srk news
Rock Engineering & Slope Stability - Global Perspectives

Increasing complexity raises bar for rock engineering

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Lubambe copper mine Zambia© 2021

With the world's most accessible mineral deposits already discovered and developed, extraction conditions are becoming progressively more difficult – making rock engineering more demanding. In open pits, slopes are often required to be steeper, with increased production pressures. As underground mines deepen, there is growing risk of mining-induced stresses and rock bursts. Orebodies also tend to be geologically more disturbed, making them harder to mine.

Orebodies are often exploited from surface using low-cost open pit mining, but as the orebody continues deeper, waste stripping becomes excessive and underground mining is considered. The transition from open pit to underground is challenging. Many factors, such as the shape and size of the orebody, rock mass characteristics, geological structure, economics, underground mining methods, environmental constraints, management of water, surface infrastructure and impact on local communities need to be considered.

The decision to leave a crown pillar to prevent pit slope failure and subsidence or remove the crown and manage the failure impacts needs to be made at the very beginning. This decision also significantly affects the design of the access to the underground operation, which in turn affects the timing and cost of the transition. Rock engineering plays a major role in all decisions.

Among the underground mining methods available, block caving is often favoured wherever it is feasible, as its cost-effectiveness makes it possible to mine even low-grade deposits economically. However, it does require higher capital costs, including intensive upfront investigation and analysis. While some other methods provide opportunities to learn lessons as mining progresses, block caving is less forgiving – the correct strategies must be adopted from the start.

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Increasing complexity raises bar for rock engineering *(continued)*

All this points towards the growing importance of rock engineering design and the various technical inputs that contribute to this complex field. This applies not only from an economic perspective, but equally from the point of view of health and safety as well as operational risk. More geologically disturbed environments present a higher safety risk, requiring greater engineering effort to execute the mine plan.

A comprehensive, integrated approach using a multi-disciplinary team is required, taking into account geological, geotechnical, structural and hydrogeological data. The interpretation of structures and rock mass is vital to anticipating hazardous conditions and can be incorporated into the mining strategies we recommend. The significant impact of water on the stability of pit slopes and underground excavations, especially in shallower operations, highlights the role of the hydrogeologist.

Various methods of analysis are available. Complex numerical modelling can assist in quantifying failure mechanisms, for instance, while a quantitative risk evaluation approach can be used to estimate the impact of slope failure on a mine's net present value.

The quality of the analysis is, of course, only as good as the quality of the data. The tools at our disposal to gather the necessary data are constantly improving. SRK makes the most of existing data to focus engineering works from an early stage. Incorporating new technologies improves our investigation methods into rock mass conditions and allows data collection to be conducted remotely where access is unsafe or inaccessible. Some remote tools are also proving useful during the COVID-19 pandemic, when it is difficult to travel and to gain access to mine sites. LiDAR drone surveys have been employed to scan narrow-vein stopes before backfilling, for example. Bathymetric and three-dimensional sonar surveys have even been taken in a mine closed over 50 years ago, improving the spatial understanding of the mine workings themselves, as well as the quality of the rock mass and the stability of the excavation.

The data and analysis must lead to a practical solution, and here there is no substitute for experience. At the end of a complex analysis, the experienced engineer must understand the risks that have been quantified and mitigate these in a safe and cost-effective strategy. SRK can match the most appropriate team from its global network of consulting practices with the project deposit and operating conditions, including structural geologists, hydrogeologists and numerical modellers.

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WILLIAM JOUGHIN

William has 30 years of experience in the field of underground rock engineering, which includes 10 years on South African deep level gold mines and 20 years of consulting. He specialises in underground rock engineering investigation and design and has provided consultancy services for mining projects on six continents, with various orebody geometries and rock mass characteristics, exploited with a wide range of mining methods. His expertise encompasses geotechnical investigations, numerical modelling, mining method selection, design of mining excavations, investigation of shaft stability and geotechnical risk. William has a special interest in deep, high stress mining and seismic risk. He has published over 50 articles on rock engineering and is the recipient of an SAIMM gold medal and the Alec Wilson Award for outstanding papers.

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Uncertain failure limits in an uncertain rock mass

Copper mine

In June of 2020, the geomechanics group in Denver, Colorado, was contacted by a subsidiary of Waterton Global Resources to assess the stability of a slope at an open pit copper mine in North America.

The slope consisted of four 25-ft benches beneath a crushing station, which was located roughly 60 ft from the crest. The mine manager had observed the formation of tension cracks roughly 8 ft from the crest and was concerned about the overall stability of the slope and the crusher's foundation. In addition to the recent tension cracks, mine personnel had observed the progression of a wedge-shaped failure in another portion of the crest, which had consumed about 20 feet of the working surface between 2015 and 2020. Finally, large gaps between concrete slabs near the base of the crushing station highlighted the possibility that large-scale deformations were occurring, as the mine personnel did not know when the gaps formed or if they had recently increased in size.

Because the mining property had changed hands, the client's engineering staff could not obtain detailed records from construction of the crushing station or any geologic core within 500 ft of the area, which made it difficult to conduct a meaningful analysis. Rock mass strength properties were calibrated by reproducing failure of the bench crest in a limit-equilibrium model, but application of these properties to the entire slope resulted in unrealistic failure limits.

A geotechnical report from another consultancy was provided, but the rock type that was assumed prevalent throughout the slope had a fairly high strength, and was therefore not representative of the materials currently failing near the bench crest.

SRK recommended the installation of two piezometers, two inclinometers, and a series of prisms for surveying, as well as collection of geotechnical data from holes that would be drilled for the instruments. Eric Poeck travelled to the site in November 2020, logged the core, and directed the installation of the piezometers and inclinometer casing. Transitions in rock quality were clearly observed in the core. Highly weathered schist with a rock mass rating (RMR) in the order of 20 existed in the first 7 to 9 ft, while a transition to fresh schist, with an RMR in the order of 70, occurred at depths of roughly 50 ft. The depth of the weakest material corresponded with the observed thickness of failure near the crest, and the fresh core matched observations of the rock type in the geotechnical report.

Stability models were updated, and the results showed that the likelihood of large-scale failure in the slope was very low. Data from the monitoring program confirmed that deformations over a six-month period were below the noise threshold of the system. The mine can now seek remediation of the bench crest without worry of a larger failure undermining the work.

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DIANE WALKER

Diane has 23 years of experience in the fields of engineering geology and geotechnical engineering. Diane has extensive experience in geotechnical investigation, domaining, modelling and slope design for open pit mines. She is experienced in geotechnical design of in a variety of soil and rock conditions, with incorporation of hydrogeology and structural geology inputs. Her projects have included conceptual studies, feasibility studies, support for operating mines and geotechnical review for due diligence audits. Diane has also conducted site characterisation for underground operations and mining infrastructure projects.

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JOHN TINUCCI

John has over 40 years of professional experience with 20 of those years spent leading project teams and managing P&L operations. He has extensive technical experience in mine design, pre-feasibility studies, feasibility studies, geomechanical assessments, rock mass characterisation, project management, numerical analyses, underground mine stability, subsidence, tunnelling, ground support, slope design and stabilisation, excavation remediation, induced seismicity and dynamic ground motion. His mine design experience includes open pit, room and pillar, (single and multi-level), drill-and-blast, and mechanical cutting, longwall continuous mining, narrow-vein stoping, cut and fill, block caving, sublevel caving, longhole stoping, and CRF and paste backfilling.

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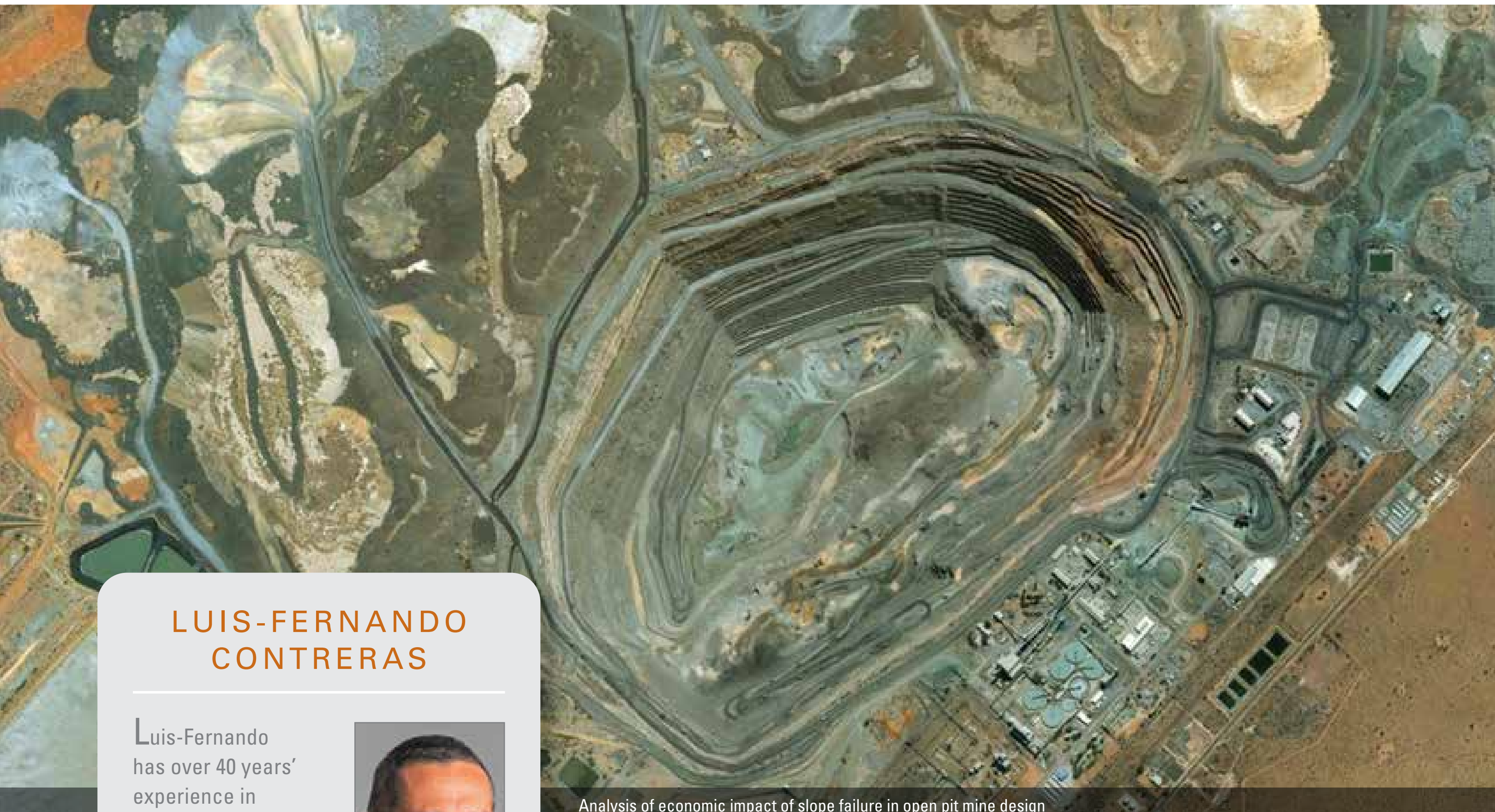
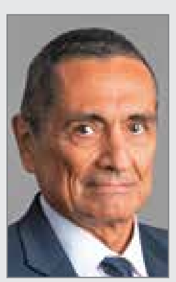
Economic risk evaluation at the Jwaneng mine



Analysis of economic impact of slope failure in open pit mine design

LUIS-FERNANDO CONTRERAS



Luis-Fernando has over 40 years' experience in geotechnical analysis and design, tunnel and dam engineering, slope analysis and risk evaluation studies. He is proficient in risk analysis for project optimisation, reliability analysis for geotechnical design, and Bayesian analysis for inference of parameters. He has worked on geotechnical studies including site investigations, rockfill and earthfill dam design, instrumentation studies and rock mechanics analysis. Luis-Fernando has published over 20 papers on rock mechanics, risk analysis and geotechnical design and has considerable recent experience in probabilistic methods of analysis.

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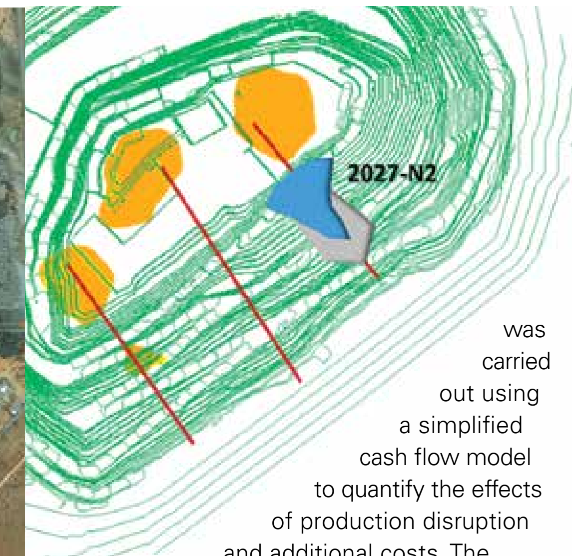
The Jwaneng diamond mine located in the Republic of Botswana is an open pit mine that has been in operation since 1982. The mine has been developed in stages with mining taking place on the western and eastern sides of the pit. The Cut 8 stage is located on the eastern wall of the open pit where the bedding orientation of the rock units runs subparallel to the slopes, making this wall susceptible to instability events. Different slope design scenarios were developed for Cut 8, aiming to reduce the likelihood of slope instability in various critical locations, while maintaining the planned production targets to avoid significant economic impacts. Two slope design scenarios were selected for an objective comparison in terms of economic risks using a quantitative risk evaluation approach for slope design developed by SRK (Contreras, 2015). The purpose of the analysis was to assess the differential risk between a base case and an alternative design scenario, where the slope configuration improved the stability of certain areas of concern in the pit wall, but with some effects on the mine scheduling and the economics of the project.

