruce worked in mining operational rock mechanics from 1989, in both hard rock open pit and underground operations, including gold, copper and iron ore, before joining SRK in 2002. Since then, Bruce has undertaken operational support/project evaluations in a number of open pit/underground mining operations/projects, in Africa, Europe, Asia, North and South America. His strong experience includes operating open pits under difficult mining and stability conditions (failures) and underground mining in weak ground conditions.



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survey to characterise the nature and extent of the degradation. Basic but effective data collection practices, including graphic re-logging of historic core for the presence of hydrothermal alteration, degradation, and structure, and core photo reviews were complemented by Terraspec visible-infrared spectrometer surveys.

Additional protocols were established to assist project geologists in recognising hydrothermal, breccia and vein-related alteration products. Leapfrog Geo 3D software was then used to model confidence envelopes illustrating the extents of the degradation zone, which formed one component of the final geotechnical model for the project.

Identifying the root cause of the degradation and its impact on geomechanical and geometallurgical properties had a significant bearing on rock mechanics, water quality, water management, and ultimately mine planning aspects of the project.

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Drive supported with bolts and mesh

The objective of installing ground support is to mitigate the risk of injuries and costs associated with rehabilitating excavation damage and associated production downtime. It follows that the greater the likelihood of stress damage or rockfalls, due to the inherent rock mass conditions, the more work is required from the support system. In addition, the exposure of personnel in these excavations and the quantity of production serviced by the excavation will significantly influence the support requirements.

While support systems have evolved over many years to meet these demands and experienced rock engineering practitioners generally apply appropriate engineering judgment, most design methods are based on a simple factor of safety and do not account for proper risk evaluations. In nature, rock mass characteristics are variable and considerable effort is required to understand the variability, particularly when the geology is complex. Stress fields are often unknown or are



Planned underground mine design for the extraction of the Fruta del Norte deposit



## A risk-based approach to support design



Jointed bounded rockfall

Stress damage

simply inferred from one or two stress measurements. Model bias and other uncertainties also need to be considered.

SRK, in conjunction with the Australian Centre for Geomechanics, has developed a risk-based approach to support design, which takes the variability of rock mass conditions and uncertainty into consideration. The approach includes methods of data collection and determining the variability of inputs into the subsequent analyses. Two potential failure modes are considered, namely joint-controlled rockfalls and stress damage.

The probability that rockfalls of different sizes occur in a given length of tunnel is estimated using a statistical block stability method. A simple discrete fracture network is used to generate blocks, which are analysed using limit equilibrium methods in a Monte-Carlo simulation. The results are presented as a frequency distribution of potential rockfalls for a range of rockfall dimensions.

Stress damage can be analysed using elastic and elasto-plastic numerical methods and excessive stress damage can be represented by the depth of

failure or deformation exceeding a prescribed serviceability criterion. Monte-Carlo simulations are not practical if the analyses are complex and time consuming. Probabilistic methods, such as the Response Surface Method or the well-known Point Estimate Method, are then used to estimate the probability of excessive stress damage. A probability distribution of the length of the tunnel that exceeds this criterion is then determined by applying a binomial distribution.

The potential financial losses due to excavation damage are determined by estimating the rehabilitation time and production downtime based on the mining layout and site specific considerations. These are presented on a typical risk matrix for decision making.

The risk of injury is determined by assessing exposure of personnel and spatial coincidence. In this way, both the economic and safety risks are evaluated. Better ground support systems can be introduced to mitigate the risks, if required.

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### WILLIAM JOUGHIN

William spent the past 25 years in underground rock engineering, working on South African deep-level gold mines before joining SRK in 1998. He specialises in underground rock engineering investigation and design, with expertise in numerical modelling, selecting mining methods, designing excavations, investigating shaft stability and geotechnical risk, while providing consultancy services for mining projects on five continents. William is Vice President, African Region, International Society for Rock Mechanics. He received the Southern African Institute of Mining and Metallurgy's gold medal and the Alec Wilson Award for outstanding papers.



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## Slope design at Cuajone pit, Peru

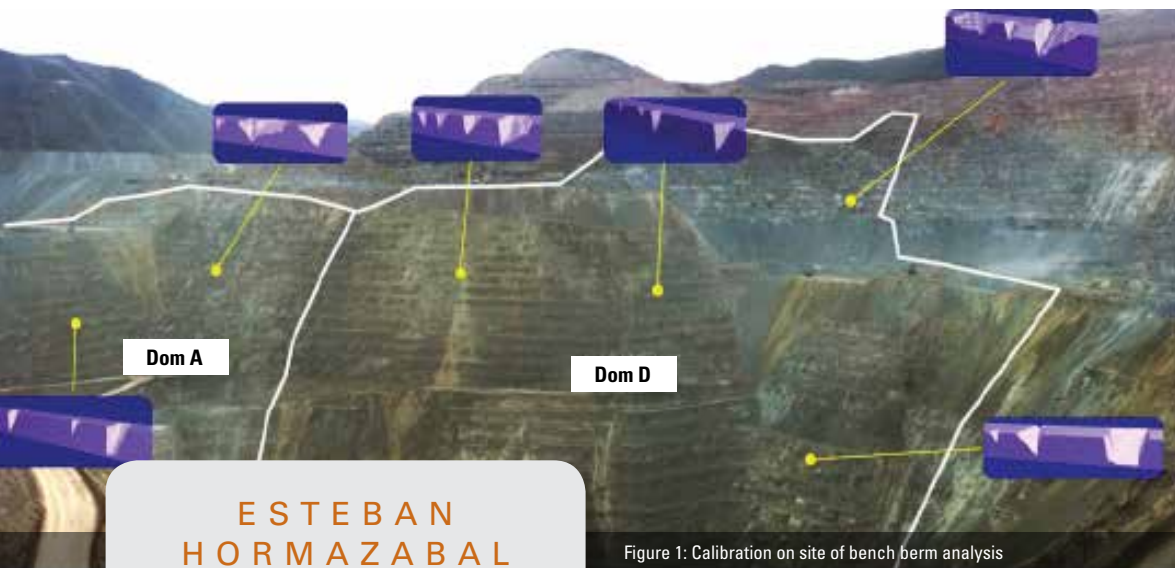


Figure 1: Calibration on site of bench berm analysis



Figure 2: East wall failure (D15) at Cuajone mine in 1999

### ESTEBAN HORMAZABAL

Esteban, a Civil Mining Engineer with a Masters in Geophysics, specialises in applied hydrogeology. He has 22 years of experience in geotechnical engineering, rock mechanics and geotechnical instrumentation, leading important open pit and underground mining projects in Chile, Colombia, Mexico, Peru, Argentina, Uruguay and Russia. In addition, Esteban is an expert in analysis and geomechanical design of underground mining and surface excavations using 2D and 3D numerical modelling, stability analysis and slope design in open pits and waste dumps.



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**SRK Chile's Rock Mechanics team** completed a study of the slope design at Cuajone pit. The Cuajone porphyry copper deposit is located on the western slopes of Cordillera Occidental, in the southern Andes of Peru. The current pit measures about 2.5km east-west, 3.0km north-south, and has a maximum depth of 950m. Mining by open pit methods commenced in 1976 and has continued since then. Ore production is 90ktpd.

SBLOCK software (Esterhuizen, 2004) was used for the bench berm design. This software uses the Key Block principle (Goodman & Shi, 1985) and joint set statistics to simulate a large number of potential blocks in open pit benches. For a given structural domain, several slope orientations were conducted and the results matched with the bench behaviour. A 3D plot of the benches located failures with SBlock software. Figure 1 presents a visual correlation with the observed frequency and type of failure noted in the pit benches.

The failure volume and bench widths predicted by SBlock agree sufficiently with the observed instabilities of the slope benches. This initial study validated the methodology, and further bench stability evaluations will be undertaken using SBlock, where the minimum berm width required for single benches (15m) ranges from 6.5 to 8.0m.

At Cuajone, past failures provide an excellent basis for designing the proposed push-back or final pit design. The geological and structural information holds good data for confidence in design. Since the past raised doubts about the design, analysing these failures was essential to provide the confidence needed to proceed with the next push-back.

Cuajone's history displays a number of classical failure mechanisms: large scale wedge failures and circular arc failures in highly altered soft rock. In mid-February 1999 a failure of approximately 12 million tonnes occurred (Figure 2). The failure



# A smart data management tool for rock mass classification



is typical of a soft rock circular arc failure mode, with shear strength controlled by cohesion rather than friction. There is strong evidence that groundwater pressures played a significant role. Immediately before the failure, there was a period of heavy rainfall.

As part of the slope design program and slope optimisation for the next push-back, the past and present performance of the pit slopes were evaluated to assess the potential behaviour of future pit expansion. A geomechanical assessment is underway to evaluate the stability of the walls for expansion over the next 15 years. A series of geotechnical studies were performed to analyse slope stability, based on limit equilibrium methods, finite element bidimensional numerical models and discrete element tridimensional numerical model 3DEC.

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**F**or any mining geotechnical study, an understanding of the characteristics of the rock mass within which an underground or open pit mine will be excavated is essential. The condition of the rock mass will determine, for example, the maximum stable slope size that can be formed in an underground mine, the rock support requirements for underground tunnels, the primary fragmentation sizing for a caving mine, or the maximum stable slope angle for an open pit mine. The basis of developing this understanding lies with Rock Mass Classification (RMC). Each RMC system uses sets of discrete input parameters – measures for material strength, discontinuity properties, fracture spacing, number of joint sets, water, stress, adjustments for the excavation environment, etc. - which need to be consistently and unambiguously recorded.

As semi-automated Excel spreadsheets used for the collection, storage and manipulation of RMC data have evolved, SRK has developed a comprehensive geotechnical database management system (GTDMS). The system allows for collecting parametric data for the calculation of four main rock mass classification systems: Bieniawski's RMR; Laubscher's MRMR; Laubscher/Jakubec's iMRMR and Barton's Q. It uses MS Excel for data capture and reporting, with MS Access for collation, quality checking, and analysis of the logged data.

The system is fully customisable and can integrate existing data sets. At the start of a project, deposit-specific tables related to attributes such as lithology, alteration, and weathering are created. Project-specific logging codes can also be generated. The RMC's to be used for the project are selected and fields in the database not required for calculation can be switched off and hidden. This initialisation process generates a customised MS Excel logging sheet containing only the fields and the logging codes (using drop down menus) required for collecting geotechnical data appropriate to that particular project,

with built-in quality and error checks. As well as allowing for the collection of core logging interval data, the system also accepts point data into the log from core orientation, geophysical logging, and strength testing. Where core orientation data are present, these are integrated into the interval log to avoid re-counting fracture sets, thus speeding up the logging process.

The system is particularly useful in situations where the client collects the geotechnical data and then provides the database to SRK for interpretation and analysis. SRK will set the system up on site, carrying out customisation and providing training in the use of the system and basic geotechnical logging, if required. The GTDMS has already been used successfully on a number of mining projects. Its primary advantage is the ability to cost-effectively generate a clean geotechnical data set without the need for time consuming error trapping, data validation and verification.

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## NEIL MARSHALL

Neil, MSc, DIC, BSc (Hons), CEng, MIMMM, is a Corporate Consultant with more than 30 years' experience in geotechnical engineering for mining. While consulting, half of his time was spent working in underground and open pit mines in Zambia and Ghana where he held various technical positions. Neil specialises in the geotechnical characterisation of rock masses, open pit slope design, underground mining method design and evaluation, underground support and excavation design and numerical modelling.



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# Potash: data collection and processing

Since 2012, SRK has been working with a major North American producer of agricultural nutrients that owns and operates production facilities in Canada and the United States. SRK has been helping the company's Mine Engineering department to expand their rock mechanics program, with a focus on collecting data to aid decision making for daily operational and long-term mine planning.

## TIM COLEMAN

Tim is a Principal Consultant BEng. (Hons), ACSM, MSc, DIC in SRK's Vancouver office. He has over 19 years' experience in the mining industry with strong operational experience in underground mining. He specialises in soft and/or weak rock; the practical application, selection, testing and design of ground support/reinforcement; geotechnical instrumentation; numerical modelling; and underground mine design and review. Tim has extensive experience in salt and potash operations ranging from 7 years as a Rock Mechanics Engineer at the Boulby Mine in the UK through to projects requiring incident investigation, litigation support, and geotechnical risk assessment.



