Volume 19 | Issue 5 | October 2022

MINING & QUARRY WORLD

Volume 19 • Number 5 • October 2022

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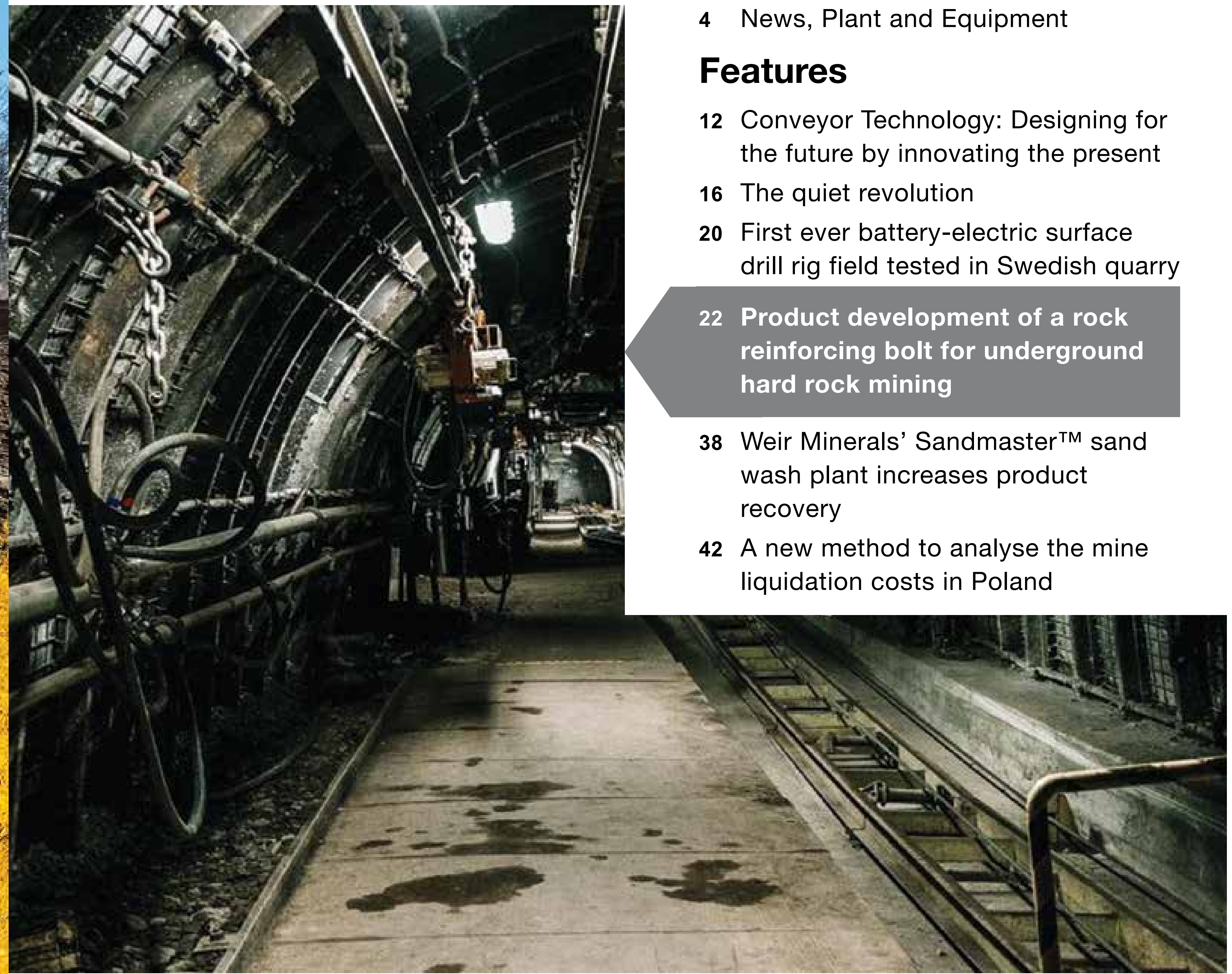

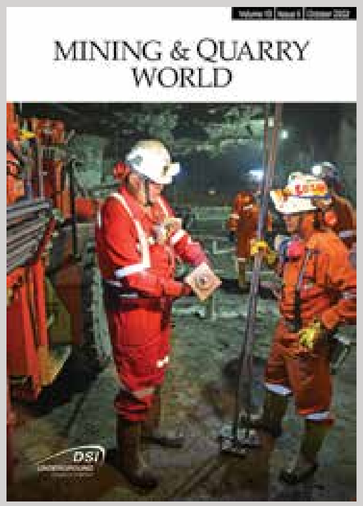

DSI Underground is the global market leader in the development, production, and supply of specialist ground support products to the underground mining sectors. We offer a wide variety of rock bolts consisting of steel bars, strand and hollow bars, and GRP glass fiber reinforced systems. Our product portfolio also includes high-quality injection chemicals for sealing, stabilization, filling, and bonding – and several virtual reality simulator trainings. In 2021, DSI Underground became part of the Sandvik family. We reinforce Progress.

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Published by: Tradelink Publications Ltd.
16 Boscombe Road, Gateford Worksop, Nottinghamshire S81 7SB

Tel: +44 (0) 1777 871007
+44 (0) 1909 474258
E-mail: admin@mqworld.com
Web: www.mqworld.com

All subscriptions payable in advance.
Published 6 times per year, post free:
UK: £60.00 **Worldwide:** £70.00 | ISSN No: 2045-2578 | D-U-N-S No: 23-825-4721

Tracking underground miners more efficiently with smart technology

Researchers in Kazakhstan recently developed a smart safety system for underground miner tracking. The machine learning-based technology uses Wi-Fi spot signals and inertial measurement unit (IMU) sensors to track miners' whereabouts underground, and could drive up safety standards in mines worldwide.

Manual Underground Miner Tracking: Problems Beneath the Surface

Underground mining operations use manual tracking systems to monitor their miners' locations. This job is usually carried out by the mine foreman who works with a dispatcher to draw up a precise list of everybody's name and location in the mine.

If miners need to move to a different work area within the mine, they must contact the dispatcher using a tethered phone connection. The dispatcher then updates the location list accordingly.

Manual tracking systems have several drawbacks, with the US Department of Health & Human Services even warning against using them.

For example, the department says that if the work area that has been designated for a miner is too large, it will not be possible to pinpoint their location. The system is vulnerable to human error and has no fail-safe backup safety measures to detect or prevent failures in the safety system.

The US government passed the MINER Act in 2006. This requires coal mines to put electronic tracking systems in place to enable rescue operations to take place if necessary.

Electronic Underground Miner Tracking Systems

Related Stories

- Green Mining: Paving the Way to More Sustainable Metal Extraction
- Smart Guidance and Automation Technology for the Mining Industry
- K9 Gold Obtains More Funding to Find More Potential Targets on its Stony Lake Project

Electronic tracking systems are making their way into increasingly more mines every year. But currently available electronic methods such as GPS and Wi-Fi tracking still have some limitations.

Underground and open-cut mines present terrain restrictions for GPS and Wi-Fi sensing devices. Similarly, these systems struggle in disaster zones where the existing infrastructure has been destroyed.

Reader-based tracking can overcome these limitations. Using the same radio frequency identification (RFID) that prevents retail theft, mines can create ultra-low-cost electronic tracking systems over relatively small-scale operations.

Node-based electronic tracking technology creates a communications link between the radio and nodes. A chip analyzes the signal strength coming from a radio carried by the miner and determines the miner's distance from a number of nodes around it to triangulate the miner's location in three-dimensional space.

One proposed technology for miner tracking is known as inertial navigation or inertial guidance. Systems like these are carried by miners and passively measure accelerations, turns, and so on to calculate the miner's distance from a fixed start point.

New Algorithm for Wi-Fi and IMU Method Could Be Used in Underground Mining Safety

Researchers at the Nazarbayev University's Institute for Smart Systems and Artificial Intelligence in Kazakhstan recently developed a neural network algorithm designed to improve Wi-Fi-based localization and tracking systems.

The researchers say that their method, which combines data from Wi-Fi localization with IMU sensors data gathered in a handheld device, could improve mining safety by making a cost-effective smart tracking method more accurate, even with a poor Wi-Fi signal.

The algorithm was trained initially within the university building, which researchers used to simulate an underground mine.

By sending pairs of "workers" around the building, the team established a dataset with geospatial information from three floors using only information from Wi-Fi signals. They continued to "train" the algorithm that was generating a model of the building until it had an error distance of approximately 2.5 meters.

At this point, the researchers added data from IMU sensors to the algorithm's feed.

IMU sensors will mean the tracking devices will still be able to localise themselves when the algorithm feed is offline by calculating the distance it has been displaced through IMU signals. This can give an overall estimate of the device's position, which will become more accurate over time as the algorithm matures.

IMU sensors are already found in smartphones and pedometers. They are relatively inexpensive devices used to measure acceleration relative to the motion of the earth to calculate location.

The research is now focused on gathering more data to train the artificial neural network algorithm using machine learning. This process involves walking around the university building with handheld devices, feeding Wi-Fi access and IMU information back to the neural network.

The machine learning element will continue to refine the algorithm as more real-world data is fed into it. Researchers say this should result in a robust algorithm that can withstand the demands of localization in an underground mine.

While the neural network is still "growing," the team is using fiducial markers that enable camera sensors to calculate their precise position relative to the marker. This provides real-world feedback for the algorithm to develop itself with machine learning.

In the future, the team plans to incorporate 5G connectivity into the system. This will increase the capacity of networks based on their system because 5G networks have a much higher density than Wi-Fi.

NEWS, PLANT AND EQUIPMENT

Gold miners predict $1 800/oz comeback

Not even the most hawkish Federal Reserve in decades can beat down the exuberance of gold enthusiasts at the industry's biggest annual gathering.

Bullion prices will reach $1 806.10 an ounce by year end, according to the average estimate in a survey of 10 participants at the Denver Gold Forum, the yearly meetup of mining executives, investors, bankers and analysts.

The forecast is 7.8% above Monday's spot closing price. The last time gold settled that high was at the beginning of July.

"You'll continue to see investment globally interested in owning gold strategically" including from central banks, World Gold Council's Joseph Cavatoni said in an interview at the 34th annual event. "Plus the geopolitical risks are going to keep it front and center, on the mind of every investor."

Still, Cavatoni predicts "a bumpy ride" between now and the end of the year, with gold fluctuating until central banks around the world give more clarity on their fight against inflation.

Bullion had held above $1,700 an ounce for most of September, but tumbled last week after breaking through a key support level that has held since 2020. The selloff came amid investor jitters across the financial markets that the Fed will likely to raise interest rates by at least 75 basis points Wednesday and that an even bigger increase could lead to more volatility across all asset classes.

Central banks' monetary tightening to rein in inflation has pushed up rates and the Fed's aggressive tightening led to a supercharged greenback. Both are bad news for gold, since the precious metal pays no interest and is priced in the US dollar.

"The momentum is clearly in favor of the US dollar," Randy Smallwood, CEO of Wheaton Precious Metals, said in an interview.

The next Fed rate decision will come on the final day of the Denver Gold Forum. The next moves of the precious metal will be driven by the rate decision along with the bank's language around inflation and future hikes.

Investors have been fleeing gold of late. Hedge funds and money managers have turned net bearish on the precious metal, according to the latest Commodity Futures Trading Commission data.

Holdings of gold-based exchange-traded funds – a key pillar in pushing bullion prices to record highs in 2020 – have been sliding for four straight months to the end of August. The downward trend has continued into September, with gold ETF holdings down 1% this month.

Still, bullion has held up relatively well, down only 8.4% this year. Its support comes from heightened geopolitical and economic risks. There are concerns that the Fed's aggressive tightening to fight in stubbornly high inflation may tilt the US economy into recession.

Russia's ongoing war in Ukraine presents a good case to own gold amid geopolitical risks. And Europe's ongoing energy crisis and China's zero-Covid policy also point to a global economic slowdown, which may prompt investors to hold onto gold as a hedge against such uncertainty.

"It's a defensive asset during a time when there is macroeconomic and geopolitical uncertainty," Yamana Gold executive chairman Peter Marrone said in a Bloomberg Television interview from the gathering. "China has been in Covid restrictions for a long time," he added, "as they come out of that, we will see strong prices again."

Epiroc to acquire majority ownership in Australian mine connectivity provider

Epiroc, a leading productivity and sustainability partner to the mining and infrastructure industries, has agreed to acquire a majority stake (53%) of Radlink, an Australian company that provides mines with wireless connectivity solutions.

Radlink, headquartered in Perth, Australia, designs, delivers, and integrates wireless data and voice communication networks and supporting infrastructure to surface and underground mines throughout Australia. Robust wireless networks are vital to support mining automation, including autonomous and teleremote solutions, which in turn strengthen safety and productivity. The company has approximately 330 employees and had revenues in the fiscal year ending 30 June 2022, of about MAUD 145 (MSEK 1 040).

"Radlink's powerful network connectivity solutions will support Epiroc as we continue to provide mining companies with automation and digital solutions that make operations safer and more efficient," says Helena Hedblom, Epiroc's President and CEO. "We look forward to welcoming the strong team at Radlink to Epiroc." The acquisition is expected to be completed in the fourth quarter 2022. The transaction is not subject to a disclosure obligation pursuant to the EU Market Abuse Regulation.

€3bn Europe hydrogen bank announced

To capitalise on the rapidly developing hydrogen economy, European Commission President Ursula von der Leyen on Wednesday announced the creation of a European Hydrogen Bank.

The bank would invest €3-billion to help building a future market for hydrogen.

"Hydrogen can be a game changer for Europe. We need to move our hydrogen economy from niche to scale," Von der Leyen said, delivering her State of the Union address.

With REPowerEU – the European Commission's plan to make Europe independent from Russian fossil fuels – the bloc has doubled its 2030 target to produce ten-million tons a year of renewable hydrogen in the EU. This domestic target, combined with hydrogen imports of ten-million tonnes a year, would replace natural gas, coal and oil in hard-to-carbonise industries and transport sectors.

"To achieve this, we must create a market maker for hydrogen, in order to bridge the investment gap and connect future supply and demand," said Von der Leyen.

Hydrogen forms a key part of the European Green Deal, which is the EU's long-term growth path to make Europe climate natural by 2050. This target is enshrined in the European Climate Law, as well as the legally binding commitment to reduce net greenhouse gas emissions by at least 55% by 2030, compared with 1990 levels.

Rio snaps up piece of TechGen project

TechGen Metals has entered into a binding farm-in term sheet with Rio Tinto Exploration – a wholly-owned subsidiary of Rio Tinto – for its Harbutt Range project in the south Paterson Province of Western Australia.

Under the agreement, Rio Tinto Exploration may earn an 80% joint venture interest in the project by sole funding $3 million of exploration within five years, including a minimum of 3000 metres of drilling.

The Harbutt Range project contains several favourable geophysics and geochemical targets.

TechGen managing director Ashley Hood said the company was delighted to have such a quality exploration partner at the project.

"This farm-in and joint venture with Rio Tinto Exploration enables the company to additionally focus and spend our exploration funds on our other up-and-coming gold and copper drilling campaigns," he said.

The Harbutt Range project is considered prospective for several mineralisation styles including intrusive related copper-gold and sediment hosted base metal (copper-lead-zinc-silver)

Bend-tech fixes cracking in Caterpillar D10T handrails

Ensuring safe access and protection when working on surface mining machines should be a priority for any operation.

Applying handrails in areas which require frequent maintenance and inspection is a proven safety measure and will ensure personnel are far less likely to fall from a potentially life threatening height.

Handrail integrity is critical. Due to the rocky terrain and the 6000 hours per year a machine such as a Caterpillar D10T would run, handrails inevitably begin to crack and have to be replaced as often as every 300 operational hours.

This becomes extremely costly and inefficient when also considering the downtime required to repair or replace the handrails.

A significant risk to personnel safety also becomes present if the damaged handrails are not detected early enough, where simply leaning on the handrail could cause failure and result in a serious fall incident.

The solution

Bend-tech received an enquiry from a valued client about redesigning its D10T bonnet handrails to be more robust and reduce cracking. The above ground parts team went out to site, learned more about the issue, took down measurements and discussed possible solutions.

Drawing from Bend-tech's in-depth experience with manufacturing handrails, our team developed a robust set of handrails with design features addressing the 'cracking' problem.

Features include:

- Specialised anti-vibration rubber mounting system to keep handrails rigid, while allowing flexibility to maintain strength in the welds.
- Rubber mounts clamp to further reduce vibration during operation.
- Custom designed to allow for removal and re-installation of the radiator header/water tank without handrail clashing.
- Available in two alternative designs: Fixed or a drop-in solution for temporary maintenance.
- Eliminates requirement for fall arrestor kits.
- OEM equivalent hood/bonnet also stocked.

Bend-tech has received multiple reports of positive feedback from sites running these handrails, with a notable first failure recorded at 6000 hours, working out to last 5-20 times longer than original handrails.

Further adjustments have since been made to the design and it is expected to see handrail lifetime extended further.

This significant improvement in handrail integrity will ensure greater safety for personnel and prove to be a more efficient solution for those running D10Ts.

GRT calls for prioritisation of dust suppression strategies within mining areas

Leading dust suppression specialists Global Road Technology are calling for more stringent air pollution controls for mine sites with recent data showcasing how mining sites in the Hunter Valley are risking people's health by breaching standards.

With air quality standards closely linked to rainfall, the risk is that climate change-induced drought and bushfires, coupled with the existing pollution caused by coal mining activity will drive high levels of particulate pollution in the area that is home to 41 coal mines in total – along with coal-fired power stations.