The approach considered the results of the geotechnical evaluation of the pit wall available in the form of estimates of the probability of failure of 45 slope instability events for each design scenario covering the three main Cut 8 wall areas and six representative years of the 11-year mine plan. The estimation of the economic impacts associated with the failure events



was carried out using a simplified cash flow model to quantify the effects of production disruption and additional costs. The probabilities of failure and associated impacts for each slope scenario were integrated using a probabilistic framework to define the respective economic risk maps. The risk maps were presented for annual impacts on profit and impacts on net present value during the life of mine. The risk map defines the relationship between the probability of exceeding an impact and the magnitude of that impact and accounts for different situations of occurrence of the events. These results were compared with acceptability criteria presented in the form of a risk matrix that defines four levels of risk: high (H), significant (S), moderate (M) and low (L).

The comparison of the risk maps for impacts on annual profits indicated that although a partial reduction of the risks was achieved with the alternative scenario, the deferral of the ore in this scenario caused a reduction of the effectiveness of the risk mitigation, due to the increase of potential impacts in the final years relative to the base case scenario. The results of the evaluation provided useful information to help the mine design team's decision-making process.

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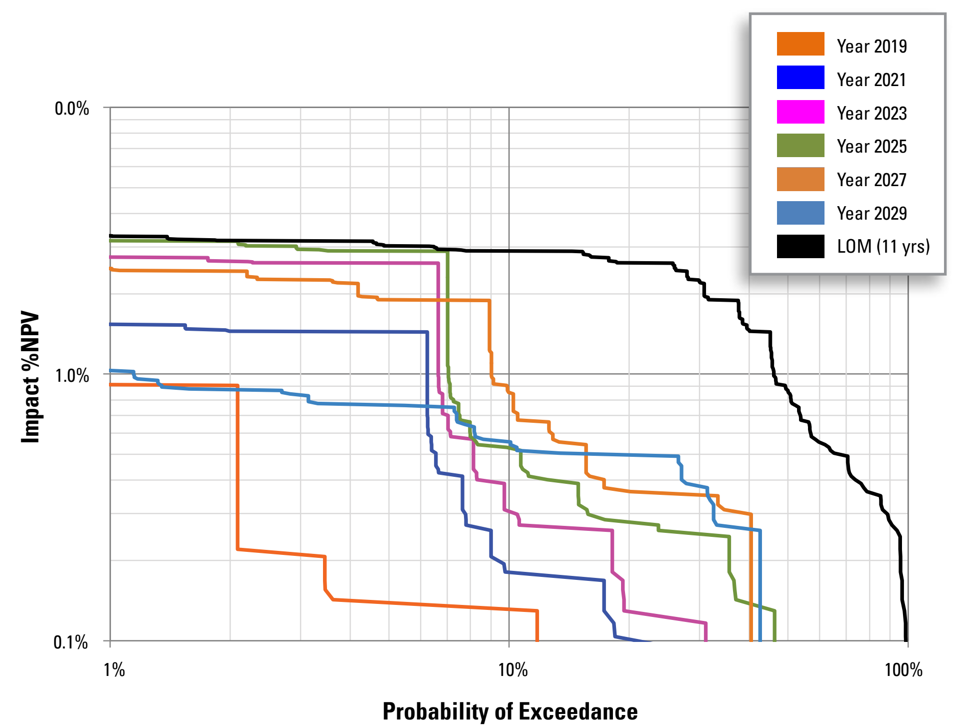

DES MOSSOP

Desmond has more than 25 years' experience in engineering geology and mining geotechnics with specialisation in the design, optimisation, project and due diligence studies, operation and monitoring of mining excavations such as box cuts and portals, rock slopes, large open pits and underground massive mining operations (block caving, sub level caving, vertical crater retreat, and open stoping). He also has expertise in the transition of mining operations from open pit to underground and the associated rock engineering/geotechnical interactions, and with particular reference on open pit slope stability risk management and operational implementation

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TAFADZWA CHINDEDZA

Tafadzwa has been in the mining industry for 6 years. She is currently a mining geotechnical engineer at SRK Consulting, specialising in open pit and underground rock engineering, numerical modelling and risk-based design. She has been involved in geotechnical feasibility studies, design of mine excavations and support systems as well as slope stability analyses. Tafadzwa is a committee member of the South African National Institute of Rock Engineering (SANIRE) Gauteng.

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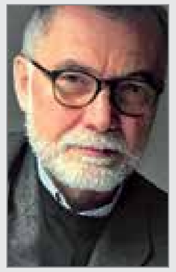

Jarek leads the mining and rock mechanics business unit for SRK Vancouver. He has worked in the mining industry since 1984, specialising in mass mining methods, diamond mining and rock mechanics. Jarek regularly leads teams in operational audits, feasibility studies and bankable due diligence studies. He is a sought-after member of geotechnical review boards and has worked on more than 160 mining projects and operations. He has authored and co-authored numerous publications, including the Large Open Pit Guidelines and Guidelines on Caving Mining Methods, and received the CIM Mining Engineering Outstanding Achievement Award in Cave Mining in 2019..

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ANDY THOMAS

Andy leads mining geotechnical engineering group in SRK Vancouver and has been practicing internationally since 2004. He has a broad knowledge base in geology, geotechnical engineering, and rock mechanics for both open pit and underground mines. He has extensive experience in designing, managing, and implementing geotechnical and hydrogeological investigations for projects in the mining and civil sectors. Andy also implemented several geotechnical data collection training programs and worked on a variety of open pit and underground mining projects.

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Keeping abreast of new technologies

Mapping using the Axis Mapper (left) Discussion about the installation methodology of Geo4Sight with traditional instruments (right)

SRK continues to be involved with new technologies in the field of geotechnical engineering and rock mechanics for underground and open pit mining.

Andy Thomas and the mining rock mechanics team is spearheading this effort and recently trialled a new underground rock mapping tool: Axis Mapper developed by Rock Mass Technologies Inc. Axis Mapper uses LiDAR to collect structural orientation measurements and produces stereonets in real time. The scan and accompanying high-resolution images can be annotated with mapping observations. Rock properties can also be recorded using the built-in and customisable RMR templates. Using Wi-Fi, the data can then be sent to surface and imported into geotechnical databases and standard industry software.

The trial found that the integration of data collection and visualisation enhanced the quality of the mapping. The ability for real-time data transfer could also be particularly useful for rapidly and clearly communicating observations. It is a promising digital data collection system, and the SRK team plans to continue collaborating with Rock Mass Technologies as development of the tool advances.

SRK's rock mining group is also collaborating with Elexon Mining Pty Ltd, a Brisbane-based innovation company that is the main supplier of monitoring and tracking technology for caving mines. Elexon recently developed a new networked "smart marker" platform called Geo4Sight for monitoring sub-surface deformation. Geo4Sight uses a mesh of battery-powered wireless markers which contain high-resolution sensors for measuring tilt and porewater pressure.

SRK recently conducted trials of Geo4Sight for open pit wall and subsidence monitoring applications. The trials found that the system enabled continuous collection of data long after traditional cabled instruments had failed. The ability to monitor larger displacements typical of these applications has provided greater insight into the failure mechanisms and their behaviour over time. More information on these trials can be found in the following papers:

Kamp C, Thomas A, Hamilton D & Davies A, 2020, 'Smart technology for monitoring caving subsidence', Proc. of MassMin2020, 9–11 December, online.

Beingessner T, Yost R, Steffen S, Whiteman D, Thomas AM, Royle M & Widzykcapehart E, 2020, 'Post-shearing data collection with enhanced network smart markers', in PM Dight (ed.), Proc. of Slope Stability 2018, 10–13 April, Seville, Spain.

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DENNIS LAUBSCHER, friend, colleague and mentor

Described as pioneer of block caving and a legend of the mining industry, Dennis Laubscher, the world's foremost authority on block cave mining, died on 3 February at the age of 91.

Dennis was born in the Western Cape of South Africa. He earned a BSc (Eng.) in mining geology in 1952, and a PhD in 1964 at the University of the Witwatersrand. He worked initially as an exploration geologist and joined African Associated Mines in Rhodesia (now Zimbabwe) as a mining geologist and Head of Geomechanics. He joined Steffen Robertson and Kirsten, the forerunner of today's SRK Consulting, in Johannesburg in 1984.

In the seventies, he introduced the mining rock mass rating system (–MRMR) to the mining industry. This classification system was based on work by ZT Bieniawski and was specifically designed for caving mines. The main objective of MRMR was for mining practitioners to communicate between disciplines and develop empirical guidelines for mining method selection and cave design. Dennis Laubscher and Jarek Jakubec updated this classification system in 2000 and it is still used as a "yardstick" today. His last contribution to the cave mining industry was in 2017, publishing a practical book, Guidelines on Caving Mining Methods, which was co-authored by Alan Guest and Jarek Jakubec.

An uncompromising humanist, he made an impact on people as well as projects. During his lifetime he received numerous prestigious awards: the SAIMM Gold Medal, a Lifetime Achievement Award from the South African Institute of Rock Engineering; the De Beers Mass Award at MassMin 2000, and the Brigadier Stokes Platinum Medal from SAIMM. Dennis Laubscher's contributions to the industry and its people will remain a stellar legacy.

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Dennis Laubscher

Practical challenges related to ground support implementation and installation

Ground support forms an integral part of underground mines to maintain stable excavations, sustain productivity, and most importantly, provide a safe working environment. The support designs are generally based on the support capacity, dimensions and pattern. The support capacity is based on manufacturers' specifications and published documentation. In other cases, support standards from similar operations are adopted with the expectation that these will provide the required support. While some testing might be conducted during the implementation, practices from other operations frequently form the basis for the specifications and procedures. Once support requirements are defined, the support installation process often becomes a routine task. Over time, less attention is paid to the controls required to achieve the designed support capacity. Routine testing is often infrequent, and testing is more likely to be focused on changes in ground support products. Qualitative visual assessments become the primary method of quality assurance.

SRK evaluated, planned and provided continuous support during the implementation of an underground rehabilitation project. The margin for error was minimal, and it was critical that the ground support was installed and functioned as expected. The criticality of the project justified a level of detail which is not common in mining projects. Under SRK's supervision, the contractor performed a battery of tests prior to commissioning and during execution of the project. Stringent quality control measures identified deficiencies in product selection, equipment setup and the installation procedure. It was evident that support product selection based on suppliers' specification with limited consideration of other contributing factors is inadequate. Although support installation and application procedures adopted from similar operations provide a basis, the implementation process should consider the potential differences.

This project highlighted various potential pitfalls when blindly specifying support products and adopting the "standard" installation methods. The site-specific support trials, routine testing, and continuous quality assurance proved critical to the identification of substandard support and successful execution of the project.

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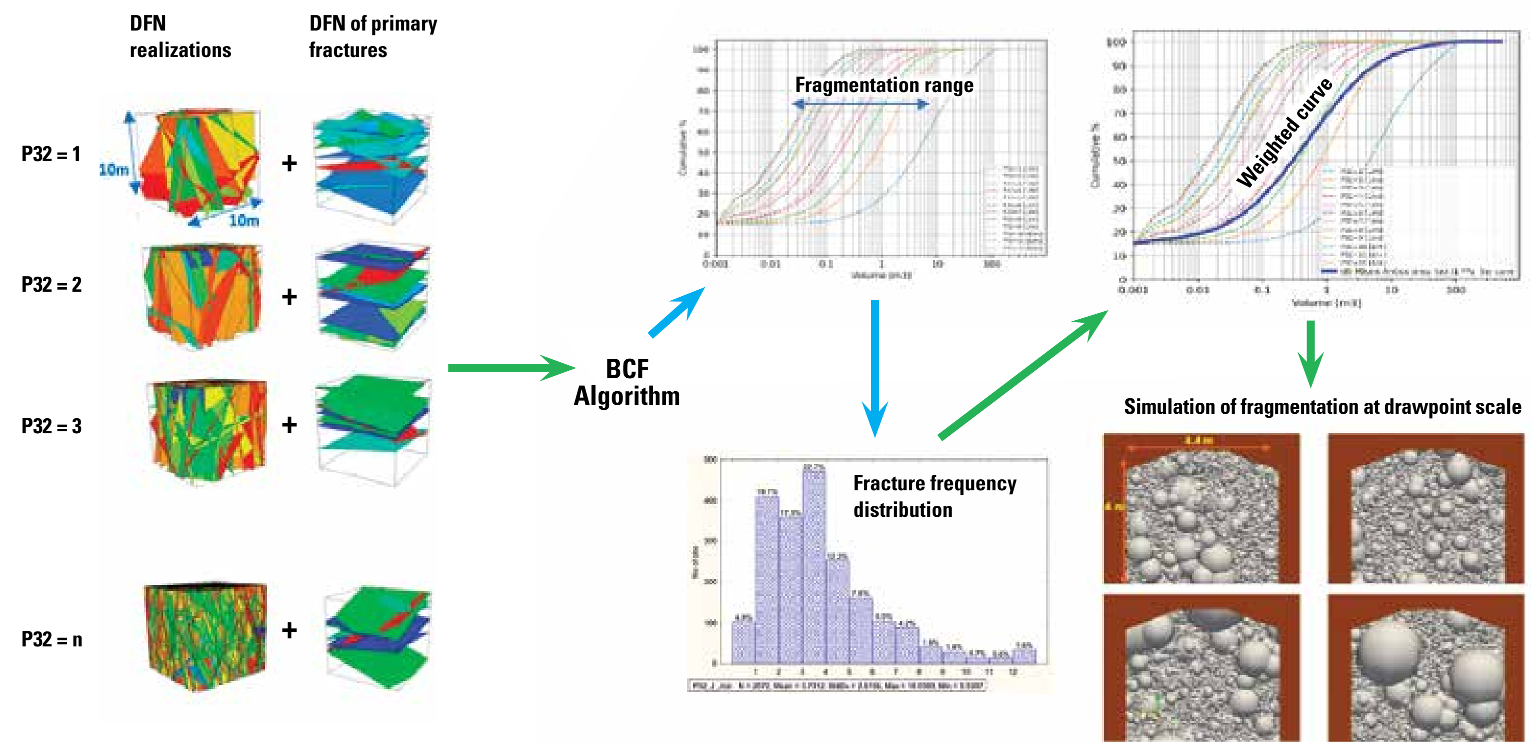
Specialised equipment allows support to be installed from a safe position, but quality control remains critical