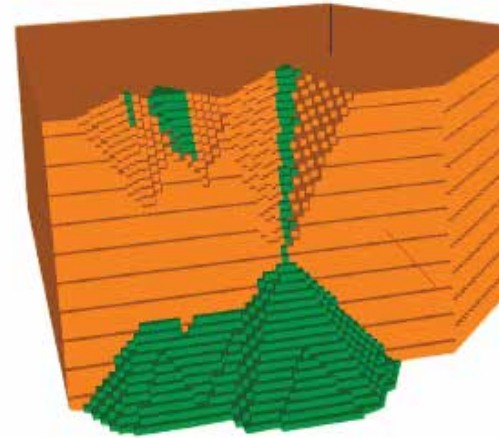
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Because data management and collection methods are integral to this program, SRK has created a centralised database to store the rock mechanics data collected by instruments installed around the mine. This centralised database enables rock mechanics engineers to access the data more quickly and efficiently than if it was dispersed across the instruments that collected it. SRK has also developed a front-end application that queries the data and makes it easy to produce charts that support daily operational decision making.

To save time with data entry, SRK has implemented the Environmental Systems Research Institute's Collector for ArcGIS application. Running on a tablet, this app allows users to record data electronically from rock mechanics instruments located underground, saving office time for data analysis and review. It also enables instrument locations to be represented spatially on a mine plan, making it easy for users to refer to the data collected for each area of the mine. Furthermore, SRK has set up the app to enable users to map geological features directly on a tablet while underground. By eliminating the need for geologists to convert hand-drawn maps into digital maps, they have more time for carefully interpreting the data in the office.

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Figure 2: Interaction of multiple wedges



For the design of a pit wall, several combinations of bench height, bench face angle and berm width may be used to satisfy stability criteria. The bench face angle and the berm width must be chosen to fit the bench stack angle. The berm must also be wide enough to contain the volume of wedge material from the bench faces above, in the event of failure.

In 2006, Gibson et al proposed two equations for calculating the required spill berm width from the wedge failure volumes, which depend on the geometry of the failed material on the berm (conical vs pyramid shape).

This article compares the berm width obtained using the equations developed by Gibson et al and the results obtained using Frac\_Rock, a computer program developed by SRK that uses a discrete fracture network to model the wedge generation and stability.

Based on the results, it seems that modelling the overspill numerically rather than deterministically gives

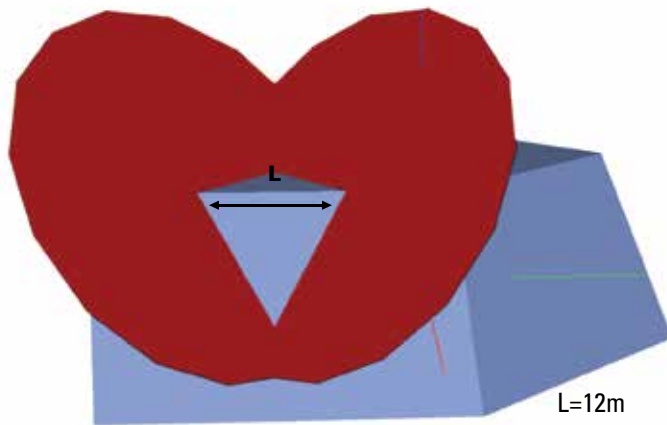


Drilling hole for magnesonic extensometer installation

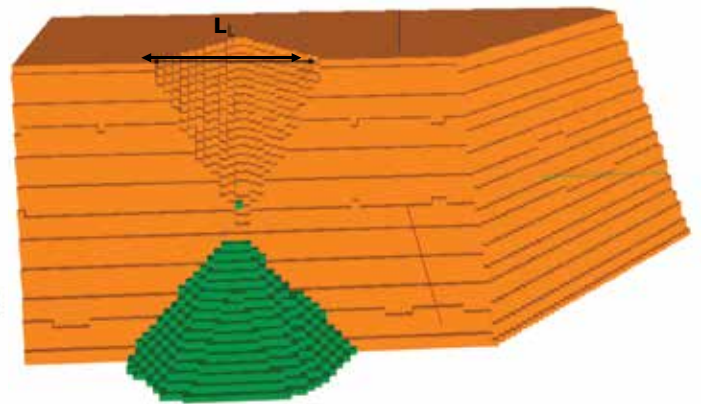
## Comparison of methods for estimating berm widths

**Figure 3: Model of a wedge and failed material calculated with Frac\_Rock**

a) Joints forming a wedge



(b) Wedge failure and material movement



a more optimal answer, even though the equations proposed in 2006 are still valid for preliminary assessment.

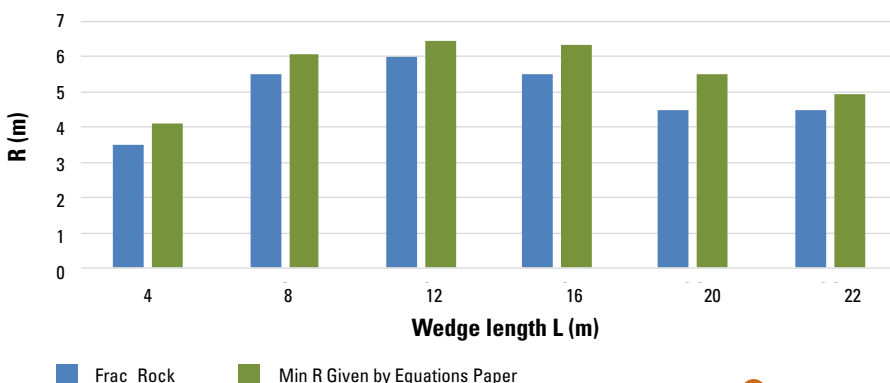
Figure 1 below shows the comparison of berm required to contain failed material calculated using the equations and the Frac\_Rock model, the results indicate the equation may be a conservative way to assess berm width. The benefit of using a program like Frac\_Rock is that the same calculation can be made for multiple interacting wedges like the example shown in Figure 2 above left.

A range of wedges with different sizes were modelled using Frac\_Rock and the volume of failed material was calculated and compared with the volumes calculated using the equations. Figure 3a above shows one of the models and Figure 3b shows the location of the failed material.

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Reference: Gibson, W, de Bruyn, I A and Walker, D J H, 2006. Considerations in the optimisation of bench face angle and berm width geometries for open pit mines, in Proceedings of The South African Institute of Mining and Metallurgy International Symposium on Stability of Rock Slopes, Symposium Series S44 Stability of rock slopes in open pit mining and civil engineering situations, pp. 557 – 579.

**Figure 1: Comparison of berm width required calculated with equations and Frac\_Rock model**



### WILLIAM GIBSON

William has over 30 years' experience in geotechnical, mining and civil engineering projects, and computer program development. His open pit expertise includes slope stability analysis in Chile, Australia and Mongolia, and analysing interaction between open pit and underground mining operations. William analyses slopes and underground excavations on static and seismic conditions, having assessed seismic risk in South and Central America and Canada. His computer programming experience includes analytical programs for rock fall 3D analysis, wedge stability, gravity flow, and generating synthetic earthquakes.



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## LUIS F CONTRERAS

Luis-Fernando Contreras is a Civil Engineer, MSc, Pr. Eng. with 35 years of experience in the field of geotechnical engineering. He has participated in such projects as hydroelectric developments, open pit mining, foundations and tunnels. Luis-Fernando joined SRK in 2000 and was a Principal and Partner in the Chilean office. In 2007 he moved to the Johannesburg office where he is a Corporate Consultant, specialising in quantitative risk evaluation for open pit mining. He is currently researching Bayesian methods to treat geotechnical uncertainty in slope design for his PhD at the University of Queensland.



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## MICHAEL LEVY

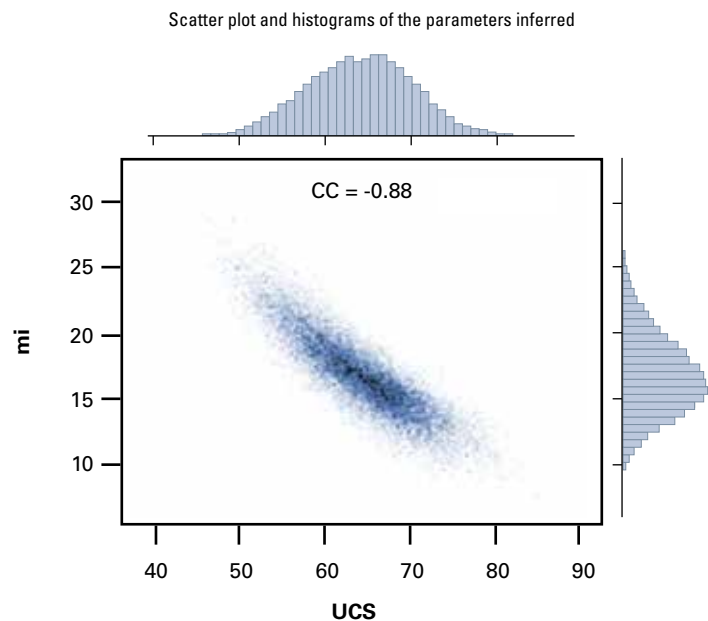
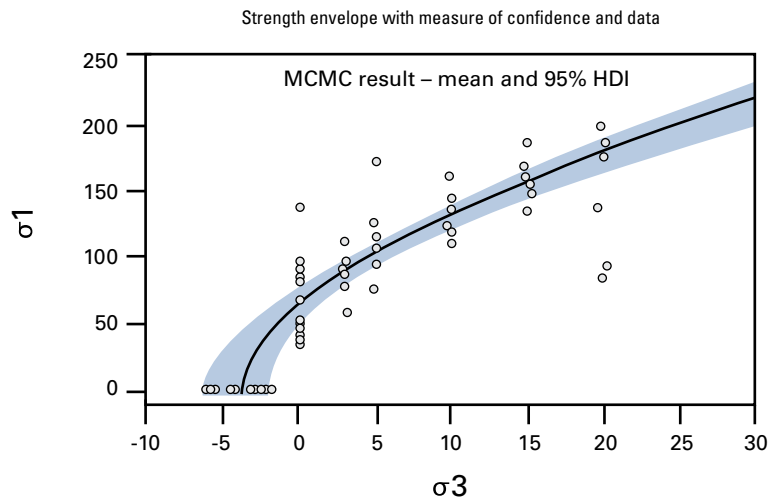
Michael is a Principal Geotechnical Engineer MSc, PE, PG, with 17 years of experience in geotechnical investigation and design, primarily in the mining industry. He is skilled in soil and rock mechanics and specialises in design and management of large open-pit slopes. Michael's technical expertise includes rock mass characterisation, probabilistic slope design, numerical modelling and the geotechnical design of several waste rock storage facilities. He has managed large geotechnical projects for the mining industry throughout North, Central and South America in various commodities. Michael has contributed to numerous feasibility, prefeasibility and conceptual studies, as well as due diligence and independent engineer reports.



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# Treating uncertainty in the geotechnical model for slope design

## Results of a Bayesian analysis to estimate intact rock strength parameters from laboratory testing data



One of the major difficulties encountered by geotechnical engineers is dealing with the uncertainty present in every aspect of the slope design process. Uncertainty is associated with natural variation of properties, and the imprecision and unpredictability caused by insufficient information on parameters and models. Probabilistic methods are traditionally used to account for the uncertainty in engineering design. However, the probabilistic approach as it is currently

used in slope design has drawbacks. The lack of a formal framework to incorporate subjective information, such as engineering judgment and the inability to provide a proper measure of the confidence of parameters inferred from data, are examples of these limitations.

The Bayesian approach is an alternate route to the conventional probabilistic methods used in slope design. The approach is based on a particular interpretation of probability and provides an adequate



## Escobal Mine: mine-scale modelling

framework to treat uncertainty in the geotechnical model for slope design. Methods of Bayesian statistics have been applied in many scientific fields, such as physics, astronomy, biology and social sciences, and in areas of engineering, such as the oil and gas industries and in the dam and foundation design disciplines. However, these methods are not used in geotechnical analysis for mine design where they would be of great benefit.

Probabilistic data analysis using the Bayesian approach involves numerical procedures to estimate parameters from posterior probability distributions. These distributions are the result of combining prior information with available data through the Bayes equation. The posterior distributions are often complex, multidimensional functions whose analysis requires the use of a class of methods called Markov Chain Monte Carlo (MCMC). These methods are used to draw representative samples of the parameters investigated, providing information on their best estimate values, variability and correlations. See the 2 figures to the left. Understanding the concepts behind the various algorithms used to perform MCMC analysis is important to properly assess the quality of results; however, the analyst does not have to develop the software to use the method. Open source packages in various programming languages, already developed by computer scientists and related specialists, have been tested extensively by these communities. These packages can be easily incorporated into ad hoc code for different model applications.