Those in the medical community are warning that pollution can negatively impact the human body and that any rise in particulate pollution will bring health consequences for the entire community.

Respiratory and cardiovascular health are not the only areas of people's health impacted through air pollution. It is now believed that it contributes to cognitive decline (incl. dementia), negatively effect foetal growth and increases the risk of heart disease.

According to Global Road Technology managing director Troy Adams, prioritisation needs to be given to dust suppression strategies in regions like the Hunter Valley to protect the local communities over the short, medium and long-term.

"Over the past two years the La Nina weather pattern has improved air quality in the region as rainfall has helped to settle particulate dust caused by mining activities," said Adams.

"What is challenging going forward is that we will enter drought conditions again over the coming decade and this will again see an increase in dust pollution that for an area like the Hunter Valley with such a high concentration of mines can lead to adverse community effects. That's why we as a company are advocating for an industry-led approach where whole-of-site dust suppression programs are implemented that stop particulate pollution from spreading beyond the mining site – this approach combines dust suppression technology and processes to deliver outcomes that protect people living nearby mines."

As an international, engineering technology company focussing on providing innovative products and solutions for the mining, civil, agricultural, resources, land development, and environmental management sectors, GRT is investing significantly in R&D and innovation to make it a leader in air pollution reduction.

Its specialisations in dust control, soil stabilisation, erosion control, and water management and investments in innovation have helped to build its reputation as a global leader in dust suppression and reducing particulate pollution caused by mining and construction activity.

Timken to acquire ggb bearing technology, expanding its engineered bearing portfolio with complementary products

The Timken Company, a global leader in engineered bearings and industrial motion products, has reached an agreement to acquire GGB Bearing Technology (GGB), a division of Enpro, Industries (including exclusive negotiations with respect to the French operations of GGB). Founded in 1899, GGB serves a variety of diverse customers, markets, geographies and applications with a product portfolio that complements existing Timken industry-leading engineered bearing solutions. GGB revenue is expected to be around $200 million in fiscal year 2022.

"GGB has a strong heritage of delivering high-performance products to well-established customers who are leaders in their respective industries," said Richard G. Kyle, Timken president and chief executive officer. "This acquisition provides strong synergies and meaningfully expands our business by adding complementary products with a solid growth outlook. GGB's leading portfolio of metal-polymer bearings will further Timken's ability to deliver the best solution to our customers' most challenging friction management applications. GGB also presents an excellent cultural fit for Timken, including a commitment to corporate social responsibility with a portfolio of environmentally sustainable solutions."

GGB is a global technology and market leader of premium engineered metal-polymer plain bearings with expertise in material science, surface engineering and tribology. With manufacturing facilities across the United States, Europe and China, GGB employs approximately 900 people and has a global engineering, distribution and sales footprint. The company's tribology solutions in plain bearing coatings complements Timken's leading positions in roller and ball bearings. GGB's products are used mainly in industrial applications, including pumps and compressors, HVAC, off-highway, energy, material handling and aerospace.

Timken will fund the transaction with cash on hand and its existing revolving credit facility. The deal is subject to customary closing conditions and is expected to close in the fourth quarter of this year. Timken anticipates the acquisition will be accretive to earnings in the first full quarter after closing.

NEWS, PLANT AND EQUIPMENT

Artificial Intelligence's Role in Determining Slope Failures

Slope stability is essential in mining operations since slope failure endangers safety and productivity. The complexity of conventional geotechnical methods makes slope failure prediction challenging. Artificial intelligence (AI) has helped mining companies forecast slope failures quickly and efficiently through detailed analysis.

Slope Failure in Mining

Due to the development of more advanced mining techniques and the growing demand for mineral resources, most mines are constructed to extract more minerals from steeper or deeper areas.

The steeper slope angle makes these mines more vulnerable to slope failure. It can cause injury to workers, damage to mine equipment, and halt production, negatively influencing mining productivity.

How Can Slope Failures Be Prevented?

Slope failures are prevalent in mines, becoming increasingly difficult to avoid as the excavation gets more profound and challenging to control.

Understanding rock mass characteristics, structural geology, the impact of groundwater pressure, and other local external forces in detail is necessary for reducing the danger of slope failure.

Excavation walls are kept as steep as possible to maximise operating efficiency, which can cause slope failures. However, most slop failures are caused by shear and fracture on existing defects.

The best strategy to prevent such failures is to maintain the factor of safety (FOS) within a reasonable range (>1). In situations where the factor of safety is exceptionally low, extra consideration should be paid to prevent possible slope failure.

Slope Monitoring in Mining

The behavior of the rock structure during mining must be monitored to assess whether rock slopes pose a danger to workers' safety.

The ability to send warnings before large-scale rock movement or a possible failure is essential for a successful monitoring system.

Traditional Geotechnical Instruments for Slope Failure

Traditionally, slopes have been monitored using geotechnical instruments such as piezometers, borehole extensometers, crack meters, and stress meters.

Even though there has been significant development in geotechnical monitoring instrumentation, such as remote-sensing technologies, these processes have limitations that make predicting slope failure exceedingly difficult.

Role of Artificial Intelligence in Determining Slope Failure

Related Stories
- How Artificial Intelligence is Modernizing Mining in Latin America
- Using Artificial Intelligence for Mineral Processing and Exploration
- Liberty Gold Updates Latest Drill Results from Western and Dip Slope Zones at Goldstrike Project

Even though geotechnical techniques have successfully reduced slope failure incidents, they are complicated and involve various elements, including geological activity, ground conditions, and human behavior, which are dynamic and constantly changing. Hence, it is difficult to measure them consistently.

However, the introduction of AI in mining has tremendously benefited engineers in predicting potential slope failure through in-depth analysis.

Artificial intelligence can automatically detect factors influencing slope failures, such as bedding planes, spaces, shear zones, and fractures on the bench face. AI can spot cracks that emerge before a slope failure and toe deformations that indicate rock movement on the Earth.

By comparing daily data, AI predicts failures in the existing slope and other geologies. The AI can keep track of the data to determine not only the best slope to avoid failure but also the events that may build up to and trigger a failure in the future.

Current Research in Using AI for Slope Failures

The research that used AI to determine safety parameters in mines has shown to be successful and efficient in correctly predicting slope failures. Furthermore, AI models can process massive amounts of data simultaneously and provide predictions faster than traditional stability analysis methods.

Artificial neural network (ANN) model

Kothari and Momayez's study evaluated the predictive capabilities of the artificial neural network (ANN) and inverse velocity (IV) models to anticipate the slope collapse of an open-cast mine. They created a double-layered feed-forward ANN utilizing 22 datasets gathered using radar equipment.

The investigation showed that ANN prediction was more accurate than the inverse velocity model by 86%. Total slope failure forecasts showed that 82% of the slopes were safe, while 18% showed that the slopes were dangerous. Moreover, the ANN model provided unsafe predictions five minutes before the actual failure, indicating that the AI model is much safer than the IV model.

Back-propagation neural network (BPNN) model

In a study by Ferentinou and Fakir, a Back-propagation Neural Network (BPNN), an AI algorithm, model was created using 141 databases collected from surface mine cases worldwide and 18 input variables, including hydraulic profile, rock mass characteristics, environmental factors, geological features, blast design, slope dimensions, and the occurrence of previous instability.

This study investigated all slopes to anticipate failure to establish slope stability indices. The results suggested using BPNN as a reliable method to predict slope failure in feasibility studies, with a mean square error value of 0.0001 converging at 98%.

Recent Developments: IDS GeoRadar

IDS GeoRadar has introduced Ai.DA, a new solution for geotechnical professionals that utilises artificial intelligence to monitor slope stability.

Ai.DA anticipates possible slope failure by analyzing the compatibility of the detected rock movement trend with established slope instabilities models and behaviors, enabling experts to optimise operations and make intelligent judgments.

Ai.DA assists users in deciphering large amounts of data intelligently. It is fully incorporated with Guardian, IDS GeoRadar's user-friendly and powerful program for managing slope stability issues in mining operations.

Angela Patera, Guardian Product Owner at IDS GeoRadar, said, "With Ai.DA, we are pioneering the use of artificial intelligence in slope stability monitoring, and we commit to providing customers with state-of-the-art technology solutions to support radar data interpretation."

Future Outlooks of Slope Failure Monitoring

Technology advancements have improved slope monitoring methods and enabled the evaluation of slope stability over time to provide insight into slope dynamics. In operational open-pit mines, it is crucial to accurately predict slope failure to avoid it and protect machinery and workers from harm. It is essential to evaluate the slope stability-affecting factors while determining a slope's stability.

Numerous researches have demonstrated the ability of AI models to anticipate mining slope failure quickly and accurately. However, it is necessary to compare multiple AI models' outputs to identify the best accurate model for slope stability forecasting.

NEWS, PLANT AND EQUIPMENT

World premiere of the new 280 SM(i) surface miner

100% mining – environmentally friendly, efficient and safe extraction of primary resources in a single operation

With the new 280 SM(i) surface miner, Wirtgen has developed another efficient and practice-oriented solution for the extraction of primary resources. Its innovative technologies enable high machine utilisation rates and maximum productivity.

Cutting, crushing and loading of rock in a single operation

The 280 SM(i) is a high-performance surface miner designed for the reliable and selective extraction of primary resources by direct loading, sidecasting or cut-to-ground. Raw materials are extracted and crushed in situ in purest quality in a single operation – without drilling and blasting, and with minimal environmental impact. The 280 SM(i) is driven by four steerable and height-adjustable crawler units. The machine is highly manoeuvrable and can be quickly turned at the end of a cut. The LEVEL PRO ACTIVE automatic levelling system maintains the specified cutting depth with consistently high precision and without further aids.

Efficient cutting technology

The 280 SM(i) is an all-rounder for all rock hardnesses and applications. The 2,750 mm cutting drum unit with a cutting depth of up to 650 mm is precisely adaptable to each specific application and achieves outstanding cutting performance with minimal pick wear. Wear-resistant toolholder systems ensure optimal pick utilisation and minimal downtimes. The soft rock cutting drum unit is designed especially for high material flows in soft rocks. In contrast, the hard rock cutting drum unit ensures maximum durability and long life in hard rocks.

Maximum utilisation rates for maximum productivity

In the extraction of primary resources by open cast mining, the key priority is always a combination of highest possible productivity, maximum purity of the material mined and the reduction of impact on people and the environment to a minimum. Aside from performance, the productivity of mining equipment depends primarily on constant operational readiness and optimum machine utilisation. Only a reliable and maintenance-friendly machine assures high utilisation rates. The innovative operator's cabin contributes to the operator's ability to exploit the full potential of the machine and maximise productivity. The 280 SM(i) surface miner is therefore the tool of choice for cost-efficient mining processes in the 120-ton class.

High-performance belt conveyor unit with high material flow

The high-performance, hydraulically height-adjustable, rear discharge conveyor with a movable counterweight can be slewed to the right and left by 90° and enables the loading of mining trucks with payloads of up to 100 tons. What's more, the operator can continuously vary the speed of the belt independent of the engine speed to reduce belt wear dependent on the material volume and the piece-size of the mined material.

Outstanding operator comfort

Entirely new standards are set by the dust-sealed and air-conditioned positive-pressure cabin with fresh air filtration, which effectively prevents the ingress of dust into the operator's workplace. Mounted on the front left chassis column, the operator's cabin with all-round glazing is decoupled from the machine body and can be rotated by 90° in both directions. Up to six cameras can also be installed to provide even better all-round vision. Various automatic functions also contribute to the operator's comfort, reduce the risk of fatigue, assist the operator in the achievement of high productivity rates and make the overall process more efficient.

The Wirtgen 280 SM(i) is a high-performance surface miner for reliable, selective extraction of primary resources by direct loading, sidecasting or cut-to-ground.

With the 280 SM(i) surface miner, primary resources are extracted in purest quality and crushed in situ in a single operation – without drilling and blasting, and with minimal environmental impact.

The 280 SM(i) surface miner's air-conditioned and soundproofed operator's cabin with all-round glazing is swivel-mounted on the front chassis column and provides a productive working environment with a low risk of fatigue.

Conservation of resources and environmental awareness

These days, the reduction of carbon emissions, noise, dust and vibration while maintaining consistently high extraction rates and productivity is more important than ever before. With the new surface miner, Wirtgen offers innovative technologies that minimise impact on the environment and conserve valuable natural resources. Thanks to the reduction of carbon emissions by low specific fuel consumption, an efficient water management system and effective solutions for the minimisation of dust pollution, the 280 SM(i) shows that ecological and economic considerations are actually compatible and closely interconnected.

The future of more sustainable rare earth mining

Many of the required materials for renewable infrastructure and electronics come from rare earth minerals. Yet, mining has not been considered an environmentally friendly industry. New funding between Australia and India, and research at the University of South Australia, may establish ways of sustainably mining rare earths to support our electronics and green energy sectors.

Despite their name, rare earth elements (REEs) are not rare. Also known as rare earths, they comprise 17 metallic elements, including lanthanides, scandium and yttrium. These materials are used in many of our electronics and modern-day technologies, making up many high-tech products such as computer hard drives, electric and hybrid vehicles, flat-screen monitors and televisions, and even other forms of electronic displays, lasers, radar and sonar systems.

Conveyor Technology: Designing for the future by innovating the present

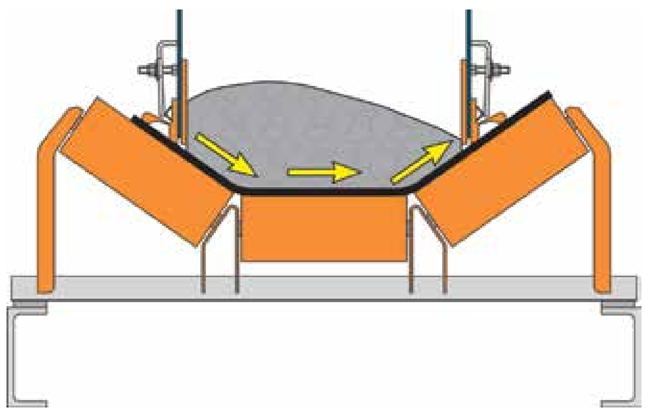
Higher production demands across all bulk handling segments require increased efficiency at the lowest cost of operation, in the safest and most effective manner possible. As conveyor systems become wider, faster and longer, more energy output and more controlled throughput will be needed. Add an increasingly stringent regulatory environment, and cost-conscious plant managers must closely review which new equipment and design options align with their long-term goals for the best return on investment (ROI).

SAFETY AT HIGHER BELT SPEEDS

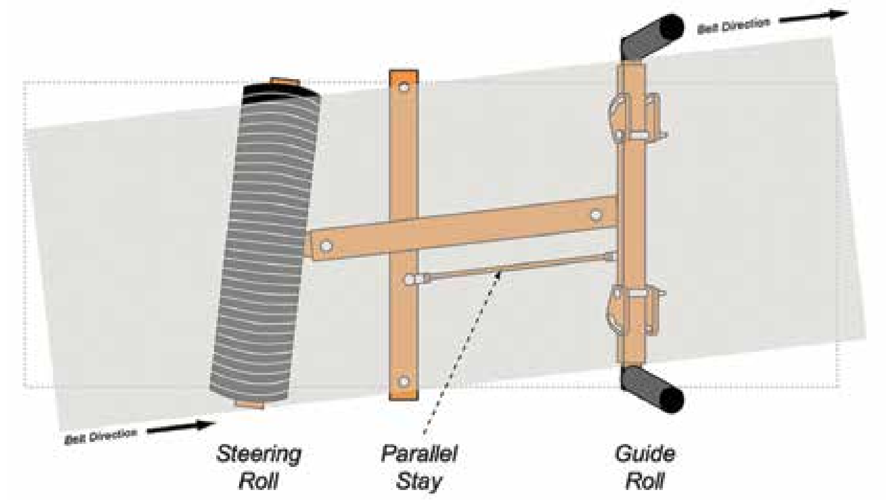
Safety is likely to become a new source of cost reduction. The percentage of mines and processing facilities with a robust safety culture are likely to increase over the next 30 years to the point where it is the norm, not the exception. In most cases, with only a marginal adjustment to the belt speed, operators quickly discover unanticipated problems in existing equipment and workplace safety. These problems are commonly indicated by a larger volume of spillage, increased dust emissions, belt misalignment and more frequent equipment wear/failures.

Higher volumes of cargo on the belt can produce more spillage and fugitive material around the system, which can pose a tripping hazard. According to the US Occupational Safety and Health Administration (OSHA), slips, trips and falls account for 15% of all workplace deaths and 25% of all workplace injury claims[1]. Moreover, higher belt speeds make pinch and sheer points in the conveyor more dangerous, as reaction times are drastically reduced when a worker gets clothing, a tool or a limb caught from incidental contact[2].

The faster the belt, the quicker it can wander off its path and the harder it is for a belt tracker to compensate, leading to spillage along the entire belt path. Caused by uncentered cargo, seized idlers or other reasons, the belt



When a conveyor isn't center-loaded, the cargo weight pushes the belt toward the more lightly-loaded side.



can rapidly come in contact with the mainframe, shredding the edge and potentially causing a friction fire. Beyond the workplace safety consequences, the belt can convey a fire throughout the facility at extremely high speed.

Another workplace hazard – one that is becoming progressively more regulated – is dust emissions. An increase in the volume of cargo means greater weight at higher belt speeds, causing more vibration on the system and leading to reduced air quality from dust. In addition, cleaning blade efficiency tends to decline as volumes rise, causing more fugitive emissions during the belt's return. Abrasive particulates can foul rolling components and cause them to seize, raising the possibility of a friction fire and increasing maintenance costs and downtime. Further, lower air quality can result in fines and forced stoppages by inspectors.