Application of discrete fracture network to block caving fragmentation: a hybrid approach



A block caving fragmentation assessment using the hybrid DFN-BCF method. The final product is the secondary fragmentation curve and a drawpoint scale simulation

Block caving is the most cost-effective and productive underground mining method for massive ore bodies. The feasibility, design and continuous production of the block caving method depend on key parameters related to the geological and geotechnical characteristics of the ore body. The forecasting of the size distribution of the fragmented rock is one of these parameters. The fragmentation distribution depends mainly on rock strength and defects, in-situ and induced stresses and the degree of fracturing. In addition to the challenge of characterising each of these parameters, the size fractions of interest are located at the extremes of the distribution, where data are scarcer and statistics are more affected by random variations. Thus, average and central tendencies of the distribution are not of much practical use.

One of the most often used tools to assess fragmentation for block caving projects and mines is the Block Caving Fragmentation (BCF) software, created by G Esterhuizen. In the new DFN-BCF hybrid approach, BCF's primary blocks generator is replaced with a Discrete Fracture Network (DFN) model of the rock mass, making use of the full geometry of the relevant discontinuities that drive the fragmentation process. The final product of the assessment corresponds to a weighted fragmentation curve, representing the complete block to be caved, and its corresponding range of variation. The DFN realisations are generated in the software FracMan®.

The primary blocks from the DFN realisations are then processed using the BCF algorithm, then coded into a Python program to compute the splitting of blocks and produce the secondary fragmentation curve. A novel graphical output has been added to the assessment, consisting of a scaled graphical representation of the actual size distribution using 3D spheres.

Since its creation in mid-2020, the DFN-BCF hybrid approach has been successfully applied to two world-class orebodies. The results from the early stages of operation from one of these has shown a good agreement between the forecasted fragmentation and the actual block sizes at the drawpoints.

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NICO VILJOEN

Nico has over 15 years of operational and consulting experience with a speciality in hard rock underground mining. His focus is on operational support, geomechanical site investigations, and the design and implementation of underground mining layouts and support systems. In the past 9 years, he has been actively engaged in a number of international projects including the application, review and audit of selective and bulk mining methods. These projects include a range of mining methods from longhole open stoping to block caves. Nico is also active in numerous due diligence audits and engaged in various levels of studies as a geomechanical and mining engineer.

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CRISTIAN GUAJARDO

Cristian is a professional geologist with over 13 years of experience in the mining industry, performing geological and geotechnical characterization and engineering analysis in open pit mines and underground projects, participating along the entire geotechnical process, from the capture of basic information to analysis, design, excavation, and monitoring of stability. He has extensive experience in geotechnical data acquisition and data analysis from drill holes, tunnel, and bench mapping. Cristian is skilled in the analysis of structural information for Discrete Fracture Network (DFN) modelling, geological and geotechnical characterization and modelling, and geostatistics applied to geotechnical parameters.

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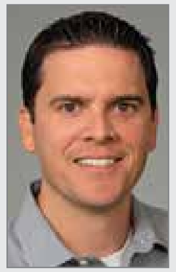
ERIC POECK



Eric has 8 years of experience in the field of mining geomechanics, with expertise in numerical modelling. Eric works on a variety of projects including coordination of geotechnical drilling, logging, and laboratory programs, rock mass characterisation, stability analyses, underground excavation and ground support design, and back-analysis of failure events. He has practical experience engaging with mine staff to address challenges and oversee technical studies from initial data collection to final report.

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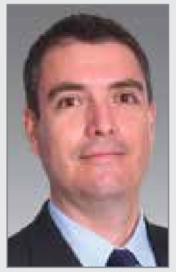
DANIEL PRADO



Daniel has over 17 years of experience specialising in stability assessment and geotechnical data analysis. Daniel's experience includes stability assessment of open pits and underground mines in various rock mass conditions and environments in Australasia and North/South America, for pre-feasibility, feasibility, operational and closure studies. He is experienced in geotechnical data analysis, rock testing interpretation, rock mass characterisation, geotechnical domaining, 2D/3D analysis and numerical modelling (using Rocscience, FLAC2D, FLAC3D, and Map 3D software), as well as 3D geological modelling using Leapfrog Geo software.

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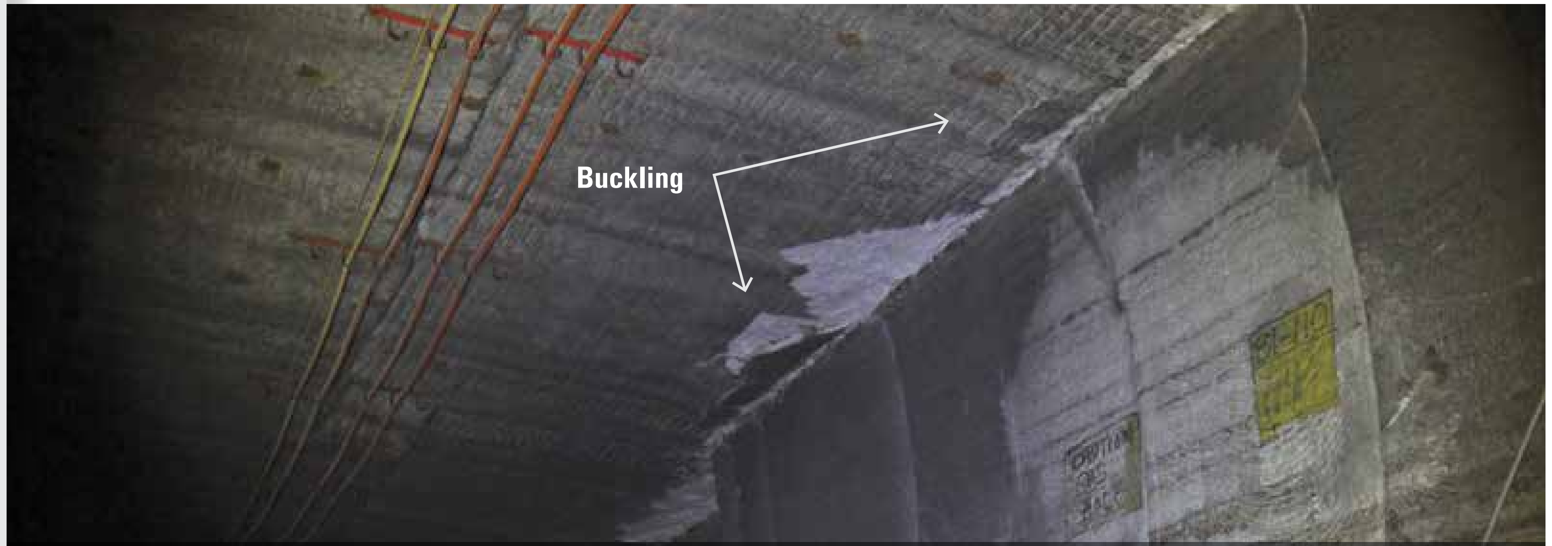
Modeling a ground control problem – the solution was not more bolts!



The Goderich Salt Mine

The Goderich Salt Mine, located on the shoreline of Lake Huron in Ontario, Canada, has been in operation for more than 60 years. The underground production rooms are roughly 52 ft tall and 60 ft wide and are located about 2,000 ft below the surface of the lake. Their mining method has changed in recent years from drill-and-blast to mechanical excavation, advancing the rooms progressively in four cuts.

Since 2014, the geomechanics team in Denver, Colorado, has provided support on numerous projects involving stress analysis, creep calculations, panel design, cut sequencing, ground support design, and drift rehabilitation. In October of 2018, Goderich requested assistance in determining the mechanism behind a series of buckling failures that were observed in the upper corners of the mechanically excavated, rectangular rooms. Buckling generally occurred in a layer of salt 4 to 10 inches thick after the room was opened to a height of 26 ft. The fractured slabs of salt posed a groundfall hazard and were identified by state regulatory agencies during a safety inspection.

Eric Poeck conducted a site visit to inspect the working sections of the mine and document the size and location of observed failures. The buckling did not occur in all rooms and could not be correlated with any geologic anomaly, gas pressures, presence of moisture, or proximity to mining activity. A series of quasi-2D numerical models were run in an effort to reproduce the failure. The model included explicit horizontal bedding seams spaced 0.5 to 4 ft apart and ground support elements in the roof. The investigation included variations in salt strength, stiffness, creep parameters, and bedding seam shear strength.

The results of the analysis revealed that a reduction in the assumed shear strength of the bedding seams accommodated horizontal displacement of the salt immediately above the roof. The increase in room height from 13 to 26 ft was accompanied by a significant increase in horizontal stress in the salt near the room corners. The shear strength of the bedding seams had never been tested, but the model identified the threshold at which horizontal stress concentrations were relieved by shear deformation, which in turn was relieved by the buckling of the lowest slab.

SRK worked with the engineering staff at Goderich to implement new machinery and improve its scaling methods. The mine now utilises a wheeled, telescoping-boom grader fitted with a hydraulically powered, toothed drum instead of a bucket. In addition to removing loose ground, the drum is used to excavate shallow cuts in the room corners, which prevent the transmission of horizontal stress through the thin slabs. The results of the numerical analysis and the modified scaling plan satisfied state regulators, and the risk of groundfall in the room corners has been greatly reduced.

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Operational support for continuance of mining after a large-scale instability

After rainfall, a deep open pit in Western Australia experienced a large-scale instability which hampered access to the pit and restricted mining activity. At the client's request, SRK undertook a site visit and developed a work program to provide analytical and operational support for resolving the stability issues. SRK's team, compromising Daniel Prado and Ian de Bruyn, performed 2D and 3D numerical stability analyses for back-analysis of the existing instability to understand the mechanism of failure and the critical elements affecting the performance of the slope and to calibrate a model to analyse options for further mining. A staged work methodology was fundamental to rapidly identify recommendations for risk mitigation and continuance of mining.

The first stage involved careful reassessment and understanding of the 3D structural model, followed by RS2 (Rocscience software) 2D finite element analyses to recreate the failure at strength reduction factor at or marginally below 1. The likely failure mechanism was confirmed by varying the strength parameters of the pit wall materials and fault structures that were thought to be contributing to the failure. Once the back-analysis was deemed representative of the expected conditions on site and the failure mechanism reproduced, further mining options were considered. In agreement with the client, construction of an intact rock buttress at the toe of the instability was identified as the most suitable solution for mitigation of risk and to allow for continuation of mining.

FLAC3D (Itasca software) finite difference stability analyses were completed to confirm the model inputs from the 2D back-analysis and to further assess the complex failure mechanism in 3D. Appropriate measures to allow safe mining down to the proposed final pit depth were evaluated, considering the location and dimensions of the intact rock buttress and the expected position of the phreatic surface. The recommendations provided by SRK in terms of slope angle, buttress width and extension were included in the client's operational plan, and the mining of the pit was successfully achieved.