The author is working on a research project aimed at developing a system to quantify the uncertainty in the geotechnical model for slope design using methods of Bayesian statistics.

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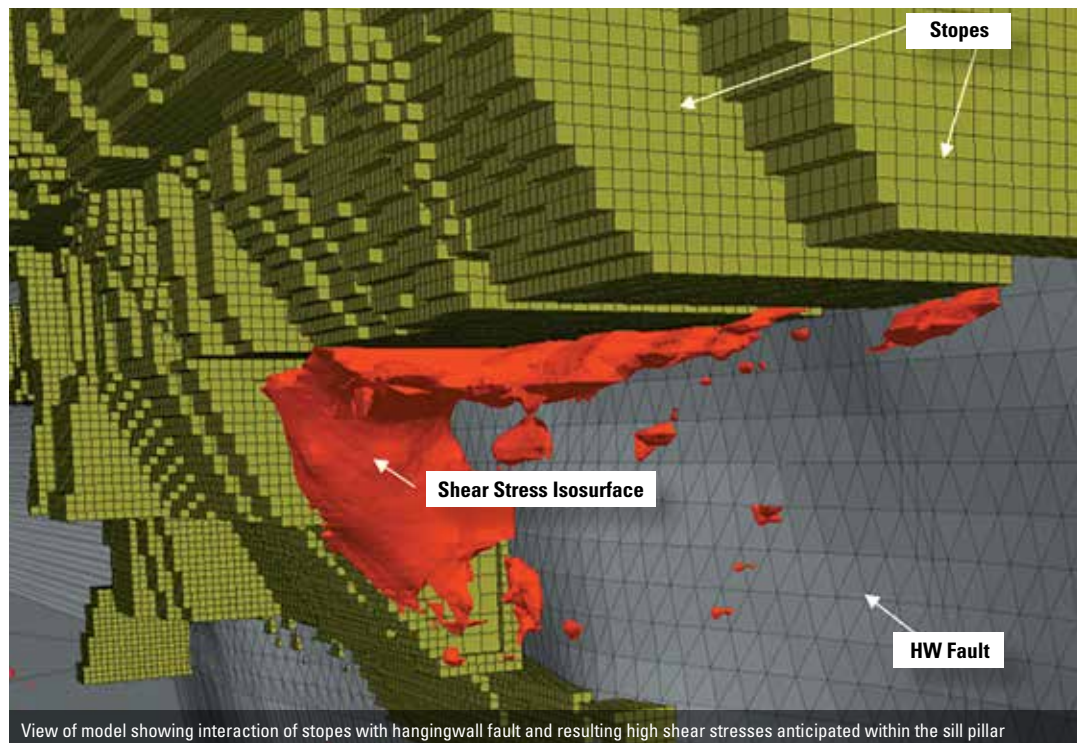
**SRK** conducted a numerical stress analysis to evaluate sill pillar stability for Tahoe Resources' Escobal Mine located in southeast Guatemala. The Escobal mine uses LHOS methods to extract 4,500 tpd of high-grade silver ore. The mineralisation is typically wide with mining widths of up to 55m. The overall depth extends to approximately 1,200m below ground surface. Mining such large open stopes is often challenging due to the location of a major fault zone anastomosing within the hanging wall and mineralisation as well as with elevated horizontal stress conditions.

SRK developed a mine-scale FLAC3D model to evaluate mining-induced stress conditions and deformations as mining approaches a sill pillar that was left during the early stages of mining. An initial simulation was conducted incorporating the as-built mining sequence to date, allowing stress states to develop naturally within the model over time. After further calibrating the model's input parameters to reasonably match observed ground conditions and excavation performance, different

potential future mining sequences were simulated within the model. The goal was to determine the optimal sequence for shedding stresses away from each of the mining areas, long-term infrastructure and access headings.

The results of this analysis indicated that full sill extraction would be unlikely using the current mining method, extraction rate and sequence. It was also determined that rock mass disturbance (i.e. high shear strain and confinement loss) should be expected within the sill. With the results of the model, SRK was then capable of providing the mine with valuable information about the anticipated rock mass and stress conditions within the sill pillar, as well as further guidelines for developing a more suitable mining and backfilling sequence. The modelling also determined that more favourable ground conditions and increased ore recovery could be expected as a result of decreasing the mining rate within the sill area.

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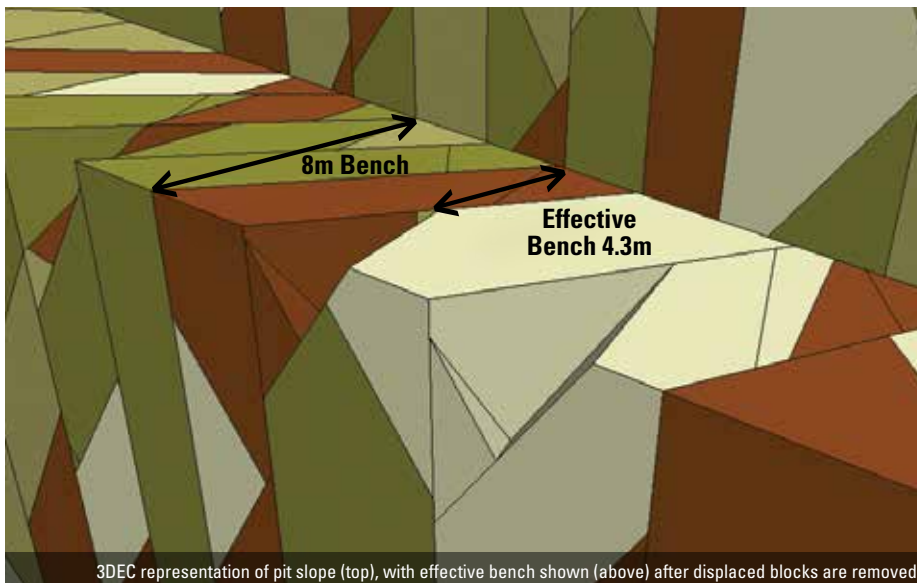
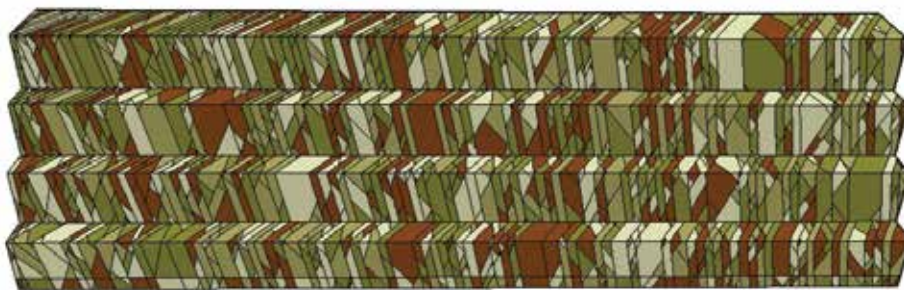
# Simplified 3D modelling of bench-berm design

**E**ffective bench-berm management is critical for safety at operating open pit mines. SRK Vancouver's Geotechnical Group developed a simple and practical 3D modelling tool that can be used to quickly assess the stability of bench scale failures and the minimum berm width within a given design without advanced numerical knowledge. The user inputs basic information on the bench face (height, orientation, angle, and number of benches), rock mass (density), and joint sets (dip, dip direction, persistence, spacing, etc) within a simplified 3DEC code to create the blocks and wedges calibrated from site mapping. With this entry the user can create a discrete fracture network that can be calibrated from known discrete features. Multiple representations of the potential failure blocks are then created from the joint set information on several bench faces to help maximise the inter-ramp angle without being limited by block shape or size. This tool can allow a quick estimation of potential back break, bench face stability,

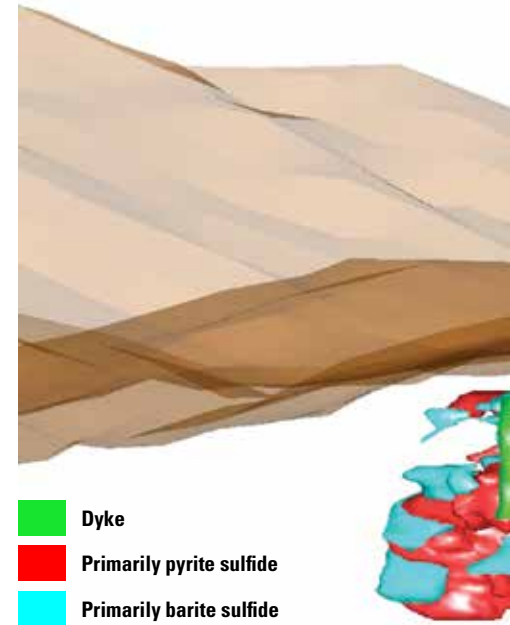
developing multi-bench failure mechanisms and progressive wedges, bench carry capacity, and spill volume.

The main advantages of this approach are: 1) multiple benches can be modelled, 2) the block shape is not limited to a wedge but rather the intersection of measured joints, 3) the program is based on an accepted industry program, 4) bench scale concerns to multi-bench scale instabilities can be modelled in one program, 5) individual blocks can be removed to represent scaling or sliding, and 6) mapped geological features can be generated within the model at their mapped location. Limitations of the approach are: 1) the user must gain access to the 3DEC program from Itasca Consulting Group, 2) model sizes must be kept relatively small to allow for multiple representation, 3) blocks are kept rigid, which does not allow for internal deformation, and 4) breaking of rock bridges is not accounted for.

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3DEC representation of pit slope (top), with effective bench shown (above) after displaced blocks are removed



**T**he Cerro Lindo Mine is the largest underground mine in Peru, currently mining more than 20,000 tonnes/day. The sublevel stoping method was used with paste backfill, which had been experiencing over-excavation issues at the hangingwall and the front wall of the stopes.

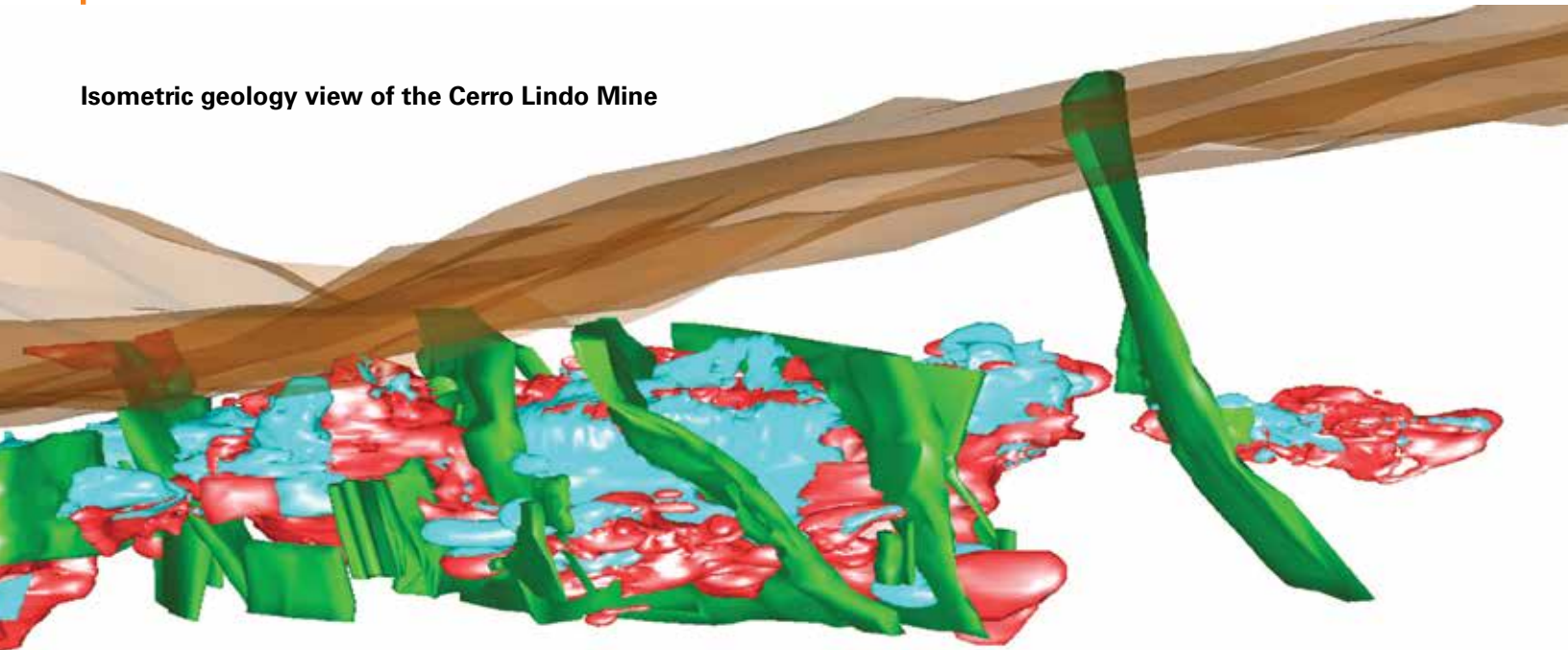
The geology can be described as a volcanogenic massive sulphide (VMS) deposit that strikes NW and dips 65° SW on average. Its dimensions are 1,350m long, 83m wide and 245m deep. It features a jointing system that predominantly strikes NE-SW and a secondary orthogonal system that strikes NW-SE at the mineralised zone. The rock mass quality is mainly rated as fair (RMR = 40 to 50) and in some specific sectors as poor (RMR = x to y).