CORRECTING MISALIGNMENT BEFORE IT HAPPENS

As belts get longer and faster, modern tracking technology becomes mandatory, with the ability to detect slight variations in the belt's trajectory and quickly compensate before the weight, speed and force of the drift can overcome the tracker. Typically mounted on the return and carry sides every 70 to 150 feet (21 to 50 m) – prior to the discharge pulley on the carry side and the tail pulley on the return – new upper and lower trackers utilise innovative multiple-pivot, torque-multiplying technology with a sensing arm assembly that detects slight variations in the belt path and immediately adjusts a single flat rubber idler to bring the belt back into alignment.

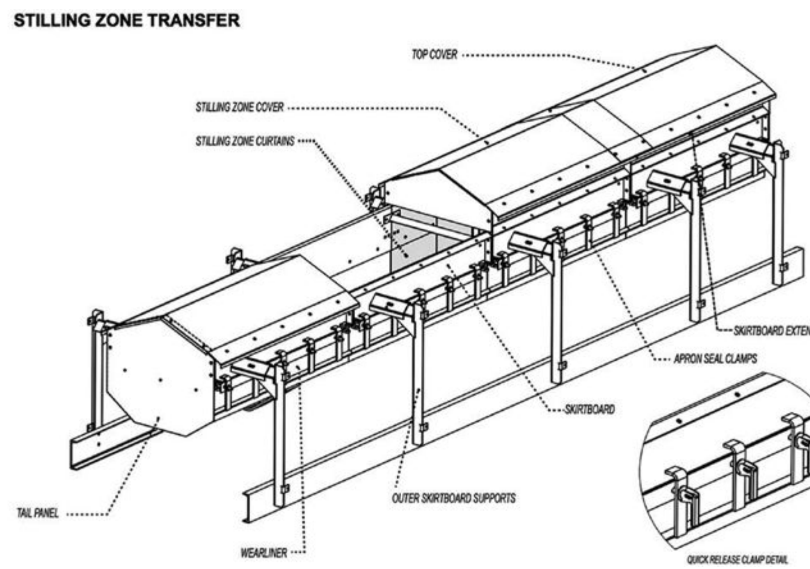
MODERN CHUTE DESIGN

To drive down the cost per ton of conveyed material, many industries are moving toward wider and faster conveyors. The traditional troughed design will likely remain a standard. But with the push toward wider and higher-speed belts, bulk handlers will need substantial development in more reliable components, such as idlers, impact beds and chutes.

A major issue with most standard chute designs is that they are not engineered to manage escalating production demands. Bulk material unloading from a transfer chute onto a fast-moving belt can shift the flow of material in the chute, resulting in off-center loading, increasing fugitive material spillage and emitting dust well after leaving the settling zone.

Newer transfer chute designs aid in centering material onto the belt in a well-sealed environment that maximises throughput, limits spillage, reduces fugitive dust and minimises common workplace injury hazards. Rather than material falling with high impact directly onto the belt, the cargo's descent is controlled to promote belt health and extend the life of the impact bed and idlers by limiting the force of the cargo at the loading zone. Reduced turbulence is easier on the wear liner and skirting and lowers the chance of fugitive material being caught between the skirt and belt, which can cause friction damage and belt fraying.

Longer and taller than previous designs, modular stilling zones allow cargo time to settle, providing more space and time for air to slow down, so dust settles more completely. Modular designs easily accommodate future capacity modifications. An external wear liner can be changed from outside of the chute, rather than requiring dangerous chute entry as in previous designs. Chute covers with internal dust curtains control airflow down the length of the chute, allowing dust to agglomerate on the curtains and eventually fall back onto the belt in larger clumps. And dual skirt sealing systems have a primary and secondary seal in a two-sided elastomer strip that helps prevent spillage and dust from escaping from the sides of the chute.



Modern stilling zones feature components designed to reduce maintenance and improve safety.

RETHINKING BELT CLEANING

Faster belt speeds can also cause higher operating temperatures and increased degradation of cleaner blades. Larger volumes of cargo approaching at a high velocity hit primary blades with greater force, causing some designs to wear quickly and leading to more carryback and increased spillage and dust. In an attempt to compensate for lower equipment life, manufacturers may reduce the cost of belt cleaners, but this is an unsustainable solution that doesn't eliminate the additional downtime associated with cleaner servicing and regular blade changes.

As some blade manufacturers struggle to keep up with changing production demands, industry leaders in conveyor solutions have reinvented the cleaner industry by offering heavy-duty engineered polyurethane blades made to order and cut onsite to ensure the freshest and longest lasting product. Using a twist, spring or pneumatic tensioner, the primary cleaners are forgiving to the belt and splice but are still highly effective for dislodging carryback. For the heaviest applications, one primary cleaner design features a matrix of tungsten carbide scrapers installed diagonally to form a 3-dimensional curve around the head pulley. Field service has determined that it typically delivers up to 4x the service life of urethane primary cleaners, without ever needing re-tensioning.

Taking belt cleaner technology into the future, an automated system increases blade life and belt health by removing blade contact with the belt any time the conveyor is running empty. Connected to a compressed air system, pneumatic tensioners are equipped with sensors that detect when the belt no longer has cargo and automatically backs the blade away, minimizing unnecessary wear to both the belt and cleaner. Additionally, it reduces labor for the constant monitoring and tensioning of blades to ensure peak performance. The result is consistently correct blade tension, reliable cleaning performance and longer blade life, all managed without operator intervention.

POWER GENERATION

Systems designed to operate at high speeds over considerable distances are generally powered only at vital locations such as the head pulley, disregarding adequate power for autonomous 'smart systems,' sensors, lights, accessories or other devices along the length of the conveyor. Running auxiliary power can be complicated and costly, requiring transformers, conduits, junction boxes and oversized cables to accommodate the inevitable voltage drop over long runs. Solar and wind can be unreliable in some environments, particularly in mines, so operators require alternative means of reliable power generation.

By attaching a patented mini-generator to idlers and using the kinetic energy created by the moving belt, the accessibility obstacles found in powering ancillary systems can now be overcome. Designed to be self-contained power stations that are retrofitted onto existing idler support structures, these generators can be employed on virtually any steel roller.

The design employs a magnetic coupling that attaches a "drive dog" to the end of an existing roller, matching the outside diameter. Rotated by the movement of the belt, the drive dog engages the generator through the outer housing's machined drive tabs. The magnetic attachment ensures that electrical or mechanical overload does not

A single Roll Generator has enough power output to run a variety of accessories.

force the roll to stop; instead, the magnets disengage from the roll face. By placing the generator outside the material path, the innovative new design avoids the damaging effects of heavy loads and fugitive material.

BULK HANDLING, SAFETY AND AUTOMATION IN THE FUTURE

Automation is the way of the future, but as experienced maintenance personnel retire, younger workers entering the market will face unique challenges, with safety and maintenance skills becoming more sophisticated and essential. While still requiring basic mechanical knowledge, new maintenance personnel will also need more advanced technical understanding. This division of work requirements will make it difficult to find people with multiple skill sets, driving operators to outsource some specialised service and making maintenance contracts more common.

Conveyor monitoring tied to safety and predictive maintenance will become increasingly reliable and widespread, allowing conveyors to autonomously operate and predict maintenance needs. Eventually, specialised autonomous agents (robots, drones, etc.) will take over some of the dangerous tasks, particularly in underground mining as the ROI for safety provides additional justification.

Ultimately, moving large quantities of bulk materials inexpensively and safely will result in the development of many new and higher capacity semi-automated bulk transfer sites. Previously fed by truck, train or barge, long overland conveyors transporting materials from the mine or quarry site to storage or processing facilities may even impact the transportation sector. Stretching vast distances, these long bulk handling networks have already been built in some places with low accessibility but may soon be commonplace in many areas around the world.

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Images: ♥ Martin Engineering 2022

The quiet revolution

Situated in the UK in the beautiful Cambridgeshire countryside lies a 127 hectare (1.27 km2) biological Site of Special Scientific Interest. Part of it is also a hugely popular Local Nature Reserve. These flooded former gravel pits are of national importance for wintering wildfowl including large numbers of herons, coots and moorhens. Amazingly, immediately adjacent is a flourishing sand and gravel quarry owned by Aggregate Industries. The very fact that such harmony between heavy industry and nature is possible is an achievement in itself but what makes this whole situation even more remarkable is that the quarry is the scene of a quiet revolution of its own.

LITTLE PAXTON QUARRY

Although quarrying in Little Paxton has been going on for more than 30 years, the quarry remains highly productive, producing some 360,000 tons of sand and gravel annually with plans to increase output further still. Within that picture of normality are two rather unusual factors, both of which involve the network of conveyors.

As with any operation of this kind, the efficiency and effectiveness of the conveyors is key. The first unusual aspect is that although Aggregate Industries own the central plant conveyors, all of the field conveyors are owned and maintained by Leicestershire-based conveyor specialists, MES International. This came about because a few years ago, the Little Paxton quarry had been 'mothballed'. When Aggregate Industries decided to re-open the quarry, they approached Leicestershire-based conveyor specialists and Dunlop Service Partner, MES International. A contract was agreed whereby MES build, own and maintain the site's six field conveyors. In addition, MES were also contracted to provide maintenance services for the main plant conveyors, which continued to be owned by Aggregate Industries.

Very significantly, MES are paid a rate per ton, which therefore puts the pressure to maximise output fairly and squarely on their shoulders. "It is a good arrangement for both parties", explains MES owner and managing director

The field conveyors at Little Paxton are owned and maintained by MES International.

Paul Anderson
Managing Director of MES International.

Paul Anderson. "Owning and operating the conveyors means that we are in control of our own destiny and being paid on output is the perfect incentive".

EFFICIENCY INCENTIVE

Having an outside contractor own conveyors is certainly unconventional but it clearly works in this case. Some quarry owners employ their own on-site conveyor engineers and maintenance crews but the most commonly found arrangement is where an external vulcanizing and maintenance company is contracted to carry out the routine conveyor maintenance, repairs, splicing and belt fitting. This usually also includes the supply of replacement components such as rollers and the conveyor belts themselves. However, this exposes the site owners to potential waste and inefficiency in comparison to paying the contractor based on site output.

"In our view, if a contractor is charging for carrying out repairs, supplying replacement components and charging labour costs then you could reasonably argue that there is insufficient incentive for that contractor to provide the highest quality, most reliable and longest lasting equipment" explains MES purchasing manager Jack Allen. "However, if that same contractor was, as we are, being paid on the basis of output then it is very much in the contractor's best interest to invest in higher quality components and equipment that will last longer and need far less intervention in terms of repairs and replacements. Less unplanned stoppage means greater output; to us it really is as simple as that".

Out with the old – ruined and worn out imported multi-ply belting from the pre-Dunlop days.

BLUEPRINT FOR THE FUTURE?

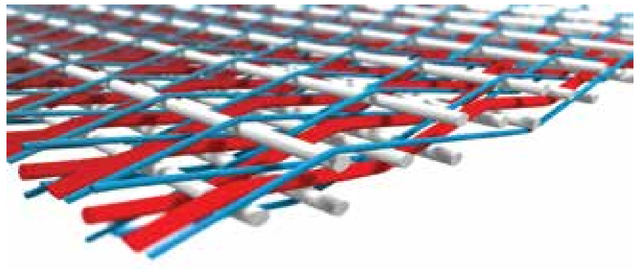
Some eighteen months ago, MES built conveyor No. 6. At 650 meters long, it is the longest conveyor on site. Initial trials took place using a conventional 500/4-ply belt imported from China that had been supplied by a former contractor. MES then replaced it with a revolutionary single-ply belt, Ultra X, which had been developed and produced by Netherlands-based Dunlop Conveyor Belting who MES represent as a service partner. The change to Ultra X impressed everyone so much that MES were encouraged by Aggregate Industries on-site management to change the other field conveyors over to Ultra X. At the same time, they are also replacing their own plant conveyors with Dunlop Ultra X3. So far, three have already been changed. "We have seen for ourselves that Dunlop Ultra X belts are much stronger and more reliable," says quarry operations manager Michael Kyriakos.

"We have proved to our company accountants that paying a higher initial price saves the company a lot of money because we don't have to keep stopping to repair the splices. The Dunlop belts also last three or four times longer because they have much better rip, tear and wear resistance so we do not have buy and fit replacement belts so often. This means that we are much more productive. Eventually, every belt on site will be Dunlop. I think that what we have done here could become a blueprint for many other locations in our company".

WHAT MAKES THE DIFFERENCE?

Dunlop Ultra X is a unique single-ply, super-strength 'breaker weft construction' belt based on an amazingly tough patented fabric, which is exclusively made in their Fenner Dunlop sister company's in-house fabric weaving facility in the USA. According to the technical experts in Dunlop, the specially woven carcass uses crimped warp polyester yarns to provide high strength and low stretch. These are combined with strong 'binder' and 'filler' yarns to create strength and stability under load.

Michael Kyriakos. Quarry Operations Manager. "Dunlop Ultra X belts are much stronger and more reliable".

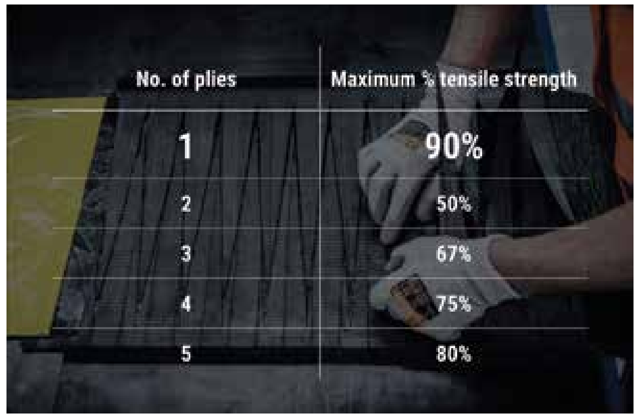


The big secret – a super-strength 'breaker welt construction' fabric made only by Fenner Dunlop.

“At the moment there are two strengths of Ultra X although there will be additional strengths added to the range very soon”, explains Paul Anderson. “ The Ultra X1 (Type 330), is designed to replace EP315/2 and 400/3 conventional ply belts and Ultra X3 (Type 550), which is what we use here, is designed to replace EP500/3, 500/4, 630/3 and 630/4 ply belts”. “The fact that Ultra X is a single-ply construction belt certainly raised a few eyebrows when we first told the Aggregate Industries team what we were planning to do. The first question, not surprisingly, is how can a single-ply belt provide sufficient tensile strength and durability?”

“The answer to that question is the unique fabric that they use. Besides being able to withstand the kind of punishment that would destroy a normal belt, Ultra X has amazing tensile strength. The longitudinal tensile strength of the X1 is 330N/mm and the X3 has a longitudinal strength of 550N/mm. We stepped away from the conventional multi-layer belting for several good reasons. First and foremost, we already knew that the Ultra X belt would give us much greater reliability, which is always important but especially so when you are being paid on tonnage. We also wanted stronger and more reliable splices. Single-ply belt requires a finger splice joint, which is a big advantage because they retain up to 90% of the belt’s tensile strength. By comparison, a 3-ply step joint only achieves a maximum tensile strength of 67%”. “Ultra X is also perfect for using mechanical fasteners on the shorter conveyors if we want to so we have the best of both worlds”.

Following training provided by Dunlop, MES splicer Aaron Johnston made the first finger splices. MES site engineer Jack Armstrong, who assisted Aaron, feels that they did a good job. “The operations managers from Aggregate Industries came over to inspect Aaron’s handiwork. It took them more than half an hour examining the belt before they eventually found where the splices actually were!”



No. of plies	Maximum % tensile strength
1	90%
2	50%
3	67%
4	75%
5	80%

Finger splice joints provide the greatest strength.

“Not only do they look good, they are also standing the test of time. On the imported multi-ply belt, we had to replace splices every three months but since we fitted the first Ultra X belt 18 months ago, we have not had to make a single splice repair or replacement. It’s quite amazing really and a huge time and cost saver”. ”But what we had not reckoned on was that there would be a lot of other benefits and advantages that we never expected."

THE QUIET REVOLUTION

When travelling around the quarry, it is very easy to forget that it is bordered by a nature reserve where peace and tranquility is essential not only for the wildlife but also for its many human visitors. Quite understandably, the quarry operators are subject to strict regulation and monitoring, including noise pollution. “The multi-ply belts used previously made the head drum squeal constantly and the rollers would emit a constant, loud rumble. To dampen the noise we had to resort to using piles of spoil as a form of sound barrier. It was a very pleasant surprise when the first Ultra X3 conveyor belts started to run because the squealing stopped completely and the whole noise level of the conveyor dropped by at least 50%. It was so quiet it was amazing. We could make it even quieter if we used nylon rollers rather than steel but there is no need and steel rollers last longer than nylon,” said Armstrong.

The engineers in Dunlop are happy to explain the ‘silent running’ phenomenon. “The biggest factor is actually the rubber because it is much higher quality compared to low grade ‘economy’ belting and contains much higher proportions of top grade polymers and essential additives such as carbon black than you would normally find in economy products. Rather than being rigid, the rubber is highly elastic, which helps to reduce its rolling resistance. This means that it requires less drive power and makes less noise as it passes over the rollers” explains Dunlop Conveyor Belting’s manager of application engineering, Rob van Oijen.