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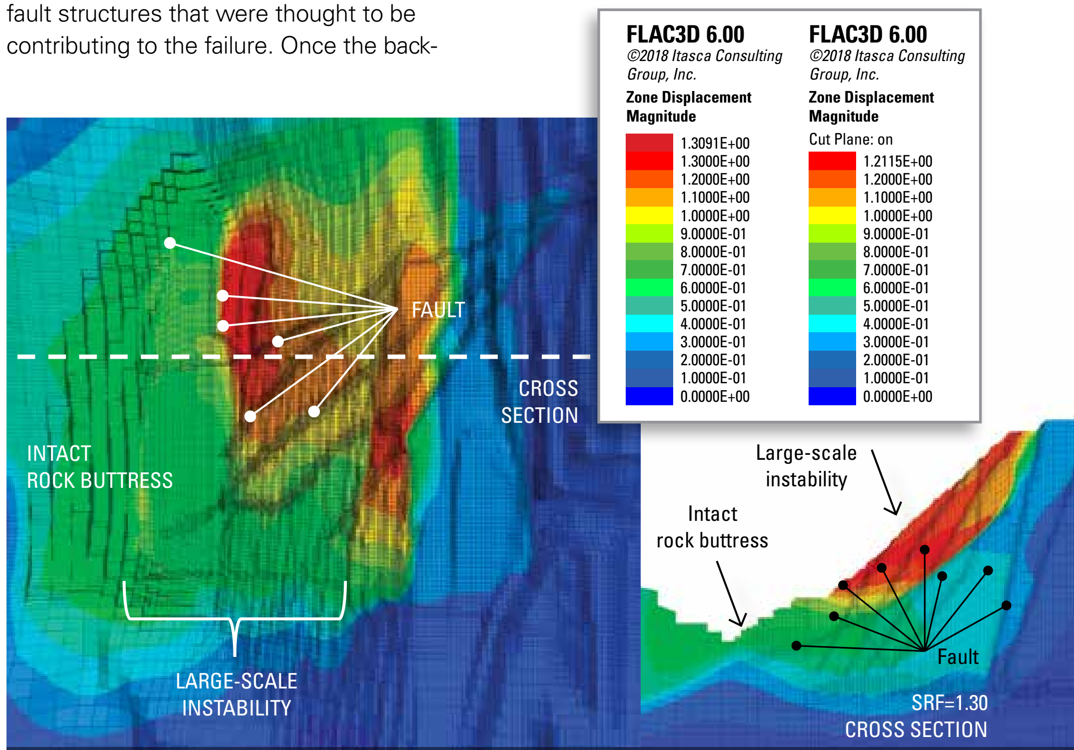

FLAC3D plots showing predicted slope displacement magnitude in plan and sectional view

Slope design at El Romeral pit, Chile

SRK Chile's rock mechanics team completed a study of the slope design at the El Romeral pit located 463 km north of Santiago. Pushback 5 is prolonging the extraction activities carried out at the El Romeral iron ore mine, extending its life of mine to 13 years through the expansion of the Cerro Principal pit.

A comprehensive geological, geotechnical and structural characterisation programme was developed to update the geotechnical units, structural model and geotechnical block model. A conceptual hydrogeological model also was updated with the latest information to incorporate a pore pressure field in the slope stability analysis.

With the experience at the El Romeral pit, the design of the future planned pushback 5 can be carried out with considerable confidence. Back-analyses play an important part in verifying the confidence of design.

As part of the slope design programme and slope optimisation for the pushback 5, the past performance of the pit slopes was evaluated to assess the future pit expansion and potential interaction with historical underground workings. A series of geotechnical studies was performed to analyse slope stability, based on limit equilibrium methods, finite element 2D numerical models and discrete element 3D numerical model (3DEC). A sophisticated mesh using Griddle software was used to incorporate old open stopes and production drifts next to the north wall.

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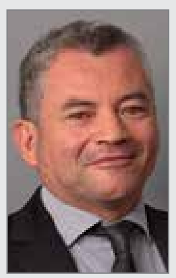
PEDRO CRIGNOLA



Pedro is a geologist and geological engineer, with over 24 years of experience in mining, civil and hydropower projects. He has been involved in the design of open pit mines, surface excavations, as well as in the design of hydropower and mining tunnels and underground mining excavations, with emphasis on geological-geotechnical characterisation of rockmass and structural analysis. He has experience in studies for the mitigation of geological and natural risks, slope stability, aggregates materials, and in construction/repairs of earth dams.

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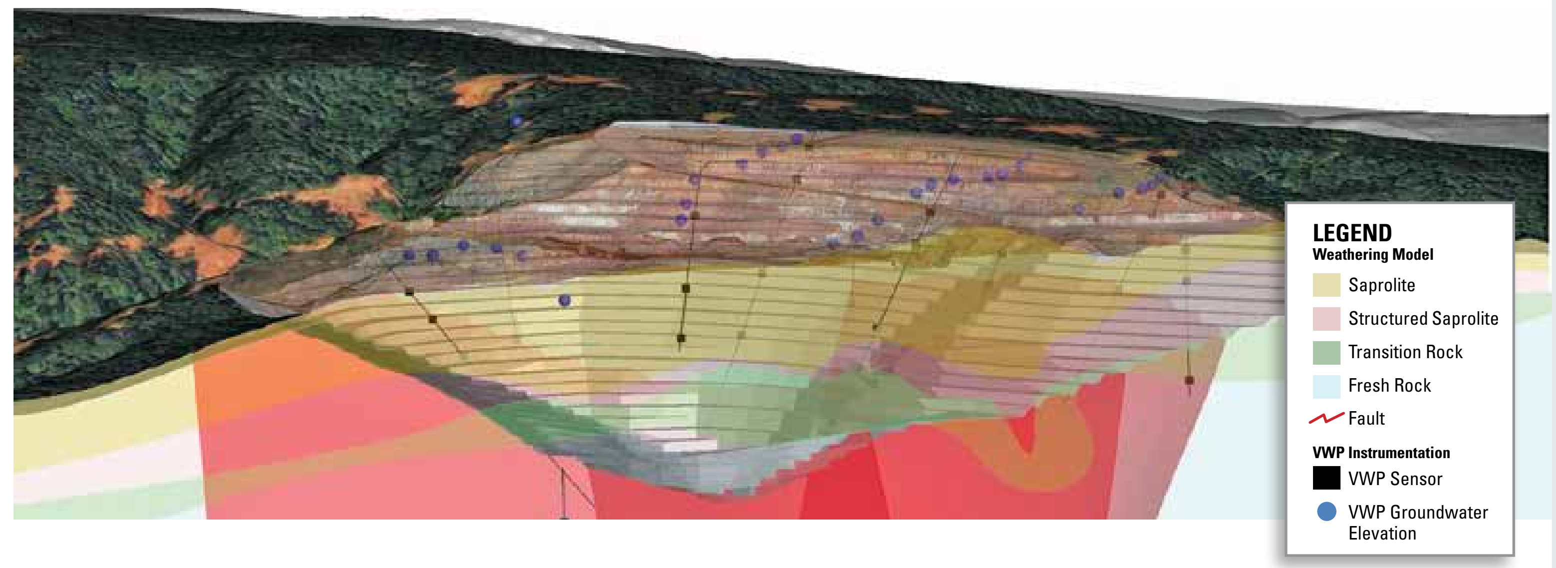
El Romeral Open Pit

Implementation of mine strategy driven by slope depressurisation

3D weathering model and groundwater monitoring for the Saramacca Operation



Successful mine plan execution at operations with high rainfall and deep and irregular saprolite profiles requires strong geotechnical, hydrogeological and hydrology design integration, coupled with a realistic assessment of mine production capabilities and clearly defined environmental objectives.

Vancouver's rock mechanics and Cardiff's hydrogeology teams have provided long-term open pit operational support to the Rosebel mine operated by Rosebel Gold Mines (RGM) in Suriname. Since 2017, this has extended to multidisciplinary support for open pit slope stability and depressurisation, waste storage, surface water and sediment dams at RGM's new Saramacca Operation approximately 25 km from the primary mine area. Saramacca's open pit comprises saprolites, both homogenous and relic structured, up to approximately 120 m in expected slope height with shallow pre-mining groundwater levels.

Fundamental to the Saramacca materials characterisation was the development of a rigorous 3D weathering model that considered the deposit lithology, structural and mineralisation controls. SRK generated the 3D weathering and structural models using implicit techniques and all exploration and geotechnical drilling data with a view to calibrate models as the open pit advances. The weathering model comprised four domains: saprolite; structured saprolite (saprolites with relic structures); transition (sap-rock); and fresh rock units that were coded into block models utilised by the RGM mine planners.

Multi-purpose geotechnical, structural geological and hydrogeological field investigations were performed. This involved a network of vibrating wire piezometers, and airlift and pumping testing to evaluate the feasibility of the proposed depressurisation strategies within the weak and strong rock units, including anisotropic controls on groundwater flow and predicted influence on stability.

An integrated 3D surface and groundwater model (MODFLOW-USG + SWAc) was developed to evaluate the dewatering and depressurisation requirements considering the seasonality at site. An optimised pumping well construction schedule was developed to depressurise the saprolite sequence to achieve the required slope design acceptance criteria, as defined by the supporting stability analyses. The 3D model exports, and more simplistic 2D sensitivity approaches were used to evaluate the expected stability conditions for the critical mine phases.

As the mine plan was developed, SRK supported mine planners to advance the pit into areas of shallower transitional rock to promote passive under-drainage of the overlying saprolites. Where depressurisation was reliant on pumping wells, in-pit and ex-pit pumping well locations are being defined. This ongoing integrated effort and the establishment of clearly defined rules for vertical advance rate and depressurisation requirements allows for early risk identification and adoption of mitigation strategies to support execution of the short-and long-term mine plans.

SRK continues to support RGM with new data collection and monitoring to evaluate the performance of the slopes and calibrate the strength, structural and groundwater parameters to improve the reliability of the geotechnical and hydrogeological designs.

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MARK RAYNOR

Mark has 20 years of wide-ranging experience in mining hydrogeology. His areas of specialisation include open pit mine dewatering and pore pressure control, underground mine dewatering and sealing, water balance modelling, groundwater recharge, field hydrogeology, and water resources assessment. He has carried out numerous dewatering evaluations and reviews at operational open pit and underground mines. He has extensive slope depressurisation experience and was a contributing author to CSIRO's "Guidelines for Evaluating Water in Pit Slope Stability" and continues to support the Large Open Pit (LOP) group with hydrogeological research.

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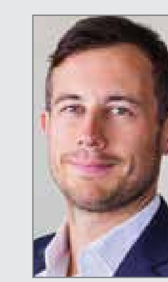
ED SAUNDERS



Ed is based in SRK's Vancouver office. Ed has performed geotechnical slope design work at over 40 operating mines with experience from hard rock, structurally controlled deposits to weak or altered materials requiring depressurisation. He currently supports technical studies and operations through investigation, stability, design, implementation, and monitoring. This operational environment experience extends to day-to-day support of geotechnical personel. Ed has managed multi-disciplinary studies (pre-feasibility, feasibility, operational) and is experienced with highly interactive geological, hydrogeological, hydrology and mine engineering design.

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The unseen: a case study of innovative methods for investigating historical mine workings

Canadian mining operations have long been key contributors to economic vitality. This has resulted in Canada standing at the forefront of implementing best practices that relate to mine closure projects. In the case of closing historical mines this can be a particularly challenging task as often the level of information available is much less than active mines preparing to close. Closing historical mines provides an opportunity to apply new, and innovative methods to collect the data required to design and execute a successful mine closure plan.

The site discussed in this study is in northern Canada and used interconnecting open pit and underground mining methods while in operation but has been closed for over half a century. Historical documents indicate that the mine was closed after a failure occurred at depth and some backfill material was lost. A pond currently exists where the open pit was located. This study is focused on rock mechanics and discusses the methods used to assess the geometry and stability of the historical mine workings. The need for innovation stemmed from the limited historical plans and documentation that existed. Empirical methods suggested that the crown pillar at the site was unstable and should have failed, which did not align with on-site observations.

Therefore, an alternative method of assessing the stability was required which involved undertaking bathymetric and 3D sonar surveys to gain a better spatial understanding of the open pit and underground environment.

These surveys improved the spatial understanding of the geometry of the mine workings, the quality of the rock mass, potential geologic structures exposed, the excavation conditions, and the stability of the excavation.

The quality of the data allowed the identification of joint sets and potential failure planes in the rock. Additionally, visualisation of the bottom of the mine workings allowed observations to be made that reflected the stability of the excavations. A lack of failed material suggested that minimal failures had occurred in the excavation walls and the crown pillar. This information made a positive contribution in assessing the future stability of the site.

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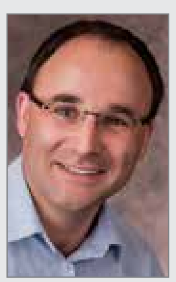
TIM COLEMAN



Tim has over 20 years of experience in the mining industry with strong operational experience in underground mining. His specialisations are in soft and/or weak rock; the practical application, selection, testing and design of ground support; geotechnical instrumentation; numerical modelling; and geotechnical aspects of underground mine design and review, feasibility, risk assessment, and hazard management.