Our scope was to design the openings and dilution control for stopes without personnel entry.



# Optimising sublevel stoping dimensions in orebodies: Cerro Lindo Mine

## Isometric geology view of the Cerro Lindo Mine



For this purpose, the Potvin Modified Stability Graph method was used to correlate with Clark and Pakalnis's Equivalent Lineal Over-Excavation (ELOS).

Stope dimensions were recommended for both fair and poor quality rock, taking into account the results of the rock mass geomechanical model and the current status of the mining activity. Based on the back analysis results of mined stopes and on the kinematic wedge analysis, we prepared a standard support design for the roof of the stopes.

After making a comparative analysis of the over-excavation height at the dome of the stope versus the stope width without support, we observed that the height of the unsupported dome is almost half the width of the stope. This indicates that the fault depth is mostly controlled by the rock mass quality.

Regarding the stopes with cable bolting (fan-type) support at the roof, we observed that the over-excavation in

the stopes had been eliminated. Also, reducing the stope lengths helped control ELOS efficiently at the front walls.

### Conclusions:

- The stability graphic method and ELOS were complemented with a back-analysis of the mined stopes. These methods were useful in determining efficiently the dimensions of the stopes.
- Understanding the over-excavation type and its magnitude, measured at the existing stopes, helped to determine efficiently the dimensions of the cable bolting support needed at the stope domes.
- The over-excavation control at the front walls and hanging wall of the stopes favors the continuity of the mining cycle and the mining of secondary or adjacent stopes.

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## JOEL CABRERA

Joel is a Mining Engineer with a Master's degree in Geotechnical Engineering. He has over 15 years of experience in geotechnical engineering for

mining projects, working in project design and construction supervision of open-pit and underground mines. Joel's expertise is mainly related to slope stability work, the design of underground excavations, geomechanical evaluation of underground mining methods and mining sequence, tailings and waste storage facilities.

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## EDWARD WELLMAN

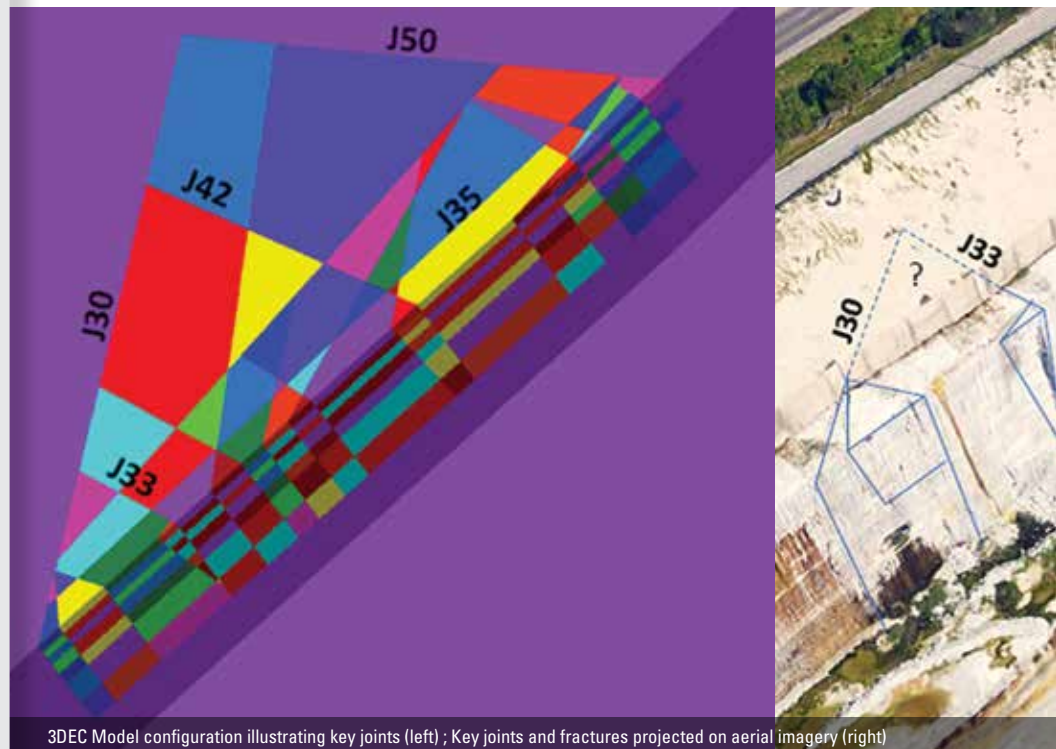
Edward is a Principal Consultant, PE, PG, CEG, in Rock Mechanics with over 20 years of experience in mining and civil tunneling for public utilities, and the private sector.

His surface experience includes slope stability analysis of open pits, waste rock and heap leach piles, and preparation of analytical and technical reports. Edward's underground areas of expertise include rock mechanics for block cave mining, large excavations and shafts, cavability studies and subsidence, including surface and underground interaction. He is versed in geotechnical instrumentation and monitoring programs, from inception to evaluating excavation performance. Edward's experience includes rock mass characterisation and probabilistic analysis for pit slope and ground reinforcement design.

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## McCook reservoir quarry: block stability predictions



3DEC Model configuration illustrating key joints (left) ; Key joints and fractures projected on aerial imagery (right)

## IÑAKI GARCÍA MENDIVE

Iñaki is a Civil Engineer at SRK's Buenos Aires office. He has five years of experience in the geotechnical design and numerical analysis of open pits, underground stopes and infrastructure works, including excavations and tunnels in rocks and soils. He has provided office and on-site services to open pit and underground projects, both in Argentina and abroad, including Veladero and Pascua-Lama (Barrick), San Gregorio and Arenal (Orosur Mining) in Uruguay, and Fenix and Montúfar (CGN) in Guatemala.

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**SRK** was contracted by Strata Earth Services to perform a numerical analysis of the McCook Quarry near Chicago, Illinois. The 3DEC analysis was performed to evaluate a series of 3DEC models previously constructed and compare numerical model results with slope monitoring data for different mining scenarios. The client had concerns that large scale blocks would work their way loose due to mining stress relief, resulting in dramatic increases in groundwater inflows to the quarry. The 50m deep quarry is situated between the Chicago River 100m to the north and the Shipping canal 100m to the south, with the Stephens Expressway immediately adjacent to the quarry walls.

The numerical model was designed to analyse sensitivities to joint orientation, joint strength, rotation of the stress

field, and dip of a shallow-dipping clay seam. SRK studied the joint orientation from mapped key joints provided by the client.

The model results were used to estimate deformation of rock walls due to excavation and to evaluate their potential influence on adjacent infrastructure.

Local 3DEC models with 755 to 1,615 discrete blocks in critical sections of the walls were constructed and analysed by SRK for stability. One local-scale model was used to analyse the stability of the north wall of the quarry on the riverside (illustrated in the figures above), and an additional model was built to assess the stability of the rock weir between quarry lobes. The magnitude of displacements at specific locations from 3DEC modelling is in general agreement with field observations. SRK



## Validating our tools for rockfall hazard analysis

**O**rosur Mining operates the San Gregorio Gold Mine in northern Uruguay. The 300m deep open pit, flooded for eleven years, was dewatered in 2015 to carry out underground mining. The exposed pit walls showed a large wedge failure, leaving a 25-ton block hanging high above the projected mine portal. Taking the block down, though feasible, would have overly delayed mining works. SRK was called in to assess the risk of leaving the block in place.

SRK's rockfall analysis tool RFall3D, developed by William Gibson, was employed. The software can carry out deterministic and probabilistic calculations and assess the trajectory, velocity and energy of falling boulders. Impact points can be singled out and their distance to any reference point can be calculated. The real volume of blocks and their rotational inertia can be incorporated, highly enhancing the precision of the computed trajectories.

A probabilistic analysis was performed using two thousand realisations, each one defined by the stochastic position and

velocity of the block immediately after being released, and by changes in the internal parameters of the model.

Thousands of simulations produced data points in the range of several millions, handled by means of a Python code developed in-house. Results were grouped in ranges and the probability of impact was calculated for each range.

It was concluded that the chances of a fall could not be overlooked. The most probable landing zone was located some 30m away from the portal with a +50% chance of being hit. At the portal, the probability of impact was estimated as 0.35%, a low and tolerable value.

This little story has a funny ending: weeks after the analysis was delivered, when construction of the portal had not yet begun, the block spontaneously came down one Saturday at lunch time and happened to end its journey right where RFall3D had predicted. Good job, William!

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is currently using the model to make forward predictions of rock wall behaviour for the final excavation geometries, and for future use as a combined outfall stormwater retention facility.

Results from these analyses have allowed the client to make modifications to the mining sequence and provide evidence to the regulatory authorities that block movements are anticipated to have a negligible impact on inflows as mining advanced to the next benches.

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Rockfall trajectories superimposed on pit wall



# Collahuasi structural geology support

**T**he Collahuasi Mine is the world's third largest copper mine with one of the largest deposits of copper mineral resources. It is located in Chile's Tarapaca region, 4,400 metres above sea level. Since 2013, SRK has been assisting Compañía Minera Doña Inés de Collahuasi with understanding the structural geology of the Rosario open

pit, and the influence of structures on pit stability. The Rosario open pit is currently two kilometres wide and 700m deep. In addition, geologically it has been the location of multiple intrusive, mineralisation/alteration, and structural events, which, combined, have resulted in complex structural geometries, variations in rock strength, and age relationships that need to be deciphered to clarify the continuity and distribution of major faults.

To date, SRK's role with Collahuasi has included structural geological training for the geology-geotech team onsite, audit and review of structural mapping and modelling procedures, and in-pit mapping and refinement of the structural model for the Rosario pit. This work has produced significant gains in developing and modifying the 3D structural geology model, helping to define the continuity and distribution of pit-scale major faults, including cross-cutting relationships. This not only affects our comprehension of the influence of structures on bench, stack, and wall stability but also in addressing the controls on the distribution of mineralisation.

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## JAMES SIDDORN

**D**r James Siddorn, PGeo, is a Practice Leader in Structural Geology, based in SRK's Toronto office. He has over 20 years of experience in the structural analysis of mineral deposits.



James is an expert in deciphering deposit-scale controls on ore plunge in precious and base metal deposits, the structural inputs to geotechnical/hydrogeological studies and mine seismicity, and applied 3D geological modelling. He also assists clients with strategy and technical reviews for exploration and mining projects worldwide, and has undertaken projects in Europe; North, South and Central America; Asia; and Africa. James has taught more than 30 Applied Structural Geology courses to over 1000 exploration and mining geologists and engineers.

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Manual caving induction, Yauricocha Mine, Peru

**SRK** has been working for Sierra Metals at the Yauricocha Mine in Peru to help improve ground conditions that have historically resulted in mud rushes. The work has employed risk assessment tools to reduce the risk of fatalities and property damage due to uncontrolled mud rush events.

Published literature of mud rushes is limited to block caving or sub-level caving events in fractured hard rock. Ground conditions at Yauricocha are unique because the mineralised ore is soil-like at depths greater than 800m. The challenge facing the SRK team was to understand the trigger mechanisms associated with fine wet material and the large number of groundwater inflows.