MIND BLOWING

Paul Anderson is clearly not only proud of what is being achieved but also very excited. “Everyone here in Little Paxton quarry has been blown away by how well these belts run and what they are capable of doing compared to conventional belting. We have found so many advantages it is hard to know where to start. Apart from being much quieter, one of the first things we noticed is that with multi-ply belts we had to use double drum drives but with Ultra X we only need a single 37kw drum, even when the sand is wet. The capacity is no longer limited by the belt; it is only limited by the drive head. Also, if you overload multi-ply belts they will eventually snap but Ultra X seems to be able to handle everything we put on it”.

“Yet another big advantage is how well the covers stand up to abrasive wear, trapped rocks and stones and the damaging effects of ozone and ultra violet light. Even belts that have been running for more than 18 months look like they were fitted only a few weeks ago. We also have far less wear on the drums and bearings because we do not need to run at high tension, in fact the belts are almost slack but they seem to have a lot more grip so they are no problem at all even in the cold and rain” continued Anderson.

ON THE RIGHT TRACK

Site engineer Armstrong certainly shares Paul’s enthusiasm. “For me personally, I would say that a big advantage of these belts is that they are very quick and easy to re-align. When multi-ply belts run out they are quickly damaged by the framework of the conveyor”.

“With the Ultra X belts I can see a response to my tracking adjustments almost instantly, usually within the space of only three or four rollers”. “It’s a big time saver, especially because we are regularly adjusting the length of the conveyors”.

EXCEEDING EXPECTATIONS

Although the praise is no doubt welcome, the most important thing in business are results. Some might argue that MES took a gamble by introducing single-ply construction belts but Paul Anderson did not see it as a risk. “Actually, it would have been much riskier and ultimately much less successful if we had stuck with conventional multi-ply belting.

The results speak for themselves. Before we introduced Ultra X the maximum hourly output was around 170 tons, normally less in the winter, but with Dunlop Ultra X belts it has increased to over 200 tons per hour all year round. In fact we are now delivering over 50% more than the contracted volume”

NOT SURPRISED

Andries Smilda, Dunlop Conveyor Belting’s sales & marketing director, is naturally delighted about the enormous success at Little Paxton and the contribution made by Dunlop Ultra X belts but he is not surprised. “The original objective of our R & D teams in The Netherlands and the USA was to design a belt that had a much higher resistance to impact, ripping and tearing while at the same time be more economically priced”. “We knew that the solution lay in the construction of the carcass because our

Misaligned multi-ply belts are quickly damaged when they hit the framework of the conveyor.

With Ultra X belts, output has increased significantly.

rubber compounds were already well-recognised as being the hardest wearing and longest lasting” explains Smilda. “What they came up with was actually beyond our wildest dreams because Ultra X possesses more than 3 times greater longitudinal rip resistance, up to 5 times better tear resistance and a far superior resistance to impact compared to traditional 3-ply or even 4-ply belting. At the same time, it also has incredible tensile strength. An Ultra X3 single ply belt is able to pull up to 56 tonnes in weight, which as you have seen at Little Paxton, means that it can even handle adverse weather conditions without losing productivity”. “The teams at MES and Aggregate Industries in Little Paxton deserve a lot of credit for what has been achieved there”.

SETTING NEW TRENDS

The undoubted success of Dunlop’s single-ply revolution is certainly not an isolated case, with other operations such as an alluvial sand & gravel quarry in France reporting an incredible 87% increase in output as a result of changing to Ultra X. However, the catalyst for the success in Little Paxton has clearly been that the conveyor contractors are paid on the basis of output rather than effectively being ‘rewarded’ for each repair, failed component and prematurely replaced conveyor belt, as is the case with conventional ‘maintain and repair’ contracts.

Although MES and Aggregate Industries have an ‘own and maintain’ agreement, it is not strictly necessary for the vulcanising and maintenance service provider to actually own the conveyors. For example, they could simply lease belts as part of a ‘supply and maintain’ contract in return for an agreed rate per ton. Such arrangements certainly provide both site operators and service providers with a win-win situation. Firstly, they are an excellent way of overcoming the obstacle of obtaining CAPEX approval from head office. At the same time, they reward the service provider for supplying belts and components that minimise downtime and maximise efficiency and output. It could well be that Aggregate Industries and MES have created a winning blueprint for the future. There are certainly lessons to be learned and hopefully what has happened in Little Paxton will help set a new trend in the mining and quarrying industry.

BOB NELSON

With thanks: The author would like to thank everyone at MES International, the Aggregates Industries team in Little Paxton and Dunlop Conveyor Belting for their help and cooperation in the compilation of this case study.

First ever battery-electric surface drill rig field tested in Swedish quarry

Epiroc has entered an agreement with Skanska Industrial Solutions AB to trial the first ever tophammer battery-electric rig in Sweden. This trial marks a significant milestone in the journey towards zero emissions drilling in surface mines and quarries all over the world.

Ulf Gyllander

"This is a proud day. For many years we have been leading the development in lowering fuel consumption within tophammer drilling. With this new solution we are taking a giant leap in the low emissions field – we are practically removing emissions from the actual drilling process," says Ulf Gyllander, Product Manager tophammer drill rigs, Epiroc Surface division.

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The design of the rig is based on the well-proven SmartROC T35 surface drill rig. In combination with invaluable experience gained from the development of Epiroc underground battery rigs, this SmartROC T35 E is designed to enhance the environmental standards of quarries and larger construction sites. Besides the low emissions, this rig comes with a range of smart features, options and enhanced automation solutions for high safety, reliability, and performance.

"With this achievement we show that the innovations of Epiroc will play a significant role in the shift to low-carbon operations within quarries and large construction applications," says Jose M. Sanchez, President Epiroc Surface division. "As our sustainability agenda goes hand in hand with those of our customers, we are very pleased to be collaborating with Skanska Industrial Solutions AB in the trials of this important solution."

The tests will commence in September 2022 in one of Skanska Industrial Solution's quarries in the Stockholm area:

"A milestone has been reached and a new opportunity has come to reduce our climate impact. I am very happy about the long collaboration between Epiroc and Skanska, and it is exciting to be able to do this project together. Both companies have set bold environmental goals – this project really takes a great step towards Skanska´s goal of being completely climate neutral by 2045, which is an important part of our promise to build a better society", says Johan Eliasson, Project Manager, Skanska Industrial Solutions AB.

Peter Beckman, Business Line Manager, Epiroc Customer Center Sweden comments: "Skanska is a perfect partner for this trial as they have their own quarries which are fitted with the infrastructure required to handle the operation of this new technology. I am looking forward to following this exciting project during the coming months."

The SmartROC T35 E rig is equipped with both a battery and an electric cable, which improves flexibility considerably. You can choose to drill with the most suitable alternative for the location and occasion. It also allows for quick and smooth transportation in and between sites.

The surface drill rig is fitted with the same type of well-proven batteries and subcomponents as in the Epiroc underground battery solutions. This streamlines spare parts handling and service for customers with several different operations.

SURFACE DRILLING RIGS

Product development of a rock reinforcing bolt for underground hard rock mining

The demand for mineral resources has dramatically increased over the past few decades; this increase directly correlates to an increase in underground mining activity. There are different mining methods for different minerals, and each have their risks. In hard rock mining activities such as mining for gold, rockfalls are the most significant deterrent to obtaining mineral resources. This paper focuses on rock reinforcement systems to prevent fatal rockfalls in underground excavations. Presently, there is a global steel shortage and an increase in prices that has impacted the productivity of the mining operations that support most national economies. The paper's main objective is to present the improvement of a rock bolt design used to support the roof in underground mining activities and keep working personnel and equipment safe from rockfalls. This study presents two rock bolt designs: a preliminary design and an improved model of the rock bolt. The paper discusses the operation of the rock bolt and provides laboratory test results on the bolt in operation. The principle of operation of the yield bolt is based on the science of radial expansion of hollow tubes in tension, to provide integrity to underground excavations. This functional design of the rock bolt requires less steel and has the same performance as the current rock reinforcement elongates. The research methodology involved interviewing rock mining engineers to determine their desired rock reinforcement device that would adequately meet the unpredictable dynamic and static behavior of underground rocks. The methodology also included experimental tests of a rock bolt design that was aimed at meeting the desired and acceptable performance determined from the interviews. The experimental results were obtained from a 60-ton hydraulic press that simulated seismic activity underground. The experimental results showed several modes of failure for the bolt; however, the improved rock bolt yielded at an average of 200 KN, as designed. During testing of the preliminary bolt design, there were failures that resulted from the manufacturing process of the bolt, such as splitting of the tube due to the welded end components. After a dynamic test, the preliminary bolt tube bent, creating huge forces on the tube which may cause fracture. The coefficient of friction during dynamic testing was lower than during static testing, leading to undesirable results for the preliminary bolt. The optimised bolt design addressed the failures and the low yield tonnage of the preliminary bolt design. It successfully yielded at 20 tons, even during the dynamic event. The bolt had similar alignment issues which caused failure during testing, as can be seen from the results. A guide tube was implemented in the design and the manufacturing process changed; these changes resulted in the bolt having a more reliable performance that met the requirements throughout.

INTRODUCTION

During the 20th century, there have been tremendous developments in technological devices. These developments have aided the exponential growth of world economies and rapid industrialisation throughout the globe[1]. The development of these technological devices requires mineral resources to be extracted from the earth, raising the demand for mineral resources worldwide. Hence, mines must excavate minerals at greater depths than ever before[1]. The top three deepest underground excavations are for gold mining and are found in South Africa. Mponeng mine, at a depth of 3.84 km, is the deepest, followed by Driefontein and Kusaselethu mines at 3.42 km and 3.38 km deep, respectively[2]. Mining activities at these depths give rise to very high safety concerns for working

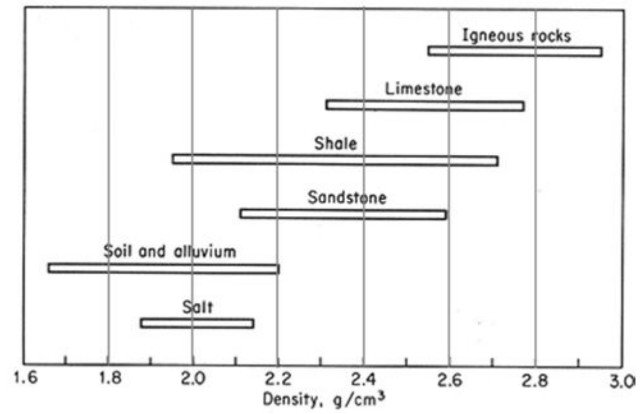

Figure 1: Density of various rock types[3].

personnel and machinery. An adequate rock reinforcement system is required to ensure safety for working personnel and the equipment used.

There are three main rock types, namely: igneous, metamorphic, and sedimentary rocks. The exploration and excavation of igneous and metamorphic rocks are termed hard rock activities, due to the rocks' metalliferous mineral content, making them generally harder than sedimentary rocks which contain oil, natural gas, or coal. The exploration and excavation activity within sedimentary rocks is termed soft rock mining. Limestone and shale are sedimentary rocks; granite and gneiss are igneous and metamorphic (crystalline) rocks. Calcite and marble are found in limestone and are also significantly hard, as is quartz in sandstone. These are outliers in soft rock mining. **Figure 1** shows the densities of different rock types, with increasing hardness on the y-axis.

This paper focuses on the products available in South Africa to reduce fatalities and injuries due to rockfalls in underground mining. The rock reinforcement market is saturated with support systems that hinder the working space of miners and machinery. The available roof anchors are difficult and time-consuming to install, have unsuitable load-bearing characteristics or have too many variables that make it hard to achieve proper and sufficient installation. This paper presents a rock bolt concept developed by[4] at the Mine Support Products (MSP) company in Johannesburg, South Africa. It addresses the shortcomings of the preliminary rock bolt design reported by[4], after testing, and presents an improved rock bolt design, together with the bolt's performance results from the research and development department at MSP. This paper briefly discusses the currently used rock reinforcement devices in South Africa and further elaborates on the product development of a rock bolt for underground hard rock mining. This study aims to increase the safety of mine workers underground and ensure the continual production of gold that supports the South African economy.

There are several rock bolts currently available on the market and used for roof reinforcement; their shortcomings are low yield tonnage, low ultimate tensile strength, and small yield length. The rock bolts have become less effective as mining depth has increased, as deep mines require high-load-bearing reinforcements[5]. The performances of these rock bolts are fully discussed in *Types of Rock Bolt Reinforcement Available*.

During underground visits to investigate new technological devices for use in rock reinforcement, it was observed that the deeper one goes, the more the available resources for rock reinforcement are lacking. Thus, mining activities at greater depths become more dangerous. Under these difficult conditions, mine workers still need to retrieve mineral resources at a profitable rate. The motivation for this research is therefore to make available a reliable solution to keep mine workers safe, which is the priority of the mine regardless of all other resources that ensure that the productivity of mine workers is efficient. The rockfall risk evaluation conducted showed that the deeper one goes, the higher the contrast between the mining standards set by management and the reality. This paper therefore contributes to the safety aspect of underground mining practices via the design of rock bolts to support the roof of the excavation tunnels.

MINING ACTIVITY

There are three types of mining operations employed to retrieve minerals[6]. These are open pit, underground, and underwater mining. Open pit and underwater mining operations occur with the working personnel above ground or water. Machines generally lead both these mining operations with humans operating at a safe distance to retrieve the mineral ores. Underground mining operations require strategic mining methods, which generally involve manual labor to extract rich mineral ores. The fatalities and injuries experienced in open pit and underwater operations are generally due to poor working ethos with regard to legislature, maintenance, or operations, or to human error. Underground mining requires many active personnel to facilitate the extraction of mineral ores, and the major cause of fatalities and injuries in this type of mining is rockfalls[7].

Underground Mining Operations and Related Fatalities

Different minerals require different mining methods. Therefore, due to the different characteristics of the rock sediments, different rock reinforcements are used in these operations to ensure they are safe for workers. There are five methods of underground mining; the method applied depends on the type of rocks (soft or hard)[6]:

a) Room and pillar – coal – soft rock.
b) Narrow vein stoping – platinum – hard.
c) Short and longwall mining – coal – soft.
d) Sub-level caving – diamonds and gold – hard.
e) Block caving – copper – soft.

Most mining accidents occur in third world countries; coal mining in China is considered the world's deadliest, with a mean fatality rate of 13 miners per day[8]. The fatalities are mainly attributed to consecutive explosions of coal dust containing methane, which is a very volatile, explosive, and poisonous gas. The United States of America had a mean of 30 coal mining fatalities per year between 2001 and 2005[9]. The high fatality rate in the coal mining industry is firmly attributed to the presence of high volatile gas concentrations and multiple igniting sources in a highly flammable environment[10], it is not structural failures in the mining methods involved in this environment.

Underground soft rock mining includes a group of underground mining techniques used to extract coal, oil shale, potash, and other minerals or geological materials from sedimentary ("soft") rocks. Because deposits in sedimentary rocks are commonly layered and are relatively less hard, the mining methods used differ from those used to mine deposits in igneous or metamorphic rocks. Soft rock underground mining methods are considered structurally safer than hard rock methods. Underground hard rock mining refers to various underground mining techniques used to excavate "hard" minerals, usually those containing metals, such as ores containing gold, silver, iron, copper, zinc, nickel, tin, and lead. It also involves the same techniques used to excavate ores of gems, such as diamonds and rubies.

There is great potential for rockfalls and mining-induced seismic activity in underground hard rock mining. As of December 2017, statistically, 37% of fatalities were caused by fall of ground in South African mines[11]. The pie chart in **Figure 2** depicts this.

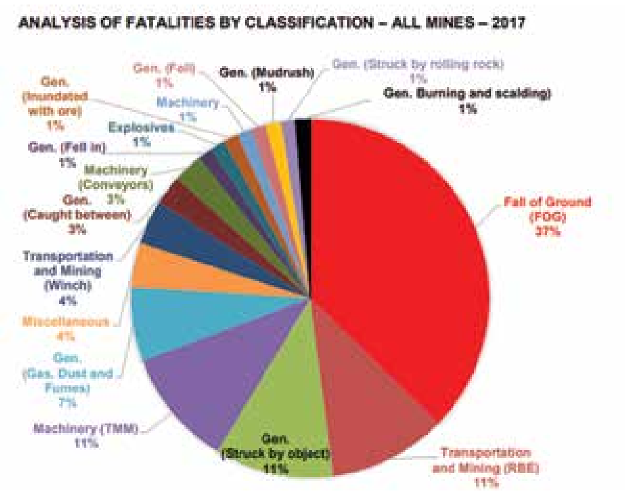

Figure 2: Analysis of fatalities by classification [11].

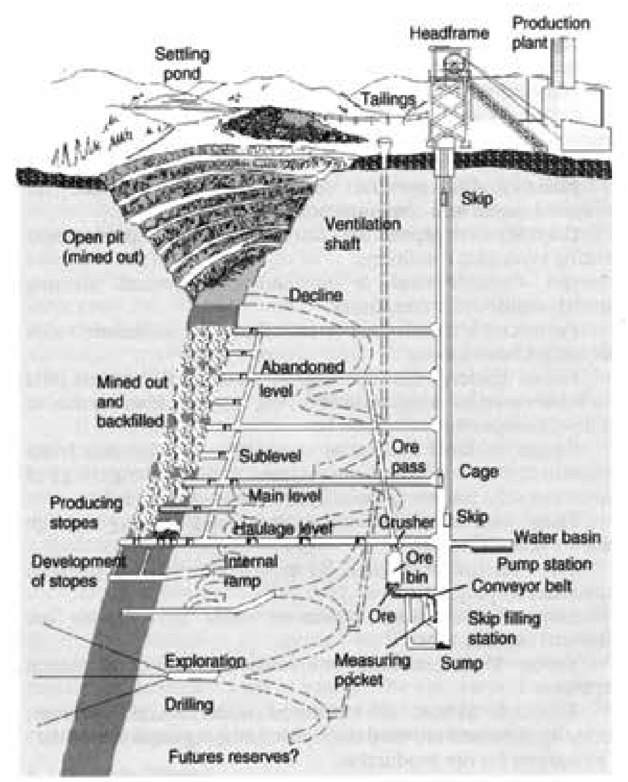

Figure 3: Sub-level caving for gold mining[12].