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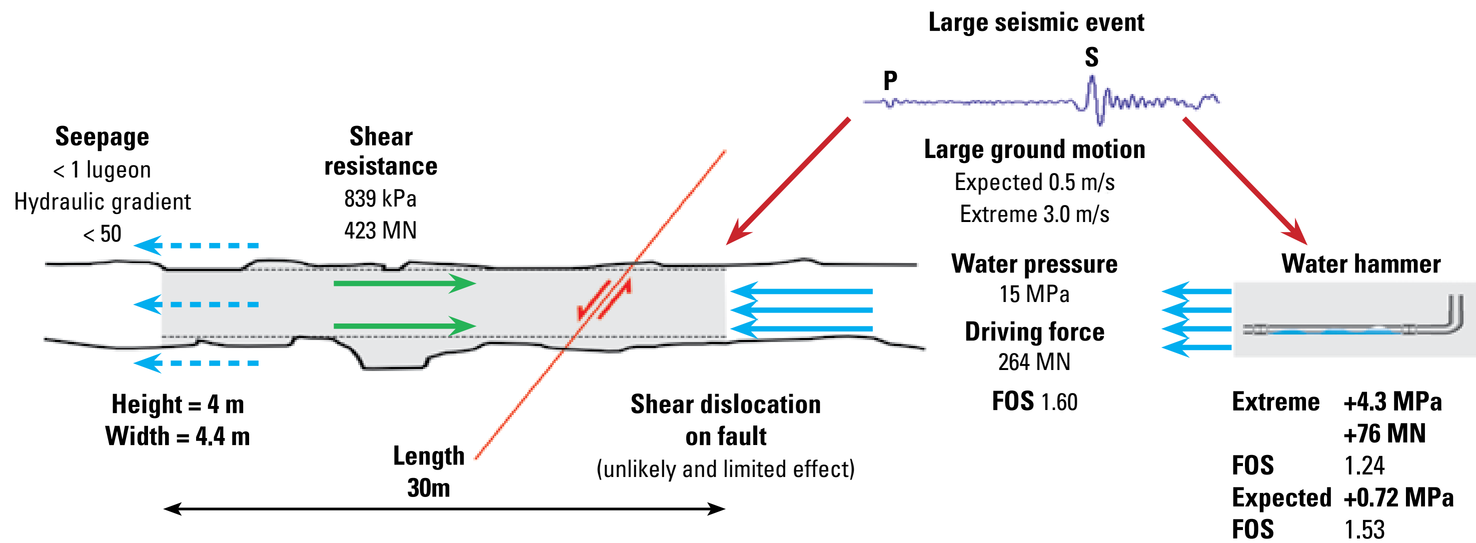
Design of water barrier pillars and high-pressure concrete water plugs for mine closure



Many South African gold mines have reached the end of their life and have closed or are in the process of closing. Dolomitic aquifers overlie the gold-bearing reefs of the Witwatersrand Supergroup, and many of the gold mines have been disrupted by the inflow of extraneous water into the underground workings during their operational life. Expensive underground pumping has been necessary to dewater the mines. When mines cease operating, the cost of pumping is a major burden on the owners. As a result, some mines have stopped pumping and rewatered the abandoned mine workings. Where there are adjacent mines that are still operating, it is necessary to ensure that appropriately designed water barrier pillars and concrete water plugs are installed to prevent the ingress of water. SRK has assessed several water barrier pillars and carried out detailed concrete water plug designs and supervised the construction.

The first step in the process is to scrutinise mine plans and identify existing pillars that are wide enough to function as a water barrier pillar and extend across the entire mine boundary. Pillar stability needs to be assessed using numerical modelling, available geotechnical data and empirical design guidelines, which are based on a century of Witwatersrand gold mining experience and research. Potential seepage through major geological structures that traverse the pillar also needs to be considered.

It is then important to identify tunnels that traverse the boundary pillar and to assess suitable sites for the construction of concrete water plugs, which can prevent water flow through these tunnels. Major geological structures, weak rock mass conditions and adverse stress conditions should be avoided. Detailed mapping of the joints and minor faults, permeability testing and pre-grouting must be completed. The concrete plugs must be designed to resist shear along the interface between the concrete and rock, under the maximum water pressure when the mine is fully rewatered. Simple analytical models assuming a planar interface are normally used for design. More detailed numerical modelling can simulate the increased shear resistance due to interlocking as a result of the irregular rock surface, which demonstrates that the true safety factors are much higher. Ensuring that the hydraulic gradient along the interface is less than 50 and high-pressure grouting after casting the plugs are important for minimising seepage. Aggressive water conditions also must be taken into consideration in the selection of materials for construction.

Analysis of historical mining and fluid-induced seismicity during rewatering is essential. The plugs must be capable of resisting the water hammer and damage due to extreme seismic events.

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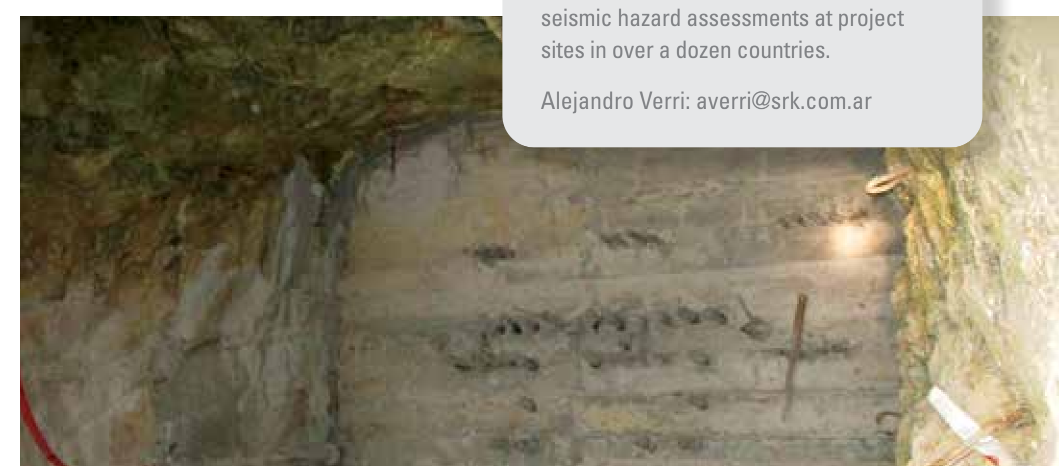
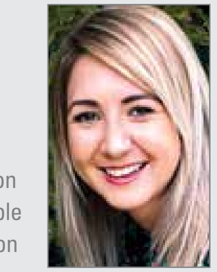


Concrete water plug failure modes

ALIDA HARTZENBERG



Alida has 8 years of operational experience in hard rock underground mines providing geological information and being accountable for the implementation of rock engineering processes and the application of systems aligned with best practices to optimise safe extraction through advice and support. Alida joined SRK Consulting in 2019, working on geotechnical drilling programs, instrumentation installation, support design and mine closure projects.

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ALEJANDRO VERRI

Alejandro heads up SRK Argentina's civil and mining infrastructue team with 25 years of experience. He has expertise in reliability-based analysis, seismic design and constructability analysis of underground structures and mining infrastructure. He has participated in environmental rehabilitation projects and mine closure studies. He was the design leader for the closure and environmental rehabilitation of the Pascua-Lama Tunnel between Argentina and Chile. He has conducted site response studies and probabilistic seismic hazard assessments at project sites in over a dozen countries.

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Cascabel Project

The Cascabel Project is a copper-gold porphyry deposit located in northern Ecuador. SRK UK was commissioned in early 2019 to acquire data in support of a preliminary economic assessment and subsequent pre-feasibility study.

In 2019, SolGold undertook a geotechnical drilling programme targeting the proposed decline and mine areas. SRK undertook permeability testing on boreholes using both the IPI Standard Wireline Packer System (SWiPS®) and the STX-60®. These tools allow sections of a borehole to be segregated and tested.

During a packer test, water is injected at a specified pressure into isolated intervals of a formation. The data are used to derive a permeability of discrete structures or longer intervals of rock mass. For extremely low permeability sections, 'shut-in' tests can be completed. During such a test, the STX-60® allows a specified pressure to be locked into the test formation. The pressure is then left to dissipate and these data can be used to derive a permeability result.

At Cascabel, both packer testing types have been used successfully. To date, 70 successful tests have been completed in 11 boreholes.

SRK provided technical training to SolGold site staff on both packer systems. SolGold personnel now perform the packer testing with remote support from SRK as required. SRK Chile has been supporting SolGold in carrying out the geotechnical and geomechanical studies required for the pre-feasibility study.

The geotechnical and structural data were used to assess the rock masses at Cascabel according to the main classification systems such as Bieniawski RMR (1989), Laubscher RMR (1990), Laubscher & Jakubec IRMR (2001), Grimstad & Barton Q (1993) and Hoek et al. GSI (2013).

Structural data collected from oriented cores and televiewer were used to build a 3D structural model at mine scale and to define and characterise structural domains.

Geotechnical and structural assessment were used as input to estimate caveability, fragmentation, subsidence and pillar stability, rock support, seismic risk analysis and requirement for dynamic rock support and recommendations for geomechanical monitoring.

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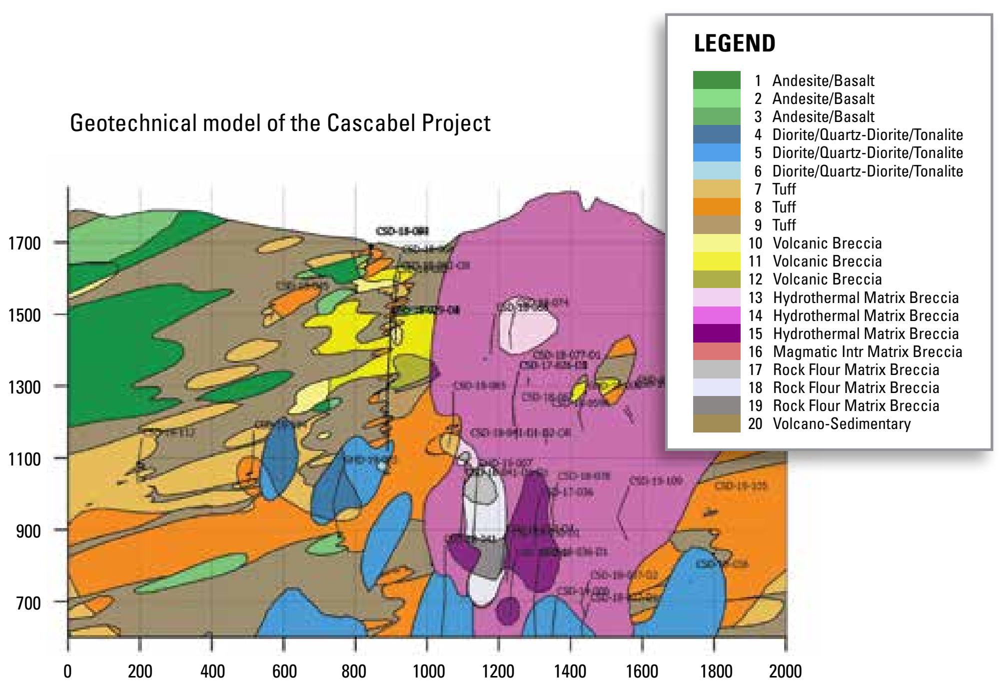
Geotechnical model of the Cascabel Project



Quantification of the intact geological strength index for rock masses in a hypogene environment


Figure 1 Example of primary rock mass

The Geological Strength Index (GSI) was introduced as an empirical tool to scale the intact rock properties, from samples to a rock mass scale. Since its conception, GSI was estimated empirically according to a visual estimation of degree of fracturing and joint condition. Over time, GSI has been modified for a better rock mass characterisation and different methods have been proposed to quantify GSI in jointed rock masses.

At the present, mine operations are facing the challenge to mine ore deposits at deeper conditions, with higher stress, and in rock masses characterised by cemented and sealed veins.

The Los Sulfatos orebody, owned by Anglo American Sur, represents a porphyry copper deposit in a hypogene environment and is characterised by a stockwork of cemented veins (Figure 1). The geotechnical assessment of the different geotechnical units, according to the traditional classification systems, shows a high degree of uniformity between them, requiring a better characterisation of the primary rock mass. Because of this, SRK Chile developed a new method to quantify the GSI.

The proposed intact GSI (IGSI) is quantified based on the spacing between cemented veins and the Mohs hardness of the mineral infill. The potential degree of fracturing of the rock mass is evaluated according to the spacing between cemented veins that have a Mohs hardness up to 5, representing the weaker mineral infill that could be open during drilling or mining activities, such as blasting and caving. The range of spacing that defines different categories of rock mass is assigned according to spacing.

Cemented veins, in a geotechnical interval, are counted according to the mineral association and the Mohs hardness scale. The veins with a Mohs hardness of 2, then 3, etc. up to >5 are counted and then a representative Mohs hardness of the geotechnical interval is calculated by applying a weighted average as a function of the vein spacing. Once the spacing and the Mohs hardness are calculated, it is possible to assign their ratings and calculate the final IGSI.

This method to quantify the proposed IGSI has been tested by characterising almost 1,000 geotechnical intervals from several drill cores of the exploration campaign. The calculated IGSI has been compared with the conventional GSI and with the main classification systems. Results indicated a better geotechnical quality differentiation among geotechnical units, due to the different mineralogical infill strength and different alteration types, compared with the traditional geotechnical assessment.

The proposed method has been developed for primary rock masses and should not be used in a jointed rock mass characterised by open and weathered joints.

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ESTEBAN HORMAZABAL

Esteban, a civil mining engineer with a Masters in Geophysics, specialises in applied hydrogeology. He has 25 years of experience in geotechnical engineering, rock mechanics and geotechnical instrumentation, leading important geotechnical studies for world-class open pit and underground mining projects/operations in Argentina, Brazil, Chile, Colombia, Ecuador, Kazakhstan, Kyrgyzstan, Mexico, Peru, Russia, Uruguay, USA and Uzbekistan. 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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ANDREA RUSSO

Andrea has 25 years of experience in the mining industry. He worked on many underground, mostly block caving, and open pit projects in Chile, Ecuador, Brazil, Canada, USA, Mongolia and Russia, from scoping to detailed studies. He is widely experienced in the geotechnical and structural rock mass characterisation of porphyry copper and epithermal deposits. He also has expertise in the estimation of intact and rock mass properties, caveability and fragmentation assessment, rock support and stability analysis.