SRK was able to demonstrate that mud rush conditions at the mine are the result of elevated pore pressures in medium permeable materials and the strain-softening effects, due to mining-induced stresses, that



Collahuasi: Rosario pit



## Mud rush at Yauricocha Mine, Peru



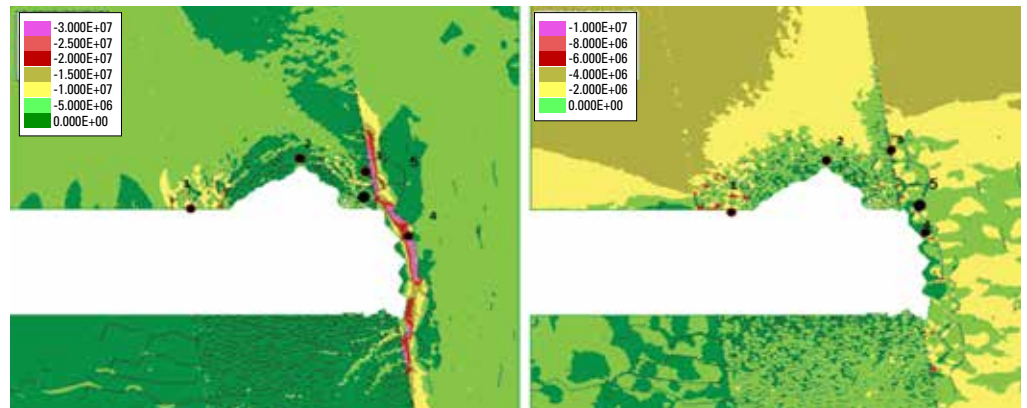
result in soil particle mobilisation. The dilated in-situ material increases in water content that results in plastic or liquid flow depending on the fines content and the plasticity index of the ore-material. The conceptual model was tested with UDEC numerical models to define the trigger magnitudes contributing to flow deformations that simulated mud rushes.

The practical results from this work were the development of a risk chart describing the triggers that can cause mud rushes and the laboratory test protocols to be followed. A set of field procedures were developed for sampling and testing so that the engineers could rank the risk potential for each drawpoint. Mining in the highest risk area of the mine had been shut down by the Peruvian mine authority due to the recent mud rush activity, but as a result of this work, the authorities have allowed mining to continue.

SRK has also worked with the mine to improve ground support so that the

large strains of these soft material loads underneath are properly transferred to the support elements. Modifications to the steel set installation procedures and application of shotcrete have contributed to the mine's safety and business sustainability.

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Numerical simulation: maximum stress  $\sigma_1$  (left) and minimum stress  $\sigma_3$  (right)

### FREDY HENRIQUEZ

Fredy, MS Eng., SME, ISRM, is a Principal Geotechnical Engineer with SRK. He has over 17 years of professional experience in the mining industry, leading geotechnical projects for several open pit and underground projects in South America, Australia and North America. Fredy has technical experience in rock mass and soil characterisation, numerical analysis and underground and open pit mine design. He is versed in prefeasibility and feasibility studies. His industry commodities experience includes salt, iron, lead, silver, zinc, diamonds, gold and copper. Fredy combines balanced ground operational experience and geotechnical project management, from conceptual level to execution.



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## Comparing traditional and televiewer methods of structural data collection

### MAX BROWN

Max, MSc, MCSM, CEng, is a Principal Consultant, Geotechnical Engineering, with over 15 years of international experience in the extractive industries specialising in rock mechanics within both open pit and underground mining. He is experienced in developing and interpreting geotechnical criteria for open pit slope and underground excavation design in addition to providing management and operational support. Max is conversant with 3D modelling and specialist limit equilibrium and finite element software.

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### MARK RAYNOR

Mark has 16 years' experience in Mining Hydrogeology. His areas of specialisation include open pit and underground mine dewatering and pore pressure control, water balance modelling, groundwater recharge, field hydrogeology and water resources assessment. He has carried out numerous dewatering evaluations and reviews at operational mines globally. Mark has extensive slope depressurisation experience and was a contributing author to CSIRO's "Guidelines for Evaluating Water in Pit Slope Stability".

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Examples of appropriately designed rock slopes

**All mining excavations should** have an appropriate geotechnical design that takes into account the rock mass structure. The level of geotechnical investigation and design required will be governed by the geological and geotechnical complexity of the deposit, in addition to the sensitivity of the slope to geotechnical risk.

Acoustic (ATV) and Optical (OTV) Televiewer Tools:

Downhole televewers can be considered a reliable, visual, fileable method for capturing structural data. Both systems collect images of discontinuities in a borehole using downhole geophysical survey equipment that can be orientated for structural logging. The acoustic televiewer transmits ultrasound pulses from a rotating sensor, recording the amplitude and the travel time of the signals reflected from the borehole wall to provide an image of the borehole wall.

While downhole televewers have previously been considered expensive, the costs are not adversely comparable

to using traditional core orientation. Such methods require the daily hire of the orientation tool with geotechnicians and geologists supervising and logging (often twenty-four hours a day) at each working rig. The quality of data captured and the influence that high confidence structural data can have on a slope design can far outweigh the upfront costs of using the televiewer system.

The use of downhole televiewer methods can result in much improved confidence in rock mass conditions and structural data sets, which can produce greater confidence in slope designs. Such systems can be used in all rock masses. Very heavily fractured rock masses can be lined with PVC to ensure borehole stability and orientation by ATV. The use of televiewer systems maximises data from boreholes and is a minimal cost in relation to a drill programme – typically 10% to 20% of the total drill cost – but can cost much less if using existing open holes or very deep boreholes. The advantages of using the system are:



# Saprolite slopes: operational slope design at the Rosebel Gold Mine



- Increased Rock Mass Rating (only logging natural open structures)
- More accurate calculations of fracture frequency/joint spacing
- Reduced variability in orientating major joint sets
- Higher confidence in small scale structures within the rock mass
- Increased confidence in the orientation, locations and thickness/intensity of major structures
- Provision of fileable data that can be reassessed if necessary
- Suitable for stable old boreholes and doesn't always require new drilling programmes

These, benefits can manifest themselves in greater optimisation of pit slopes, which in turn can lead to financial benefits when designing economically sensitive slopes, and confidence in design when developing slopes near critical pit infrastructure.

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**T**he Rosebel Gold Mine, located in Suriname, is comprised of a number of open pits which have been developed to varying depths. Due to their origin and tropical climate setting, the rocks throughout the site are deeply weathered with saprolite and transition (sap-rock) extending to depths greater than 70m. Existing interim saprolite and transition slopes have been excavated in several of the operating pits. Saprolites are complex materials with variable geomechanical behaviour that is not fully understood. The performance of these slopes is extremely variable, due to the impact of relict structures, groundwater, intense rainfall, and protolith.

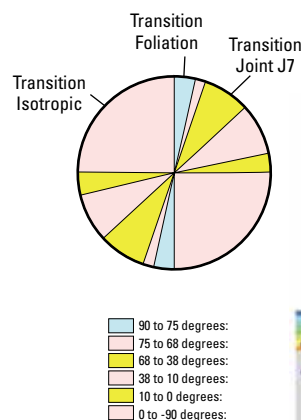
A detailed geotechnical investigation program was undertaken during 2013 through 2014 to provide slope design configurations that could be implemented practically in this high-rainfall tropical environment, using the capabilities of the equipment on site. The slope design approach involved a detailed review of existing pit slope failures in various geotechnical settings, along with findings from the geotechnical drilling program, to aid in estimating strength parameters of the materials and analysing the factors controlling slope stability. A series of simple numerical models were generated to support the slope designs. One of the controlling factors was found to be the orientation of relict structures and foliation. Groundwater control was

highlighted as another major controlling factor. Back-analysis indicated that the most critical period from a groundwater perspective was when the mine floor was located at the base of the saprolites. This is due to elevated pore pressure in the toe of the saprolite slopes. As mining progresses into the more permeable transition material, passive drainage of the transition layer acts as a natural drain beneath the saprolites. Identifying this process enabled mine plans to be modified so that the natural drainage could be used to depressurise the slopes. Adjusting mine plans to take advantage of these natural processes reduced the need for a more complex and costly dewatering system.

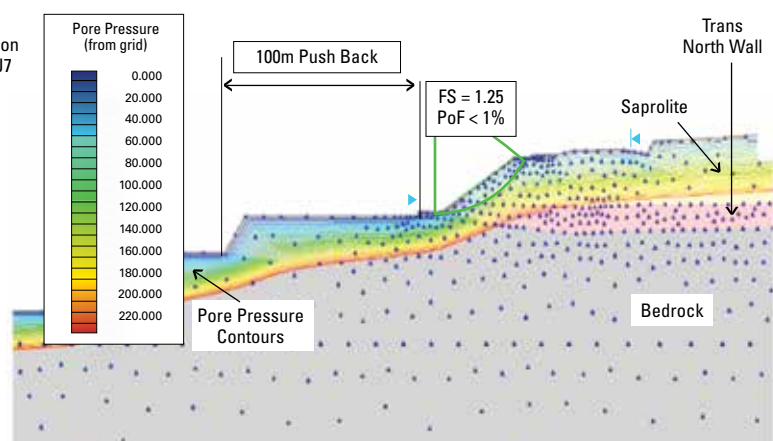
Interim slopes are mined at flatter angles until mining has progressed down into fresh rock, allowing under-drainage of the saprolites to occur without the need for more complex depressurising techniques. A network of vibrating wire piezometers is in place to verify that such under-drainage is occurring. Final slopes can then be cut to the steeper design angles once the pore pressures are significantly reduced. Mining the pits in staggered benches enables good surface water management, reduced trafficability issues, and prevents saturation of saprolite slope toes.

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**Anisotropic strength function in transition**



**2 benches into fresh rock with 100m push back incorporated into pore water pressure model**



# Discontinuity survey and brittle fracture characterisation in open pit slopes

**M**odern photogrammetry surveys can produce highly detailed 3D models of a rock slope. Using a high end DSLR camera with a long focal length telephoto lens, we can construct a model of an open pit slope with resolution in the order of a few centimetres from distances of 1km or more. Despite the continuing technological advances in remote sensing technology and numerical modelling tools, predictive modelling of rock slope stability is still limited by the intrinsic inability to observe the hidden interior structure of a rock mass, and by computational limitations restricting the explicit simulation of small scale material heterogeneity and localisation phenomena inherent to brittle fracture.

We have identified that using photogrammetry provides abundant scope to improve the workflow for rock mass mapping, and we are continually seeking to maximise the data that we extract from our photogrammetry models. By using a multi-scale approach to photogrammetry surveys, we characterise the influence of survey scale and resolution on key rock mass parameters such as discontinuity persistence, spacing, and intensity. In addition to long range surveys, we use close range photography to

comprehensively characterise the intensity of small scale damage, induced by brittle blasting, and to identify incipient discontinuities, which end in intact rock and retain cohesion and tensile strength from rock bridges.

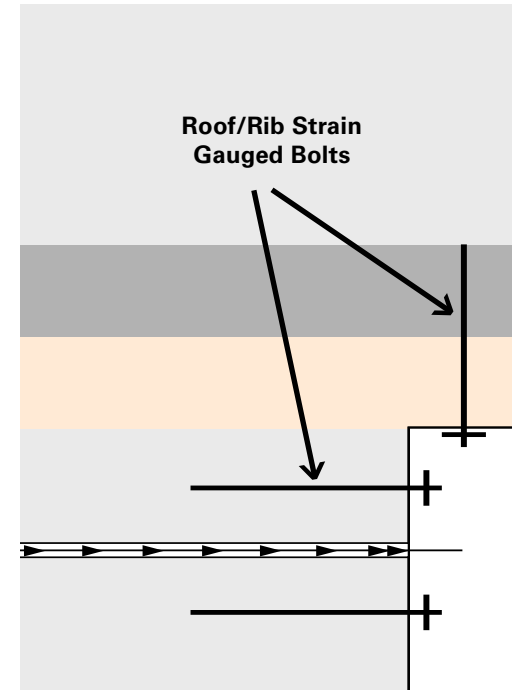
For one Australian open pit mine, we used the statistical information on joint spacing, trace length, and intensity gathered using photogrammetry, to develop a conceptual finite-element model using discrete fracture network techniques. The modelling results help to highlight the role of progressive brittle fracture in developing multi-bench scale-slope instability. We based the model sequence on the first principles understanding of progressive rock slope failure: brittle fracture is characterised by a two-stage process involving, first, the destruction of cohesion and tensile strength along incipient structures, followed by developing shear displacement and mobilisation of frictional strength. The results help to constrain critical values of cohesion and tensile strength for adversely dipping incipient discontinuities, which can be directly related to discontinuity persistence, spacing, and intensity measurements taken from photogrammetry surveys.