Sub-level caving remains the most widely used method for hard rock mining and involves blasting activity to retrieve mineral ores. **Figure 3** shows the sub-level caving mining method used for hard rocks. On the producing stope, caved-out sections within the mineral can be seen in **Figure 3**. These caved-out sections are where blasting activity has occurred in search of high-grade mineral ores. In the statistics, 80% of the reported fatalities were from hard rock mines only. Fall of ground accounted for 16.7% of injuries in the December 2017 report and was also the largest cause of injuries[11].

Rockfalls in Hard Rock Mining

There are two causes of rockfalls underground: rock bursts and rockfalls due to gravity. Rock bursts are a result of high-stress zones within the rock morphology. These high-stress zones develop due to high blasting activity underground to retrieve high-grade mineral ores[7]. The energy dissipated from blasting creates vibrations in the rock morphology, causing high-stress zones and inducing seismic activity[7]. Rock bursts occur along rock fault lines, joints, and in the presences of dykes. The size of the underground excavation influences both types of rockfall; the more extensive the excavation, the higher risk of rockfalls, and those due to gravity are more common in deep-level mining areas due to the heavy weight of the ground above. One or more of three situations must be present for a rockfall to occur[7]:

a) Rocks are falling where there is no support.
b) Rocks are falling between supports.
c) Rockfalls occur due to the failure of the installed support system.

Rock Reinforcement

Geophones are susceptible geotechnical sensors that monitor seismic activity underground. These are installed underground in the hanging wall to monitor the gradual downward movement of the ground above within a stope[13]. The geophones warn miners of rock movements above them and initiate evacuation and the necessary safety precautions. **Figure 4** shows the fall of ground light geophone manufactured by New Concept Mining, Johannesburg, South Africa. This is a monitoring device.

Blasting occurs at the stope, which is located at the end of the hanging wall. After every blasting session, an unsupported hanging wall is exposed that needs to be cleared of the rumble (mineral ores). This is then transported to the head frame for processing[12]. This exposed hanging wall accounts for most of the rockfall fatalities underground because working personnel need to clear the rumble and support the hanging wall concurrently until they reach the next stope to be blasted. To ensure

Figure 4: New Concept Mining fall of ground light geophone[14].

ROOF BOLTING AND STRATA CONTROL

a safer hanging wall for active personnel underground, adequate support must be installed. There are different types of reinforcement mechanisms on the market[15]. The support chosen depends on the rock characteristics, the mining method, and the financial resources of the mining operations. There are two types of supports: permanent and temporary, and within these types are various design mechanisms applicable to different mining environments. When a support is installed, it needs to be pre-stressed in order to apply an upward force to the downward falling roof. Highly pressurised water and air are used to pre-stress support devices.

Types of Rock Bolt Reinforcement Available

There are three main sub-categories of rock bolts[16]:

a) Continuously mechanically coupled (CMC) – fully grouted (cement or resin) and D-bolt.
b) Continuously frictionally coupled (CFC – inflated steel tube.
c) Discretely mechanically or frictionally coupled (DMFC – expansion-shell type.

Figure 5 shows the different types of rock bolts available[16]. Rock bolts "a" and "b" are fully grouted and D-bolt, falling under the CMC category. CMCs are stiff and provide high load bearing due to their mechanical interlocking characteristics during static ground movement. However, during dynamic ground deformation, they perform poorly. Nonetheless, this is the most widely used bolt in underground mining excavations[16]. The performance of fully grouted rock bolts depends on the quality of the cement or resin mixture. For resin-grouted bolts, cartridge accumulation occurs at the borehole end and decreases their efficiency. This accumulation is due to insufficient resin mixing at the borehole end. The optimal resin mix and bolt encasement occur at the middle of the bolt, making it perform unreliably at its full capabilities. Resin-grouted bolts provide more advantageous mechanical properties than cement[16]. For cement-grouted bolts, the water-to-cement ratio influences their strength; the setting time for

Figure 5: Types of rock bolts[16].

cement-grouted bolts means that they are less reliable for immediate support in high-stress and volatile areas[16].

Rock bolts "c" and "d" are DMFC and CFC types, respectively; they are flexible and capable of absorbing large ground deformations at varying loads[16]. The installation procedure involves inserting the rock bolt into the borehole and pre-stressing it by tensioning the rear end nut. All rock bolts are permanent supports. For mild rock burst environments, device "d" is widely used. When used with mesh, the rock bolt will slip rather than rupture and retain the rock burst. The maximum size of CFCs available is 46mm, and ultimate failure occurs at 16.3 tons. This remains too low for their application in underground mining at great depth.

Test blocks of highly reinforced concrete were created in order to investigate the load deformation characteristics of available rock bolts used in the mining industry.The test blocks had a uniaxial compressive force of 60 MPa. Various rock bolts were installed inside the test blocks, following the standard instructions for installation used underground[15]. The load–deformation characteristics are show in **Figure 6** were as follows:

a) Resin-grouted 20 mm diameter steel rebar. With a load of 15 tons and an elastic deformation of about 1.5 mm, hot-rolled reinforcing steel is characterised by a sharp drop in load. The maximum load is 18 tons with a deformation of 20 mm. Resin is stronger than mortar, and local breakage and bond failure is limited compared to grout reinforcement, resulting in lower final displacement when the reinforcement fails.

b) Expansion-shell anchored. At a pre-tension of 2.25 tons, the faceplate is not deformed. Under a load of 4 tons, the frame is deformed by 9.5 mm, becoming completely flat, and the propeller shaft is deformed by

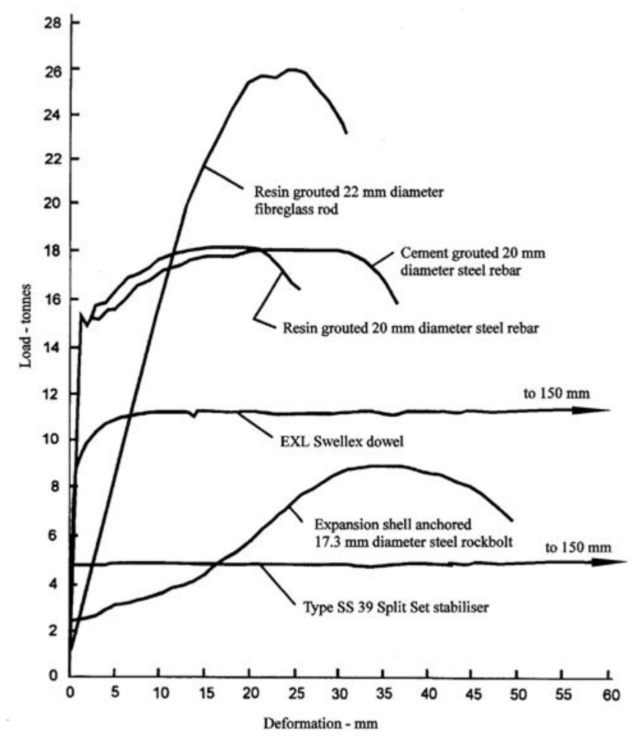

Figure 6: Load–deformation characteristics of rock bolts on the market[15].

another 3.5 mm, giving a total deformation of 13 mm under a load of 4 tons. Failure begins with a load of 8 tons and a deformation of 25 mm, with gradual failure of the expansion anchor where the cone is pulled through the wedge. The maximum load is 9 tons with a deformation of 35 mm.

c) Cement grouted rebar. With a load of 15 tons and an elastic deformation of about 1.5 mm, hot-rolled reinforcing steel is characterised by a sharp drop in load. The maximum load is 18 tons with a deformation of 30 mm.

d) Resin-grouted fiberglass rod. With a load of approximately 1.5 tons, the glass fiber/resin interface begins to crack and spread along the rod. As the breakdown of the bond progresses, the glass fiber rod deforms, increasing its “free” length. A typical bond breakage occurs with a load of approximately 26 tons and a deflection of 25 mm. The tensile strength of this assembly is determined by the bond strength between the resin and the glass fiber rod and the relatively low frictional resistance of the glass fiber.

e) Split set stabiliser, type SS-39. The pin begins to slip at about 5 tonnes and holds this load throughout the test, which in this case led to a total displacement of 150 mm.

f) EXL Swellex dowel. At a load of 5 tons, the pin begins to locally deform at the joint, and at the same time, at the joint, the ‘bond breaks’ and, with increasing load, extends outside the joint. Complete destruction of the bond occurs at 11.5 tons with a deformation of about 10 mm. The pin starts to slip under this load and withstands the load during the entire test, with a displacement of 150 mm.

The New Concept Mining MP1 rock bolt manufactured in Johannesburg, South Afrcia is shown in **Figure 7**, it is a permanent support that starts to yield at 15 tons. It is pre-stressed using a hydraulic hand pump and drilled into the hanging wall. It is a DMFC rock bolt. This rock bolt starts to yield at 15 tons and has a typical tensile stress of 22.5 tons[17]. At greater depths, the required acceptable

Figure 7: New Concept Mining MP1 rock bolt[17].

yielding average is 20 tons as per the product specification requirements from[18] the interviews with stakeholders. The failure of the bolt at 20 tons causes rock bursts underground due to the sudden release of the energy the bolt was absorbing.

Other Types of Rock Reinforcement

Timber and cement packs are permanent supports with high yield force used in any mining environment with adequate space. A jack pack is placed under the support pack and pressurised until it inflates to achieve the pre-stressing necessary to ensure a sufficient upward force is exerted by the support pack (**Figure 8**) on the roof.

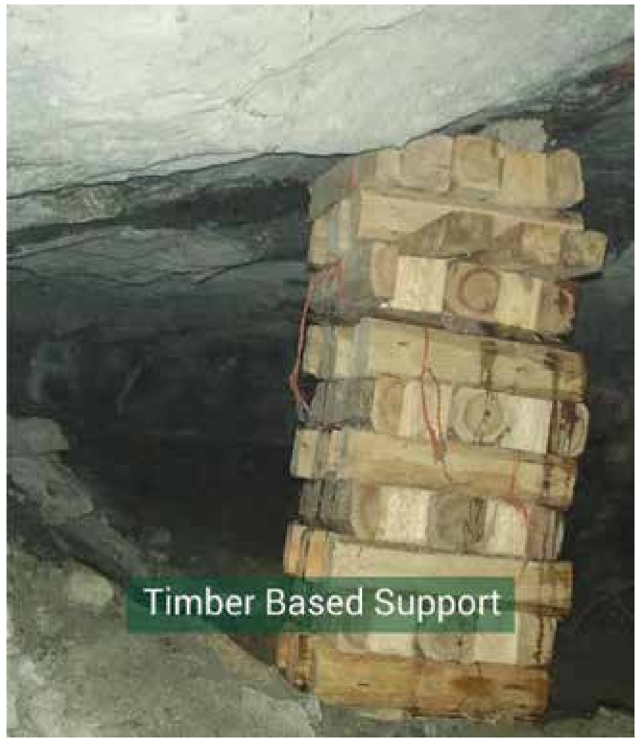

Figure 8: Bedrock timber-based support pack[20].

Figure 9: Timrite cam and pin prop[21].

This support provides no dynamic-load-bearing support, takes time to install and is difficult to install while ensuring it is firmly pre-stressed, due to the unevenness of the floor and roof. Footplates are available to place under support devices[19], there are no footplates large enough for packs.

The Timrite prop shown in **Figure 9** can be used both temporarily and permanently. It uses a cam follower for pre-stressing and a pin to lock it in place at a specific height. Lower yield tonnages for areas with stable rock characteristics are achieved. The prop does not have dynamic-load-bearing characteristics due to the pin used for locking it in place.

The Timrite pencil prop, a timber-based permanent support, uses a jackpot for prestressing and has high yield tonnage, with no possibility of adjusting the height of the prop (**Figure 10**). The props are of a fixed height, with slight variations in height as the roof underground is uneven. It is difficult find the exact height required for the pencil prop and to install the props in a sufficiently pre-stressed state. During dynamic testing, the wood fibers split, resulting in an immediate drop in the dynamic-load-bearing capability[22].

Figure 10: Timrite pencil prop[21].

Figure 11: Installed rock reinforcement elongates across stope[24].

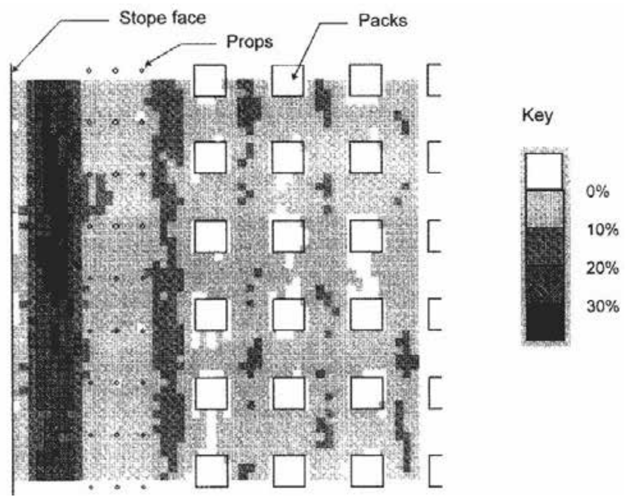

Figure 12: Layout of props and packs supporting a hanging wall[25].

The Elbroc Omni prop and the Mine Support Products (MSP) Rocprops are shown in **Figure 11**. Both these props are manufactured in Johannesburg, South Africa, Elbroc and MSP are their respective manufacturers. The figure shows MSP props installed underground as permanent supports, with a high yield tonnage, pre-stressed using highly pressurised water and air. The Elbroc Omni prop has similar structural and performance qualities to the MSP prop. However, it contains a hydraulic pressure release valve which allows it to be reusable if no yielding has occurred. During static yielding, the props yield consistently at 20 tons, which is acceptable. A slight drop of 2 tons is periodically experienced during dynamic yielding[23]. The rock bolts should be installed in a row between props to decrease the spaces between supports. The yield behavior of the rock bolt and the props is the same.

Risk Evaluation of Rockfalls

All the current rock reinforcements discussed in Sections 2.2 and 2.3 must be installed evenly at equal distances. This proves to be a difficult task due to the unevenness of the terrain. Installed props and packs greatly hinder the working space for machinery and personnel and lower the chances of evacuating mine workers in case of danger. The authors in[25] provide a means of simulating the probability of a rockfall between supports and of the failure of the support props and packs when evenly spaced (**Figure 12**). The support consists of three rows of permanent high-yield-tonnage (20 tons) props adequately installed, spaced 1 m apart down the face in rows 2 m apart. The first row of props is 3 m from the face. The back-area support consists of mat packs spaced 3 m x 3 m apart. The supporting effect of the blasting face where retrieval of mineral ores takes place is clearly shown. The probability of failure in the blasting area is lower near the blasting face due to the solid rock that still needs to be blasted. The support props are 3 m from the blasting face; this results in a probability of failure of 40% between the blasting face and the line of support props. Between the rows of props, the probability is generally less than 10%. The probability of failure increases to values of between 10% and 20% between the packs. The effect of the 2 m gap between the last row of props and the packs results in a probability of failure between 10% and 20%. In **Figure 12**, a hanging wall is the roof above miners as the travel to a producing stope face.

Figure 13 shows a bar graph of the probability of a rockfall between supports, showing the probability of a rockfall due to support failure against rock sizes. Rocprops are recommended to be installed 1.5 m apart in both width and breadth in a hanging wall. The height of the hanging wall varies by up to 6 m. We assumed a hanging wall height of 2.5 m in the following analysis.

The biggest possible rockfall between two adjacent supports would have a volume of 1.5 m x 1.5 m x 2.5 m = 5.63 m^3 and has a probability of occurrence of 13%, as shown in **Figure 13**. By installing yield bolts halfway between the lines of Rocprops, the possible size of rockfalls between supports reduces to 0.75 m x 0.75 m x 2.5 m = 1.41 m^3, with a probability of occurring of 60%. Furthermore, these rockfalls are less likely to be fatal[25]. Provided that rock reinforcement is installed adequately (situations (a) and (c) mentioned in Section 2.2), rock falls in hard rock mining can be eliminated. This is ensured by

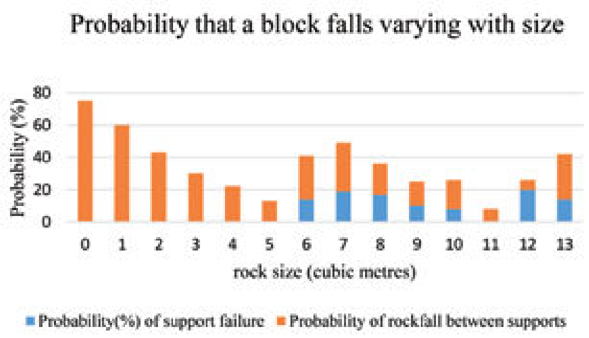

Figure 13: Probability that a block falls against size[25].

having a dedicated rock reinforcement inspector during installation and all mining activities. **Figure 11** shows a whole channel with no support between supports, which creates a high-risk area for rockfalls. It is essential to have enough working space for miners, in order not to hinder productivity and to prevent congestion that may increase the probabilities of injury; thus, the area has no support. The risk of rockfalls between the props primarily inspires the continual development of roof bolts.