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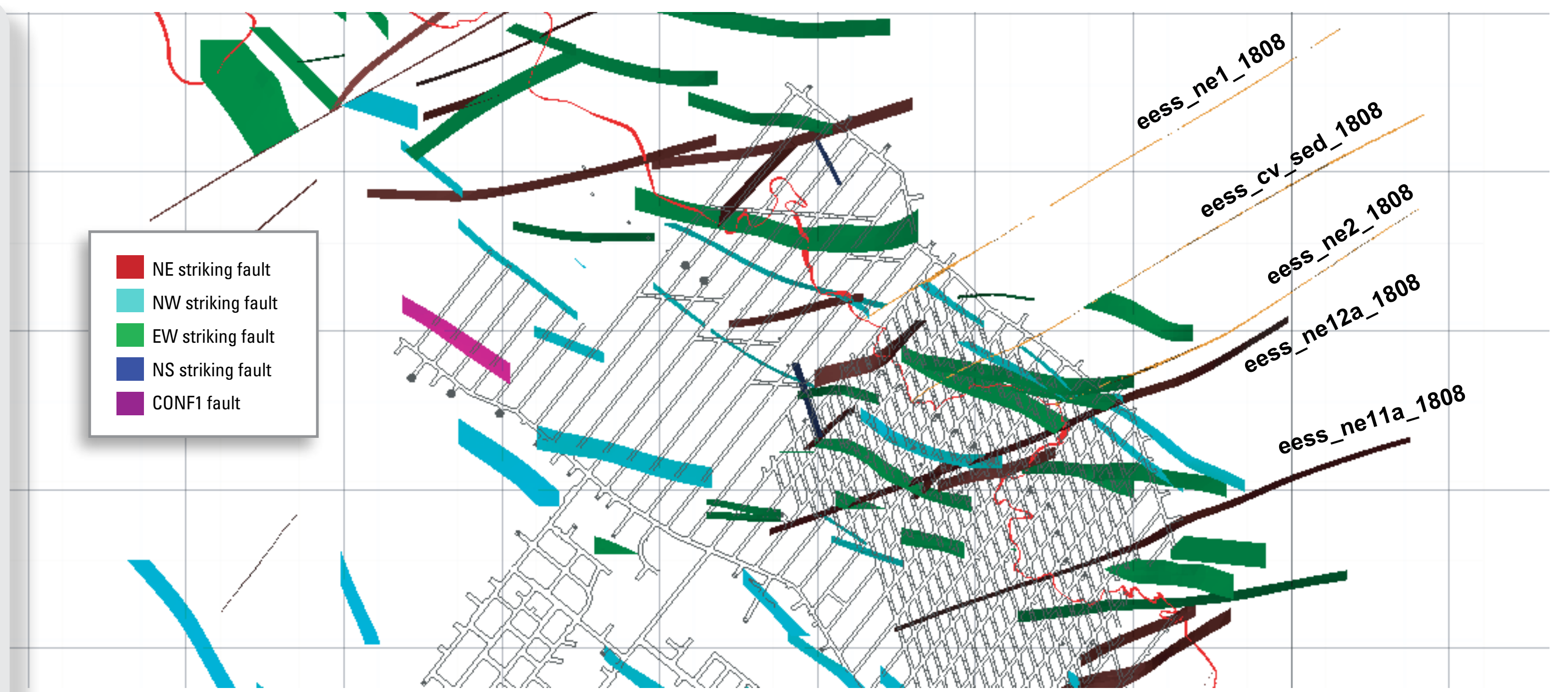
Fault modelling for rock mass studies in the Deep Mill Level Zone (DMLZ) mine of PT. Freeport Indonesia

DMLZ 2590 level showing fault model and DMLZ footprint. from Haflil et al, 2020.



SRK undertook fault modelling for rock mass studies in the Deep Mill Level Zone (DMLZ) mine owned by PT Freeport Indonesia in Papua, Indonesia. The fourth phase of the DMLZ is currently being mined at a depth of approximately 1,500 m in the East Ertsberg Skarn System and porphyry deposit. The skarn formed within a carbonate-rich sedimentary sequence on the northern contact of the large Ertsberg diorite intrusion. The induced vertical stresses combined with the competent nature of the rock mass in the Ertsberg diorite intrusion present challenges for cave propagation and rock fragmentation.

Combined underground mapping efforts by SRK and PT Freeport Indonesia in 2018, helped develop a better understanding of the fault patterns and characteristics inside the Ertsberg diorite. Underground mapping identified that the faults in the diorite are typically non-continuous, segmented, and often vein-filled, tight faults (i.e. fault-veins). The faults in the sedimentary country rock are significantly more continuous, and contain weaker fault rock, including gouge and breccia. Detailed drill hole logging from core and core photographs allowed the logging quality and characterisation of faults to be reviewed.

At the depth of the DMLZ the rock mass is more competent, with low joint and weak vein densities. The lack of natural fractures presented challenges for the block cave fragmentation. Blast fracture orientations can be variable, but in the DMLZ these are commonly parallel to pre-existing rock anisotropy defined by the vein systems.

SRK developed a revised 3D wireframe fault system interpretation in 2017 that has been incorporated and continually developed by the mine geologists to keep the 3D structural understanding up-to-date and relevant for mine planning, seismic risk and damage management.

SRK provides regular peer review of the fault models as they are developed by incorporation of new mapping and drilling data.

The fault systems have reacted to high excavation stresses, influencing seismicity during the mine development and initial block caving. It appears that some of the seismic events occur on the segmented faults systems at the intact relays between segments that are breached by stress-induced fracturing. These challenges have prompted the team to keep enhancing the quality of data collection and modelling. Caving is currently being assisted through use of a comprehensive hydraulic fracturing program. SRK continues to provide peer review, training courses and input to seminars for PT Freeport Indonesia.

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WAYNE BARNETT

Wayne has 25 years of experience in the mining and exploration industry. He worked for 8 years as an operations-based geotechnical engineer and applied structural geologist. Subsequently, Wayne has consulted in structural geology on all mining-active continents. He specialises in defining the structural geology of mining projects in order 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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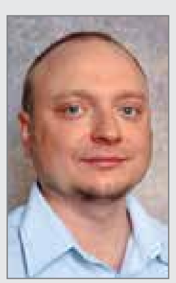
VICTOR SPIRIN



Victor has over 12 years of experience in open pit geomechanics, in particular, in open pit slope and bench stability estimation using the methods of Russian and international practice. He has experience in organising and monitoring displacement processes using modern control systems, conducting geomechanical audits in the field, documenting and analysing actual slope failures in open pits to investigate the causes and performed reverse engineering analysis.

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Regulation of open pit slope stability in Russia

SRK Moscow is involved in the development and updating of the Russian Rules for the Stability of Benches of Slopes of Open Pits and Waste Dumps (Rules). Russian and international experience was considered and adapted to meet new regulatory requirements.

The Rules are based on the outcome of the Large Open Pit (LOP) project and subsequent Guidelines for Open Pit Slope Design (2010) edited by John Read and Peter Stacey and other publications sponsored by the LOP.

Many Russian mining companies were involved in financing this program. Several universities, consulting and scientific organisations were engaged in the development of the Rules. SRK Moscow participated in the development of the updated regulations and provided input through local and internationally gained experience. The updated legislation requires that the design must be reviewed by qualified experts and approved by supervisory state bodies before open pit mining can commence. These reviews ensure that the Rules comply with all relevant regulations.

The new Rules, brought into effect in 2021, have the force of a technical law which must be followed by all entities involved in research, justification, design, review and implementation at all stages of project development. The Rules summarise a wide range of requirements for geological and hydrogeological studies, stability analysis, monitoring methods, estimation and analysis of geotechnical risks, management of slope stability by developing special measures to reduce risks. Procedures for interaction between production and scientific specialists, designers and experts are defined.

Depending on the complexity and the stage of a mining project, specific types of studies, minimum requirements and the analytical methods are specified. The Rules document is sufficiently flexible to consider future trends. SRK supports additional guidelines, such as:

- Guidelines for geotechnical and hydrogeological studies and rock mass mapping
- Guidelines for estimating slope and bench parameters for open pits and waste dumps
- Guidelines for monitoring failure and managing risks for stability of slopes and benches for open pits and waste dumps.

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IVAN LIVINSKY

Ivan has over 10 years of experience in mining geotechnics, specialising in rock mass characterisation in accordance to international codes (Rock Mass Rating (RMR), Modified Rock Mass Rating (MRMR, iMRMR), Barton Q system). His expertise covers QA\QC of data collection, data processing, planning and supervision of geotechnical drilling, and laboratory analysis of physical and mechanical rock properties. Ivan is a professional user of various geotechnical software packages and is well experienced in geotechnical modelling. He is proficient in geotechnical drilling supervision and managing drilling subcontractors. His experience includes structural data collection at mine sites using photogrammetric methods.

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Underground design and numerical modelling

SRK carried out a feasibility level geotechnical design for an underground and open pit copper project in southern Morocco. The study included a site visit to access drifts dating from the 1970s to gather geotechnical data.

The study included various mining methods down to a depth of 600m, such as drift and fill, drift and pillar, room and pillar, open stoping and a similar-to-AVOCA method. A combination of empirical and numerical approaches was used to estimate stresses on pillars and abutments, evaluate pillar strength, assess the impact of surface subsidence and determine backfill strength and stiffness requirements.

The tributary area and Mathews methods were used for a first-pass design of pillars and spans; however, they could not be used to optimise the designs and improve extraction ratios. Therefore a simple model was constructed in FLAC3D to estimate stresses in an elastic homogeneous material. Code written in the FISH scripting language allowed several layouts, varying spans, pillar and panel sizes to be analysed with ease and makes it possible to automate the output of stress values for post-processing with MS Excel. Output of stress contours for reporting was also automated through FLAC's in-built Python capabilities.

Complementing the above, a conceptual monitoring system was designed with the aim of validating and calibrating the models used in the geotechnical analyses; such a 'design by measurement' rationale can help to manage risks, improve safety and productivity, optimise designs and reduce costs. The system was directed specifically at optimisation and roof support optimisation; the former can be achieved by measuring the loads developed within pillars as mining progresses through the use of CSIRO hollow inclusion cells. Borehole extensometers were recommended to assess how the roofs of excavations behave with respect to distance from the face and excavation dimensions.

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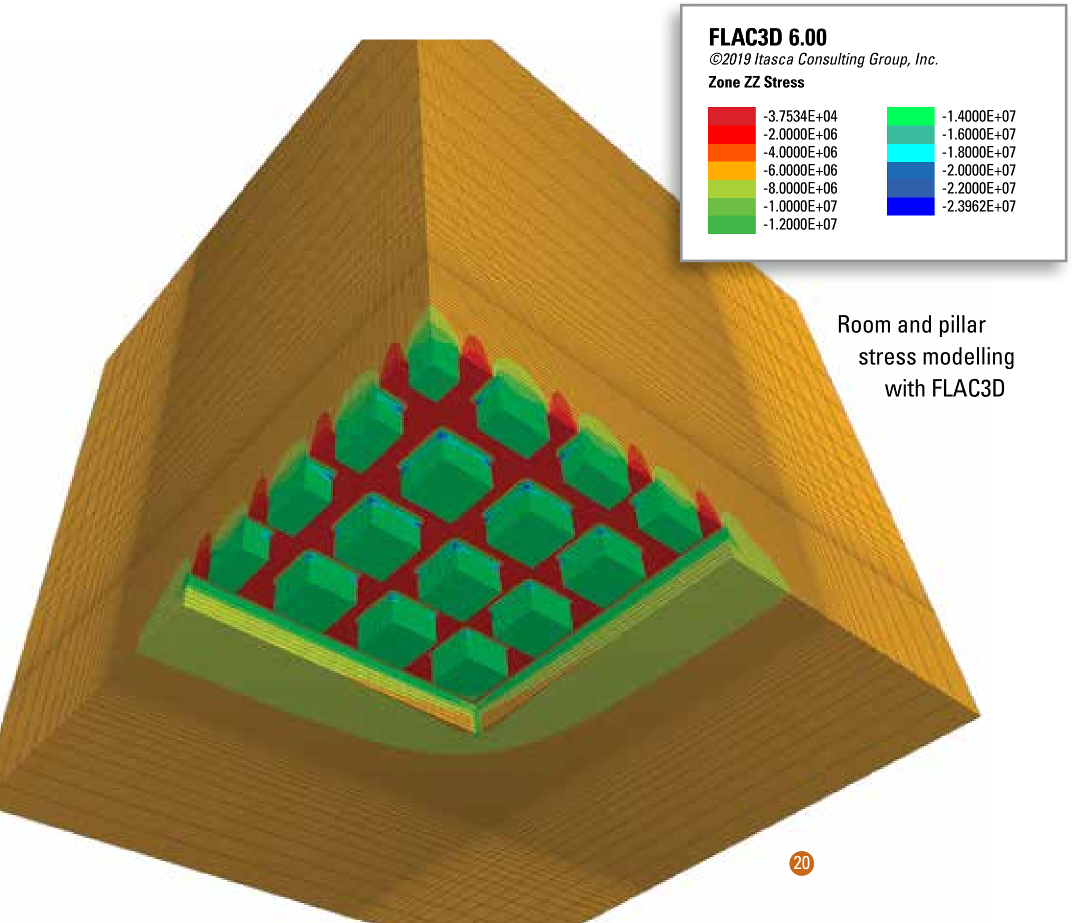

Room and pillar stress modelling with FLAC3D

Operational geotechnical assistance

Rössing uranium mine

In many engineering projects, the design engineer forms an integral part of the construction team. The design engineer can monitor the implementation of the design and assess if any construction conditions deviate from the design assumptions. Mining of an open pit slope requires monitoring; while this is mostly performed by the mine's geotechnical team, the involvement of the design team has many benefits. Open pit slopes are generally designed based on a point in time of a geotechnical model, which evolves as the pit expands. This is due to the variability associated with geological environments, limitations in data and exposure uncertainties. As the geotechnical model evolves, so too should the design. Additionally, the measures that are put in place to manage the risk associated with the slope design must be aligned with the uncertainties in the geotechnical model and design assumptions.