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Rock mass mapping using digital terrain model from long-range photogrammetry survey

Typical instrumentation layout for strata monitoring



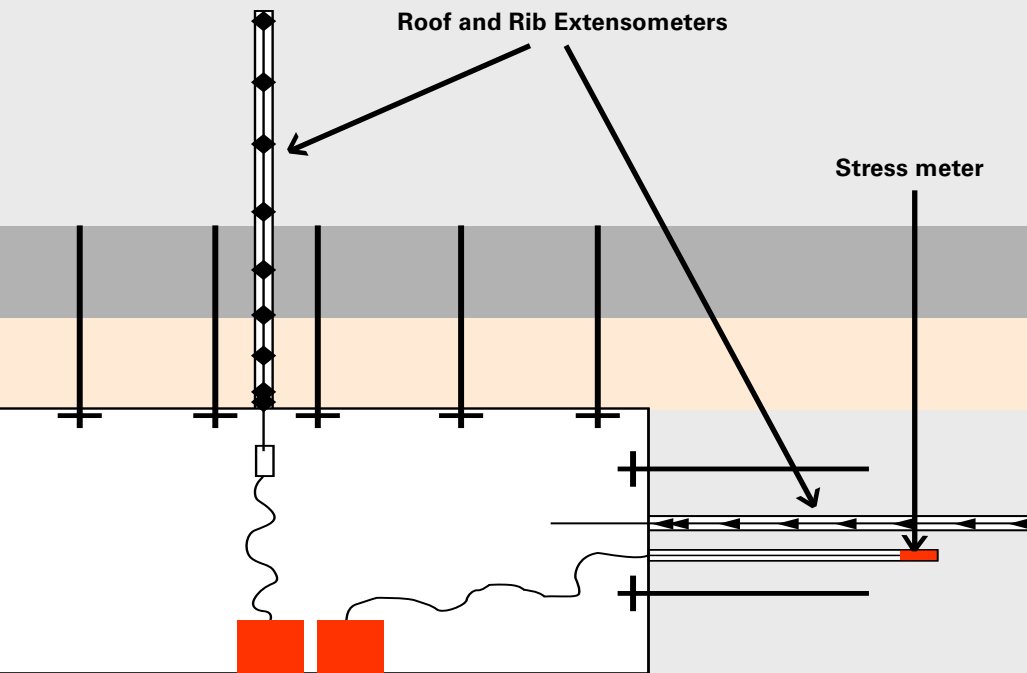
**M**echanised mining, using Continuous Miner (CM) bord and pillar sections, has been successfully introduced into Indian coal mines for more than a decade. This milestone was possible only with the concurrent introduction of advanced technology with rock bolting to provide reliable safe support. The application of this high capacity rock bolting system in India, including design based on in-situ measurement, together with systems for monitoring ground control safety, made mechanised mining successful. The success of these installations confirmed the large potential for further mechanised bord and pillar operations.

The innovative approach in rock mechanics leading to this rapid progress includes:

- An improved understanding of underground stress fields and rock failure mechanisms
- The adoption of high capacity bolting systems, based on this understanding



# Mechanisation in Indian underground coal mines: rock bolting technology and strata monitoring



- The application of new geotechnical instruments for design optimisation and for monitoring ground control safety

The introduction of high capacity roof bolting systems, pillar extraction design and monitoring, with the new mining system, allowed both safe re-access to existing bord and pillar panels and the development of new panels. For high productivity, large dimension roadways were needed to transport high capacity equipment that requires a reliable support system. The rockbolt system introduced with mechanised mining was typically a high-strength full column, resin-encapsulated bolt system, with two-speed resins and a torque tension system to facilitate good quality installation, plus dome plates to indicate overloading.

For overall improvement it was essential to follow proper installation procedures in addition to selecting appropriate roof bolting material and supplies. Training sessions, detailing basics and critical aspects on roof bolting procedures, were held to enhance the skill and

awareness of operators and supervisors. The advancing technology of mechanised mining brings on challenges and the need to understand the behaviour of strata around the workings.

This emphasised the need to introduce a proper strata monitoring scheme for keeping more detailed records of the strata movement connected with faster extraction. A detailed series of instruments consists of various remote-type sensors for roof and ribs; stress meters for monitoring change in stress over the pillars; and for monitoring roof deformation through reported experiences and instructions.

Various trials in India showed that systematic study, and the design of supports, followed by proper implementation in the field, makes a significant contribution to the productivity and meticulous monitoring that provides safety for operators during pillar extraction.

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## ATUL GANDHE

Atul is a Mining Engineer with 16 years' experience in applied rock mechanics on projects in Indonesia, India, UK and Canada. He has expertise in numerical modelling and instrumentation for designing excavations, methods of excavation, strata support systems in coal mines, slope stability in opencast mines, and strata behaviour in mining and hydro-electric projects. Atul has worked on a full range of underground methods of coal mining prevalent in India for strata control studies and support designs. He has carried out strata behaviour studies in longwall, blasting gallery, continuous miner, bord and pillar mining and partial extraction methods using geotechnical instruments in India.



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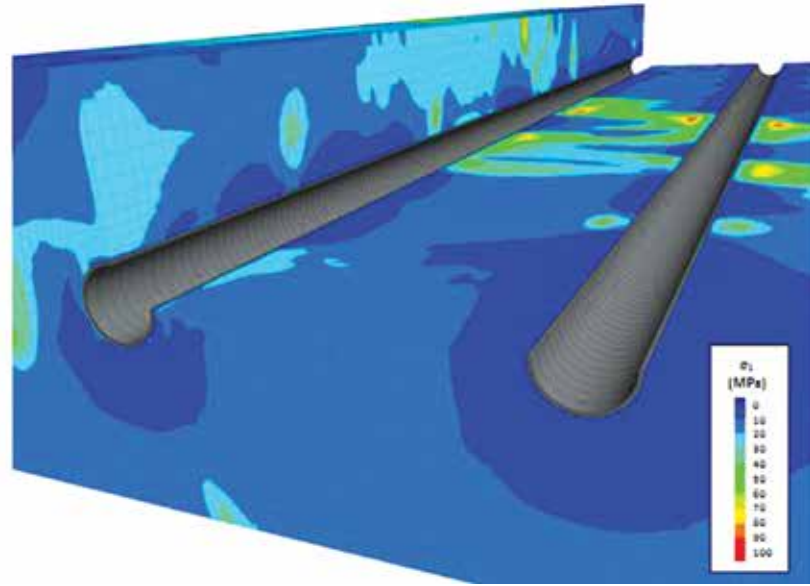
## ZACK TUCKEY

Zack is a Geotechnical Engineer with six years of experience in consulting and industry-supported research for civil and mining geotechnical projects. His expertise includes rock mass characterisation for slopes and underground excavations, slope stability assessment for natural and engineered slopes in soil and rock, shallow and deep foundation design, and assessment of squeezing conditions and brittle failure for highly stressed underground excavations. Zack is an experienced presenter to both technical and non-technical audiences.



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## Cigar Lake Uranium Mine



The formation of the artificially frozen rock mass (blue) above the crosscut was used to help calibrate the observed displacement (left). FLAC3D™ model used to calibrate the displacements observed in the crosscuts (right).

### MATTHEW CLARK

Matthew is a Rock Mechanics Consultant, BSc (GE) P.Geo., with over 10 years of experience in geotechnical investigation and design within the mining industry.

He is skilled in rock mechanics with a focus on open pit slopes. Matthew's technical expertise includes rock mass characterisation, structural domain definition, and numerical modelling with a variety of software packages. He has gained his experience primarily within Canada, Africa, and South America on projects of various sizes and commodities. Matthew has contributed to numerous feasibility, pre-feasibility and scoping level reports.

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The SRK Vancouver Rock Mechanics team has been working at Cameco's underground Cigar Lake Uranium Mine providing advanced multidisciplinary geotechnical modelling since the summer of 2015. SRK conducted geotechnical and structural geology reviews, which led to refining the existing structural and alteration model. This was critical for developing numerical models of the production drifts, which are located in highly variable geology – strong rock to weak clay alteration – and interactions from the overlying artificially induced ground freeze.

The project presents unique challenges, most notably the extreme variations of rock strength from moderate (50 MPa) to weak (less than 5 MPa), and a large-scale artificial freeze from the surface that encapsulates the orebody. The ore is extracted above the development using an innovative method by jet-boring 5m diameter stopes.

The large mass of frozen ground induces stresses and associated displacements that vary depending on the rock type, alteration, and water content due to volumetric expansion that occurs during the state change. These high and unevenly distributed stresses, combined with the highly variable geology and its contrasting physical properties, are adversely affecting the NATM production drives. This has resulted in interruptions to jet boring operations and significant expense to rehabilitate the damaged production drives.

SRK's team is modelling the existing development and ground design to develop a more resilient design that does not interrupt the jet boring of the orebody. Using Itasca code FLAC3D, SRK has modelled the volumetric expansion brought on by the freeze and interactions with the tunnels below. The complexity increases with different ground support and liner material,



# Using geological data to understand distribution of rock mass properties

limited clearance for the jet-boring machine, and a narrow pillar width.

The modelling process utilises FISH code to import the complex geology model developed in LeapFrog and the isotherms provided by Cameco and their frozen ground consultant. This approach has allowed us to move around the production development geometry and introduce the appropriate geological conditions.

The numerical models have been calibrated using monitoring data from the existing tunnels comprised of displacement and stress data as well as qualitative data from liner condition mapping. A significant challenge has been emulating the behavior of the sprayed concrete liner and HidCon yield elements with multiple excavation and rehabilitation phases.

Once the initial model was suitably calibrated, the code was modified to predict the behavior for two as-yet unmined production drives. These models allowed for optimising ground support and liner thickness for the long-term mine plan. The modelling results supported a reduction in ground support in the stronger rock units and in particular a significant reduction in ground support requirements as ground conditions are expected to improve. The high tunnel development cost for this project makes any reduction in ground support requirements and cycle time valuable with a resultant decrease in OPEX.

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(Vancouver)

**T**his case study details how geotechnical properties were linked to geology alteration types. This allowed SRK to use the geology database to determine spatial distribution of zones of very weak and extremely weak rock.

Channel iron deposits (CID) are Tertiary aged iron-rich fluvial sedimentary deposits occupying meandering palaeochannels in Western Australia. The deposits consist of weakly cemented goethite-hematite pisolite and are an important source of iron ore. The channels are incised into basement lithologies and are typically 450-750m wide and up to 100m deep. The palaeochannel deposits are many tens of kilometres in length. The banks of the palaeochannel typically dip between 15°-25° but locally can dip up to 35°.

The deposit is divided into upper and lower units. The Upper CID is unaltered and shows a prominent pisolite texture. This unit shows uniform geotechnical conditions: medium strong and widely jointed. In the lower region of the channel the rock has undergone variable alteration as a result of post depositional groundwater movement. The Lower CID unit transitions from moderately strong rock showing pisolitic texture to very weak rock with zones of friable, soil-strength ochre with increasing alteration. Clay pods are also common within the Lower CID unit. Logged strength is supported by laboratory testing values, showing strength varies from non-cohesive soil through extremely weak to weak rock. Between 20-30% of the rockmass was classified as very weak or less. Thus, whereas the Upper CID unit is a uniform material showing similar rock strength and jointing throughout the deposit, the Lower CID unit is weak and highly variable.

Geotechnical logging and laboratory testing were used to geotechnically characterise the Lower CID material, but the geotechnical drillholes were too widely spaced to meaningfully interpret the distribution of the weak zones.

Geotechnical properties were compared with logged geological properties, including alteration type, alteration intensity, geological hardness, colour, weathering and major mineral components. SRK then established a strong relationship between alteration type and intensity and the geotechnical characteristics of the Lower CID unit.

SRK used the greater geological database to interpret trends across the deposit, emphasising locality and extent of both clay pods and the highly altered Lower CID. By linking geotechnical characteristics to logged geological properties, SRK was able to use the ~30,000m geological database in preference to the ~600m geotechnical database to understand spatial distribution of weak and extremely weak rock, and adapt the pit design accordingly.

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(Perth)

## DIANE WALKER

Diane is an Engineering Geologist/Geotechnical Engineer with 18 years' experience. Her expertise lies in geotechnical slope design for open pit mines. Diane is skilled in geotechnical investigation, laboratory testing interpretation, rock mass characterisation, domaining, modelling and providing geotechnical design parameters. She is experienced in geotechnical characterisation of soil, saprolite, soft rock, strong rock and anisotropic rock. Diane conducts conceptual studies, feasibility studies and support for operating mines and due diligence studies.