METHODOLOGY

Two research methodologies were applied in this study, namely: interviews and experimental methods. Providing a rationale for this work, Mine Support Products manufactured Split Set Stabilizer rock bolts but the sale and manufacture of these rock bolts was discontinued due to poor sales and the poor performance of the rock bolts in areas of high seismic activity. To improve the rock bolts' performance, allowing re-entry to the reinforcement rock bolt market, the following questions were addressed to the interviewed rock engineers at the mining company working assisting with rock behavior information:

a) What is the static characteristic behavior of the rock?

b) What is the dynamic characteristic behavior of the rock?

c) What is the required load-bearing performance of the rock bolt?

d) What are the other environmental factors that may affect the bolt?

e) Which installation procedure is most suitable?

f) What is the working depth of the bolt?

In the experimental research, the design team met and discussed a new rock bolt design to meet the requirements arising in the interview responses. The various components of the new rock bolt were documented with their functions and were subsequently used to create a draft diagram using the computer-aided drafting software SolidWorks. An investigation into suitable materials available on the market and their properties was conducted. The additional components that were not standard were manufactured using CNC machining. The material specifications available on the market were the controlled variables; the experimental research contained multiple variables which were interchanged to examine different relationships between the dependent and independent variables.

The basic principle of the rock bolt design is a radially expanding hollow tube with a cone. In the laboratory, a hydraulic press was used to generate the pushing force to radially expand the tube. In situ, fall of ground and rock bursts generate the force to radially expand the tube. The force to radially expand the tube is applied to the surrounding rock structure to ensure its integrity. To examine this relationship, the following multiple variables were manipulated and controlled.

At the beginning, from the spreadsheet, the following properties of the tube were controlled: tube yield strength, width, length, tube internal diameter, and manufacturing process.

Cones with various outer diameter sizes were manufactured for yielding in the tube, it is the dependent variable. For a constant tube width (independent variable), all the various cones were used to yield the tube and obtain load bearing characteristics, the results were recorded.

Later, tube width was increased (dependent variable), the cone outer diameter was kept constant, and the results were recorded.

PRELIMINARY ROCK BOLT DESIGN

The Mine Support Products (MSP) Company in Johannesburg is currently the leading supplier of rock reinforcement elongates to several hard rock mining companies in South Africa, currently the highest producer of gold in South Africa. Following the fluctuation in global steel prices, shortages, and the drop in the quality of steel produced, a client of MSP requested the research and development team to present rock reinforcement solutions that would continue to ensure optimal mine productivity. The required solution must mitigate the three conditions for a rockfall to occur, as discussed in Section Rockfalls in Hard Rock Mining, without hindering the already limited space available for mine workers and machinery.

It became clear that the science of tunnel anchoring would provide the best-fit solution. However, the anchors would need to be re-designed to absorb the seismic activity occurring underground, with large rock deformations that require a yieldable support system to act as an energy-absorbing system[26]. **Figure 14** shows a cross section of rock reinforcement using yield bolts at a stope. In the **Figure 14**, 1 represents the original room size, 2 is the shape of the room after the rock mass deformation and 3 indicates the support yield bolts.

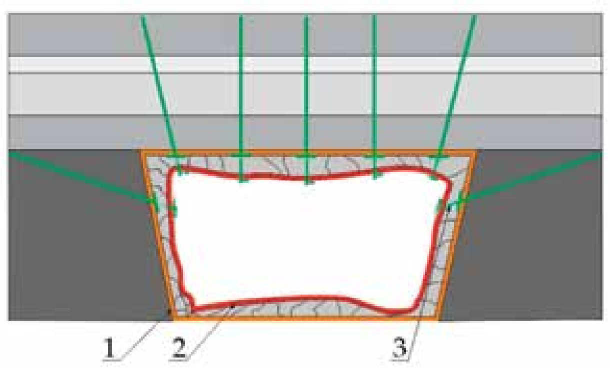

Figure 14: Cross section of rock reinforcement using yield bolts[26].

The rock bolt is expected to yield at 200 kN, at a velocity of 3 m/s during dynamic events: this amounts to 60 kJ of energy. The Richter scale measures the amount of energy dissipated by an earthquake/the energy of a seismic wave. There are plenty of Richter scales placed all over the world in points of interest, especially near large fault lines to measure the intensity of earthquakes[27]. The energy measured depends on the distance between the instrument and the earthquake's epicentre. One rock bolt should absorb 60 kJ of energy over 300 mm of yielding. Thus, 60 kJ of energy is required to radially expand each unit of length of the tube. **Table 1** shows the amount of energy dissipated by an earthquake corresponding to a Richter scale measure. The scale has a maximum reading of 9.0, which amounts to 2.0 1015 kJ. South Africa is considered a stable region because it is situated far away from the fault lines of tectonic plates[28]. South Africa usually experiences earth tremors that are not categorised as earthquakes due to the energy they dissipate. However, in an underground mined-out area, an earth tremor can trigger disastrous rockfalls. Since every underground mine has a different mine layout and rock layout, varying distances to fault lines and no uniform support devices, it is difficult to simulate and anticipate the intensity of an earth tremor. The rock bolt absorbs 60 kJ of energy. More than 100,000 earthquakes of magnitude 1 and below occur yearly. These are minimal and are not felt by humans[29]. However, at great mine depths and in highly stressed rocks with fault lines underground, they can cause rockfalls. The rock bolt absorbs approximately the energy of a Richter 0.0 earthquake.

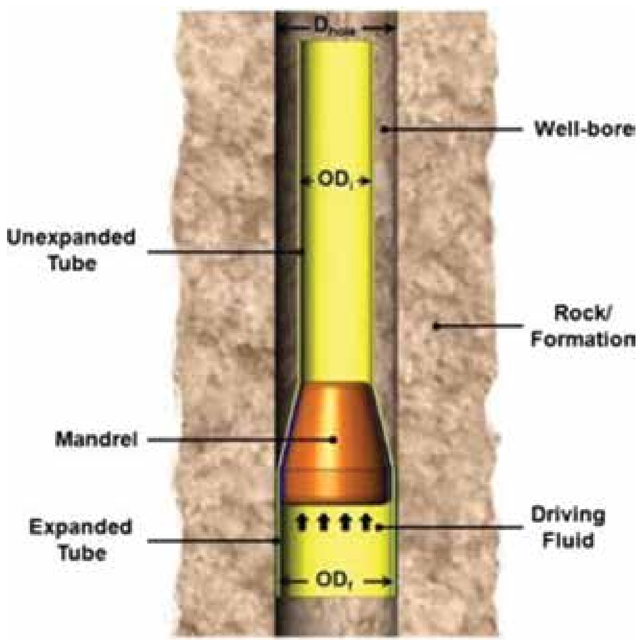

Figure 15: Mandrel yielding a tube[30].

Table 1: The amount of energy dissipated by an earthquake corresponding to the Richter scale measure[27].

Richter Scale Magnitude	Energy in Joules (kJ)
−2.0	0.063
−0.1	2
0.0	63
1.0	2000
2.0	63,000

From the product specification requirements produced by the client, we developed the physical and operational attributes of the required roof anchor. A detailed mathematical spreadsheet with the theoretical calculations of the expected yield tonnage of the rock bolt was created. The spreadsheet contained the different physical attributes of the rock bolt that were changed to produce the expected theoretical tonnage.

Concept

Research is currently being conducted on how to use the hollow expandable tube undergoing rapid radial expansion to ensure the integrity of ground excavations to retrieve oil. The aim is to replace the telescopic drilling method[30]. The telescopic method is susceptible to sporadic caving in of the side walls, which pollutes the oil being retrieved and hinders operations[30]. The idea is to allow for the controlled absorption of the energy of underground dynamic events. **Figure 15** from[30] shows how a mandrel is pushed through a tube; the energy from a dynamic event is absorbed by the mandrel thus ensuring a rigid excavation by yielding the tube.

Theoretical Calculations

The excel spreadsheet calculations were conducted to find the theoretical results of the force on the cone when yielding the tube[30]. **Table 2** shows a summary of the calculations, which are fully detailed in Appendix A.

Table 2: Theoretical calculations of the force on the cone.

Component Calculation	Result
Cone angle in degrees [ϕ]	2.01°
Lateral area of cone [Al]	10, 383.2 mm^2
Surface area of cone	12, 585 mm^2
Stress on the cone	95.11 MPa
Force on the cone	1196.96 kN
Static friction force component	179.54 kN
Dynamic friction force component	107.72 kN
Yielding force for static	221.31 kN
Yielding force for dynamic	149.49 kN

The physical design attributes that met the product requirement specification best were chosen and used for the development of the initial rock bolt design. The preliminary design of the rock bolt was drafted in SolidWorks (computer-aided drafting software) and is shown in **Figure 16**. The individual components of the design were then sent for machining and the rock bolt manufactured at MSP. The primary physical attributes that influenced the yield tonnage were the diameter of the tube, the type of tube (seamless or welded with a

Figure 16: Preliminary yield bolt design[31].

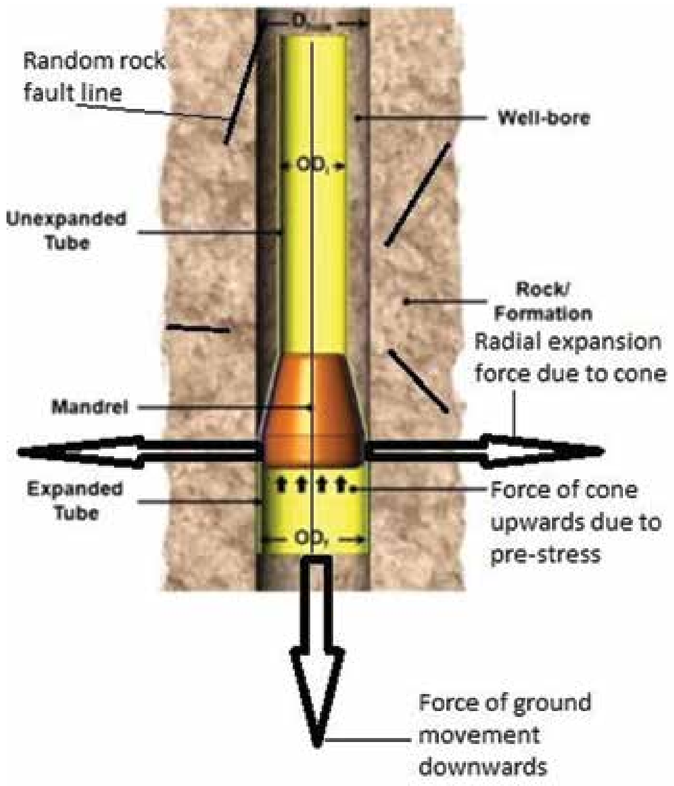

Figure 17: Cross-sectional view of forces acting on the rock bolt[30].

seam), the wall thickness of the tube, the size of the cone, and the correctness of the assumed static and dynamic friction coefficients.

The properties of the preliminary rock bolt design are shown in **Table 3**.

Table 3: Table of specifications for preliminary rock bolt design.

Specification	Quantity
Outer tube	400 mm x 45 mm x 5 mm
Cone OD	40.25 mm
Cone angle	2°

Testing of the Preliminary Rock Bolt Design

The equipment used for testing the preliminary rock bolt design consisted of 60-ton and 100-ton hydraulic presses that simulated the seismic activity that would occur underground. Both these machines are located at the MSP factory in Vereeniging, Gauteng, South Africa. The rock bolt was inserted into a steel frame which was mounted inside the hydraulic press. The bolt was fixed to the testing steel frame using a steel threaded rod, washers, and hexagonal nuts. The hydraulic press contained an extensometer and a load cell to record the force yielding the tube, the displacement, and the cone velocity[4]. The force diagram shows a cross section of the support provided by the rock bolt once installed; the downward movement force was produced by the hydraulic press. The top end of the bolt

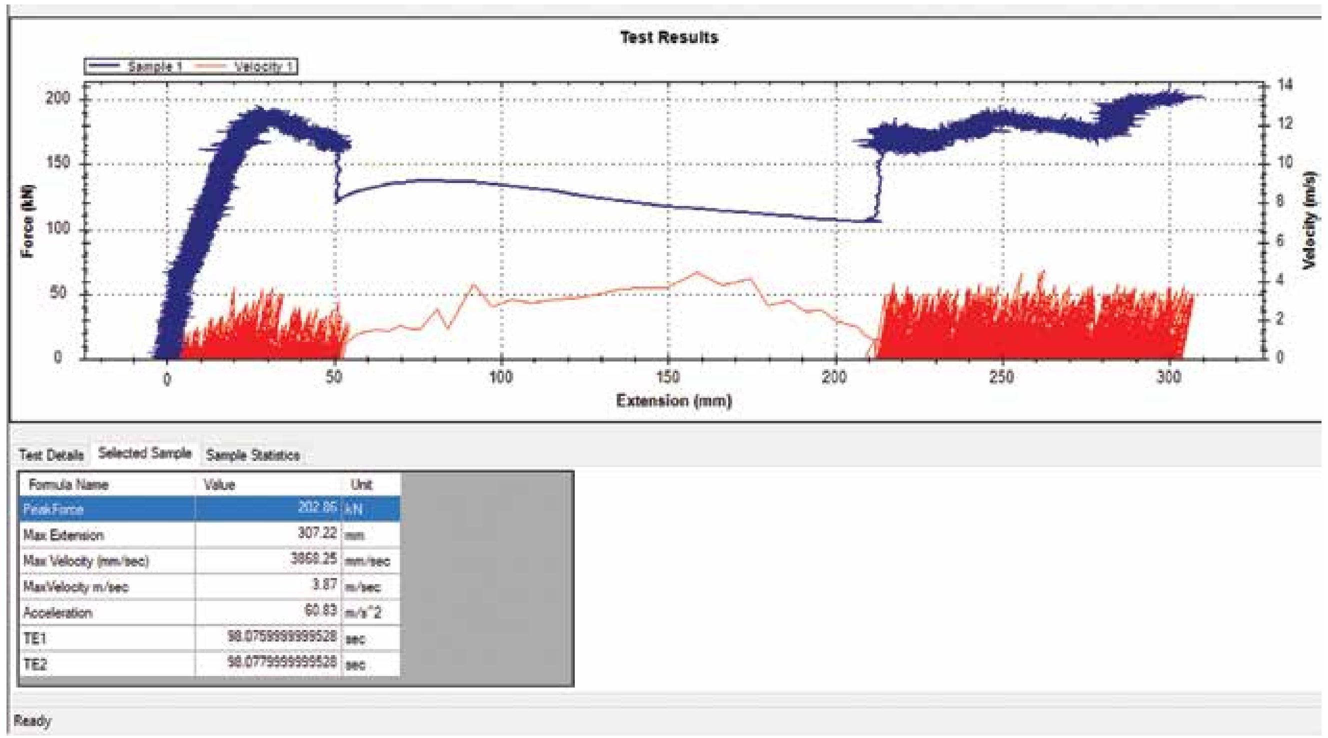

Figure 18: Data acquisition software[19].

Figure 19: Manufactured preliminary rock bolts[4].

was fixed. The well bore is drilled to be slightly bigger than the tube outer diameter, and after pre-stressing the tube yields, creating an interference tolerance with the borehole. The rock bolt aims to counter the progression of fault lines that would otherwise cause rockfalls when stressed (**Figure 17**).

These readings were plotted against each other on the computer software, as shown in **Figure 18**.

On 28 May 2020, the first batch of manufactured rock bolts was tested, pictured in **Figure 19**. Static and dynamic tests were conducted on the bolts. The static test simulated the gradual dropping of the supported roof, and the dynamic test simulated a sudden shock such as an earthquake/ tremor.

For the dynamic test, simulating dynamic events, the hydraulic press cylinder pushed against the rock bolt at a velocity of 3 m/s. When testing began, the hydraulic cylinder started to pull a wire rope attached to the cone inside the tube and yielding started to occur. The force, extension,

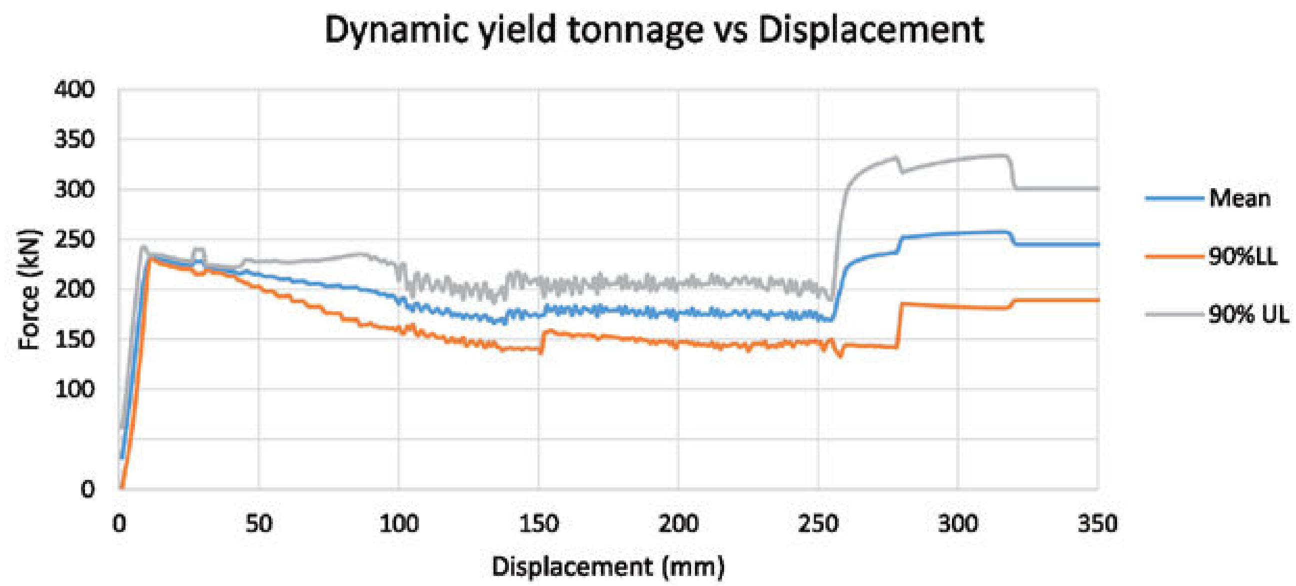

Figure 20: Preliminary yield bolt tonnage vs. displacement.