Benefits of a long-term relationship between mine personnel and the design consultant include ongoing review of the slope performance with time and continuity in understanding of the risks and geotechnical model; the ability to provide input into instability management and back analysis with an understanding of the history of instabilities and slope performance; a thorough understanding of the litho-structural model, groundwater model and the geotechnical data base, their development over time and the resulting limitations, and the ability to make contributions to future development; institutional memory preserved when mine staff change; and practical exposure of mine staff to stability analysis and the slope design process.

In addition to the above, due to SRK's long-term development in these fields, SRK can assist the mine in transitioning to UAV-based data collection and conducting detailed third-party review of the mine's micro-seismic monitoring. Additional advanced analysis of the micro-seismic data provides further input into slope behaviour analysis and model calibration.

The Rössing uranium mine is a ~20 Mtpa (total tonnes mined) ~390 m deep open pit uranium mine that has been operating since 1976. It is 70 km inland from the coastal town of Swakopmund in Namibia. SRK South Africa has been providing mining geotechnical consulting services since 2013 in the form of training, mentoring, guidance and review. Regular site visits are conducted to review and provide mentorship to the mine's geotechnical team, and to keep them abreast of developments and advances in open pit slope design, management, monitoring and data collection technologies. Additionally, design updates are conducted as new knowledge is gained for incorporation to the geotechnical model.

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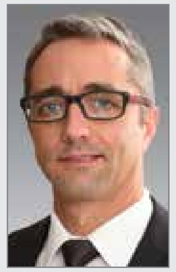
ROB ARMSTRONG



Rob is a geologist (geotechnical) in SRK's Johannesburg office. Robert has 19 years of experience in the fields of engineering geology and rock engineering. He specialises in geotechnical data collection and review, geotechnical model generation, including structural and geological models, slope designs and review and development and assistance in geotechnical slope management programs, including instability management. He has worked on multiple commodities and mineralisation types, in both hard and soft rock environments throughout Africa and in the Middle East. Robert has served on the National Council of the South African Institute of Rock Engineers for 7 years, including holding the position of vice president and president of the Gauteng regional branch. He has authored several publications on rock engineering.

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IÑAKI GARCÍA

Iñaki is a geotechnical engineer in SRK's Cardiff office. He has over 9 years of experience in geotechnical design and numerical analysis of open pit and underground operations and infrastructure projects, including excavations and tunnels in rock and soil. He has provided services to mining projects in the Americas, Europe and Africa across a wide range of commodities in both hard and soft rock environments, from on-site geotechnical data collection through to analysis and design at pre-feasibility and feasibility level and operational support.

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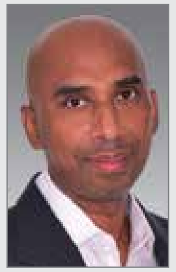
JAYA MYLVAGANAM



Jaya has over 20 years' experience in geotechnical engineering in both the mining and civil sectors. Jaya has experience in all aspects of open pit geotechnical design and has worked on various challenging projects. His experience includes complex 2D/3D stability modelling, and groundwater seepage and slope depressurisation modelling. He has conducted site investigations of rock mass ratings and hydrogeological behaviours and performed extensive interpretations of geotechnical data, including data calibrations using numerical modelling. His civil engineering experience includes the design of civil/mining infrastructure and rock dumps.

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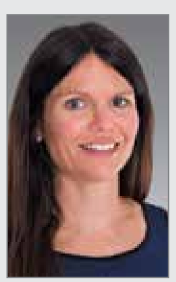
JUSTINE PAUL



Justine is a senior geotechnical engineer with over 10 years of experience in mining. She has undertaken numerous geotechnical field investigations and has considerable experience in reviewing geotechnical data including databases and consultant reports and in performing structural and kinematic analyses. Justine has extensive experience in coordinating and evaluating laboratory testing, and in characterising rock and soil masses for slope and underground excavations. She has practical expertise in limit equilibrium slope stability analysis and design, and finite element numerical modelling.

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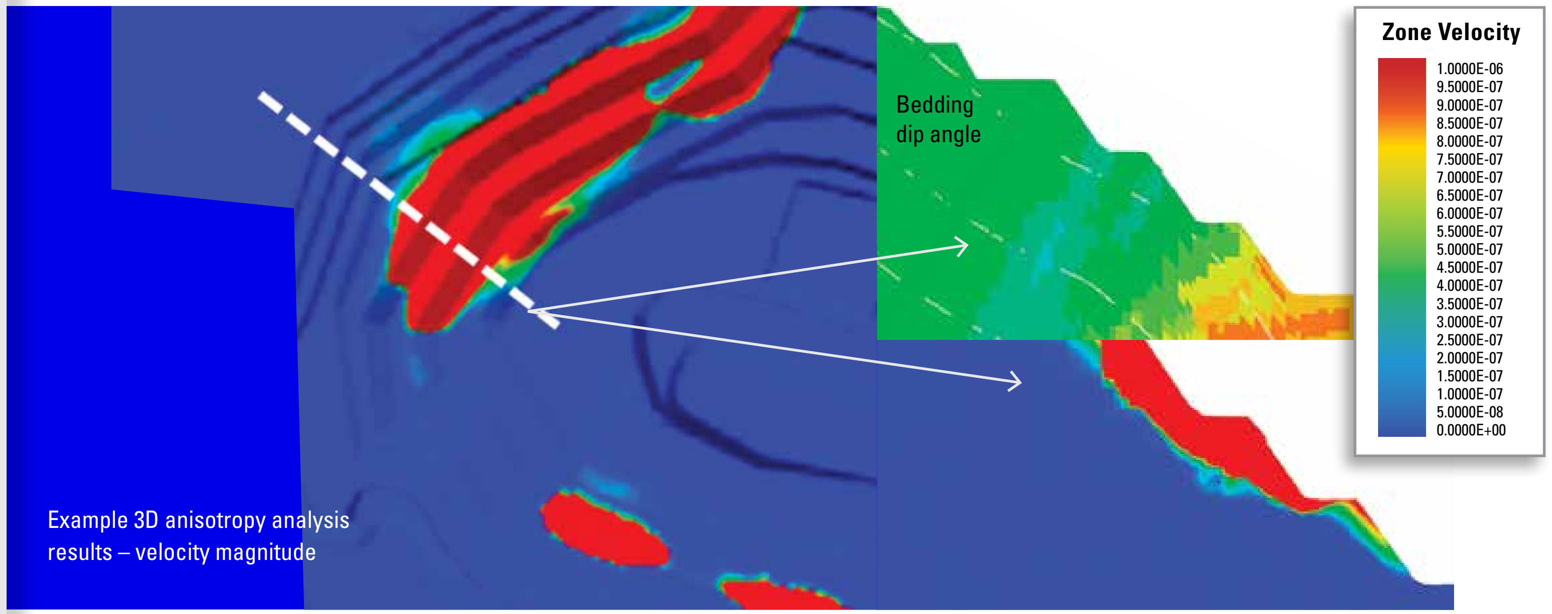
Challenges encountered in pit slope designs in anisotropic bedded rock masses



Example 3D anisotropy analysis results – velocity magnitude

Open pit slope design in the bedded units encountered in the iron ore pits of Australia's Pilbara region is challenging in many aspects. Data collection and interpretation, slope stability assessment, and implementation of design parameters in these anisotropic rock masses require specialised experience, as there are numerous complex considerations. Evaluation of bedding shear strength is a critical aspect in the process, which presents challenges in collecting appropriate samples; successful execution of laboratory testing; appropriate interpretation of the effects of infilling; and interpreting the impact of the undulations and asperities on the bedding surface. Back-analysis of failures along bedding planes and in-pit large-scale shear testing are seldom an option. The selection of an appropriate strength model for each stability analysis section depends on the rock units present and the anisotropy orientation.

2D limit equilibrium methods, incorporating the Snowden modified anisotropic linear model, are commonly used for stability assessments. The outcomes using this method are sensitive to analysis methods, slip surface search limits and methods, and key model inputs. It is important that the possible failure mechanisms are well understood and suitably analysed. A critical part of the design process is the identification of design domains and the selection of representative sections for slope design analyses. SRK has developed refined methods in this regard. In some cases, more advanced stress-strain based numerical programs, such as finite difference or distinct element codes, should be used.

It is a common assumption in anisotropic 2D analyses that slopes will be fully bedding-controlled where bedding strike is ≤30° to the strike of the slope, and that stability will be best represented by isotropic (rock mass controlled) conditions where bedding is >30° in obliqueness. However, 3D analyses can better capture failure mechanism and instability risk in the context of rock mass confinement and bedding obliqueness. SRK has performed 3D analyses that have allowed better understanding and prediction of these controls, for consideration where only 2D analyses are able to be carried out. When the bedding dip angle is greater than its shear angle, the difference between the 2D and 3D factor of safety (FoS) of a slope increases significantly as bedding obliqueness increases. The FoS in 3D is slightly higher than in 2D for bedding that is parallel to the slope.However, where the bedding strike is only 10° oblique to the slope, the difference in FoS is already significant (≥15%) and increases to >20% from 20° upwards. This demonstrates that the results of 2D analyses for bedding obliqueness ≤30° are conservative, and 3D analyses may indicate opportunities for slope steepening. Conversely, the 2D analysis of isotropic conditions where bedding obliqueness is > 30° may significantly overestimate the stability of a design (by >20%), presenting increased risk of failure.

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Remote geotechnical analysis: pit performance and optimisation

SRK undertook a remote review of pit slope performance and performed design updates for three gold mines in the Middle East.

Due to the COVID-19 pandemic, a planned site visit to gather geotechnical data was cancelled. Instead, the client's on-site team collected data from the iSite laser scanners which were then processed and analysed using Maptek's PointStudio program. These data assisted with a review of slope performance of the current pits and a slope stability assessment and subsequent update of slope design.

SRK generated heat maps displaying the variation in bench face angle and berm width across multiple sections of each pit. The data were then processed to produce histograms of inter-ramp angle variability, as well as bench face angle and berm width, enabling visual interpretations of the condition of each pit and compliance with the approved slope design. The outputs were not only informative for the mine production team, but were also used to inform design recommendation changes in later slope stability assessments.

To assess slope stability, SRK selected thousands of exposed discontinuity surfaces from the high-resolution laser scans to generate data on discontinuity orientation, area, length and spacing. The use of laser scans enabled data to be generated from all benches of each pit, which is often not possible with on-site pit wall mapping. The datasets were then used in slope stability analysis using S-Block, a probabilistic program that calculates the berm widths required to retain a given percentage of expected failure volumes from slope benches. The slope performance was calibrated, including observed bench failure modes, using SBlock. This enabled determination of slope inter-ramp angles required to retain a minimum average of 80% of expected failed material in each bench. New geotechnical domains were subsequently created with updated slope design angles based on structural variability, enabling slope angles to be optimised for several domains across the three mines.

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CHRIS MEARS

Chris has over 4 years of experience specialising in geotechnical data collection and analysis and a Master's in Applied Geotechnics. Since joining SRK, Chris has been involved in a number of open pit and underground mining projects across Europe, Central Asia and Africa, through which he has developed expertise in geotechnical logging, rock mass characterisation and geotechnical support design.