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# Structural geology: the fabric of the mine

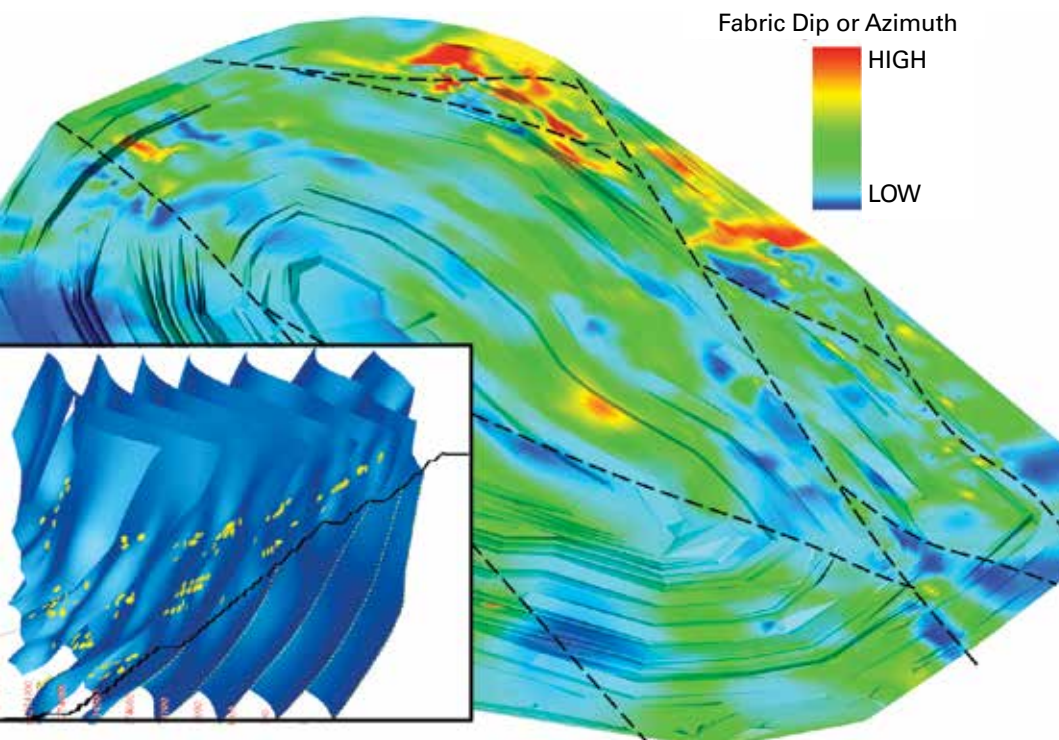
## Geotechnical studies in mining

operations rely on the ability of geologists to use measurements and observations from drilled or exposed rock to predict lithology and structural weaknesses in areas that may impact the stability of the mine, but are not yet exposed. This requires investigating and understanding the structural patterns that define the rock mass, including their continuity and cross-cutting relationships. The structural patterns not only include the primary fault systems or the associated minor faults, but also the fracture patterns associated with fault systems or located in the rock mass between fault systems.

On many projects a set of discontinuities (faults, fractures, veins or bedding) can be so frequent and repetitive that predicting the pattern is far more confident than predicting the location or continuity of individual structures. The repetitive structures impart a structural fabric to the rock mass that influences the strength and therefore the behaviour of the rock

mass in a more predictable manner. In porphyry systems, for example, structural, alteration and geotechnical domains are commonly characterised by fracture-vein systems influenced by fault patterns. In epithermal vein systems, the domains are commonly constrained by fault-vein systems sub-parallel to the orebody. The trend of the fabric can change rapidly or gradually, and knowing the trend variations can in some cases be valuable to the engineers. The figure below shows a 3D modelled structural fabric of bedding-parallel fault systems with variable dip that impacts the location of multi-bench rock failures. The fabric model orientation has then been painted onto the planned pit surface. The fabric trends are broken by faults but controlled by folding patterns interpreted by the structural geologists. Structural fabric patterns can be used to predict how rock stability and risk varies across a mining excavation.

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(Vancouver)



Fault-fabric form surfaces derived from measurements (see insert). Surface orientations can be painted onto a final pit design, to show risk areas



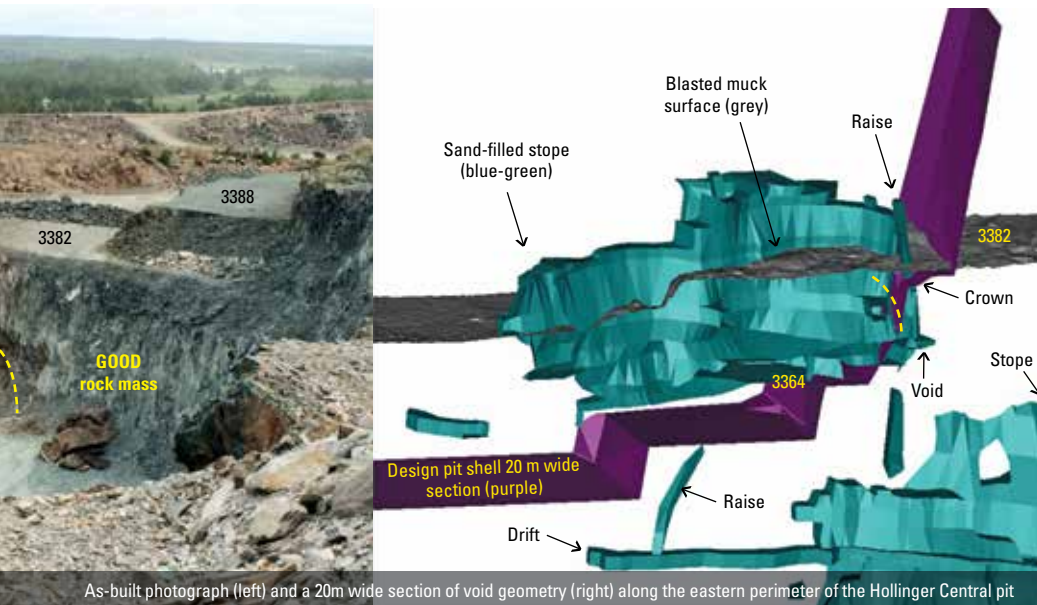
**T**he Hollinger Open Pit, one of Goldcorp's Porcupine Gold Mines, is situated in the gold-mining City of Timmins, in northern Ontario, Canada. The Porcupine Camp, located above a sequence of Archean basaltic volcanic rocks, led to the establishment of Timmins. The Hollinger underground and surface mines, discovered in 1909, operated from 1910 to 1968 and produced approximately 20 million ounces of gold. Before 1930 shrinkage mining was used, followed by cut-and-fill stoping (backfilled with unconsolidated sand) through the late-1960s. In the 1970s and '80s numerous small open pit mines scavenged the crown-pillars, and some underground mining continued until 1984. The mine workings were flooded in 1988.

SRK completed a Feasibility Study in 2010 for an open pit mine design, and since 2013, helped implement the design.

There is sufficient grade at specific gold price-points to mine a 150m



## Hollinger open pit operational support



As-built photograph (left) and a 20m wide section of void geometry (right) along the eastern perimeter of the Hollinger Central pit

deep pit, with the rock being processed at the nearby Dome Mine mill. The voids (sub-vertical stopes, shafts, and connecting drifts/drives) are sometimes spaced nearly 20-50m apart extending several hundred metres deep in a 2km square area beneath the City. The pit design was constrained by a regional highway (and the City's water tower) along the northern wall, with homes and businesses on all other sides of the Property.

The Hollinger is being mined using three 6m and two 9m cuts making up 18m high benches in mostly FAIR to GOOD ground. All blasting is done with blast-mats to reduce fly-rock and noise. Because the mine is in-town, damage needs to be minimised. Earlier, blast trials were conducted to determine the depth of blast-damage induced by varying sizes of confined blasts. These trials indicated that a three-row trim shot onto a pre-sheared final wall would not induce excessive damage. To reduce the damage further, the pre-shear drill-hole spacing is adjusted for ground conditions within the immediate vicinity of voids.

This strategy sufficiently decreases the back-wall damage to less than 4m.

The multi-use of probe holes to pre-support the rock mass before blasting is part of the production cycle. Grouting cables into the final slopes, above and alongside voids, before blasting reduces the amount of final wall crown and wall rehabilitation required. This pattern has 8m cable-bolts on 4m spacing, drilled at  $-45^\circ$  and  $-05^\circ$  from the pre-shear line. On the North Wall, the dominant fabric ( $72/155^\circ$ ) is the main control on the bench face angle. This highly foliated rock mass tends to delaminate when blasted. To reduce the bench-crest attrition from delamination, pre-support is applied using 6m cables on a 6m spacing, drilled at  $-45^\circ$  into the crest from the pre-shear line.

For each of the larger multi-bench voids encountered, individualised support designs are being implemented.

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### ANTON BLOEM

Anton is a Senior Consultant on Rock Mechanics (BSc) who has more than 20 years of mining-industry experience in rock mass characterisation aimed primarily at mine design. This experience is geared towards open-pit slope design and implementation. Anton's current interests and work include primary data collection methods, rock mass damage and dilation, in situ parameter estimation, parameter verification using downhole geophysical tools, geotechnical model development, and operational open-pit slope modelling and design adjustments.



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### WAYNE BARNETT

Wayne is a Principal Consultant with 20 years of experience. He has been employed over eight years as a mining operations-based geotechnical engineer and applied structural geologist. Subsequently, Wayne performed as consulting structural geology specialist in mining and exploration in Africa, North America, South America and Asia. He specialises in defining the structural geology of mining projects to properly characterise the rock mass for geotechnical engineering applications - for scoping to pre-feasibility studies, as well as problem-solving in active mining operations.



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## IAN DE BRUYN

Ian has 19 years' experience in Geotechnical Engineering over a wide range of mining and civil engineering projects. He has strong expertise in geotechnical studies for open pit mining operations and open pit/underground mining interaction. He has worked on projects involving very large pits in complex and challenging rockmass conditions and in which groundwater plays an important role in stability. Ian's projects have involved site investigation, rockmass characterisation, stability analysis, design and risk assessment at all levels – from conceptual through feasibility studies and working design. Ian is the Team Leader of the Geotechnical Group in Perth, Australia.

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## SANDRA LINERO

Sandra is a Principal Geotechnical Engineer with almost 30 years' experience as a consultant in design and construction control, for roads, hydroelectric and mining projects.

She holds a Bachelor's degree in Civil Engineering from Colombia's University of Medellin, she completed postgraduate studies at the University of Karlsruhe, Germany, and is currently completing a PhD at the University of Newcastle in Australia. Recently, she has specialised in geotechnics, focused on coarse material characterisation; design of very high waste dumps; heap leach design; foundation design for mine infrastructure; risk assessment; and closure.

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## Evaluation of rock field stress interpretations at the OkTedi Mine



Ok Tedi pit

Over the years, four programs of rock stress measurement and interpretation have been completed at the Ok Tedi Mine in Papua New Guinea, each providing different interpretations of the in situ field stresses. Measurements were taken at different locations and depths, and in different rock types. The hydro-fracturing method inferred a hydrostatic model, the acoustic emission method presented a highly anisotropic horizontal stress regime, and overcoring measurements using ANZI strain cells inferred a rock-type dependent but more benign intermediate stress regime.

The principal stress directions are not necessarily horizontal and vertical; perhaps impacted by rugged topography.

Even if the pre-mining in situ stress regime was uniquely consistent, considerable redistribution of stress directions and magnitudes were expected to develop due to interaction

between open pit and underground excavations.

2D and 3D numerical modelling, using finite element, finite difference and distinct element methods, was used to evaluate, in terms of stress-strain response:

- The stability of the 1000m high West Wall at each stage of its proposed cutback
- The stability and long-term ground support requirements for an existing drainage tunnel beneath the pit
- The stability and sequencing of underground excavations for sublevel open stoping beneath the East Wall of the pit, as well as the stability of pit wall with the progression of the underground mining

The modelling involved a multistage approach; interpretation of the most appropriate 'starting' stress conditions



# Geotechnical characterisation of coarse mine waste using DEM

in each of the mine areas under assessment was attempted following initial modelling phases. Comparisons of the effects of the various in situ stress field interpretations were made in the context of the continuing and progressively enlarging and deepening mining operations.

As the modelled field stresses changed through the mining sequence, the Hoek-Brown failure curves for the main material types were more closely approached or exceeded (predicting yielding of the rock mass). From observations made within the existing excavations with regards to rockmass conditions, failures and performance of ground support, it became apparent that certain stress fields may have been overestimating the stress conditions at the time of excavation.

Two stress field alternatives, the modelling of which resulted in strain that more closely approximated the observed conditions in various locations, were subsequently selected as sensitivity cases for input into further analyses for mine design.

The response and stability of open pit slopes was not particularly sensitive to the adopted pre-mining stress regime: the alternative in situ stress models produced a variation in factor of safety for the pit walls in the order of 3-5%. However, stress redistribution and concentration between surface and underground mine workings was highly dependent on the initial in situ stress regime and extraction sequence, with a 100-150% variation for the alternative in situ stress models in the near-excavation concentrated stresses for the underground openings.