Figure 21: Splitting of preliminary rock bolt during testing.

and velocity readings were plotted on a screen as the test proceeded, as shown in **Figure 18**. The tube yields 300 mm in length, which is the accepted standard for yielding rock reinforcement mechanisms in the mining industry.

Shortcomings of Preliminary Design
The preliminary rock bolt design was unsuccessful due to the following factors:

a) The yield tonnage during dynamic testing was below 18 tons, as in shown **Figure 20**. At 50 mm during testing, seismic activity was simulated, and this is where the low tonnage reading was noticed. The results show an unacceptably low yield tonnage and do not meet the performance requirement. The yield tonnage for static testing met the design performance of above 20 tons. The difference in yield tonnages was due to the different coefficients of friction between the two tests. The dynamic and static friction coefficients were 0.09 and 0.15, respectively[4]. The test results were combined in the analysis to view the overall behavior of the bolt, because it is not possible to predict which type of rockfall activity will occur.

b) The manufacturing process of the preliminary rock bolt required welding of the rear stop collar and front plug. The welding restricted the expansion of the tube, which caused the tube to split open during testing[4], as shown in **Figure 21**.

c) It is costly, and small-diameter, thick-walled hollow tubes with no welding bead inside are not readily available for purchase. The welding bead increases the friction between the cone and the tube. However, because the weld bead was not uniform throughout the tube, the results were inconsistent.

d) One end of the tube must be flared in order to insert the cone. An entirely new set of tooling was required to flare it, and additional work was required to remove the weld bead. Inserting the cone with the weld bead caused the tube to buckle due to an unequal force distribution.

e) During testing, the rock bolt yielded at a slight angle, because the cone moves across the tube on the path of least resistance (away from the weld bead). The size and width of the weld bead were not uniform through the tube. At the end of testing, the threaded rod was no longer concentric with the circular opening of the rear end stop collar, which is evidence of the misalignment. The angle at which the cone caused misalignment was approximately 3°; the tensile forces acting on the bolt reduced the angle of misalignment.

f) Seamless tubes of small outer diameter (32 mm) were manufactured by drilling the internal diameter from a solid cylinder to the desired diameter. This operation makes the tube very expensive. The tubes are manufactured for hydraulic purposes and thus had low yield strength. Increasing the cone size to increase the yield strength resulted in premature bending of the tube.

In **Figure 20**, the mean yield tonnage against displacement graph is shown for the preliminary rock bolt design. A 90% standard deviation for the upper and lower limit is also shown. The standard deviations are shown to predict the best- and worst-case scenarios of the performance of the rock bolt following the quality tolerance of the materials used. The lower limit standard deviation shows that the preliminary rock bolt yield tonnage did not meet the requirements. After the dynamic event, the cone and tube were misaligned, resulting in a massive increase in the force as the tube was yielding nonlinearly[4]. These high forces may cause the tube to fracture, resulting in a failed support system.

IMPROVED DESIGN OF ROCK BOLT

To mitigate the risk of rockfalls occurring in mining excavations, an adequate support system is required. The results from the preliminary investigation contributed to the redesign of the yield bolt, which aimed to address the failures of the preliminary design. The objective of the improved rock bolt design was to minimise the space between rock reinforcements with minimal intrusion into the working space of miners and underground equipment. The yield bolt is fixed within the roof of the stope and absorbs the energy of a rockfall. The absorption is due to a cone radially expanding a tube due to the force produced by the rockfall. **Figure 22** shows the improved rock bolt design. The main difference between the preliminary model and the improved model was the absence of internal welding in the improved model. Welding of the rear stop collar and front plug restricted the expansion of the tube, causing splitting of the tube during testing. The improved model does not require welding and is manufactured as a single cast component.

Design Details

The initial product requirement specifications for the preliminary design were used. The shortcomings of the preliminary rock bolt design ensured that an adaptive design would be used for optimisation. Three major improvements were made to tackle the shortcomings of the preliminary rock bolt. **Table 3** shows the dimensions of the preliminary rock bolt and **Table 4** shows the dimensions of the improved model, with the following parameters:

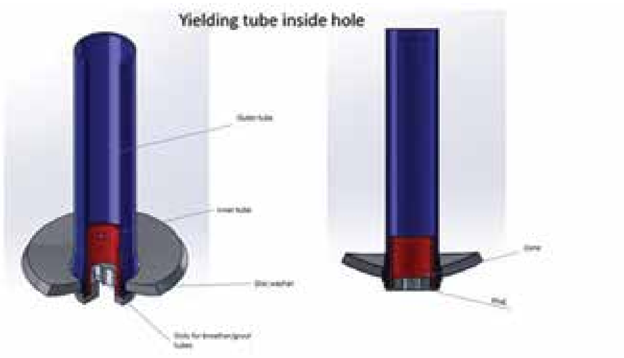

Figure 22: Improved rock bolt design.

Figure 23: Assembled improved rock bolt.

Figure 24: Experimental set-up.

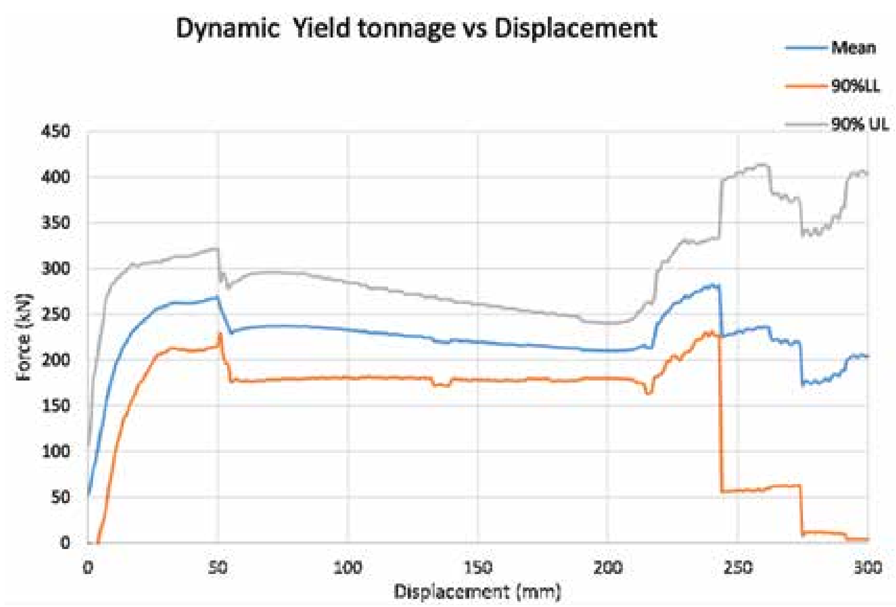

Figure 25: Yield tonnage vs. displacement.

a) Increased tube outer diameter and cone;
b) Use of seamless tubes;
c) Insertion of an inner guide tube.

Table 4: Yield bolt components.

Item No.	Component specification		Function
1	Outer tube	400 mm x 88.9 mm x 5 mm	the steel tube that yields due to force of rockfalldue to force of rockfall
2	Inner guide tube	100 mm x 76.2 mm x 6 mm	Linearly guides and houses the cone when yielding the tube
3	Cone	43 mm x 6.6°	Yields the outer tube
4	Plug	27 mm x 63 mm	Secures the inner tube during installation

Figure 23 shows the assembly of the yield bolt before testing, and **Table 4** provides details of the yield bolt components.

The Improved Model

To assemble the rock bolt, the inner guide tube is inserted into the cone. The plug is threaded onto a rod and moved in through the inner guide tube. Lastly, the outer tube is placed over the cone where it is flared, to make the complete assembly.

Experimental Set-Up and Equipment for Testing of Improved Design

The testing procedure and equipment used were the same as those for the preliminary rock bolt design. However, in the improved model test, the bolt was fixed to the testing frame using steel anchor wire rope, washers, and ferrules. In the preparation for the test, the yield bolt was pre-stressed to 20 tons instead of being firmly fixed by hexagonal nuts. A hand pump and a stainless-steel ball terminal end were connected to the rock bolt cable anchor at both ends. Once fixed, the pump starts pushing against the ball terminal, eventually pushing in the cone to pre-stress the rock bolt assembly to 20 tons. This ensures that the bolt is firmly fixed into the hanging wall and exerts an upward force on it. The hand pump with the rock bolt is shown in **Figure 24**, which shows the experimental set-up for dynamic testing.

RESULTS

Test Results

Figure 25 shows the mean yield tonnage against the cone's displacement during dynamic testing of the improved rock bolt design. A 90% standard deviation for the upper and lower limit is also shown. The standard deviations are

Figure 26: Yield bolt test 1 mode of failure.

Figure 27: Evidence of inner tube digging into the outer tube.

shown to predict the best- and worst-case scenarios of the performance of the rock bolt following the quality tolerance of the materials used. The lower limit standard deviation shows an average of 18 tons, which is an acceptable yield tonnage in the event of a poor-quality batch of materials.

Discussion

The accepted standard for the yield tonnage of rock reinforcement devices in medium-risk areas is 20 tons. This is the consensus in the mining sector[19]. For mining activities in areas of high risk, the accepted yield tonnage is 35 tons. **Figure 24** shows that the mean yield tonnage of the improved bolt was above 20 tons. Even after the dynamic event simulation at 50 mm, it successfully remained above 20 tons. Maintaining strict quality tolerances for the rock bolt allows for successful absorption of 60kJ of energy, as required. The working principle of the improved yield bolt is based on radially expanding a hollow tube to absorb the energy of seismic activity[4]. The investigation showed that after a dynamic event, tubes failed to maintain their yield tonnage. However, the preliminary design of the yield bolt contained welded components. The effect of welding on the yielding tube decreased the yield strength, the tensile strength, and the impact toughness[32], resulting in a lower tonnage when testing. The high current and voltage during welding allowed defects to be formed in the microstructure of the steel[32]. Welding at lower currents and voltages is impossible because low welding penetration results in a weak joint. The design of the improved yield bolt does not require any welding during manufacture, as shown in **Figure 23**. This is also advantageous for transportation, as components can be transported separately and assembled underground; thus, many yield bolts can be transported per shift.

A total of eight tests were conducted; only the tests that significantly changed the behavior in the test results are discussed. Tests 1 and 3 failed in two unexpected ways that greatly influenced the improvement of the rock bolt; the other six tests were successful. During testing of the improved design (test 1), because of the high yield tonnage, the plug used to secure the guide inner tube sheared off, as shown in **Figure 26**. The effects of this failure are visible in **Figure 20**, where at 250 mm, the load drops to zero. In the event of this failure underground, the supported roof would have collapsed. The plug was redesigned to support the load adequately in the optimised design.

Figure 28: Misalignment of cone.

ROOF BOLTING AND STRATA CONTROL

Figure 29: Wire rope failure during testing.

Towards the end of test 3, the yield tonnage started to increase exponentially. This was caused by the inner tube digging into the outer tube, thus restricting the cone from progressing. The dynamic event shifts and misaligns the inner tube causing the exponential increase in forces. **Figure 27** shows a cross-sectional cut through the tube, showing evidence of the inner tube digging into the outer tube.

Figure 28 shows a cross-sectional view of the cone with the inner tube and outer tube, providing evidence of the misaligned cone. To prevent misalignments of the inner tube during operation underground, the length of the inner guide tube was increased in the improved design. Furthermore, due to the failure mode of test 3, the wire rope used to pre-stress the yield bolt underground began to fail, as shown in **Figure 29**.

Cone Element

The angle of the cone was 6.67°. The angle has a major role in the yielding of the tube. Higher angles provide higher forces but threaten the structural integrity of the tube. The cone had a thickness of 5mm and hardness of 43 HRC after heat treatment; this allowed the cone to prevent the huge compressive forces from yielding the tube. The length of the cone was 43 mm, providing a large surface area of contact with the tube. In a given rock mass, each tube will yield at 20 tons; the larger the rock mass the faster the tube will yield and the steeper the gradient of the yield force. The bolts are intended to be installed at equal distances of 1.5 m from each other for optimal performance. Installing too few bolts within a rock mass will cause the bolts to yield quickly to 300 mm, causing failure and resulting in less evacuation time for workers.

During installation, the hand pump pushes the stop collar inwards. This action pushes in the cone resulting in a positive force reinforcing the roof. This pre-stress force allows the rock bolt to be firmly fixed. The wire rope inclusion shown in the diagram complicates the active working components that need to be present in the borehole (**Figure 17**).

CONCLUSIONS

The improved yield rock bolt addressed the shortcomings of the preliminary yield rock bolt. The yield tonnage was similar to that of Rocprops, ensuring no premature rock reinforcement failure of any device in the event of a rockfall. It is also evident that the yield tonnage remained sufficient during dynamic events. The improved yield rock bolt must be assembled underground; therefore, no manufacturing defects are expected, and only a strict quality check of machined components is required. MSP has a dedicated quality inspector for all internal and external products received or produced. Precision machining techniques are readily available to ensure strict quality adherence. Precision quality jigs can be manufactured to support quality checks manually once production begins.

The improved design ensured that the yielding of the tube was linear by using an inner guide tube, thus preventing any other component failures of the rock bolt in operation underground. The tubes used to manufacture the improved rock bolt with consistent performance are readily available on the market. The tooling required for manufacturing the rock bolt is already set up at MSP, but personnel would require training to meet the quality checks for manufacturing. The working personnel are already well trained for the machine operations. Arrangements are being made to have the improved rock bolt introduced underground for testing and observation in the working environment. This will form a part of another paper. Following this, the system will be simulated in suitable computational software, such as Ansys, to provide predictions of the dynamic behavior of the rock bolt beyond the window of normal operation. This will form the scope of yet another paper. Some contributions of the present paper to the field are: (1) designing a rock bolt with no welding requirement; (2) testing both the static and dynamic behavior of rock bolts and achieving linearity in the yielding of the tube; (3) designing the system to maximise the spacing underground to limit interference with working space for personnel and equipment. Furthermore, the improved rock bolt is designed to be easily assembled underground. These results will inform designers, manufacturers, and installers.

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ACKNOWLEDGMENTS

We are grateful to Mine Support Products (MSP) Company for granting us access to data and allowing use of their testing equipment and work with all their staff.

Conflicts of Interest: The authors declare no conflict of interest.

APPENDIX A

Theoretical Calculations

Cone angle in degrees [ϕ]:

$$\frac{\alpha(180)}{\pi} = \frac{0.035(180)}{\pi} = 2.01^\circ$$

Lateral area of cone [Al]:

$$\begin{aligned} &\pi(R+r) * [(R-r)^2 + L_c^2)]\hat{}0.5 \\ &= \pi(20.125+17.2) * [(20.125-17.2)^2 + 88.5^2)]\hat{}0.5 \\ &= 10,383.2\ \mathrm{mm}^2 \end{aligned}$$

Surface area of cone:

$$\begin{aligned} &A_l + \pi\left[\left(R^2 + r^2\right)\right] \\ &= 10,383.2 + \pi\left[\left(20.125^2 + 17.2^2\right)\right] \\ &= 12,585\ \mathrm{mm}^2 \end{aligned}$$

Stress on cone:

$$\frac{S_{yt} * 2 * t}{R+r} = \frac{355 * 2 * 0.005}{0.020125 + 0.0172} = 95.11\ \mathrm{MPa}$$

Force on cone:

surface area ⁎ *pressure* = 12, 585 ⁎ 95.11 = 1196.96 kN

Static frictional force component:

μ ⁎ *force on cone* = 0.15 1196.96 = 179.54 kN

Dynamic frictional force component:

μ ⁎ force on cone = 0.09 ⁎ 1196.96 = 107.72 kN

Yielding force for static:

Horizontal force component on cone + frictional force
= 41.77 + 179.54 = 221.31 kN

Yielding force for dynamic:

Horizontal force component on cone + frictional force
= 41.77 + 107.72149.49 kN

The expected static and dynamic yield forces are 22.13 and 14.95 tons, respectively.

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Weir Minerals' Sandmaster™ sand wash plant increases product recovery

Producers that use traditional sand washing equipment – bucket wheel classifiers and sand spirals, for example – lose around 10% of their production to the pond or lake it is dredged from or simply back to nature. With sand prices as high as they are currently, this is not sustainable. That is why producers are increasingly opting for more efficient equipment that allows them to recover a much higher percentage of the sand at the correct particle gradation and content of minus 63-micron material. This is what has driven the development of Weir Minerals' Sandmaster™ sand wash plant. Fully lined with Linatex® rubber, its optimised design produces a drier, higher-quality product with less ultrafine material.