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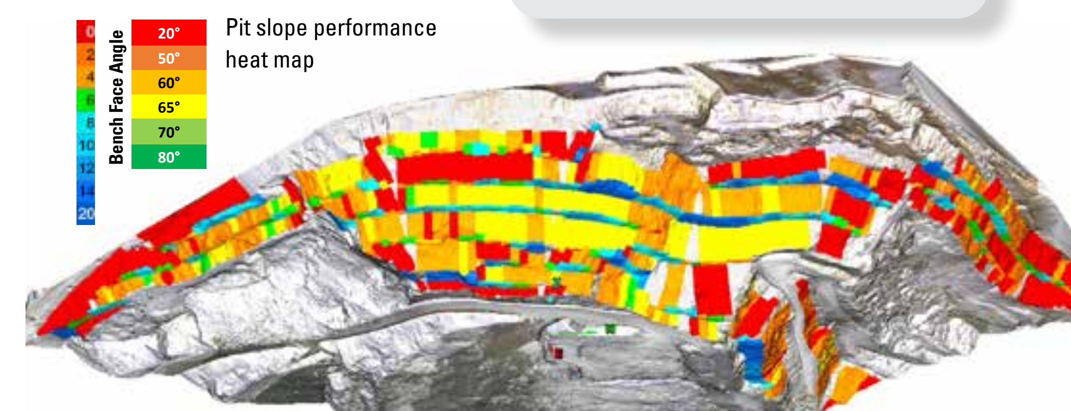
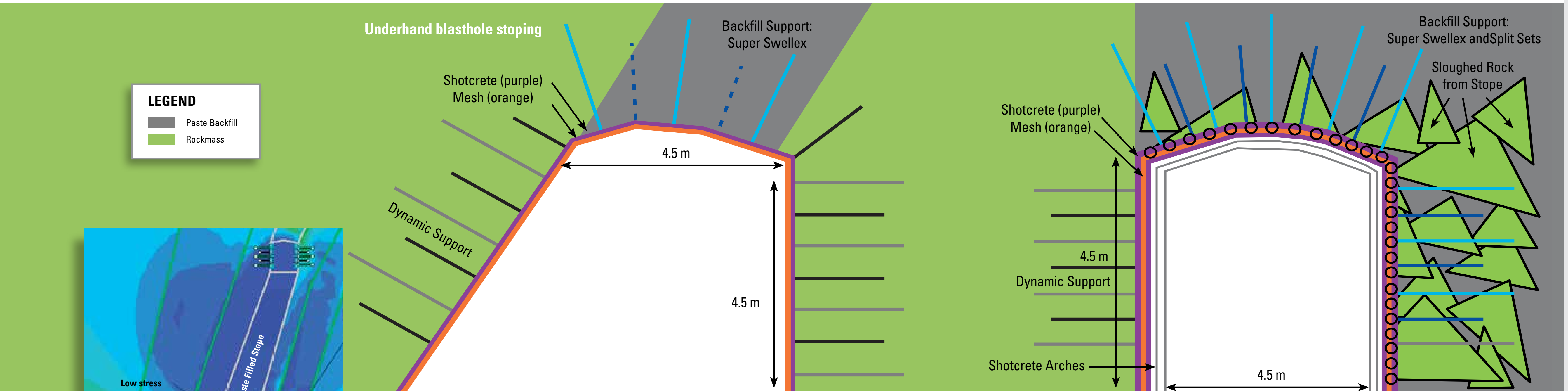
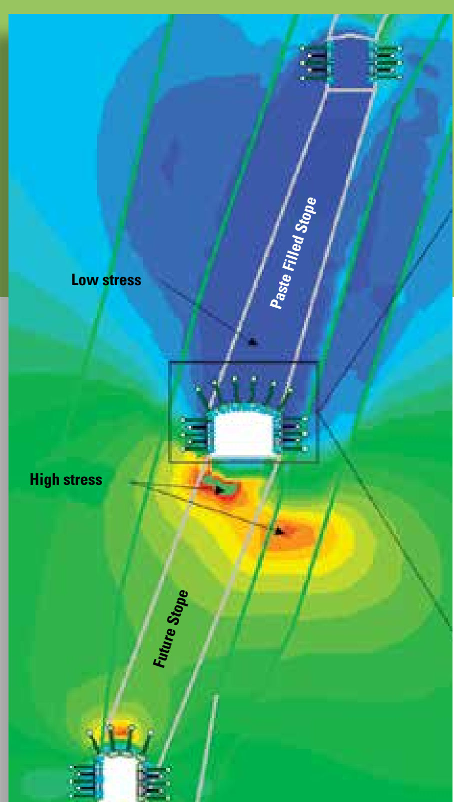


Pit slope performance heat map

Underhand blasthole stoping – re-sill mining





A narrow-vein gold overhand blasthole stoping operation that is geologically and geotechnically complicated, and seismically active, is exploring alternative mining approaches to manage these adverse conditions. Transitioning from overhand to underhand mining is being considered because the top-sill (high occupancy mining activities) is developed in the destressed paste backfill of the overlying stope and the stress concentrations will be in the floor, as opposed to the immediate back in overhand mining.

An integrated SRK team evaluated the backfill strength requirements, mining and support guidelines for re-mining the top-sill, and prepared preliminary Standard Operating Procedures (SOPs) for the initial trials. Others evaluated the seismic risk (possible floor heave) and increased stress levels that would impact stope drilling and lower-sill development. These assessments include pre-conditioning opportunities.

Although underhand blasthole stoping methods are being used elsewhere in Canada, this mine's geotechnical context presents a different case as the narrow-vein mining, in contrast to thicker orebody mining, does not afford the de-stressing of subsequent stopes, using a cut-off concept, on the same level.

SRK reviewed case studies for analogue mines and found that backfill strengths determined using empirical guidelines resulted in lower strengths than those typically used in practice for main entry excavations. However, designing backfill that is too strong can result in backfill slabbing as experienced at the Lucky Friday mine, a good analogue operation, when the backfill became stressed and spalled.

Re-establishing the top-sill in the bottom-sill of the overlying backfilled stope requires the mining and support of backfill, but also that existing rock surfaces are supported using dynamic loading-capable support. The backfill is weak enough to be free dug, but other operations have used careful drilling and blasting to maintain the drift profile and maintain production rate requirements. Mechanical mining is possible but will be challenging if substantial fall-off has occurred before backfilling. The support system in the backfill consists of Swellex/Split-sets, mesh and shotcrete. A flash-coat of shotcrete is planned but requires evaluation and testing as issues with shotcrete adhesion on paste have been cited. Installing Swellex and Split-sets in paste requires testing and continuous improvement to verify that support capacity is being achieved. In complicated development situations, spiling and shotcrete arches/steel arch sets will be applied.

Mining through paste mixed with rock from stope fall-off will add complexity and impact advance rates. It will be important to understand if a material has sloughed-off into the stope after mucking and prior to backfilling commencing. SRK recommended LiDAR drone surveys be used to accurately scan the stope just prior to backfilling. Then a decision can be made to remove the barricade and re-muck the stope or implement a change to the re-sill mining strategy/schedule.

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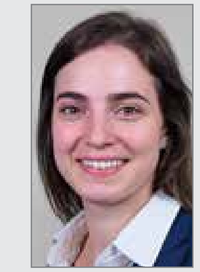
ADRIENNE JOAQUIM



Adrienne has 7 years of experience as a consultant in the mining industry. She has managed technical studies ranging from strategic level conceptual assessments to Preliminary Economic Assessment (PEA), pre-feasibility and feasibility level studies. Adrienne's technical background is in geotechnical investigations and stability analyses as they relate to open pit and underground mines. She has been involved in open pit and underground geotechnical assessment projects ranging from scoping level to feasibility level studies. Adrienne has a range of experience including field geotechnical data collection programs (drill core logging), characterisation of rock mass, slope stability analysis, review and reconciliation of old mine workings, and empirical evaluation of underground excavation stability.

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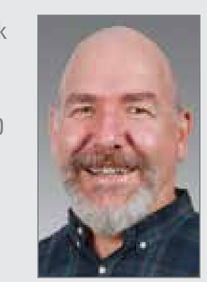
BRUCE MURPHY



Bruce leads the rock mechanics group in SRK's Vancouver office. He has over 30 years of international experience in rock mechanics, including rock mass characterisation leading to excavation and support design; mining method selection and the technical auditing of both open pit and underground operations. Bruce has been involved in mining operational rock mechanics since 1989 in open pit and underground operations, including gold, copper and iron ore. Bruce currently participates on Geotechnical Review Boards for open pit operations at the Oyu Tolgoi, Bozshakol and Essakane mines, and several underground operations.

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Mining through voids – Pamour

MAX BROWN

Max is a geotechnical engineering with over 20 years' international experience in the extractive industries specialising in rock mechanics in both open pit and underground mine. 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 and currently manages the geotechnical team in SRK UK.

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ANTON BLOEM

Anton specialises in open pit slope design. He has 20-plus years of experience in rock mass characterisation using drilling and field/mine mapping methods, and is skilled at first-pass estimation, interpretation, and development of verifiable rock mass models. Extensive exposure and experience using downhole geophysical survey methods have led to his interest in vertical alignment characterisation and design. In his operational support roles, he's developed an active interest in rock mass dilation and blast damage characterisation for excavation design adjustment.

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Crown pillar trenches

The Pamour mine, one of Newmont's Porcupine gold mines, is situated in Timmins, northern Ontario, Canada. Discovered in the early 1900s, the development of the Dome, Hollinger and Pamour mines, among others, established the hard rock mining industry in the region. Before 1930, shrinkage mining was used, followed by cut-and-fill stoping (backfilled with unconsolidated sand) of the quartz vein hosted gold mineralisation. Underground mining at Pamour started in 1936 and ended in 1996, yielding more than 4 Moz. Stopes were accessed through relatively small dimension drifts and drives connected to two shafts. Surface mining of crown pillars occurred between 1976 and 1996. Large-scale open pit mining of peripheral veins and disseminated mineralisation started in 2004, which was put on hold in 2009 and partially backfilled in 2012. The pit has been allowed to flood in the last decade.

The existing Pamour pit (12 km northeast of the Dome mine) is elongated along an azimuth of 075°, is 1.3 km long, 0.5 km wide, and 280 m deep. Once the water level is lowered, the interconnected underground mine workings will be used to underdrain the rock mass. The excavation will advance an additional 1.1 km towards the east-northeast, will widen by 300m, and will increase in depth to about 530 m. A feasibility level investigation in 2020-2021 found that even though the three mines are separated by tens of kilometres, the lithologies are essentially the same, and the rock masses are mostly FAIR to GOOD. Structurally, there are relatively narrow damage zones of V-POOR ground associated with regional scale brittle deformation, and the alteration effects can be accounted for in the geotechnical domain models. Rock mass foliation (72/155° on Hollinger's North Wall and 70/335° on Pamour's footwall) kinematically limit the achievable bench face angles.

Beyond kinematics, the dominant open pit design constraint in the Timmins area pre-mined rock masses are the size, shape and induced excavation damage associated with the voids, relative to the slope geometry and the ramp positions. When mining through the older narrow stopes like at Hollinger, where the voids are sub-parallel to the rock mass fabric, the void detection and caving, filling and wall control is done on a bench by bench basis. Where the stopes are larger, like at Dome, and there are weakened intact rock halos around the mineralisation, inter-ramp scale slope design adjustments and the use of waste rock buttresses are more appropriate. The situation seen at Pamour, however, poses more of a challenge because it is a 'hybrid' situation. It has several large open voids along the 'keel' of the pit, and some steeply dipping narrow stopes in weaker intact rock at mid-height within the hangingwall slopes.

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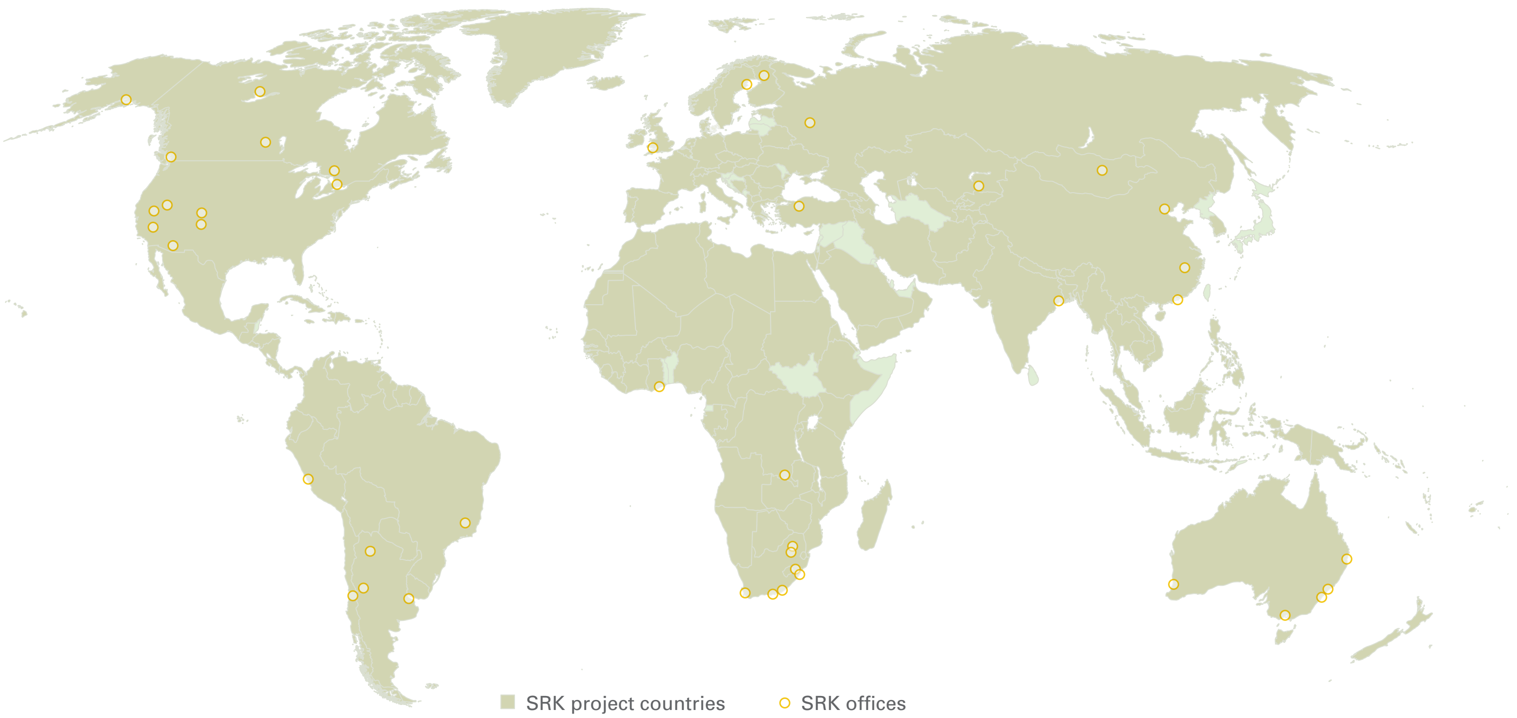

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