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**T**he study of the mechanical behaviour of mine wastes containing particles of metric order is a challenging task because commercial testing devices typically only accommodate samples composed of particles that measure a few centimeters. To overcome the equipment size limitations, testing of coarse material is conducted on samples prepared by modifying the particle size distribution (PSD) of the prototype material. Parallel scaling or material scalping are some of the techniques used to prepare coarse samples for laboratory testing. The testing sample may differ from the prototype both in the size of the particles and in the form of the PSD. Therefore, the mechanical behaviour of tested samples doesn't represent the mechanical behaviour of the prototype material.

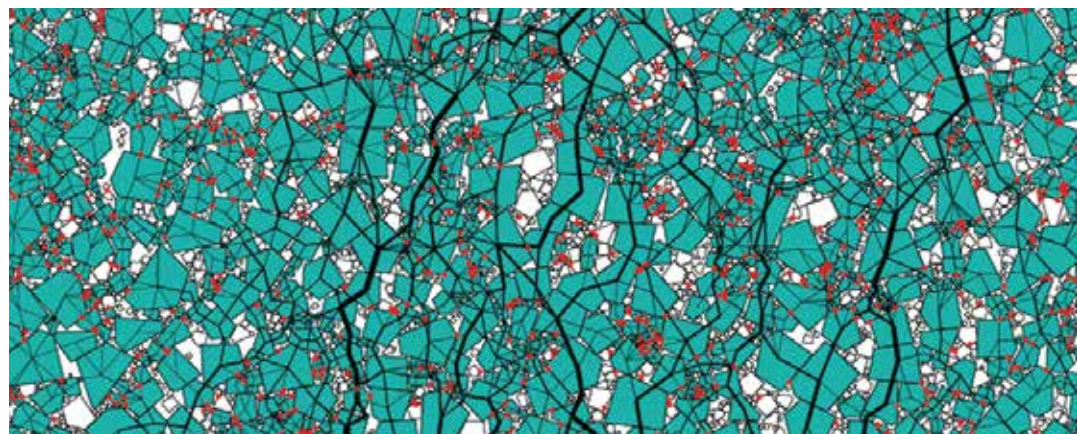
It is not trivial to define the corrections required to deduct the behaviour of a prototype material based on lab results obtained using samples that differ from it. This is due to the variety of factors that influence mechanical behaviour, which cannot be dissociated in physical investigations.

Discrete Element Method (DEM) can be used to compare the macro and micromechanical behaviour of model and prototype samples, alternating with decoupling some of the aspects that influence the behaviour, allowing them to define the corrections required for the laboratory results.

The open source code LMG90 developed at the University of Montpellier, is dedicated to modelling large collections of interacting objects with complex mechanical behaviour. It is particularly suited for the study of frictional granular samples. Its algorithm is based on the Contact Dynamic (CD) Methods developed by Jean-Jacques Moreau and does not require elaborate calibration to predefine particle contact stiffness as other DEM methods require (e.g. Molecular Dynamics). Additionally, the heterogeneity of the particles in size and shape (polydispersity) can be considered.

Researchers in granular media, Emilien Azema from the University of Montpellier in France and Nicolas Estrada from the University of Los Andes in Colombia, are currently collaborating with the authors to implement LMG90 in an investigation. This investigation seeks to develop a method to build models for mine waste prototypes that can be tested in the laboratory, where the mechanical behaviour of the prototype can be predicted, considering the effects that particle shape, particle size, particle size distribution and particle breakage resistance may have on the mechanical behaviour of coarse grained materials.

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Visualisation of the force bearing particles (pentagons) in a polydispersity granular media submitted to compression. Analysis completed using the DEM code LMG90. Floating particles (i.e., particles with one or no contacts) are shown in white, and normal forces are represented by the thickness of the segments joining the particle centers. The diameters of red circles are proportional to the friction mobilisation at each particle contact.

# Photogrammetric mapping for pit slope angle optimisation

**T**he requirement to optimise excavation design and minimise waste stripping is becoming more critical in pit engineering as pits deepen and economics become tighter. Representative structural data is critical when optimising pit slope angles and in most circumstances, the access for mapping the required data is restricted due to Health and Safety concerns accompanied by time constraints.

Photogrammetry mapping is a remote data capture system that uses digital photogrammetry to produce accurate 3D structural models of mine features. Using photogrammetry mapping software, three dimensional photogrammetric images of rock faces can be produced rapidly and safely while remaining cost effective. The 3D images are then mapped using specialist computer software, producing rock mass measurements, which can

subsequently be used for a variety of geomechanical applications.

SRK has successfully used photogrammetry mapping to collect rock mass data from a mine in the Amur region of Russia, which has been used to optimise pit slope angles with significant cost benefits for their clients.

The photogrammetric mapping is carried out on both the hangingwall and footwall. Overlapping 3D images are stitched together to form mosaics that allow mapping of larger (full bench and multi-bench scale) features that span across numerous models. Over 4,000 data points were mapped over 8 hours from the photogrammetric models. The photogrammetry mapping data was used to characterise the rock mass and carry out a stability analysis, assessing the effect of increasing slope angles for the bench stability and for the overall slope.

SRK was able to recommend an increase in the current pit slope angle configurations: the inter ramp angle was increased to 59° from 55° and the bench angle was increased to 75° from 65° allowing for a bench height of 30m and berm width of 10m. The increase in inter ramp angles reduced the amount of waste material that the client needed to remove before reaching ore. An increase of 2° over a 250m high pit saved approximately 10% in waste stripping costs when compared to the original design.

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(Cardiff)

## KARL LLEWELYN

**K**arl, Geotechnical Engineer, (BEng, CGeol, RoGEP) is a Senior Consultant with over 8 years of experience in geotechnical consultancy for mining and civil engineering projects. He specialises in collecting geotechnical data, photogrammetric mapping, interpreting downhole acoustic televiewer data, assessing and conceptualising soil and rock masses and interpreting data for the design of open pit and underground mines.



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Photogrammetric mapping of footwall

### Rating

Excellent  
(Score 10)

Above Average  
(Score 8-9)

Average  
(Score 5-7)

Below Average  
(Score 3-4)

**A** systematic approach to review and audit Ground Control Management Plans (GCMP) for both open pit and underground operations adds value and provides a clear priority list for continued improvement. The process should be based on and tailored to meet the guidelines provided by the appropriate local Mines Inspectorate jurisdiction for the operation under review, as well as reflect the in-house corporate governance requirements.

An approach has been developed to audit GCMP documentation, related operating standards, management plans, procedures and the site implementation process to ensure compliance to legislation and industry expectations. The approach is designed to evaluate and score



# Systematic review and compliance audits of ground control management plans

**Table 1: Section rating score and category descriptions**

Description
All elements are in place and of an excellent standard. These elements have been confirmed by viewing evidence of compliance.
The majority of elements are in place and of a high standard, approaching excellence. These elements have been confirmed by viewing evidence of compliance.
Elements are generally in place. There is evidence of some non-critical weaknesses. Actions need to be included in risk reduction plan with a priority appropriate for risk.
Certain key elements are not applied. High priority for prompt improvement and action implementation. Actions need to be completed before next annual review.

the mine's GCMP documentation and associated operating procedures consistently, to satisfy legal requirements and robustness to the rigours of regular Mines Inspectorate geotechnical audits.

The Mines Inspectorate recognise 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.

**Methodology:** This systematic approach provides a methodology, checklist and assessment process that auditors can follow when evaluating

GCMP documentation and auditing operational compliance to the plan.

Table 1 above summarises the overall section rating score and category descriptions that can be used to evaluate the outcome for each section based on their individual elements audited.

The auditor rates these specific element questions, which drilldown into each section according to compliance and priority for improvement, if required. Each element question is assessed and a priority level is assigned based on documentation and operational compliance.

Any comments and supporting evidence needed or provided by the mine site is noted and collected as part of this process. Each section is provided with an overall rating according to standard definitions (Table 1 above).

## LOUIE HUMAN

Louie has over 20 years' experience in the geotechnical field. His expertise in rock engineering includes: shallow to ultra-deep mining environments, managing seismicity, designing and assessing excavation stability, analysing shaft barrel stability, ground support design and shaft rehabilitation. Louie has been involved in feasibility and due diligence studies which include interaction of open pit and underground excavations, surface subsidence and undermining of surface structures, compliance audits, review of ground control management plans, geotechnical mapping and logging techniques, assessing waste rock dump stability and research projects.

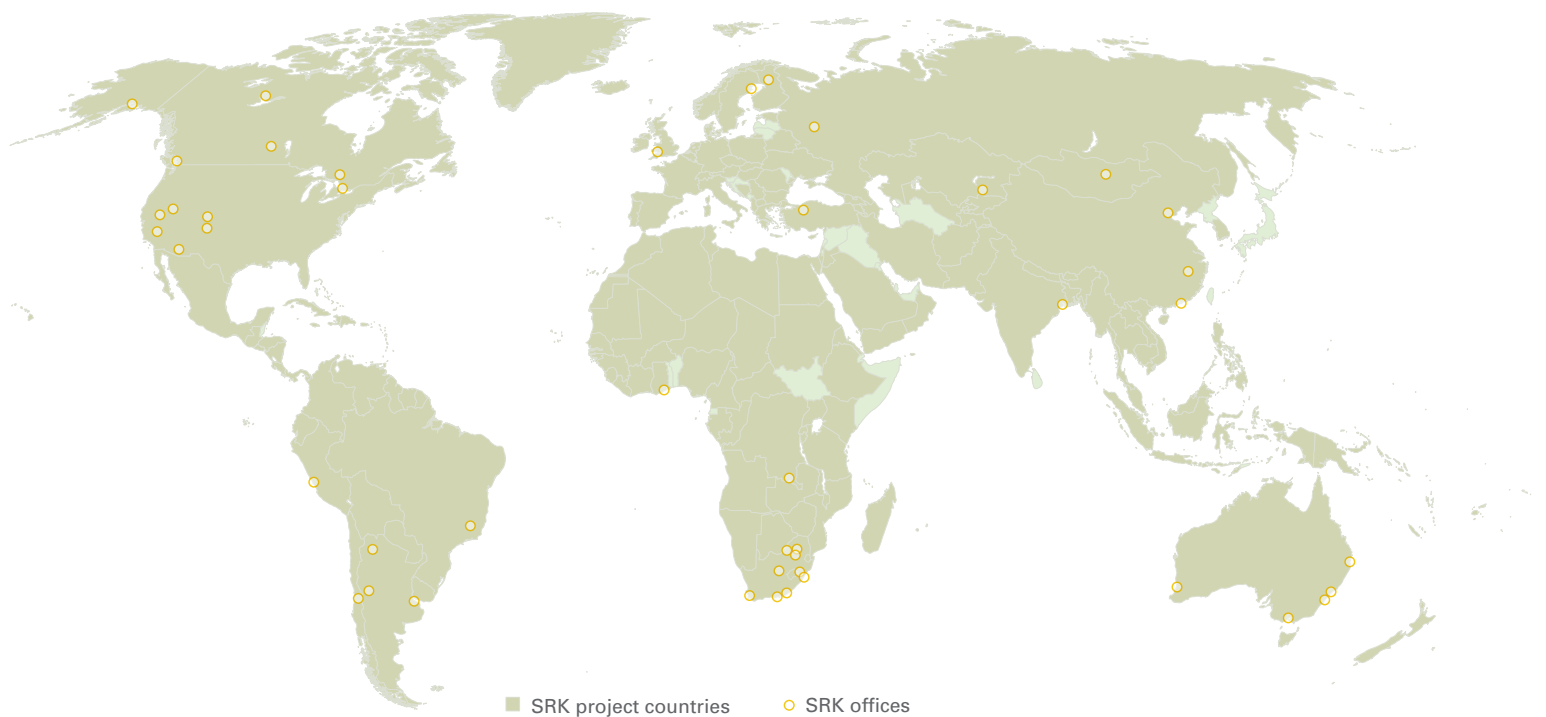


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**Results:** Following the audit, the site receives a report highlighting the level of compliance of their GCMP and supporting documentation, evaluating the effectiveness of the controls; and an action plan with priorities addressing areas requiring improvement.

**Conclusions:** This audit methodology is intended to provide transparency and identify any deficiencies or vulnerabilities in the current GCMP documentation, supporting procedures and implementation on site. In the long term, this process will encourage a systematic self-management and auditing tool of ground control-related risks, which typically improve safety and performance on site. It is important to remember you cannot manage what you don't measure.

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