INCREASE PRODUCTION CAPACITY

Pannonvest Kft's Pusztamiske site is in western Hungary and produces a variety of construction sand and aggregates through dry extraction. The raw material is then sorted into its different fractions using washing and screening equipment. The Pusztamiske site needed to replace a low efficiency dewatering wheel that was unable to provide the recovery rate or product quality they required. Weir Minerals had recently improved a neighbouring mine's fine-sand recovery process using a Cavex® hydrocyclone. After hearing about the success of this project, the management team of the Pusztamiske site approached Weir Minerals to discuss possible solutions.

Pannonvest Kft required a solution capable of efficiently producing a greater quantity of fine sand (0-1mm) in line with European standards. The removal of clay from the excavated raw material was also considered a key challenge for any proposal. Clay negatively impacts the strength of the sand and its ability to bond with other materials.

When manufacturing concrete, the inclusion of clay within the sand can increase the amount of cement required. The incumbent dewatering wheel did not reliably remove the clay and efficiently recover the sand from the slurry.

After discussing the project's requirements, analysing their feed material, and inspecting Pannonvest Kft's existing system, the Weir Minerals team recommended the installation of a Weir Minerals' Sandmaster™ SP 50 sand wash plant.

The compact sand wash plant was successfully delivered to the site on schedule. Due to the intuitive design of the plant, it was assembled and commissioned in a very short time. Using the incumbent dewatering wheel, Pannonvest Kft was able to produce approximately fifty tonnes of poor-quality sand per day, valued at approximately eight hundred Hungarian Forints (HUF) (USD 2.59) per tonne.

However, using the Weir Minerals sand wash plant, Pannonvest Kft is now able to produce four hundred

tonnes per day of high-quality washed sand worth up to 1,600 HUF (USD 5.18) per tonne.

Pannonvest Kft have calculated the increased efficiency and product quality provided by the Weir Minerals sand wash plant is worth approximately 8,000,000 HUF (USD 25K) per year.

Furthermore, as the Weir Minerals sand wash plant can process material with high amounts of clay, Pannonvest Kft is now able to extract and wash sand from previously untouched parts of the mine. Considering the increased capacity and improved product quality Pannonvest Kft have estimated that their return on investment will be realised in two years.

'Our experience in partnering with Weir Minerals has been fantastic. They successfully identified our issues, evaluated our process, and provided a solution which proved to be extremely simple to install and commission,' Tamás Molnár, owner and site manager said.

'The service from the Weir Minerals team and the quality of their products are exceptional. I look forward to collaborating with them on projects in the future,' he added.

HOW DOES THE PLANT WORK?

The sump is fed through the feed entry port at the side of the plant. The Warman® centrifugal slurry pump transfers the slurry from the sump to the Cavex® hydro cyclone at the top of the plant. The Cavex® hydrocyclone then separates fine from coarse particles, with the finer particles being discharged at the top of the hydrocyclone; these particles report to an overflow box at the side of the hydrocyclone, which, in turn, is fed to the effluent treatment via hoses and pipes.

The coarse particles report to the Enduron® dewatering screen through the underflow of the hydrocyclone. The Enduron® dewatering screen – which features spray bars if further cleaning of the material is required – removes the water and residual fines from the product. Water and residual fine material are then discharged through the screen media and passed into the sump. The resultant saleable sand is discharged at the front of the screen through chutes where it is stockpiled ready for sale.

COMPONENT PRODUCTS

Unlike other sand wash plants on the market, the Sandmaster™ plant is made up entirely of Weir Minerals products, rather than component products from third-party suppliers. As the OEM that has designed, developed, and manufactured the various component products, Weir Minerals has seen them perform in countless applications and settings and knows them inside-out.

Notably, the Cavex® hydrocyclone, by minimising flow resistance through the feed chamber, can process higher volumes of sand than conventional hydrocyclones. It also features a cut point perfectly suited to sand wash applications. Cyclone technology is by no means new, but until recently it has not been widely adopted in the sand and aggregate industry.

However, now that the benefits of the increased efficiency of the hydrocyclone and dewatering screen are commonly acknowledged, producers are increasingly embracing it as their preferred sand washing solution. This is also advantageous to the end user because the sand is of a superior quality. Typically, traditional sand washing equipment produces sand with a moisture level around 25%, whereas the Sandmaster™ plant consistently delivers sand around 12-15%. Recent customer feedback

has shown moisture levels measured at down to 8% in some cases.

The Enduron® dewatering screen is effective in reducing moisture content, while also offering exceptionally high throughput per unit screening area. A wide variety of screen media aperture sizes and shore hardness' are available, depending on the feed material make up.

It is a linear motion screen that features a lock-bolted frame with epoxy adhesive applied between all mating surfaces, adding a layer of moisture and corrosion protection. The modular screen deck panels deliver long life and easy handling and maintenance, making it simple to replace areas of localised wear.

Moulded rubber buffers are used on all four support points to isolate live frame vibrating loads. As is the case with the entire sand plant, the Enduron® dewatering screens are lined with Linatex® premium rubber to reduce abrasive wear at contact points and offer excellent water removal and high load capacity, while lowering total cost of ownership.

The Sandmaster™ plant also features a Warman® WGR® slurry pump, which has been specifically designed and engineered for sand and aggregate applications. Its improved hydraulic design includes enhanced gland options and a simplified wet-end. In addition, it has a drainage plug situated on the casing, which can be pulled in cold months so that the pump does not freeze or clog when stopped.

While these are market-leading products, the fact that they are all designed and manufactured by Weir Minerals cannot be underestimated. It understands how each product interacts with that which comes before and after it. In the same way upstream equipment impacts downstream processes in a typical flowsheet, each product in the Sandmaster™ sand wash plant impacts those preceding and following it. Weir Minerals has engineered it with this in mind – thinking about it holistically, rather than as a series of separate components.

This also has safety benefits because Weir Minerals understands the vibrational output of each component under operation. It has factored this into its design to ensure the Sandmaster™ plant operates safely and does not pose a risk to those working in its vicinity or monitoring the machine from the observational deck.

FLEXIBILITY

The Sandmaster™ sand wash plant is compact, semi-mobile and skid mounted to ensure that it is easy to transport and easy to assemble. Depending on the size, it can be assembled and commissioned in as little as three hours or, for larger machines, up to a day.

Moreover, because of its compact design, it can be easily integrated into the existing plant and the access stairway and platform can be mounted on either the left hand or right hand side of the machine.

The Sandmaster™ sand wash plant also comes in a wide range of sizes – starting with a 25TPH machine, right up to 200 TPH – so that each producer can find a solution best suited to their operation. It also comes in a single- and dual- grade series: the SP-series creates one type of sand which is discharged using the discharge chute at the front of the plant, whereas the DP-series sand plant has added functionality which enables it to create two separate sand products, simultaneously, which may also be blended at the discharge point.

MAINTENANCE

There is access to the pump all the way around, which ensures that performing maintenance is simple and straightforward. There is a drain valve on the sump and an access port that is big enough to crawl into. Alternatively, there is also an Isogate® knife gate valve, which can isolate the pump so that, if required, maintenance can be performed without draining the sump. Needless to say, these features are invaluable in helping to reduce downtime.

Maa Sarbamongala Quality Sand (MSQS) in West Bengal, India, were using six trommel screens to classify feed sand. The screens required high maintenance intervals of every 2-3 months, which involved two hours of downtime to service the wire mesh screen media. In addition, their process was limited to 100 TPH with product losses of 5%.

After running several process simulations with various feed parameters, the Weir Minerals' team specified the Sandmaster™ SP150 sand wash plant and a conveyor system. Due to excess amount of fines in the feed material, the Weir Minerals team designed a custom under-pan arrangement on the Enduron® dewatering screen to remove excess fines from the recirculation.

Since commissioning, the Sandmaster™ sand wash plant has consistently produced 150 TPH high-quality washed sand product. Additionally, the combination of the Cavex® hydrocyclone and Enduron® dewatering screen ensured a consistent

moisture content of less than 12% and a reduction in product losses by 60%.

'Our experience in partnering with Weir Minerals has been excellent. The team proposed a solution which exceeded our expectations in final product recovery. Due to the increase in productivity and sand quality we were able to recover our investment in our Sandmaster™ sand wash plant after ten months of operation,' Mr Jogendra Barman, Partner, Maa Sarbamongala Quality Sand said.

SERVICE NETWORK

Weir Minerals has an extensive service and support network, strategically located in over sixty countries. This allows Weir Minerals to be close to its customers not just geographically, but also in terms of the relationships it has with them.

It collaborates with its customers to understand their challenges and develop and implement solutions to optimise their equipment and processes. Being on hand – whether it is to provide parts or maintenance requirements – when their customers need them most is integral to Weir Minerals' customer-centric approach.

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A new method to analyse the mine liquidation costs in Poland

Coal mine closure processes are being carried out in the European Union due to the current energy transition. The use of coal-fired power plants has been significantly reduced in recent years. Because of the significant financial outlays, processes of rationalisation and minimisation of the mine liquidation cost should be carried out. In this paper, a statistical analysis of the liquidation processes in hard coal mines in Poland was carried out. A new tool was developed in order to optimise the mine liquidation costs. The mine liquidation process can be divided into ten different processes, which have been analyzed in detail in this research work. The method of the assessment of the amount of estimated liquidation costs described is based on the analysis of the total liquidation cost. The presented method of signaling deviations of the costs of the liquidation of the mining plant from the average value is a useful tool in the process approach to the issues connected with the restructuring of post-industrial property. The presented cost assessment procedure may facilitate the monitoring of conducted activities in terms of rationalization and minimization of the costs incurred. Finally, the proposed method for assessing the cost of mine liquidation is understandable, simple, and easy to use for applications in preliminary design works and on-going engineering works.

INTRODUCTION

The reduction in greenhouse gas emissions in the European Union by 2050 implies the cutting of electricity production at coal-fired power plants, and therefore the coal mines need to be closed. Grmela *et al.*[1] analysed the process of mine liquidation as an environmental, economic, and legal problem. Harat *el al.*[2] studied the economic and environmental aspects of the liquidation of coal mines. Jewartowski *et al.*[3] determined the optimal time of coal mine liquidation given the necessity of bearing the costs of post-mining reclamation. Batrancea *et al.*[4] carried out an econometric approach on production, costs, and profit in Romanian coal mining enterprises. Dvorˇácˇek *et al.*[5] developed research about the choice of the technical liquidation of underground mine workings. They analysed the mining legislation in the mine liquidation processes in the Czech Republic. Janusz *et al.*[6] investigated the changes in hydrogeological conditions in the area of liquidated hard coal mines in the north-eastern part of Upper Silesia Coal Basin (Poland). They concluded that the groundwater inflow into the analysed area was reduced by 43%. The socioeconomic impacts of mine closure were analysed by Rao and Pathak[7]. Other researchers also analysed the mine liquidation processes and the socioeconomic impacts of mine closure[8-12]. Salom *et al.*[13] carried out a critical review of environmental impacts and constraints to rehabilitation in closed and abandoned mines in Namibia. Barabash *et al.*[14] analysed the technical and economic aspects of the coal mine closure based on the geo- mechanical component assessment in Ukraine. The economic and financial aspects of mine closure were investigated by Kahn *et al.*[15]. Some research works about the optimisation of mine closure processes and the impact of mine closure and its associated cost on life of mine planning were carried out[16-21].

In addition, some alternatives can be applied in closed mines to use the disused mining infrastructure. Underground pumped-storage hydropower (UPSH) plants can be built using the underground space as lower reservoir[22-25]. Menendez *et al.*[26] carried out a research work about closed mines in Spain as energy storage systems. In addition, abandoned mines can be also used as subsurface reservoirs of compressed air energy storage (CAES) systems[27-29]. The ambient air would be stored at high pressures in the drifts. In the Polish hard coal mining industry restructuring actions are realised. A rational reduction in costs of the mining industry may be based on the liquidation of mines that are considered as permanently unprofitable. The liquidation of the mine is regulated in the Polish legislation. According to the legislation on geology and mines, in the event of liquidation of the mining plant, in a whole or in a part, the entrepreneur is obliged to:

- Secure or liquidate mining excavations and mining equipment, installations, and facilities.
- Secure the unused part of the mineral deposit.
- Secure the neighboring mineral deposits.
- Take the necessary measures to protect the excavations of neighboring mining plants.
- Take the necessary measures to protect the environment and reclaim the land after mining activities.

Since 2000, SRK S.A. mining company, as the legal successor to the previous mining ex- ploitation, has been managing the assets of the restructured hard coal mines. Eight branches of SRK S.A. are involved in the liquidation and protection of mining excavations in liq- uidated coal mines. The branch of SRK S.A. called Central Mine Dewatering Plant is responsible for securing the neighboring mines by pumping water out of the liquidated mining plants. The supervision and management of post- industrial property in the liq- uidated mines is carried out by Branches of SRK S.A. called Hard Coal Mines in Total Liquidation and Housing Resource Administration.

During the mine's existence, we can distinguish the period of the mine construction and the period of the mining deposit; however, the natural and inseparable element is the liquidation of the mining plant. The lack of cost management support instruments may make it difficult to improve the efficiency of liquidation. Although the average cost of the mine liquidation is around EUR 150 million, the scientific research concerning the rationalisation and efficiency improvement of liquidation processes is very scarce[7,8].

In this paper, a statistical analysis of the liquidation processes in hard coal mines in Poland was carried out. The proposed evaluation method of the amount of estimated liquidation costs described is based on the analysis of the total liquidation cost according to the SRK experience. The presented research is a continuation of research on the tools that support the cost management of liquidation processes. The presented method of assessing the correctness of the estimation of liquidation costs may affect the effectiveness and efficiency of a mining enterprise that liquidates coal mines.

MATERIALS AND METHODS

The process management system in SRK S.A. requires the modernisation of the available tools for assessing the course of the liquidation processes and the proposal of new ones. An additional research aim is to identify research areas and problems related to the rationalisation and effectiveness of the liquidation processes that require analysis and solutions. The aim was achieved in two stages (**Table 1**). The research plan was carried out on the basis of the analysis of the Updated Mining Plant Closure Programs for 17 examples of mine liquidation or their separate parts. The analysis refers to the period from 2015 to 2023.

In the first stage, the mine liquidation costs were analysed and compared to the expe- rience of SRK S.A. in the liquidation of coal mines in Poland. Moreover, the documentation concerning the conducted and ongoing restructuring processes in liquidated mines was analysed. The results of the analysis made it possible to propose a method to optimise the cost management of the liquidation processes. During this stage, a direct interview was conducted with experts, concerning the technical problems of the liquidation processes, their correctness, and suggestions for possible changes in the liquidation practice. Interviews with people who manage the liquidation of analysed branches dispelled the most important doubts and explained most of the cases of deviations from the established procedures. On this basis, it can be concluded that the performed liquidation process is correct and compliant with the 'mining and construction art' and that the activities that has been undertaken so far may constitute the basis for the development of the method for assessing the correctness of cost estimation of mine liquidation processes. The updated method was used in the second stage of the research.

In the second stage, basic statistical analysis of the liquidation processes in SRK S.A. was carried out. The encountered problems were explained with experts. The correct operation of the proposed liquidation process assessment tool was carried out in two stages. In the first stage, the software's reaction to the assigned cases of hypothetical new branches of SRK S.A. was assessed. In the second stage, the same cases were also presented to experts in practice managing the liquidation of coal mines. The research identified areas and research problems that need to be solved.

Table 1. Research methods and the results of their use in particular stages of research.

Research Stage	Research Methods	Results of the Use of Research Methods
I	Analysis	A statistical analysis of the cost liquidation process.
	Synthesis	A modification of data form.
	Direct interview	An actualization of proposed evaluation method.
II	Direct interview	A verification of reached results.
	Analysis	A modification of the evaluation method of the course of liquidation processes.
	Synthesis	An indication of research areas and problems.

Figure 1: Mine liquidation processes in SRK S.A. Source: Data from SRK S.A.

The research was carried out on the basis of the updated mine closure programs containing data on the performed and currently conducted mine liquidation processes. The liquidation of coal mines is financially accounted for by 10 component processes (**Figure 1**). SRK S.A. mining company has been conducting the liquidation of coal mines since 2000 and according to the updated programs for the liquidation of coal mines, it should be completed by the end of 2023[7,8]. The liquidation of the mine is carried out in accordance with several models depending on the scope of the liquidation and the target model of the restructured mining plant. SRK S.A. may carry out the liquidation of the complete mine or its ineffective part. Due to the target model, the liquidation is carried out with the pumping station so as to protect the neighboring active coal mines or as complete when protection of neighboring mines is not required (**Figure 1**). In practice, the difference between the models focuses on the first 3 processes. In **Figure 1**, processes 1, 2, and 3 marked in lighter colors relate to the complete liquidation of the mine, while their darker version reflects the course of the process when the pumping station is left. In the case of leaving the pumping station, the part of the shafts and underground workings are not liquidated. They are being transferred to the Central Mine Dewatering plant that will protect the neighboring mines and the land surface against water hazards. It has not been necessary to liquidate a marked part of the mine, leaving the pumping station so far, which means that SRK S.A. liquidates mines only in 3 variants.

RESULTS

The publication presents a statistical analysis of six cases of completely liquidated coal mines. In order to increase the credibility of the research results, the mines that are currently liquidated and grouped administratively in eight branches of SRK S.A. were also subjected to the statistical analysis. To facilitate the analysis, these branches were divided into component mines. Thanks to that another group of 11 liquidation cases were obtained, which gives a total of 17 examples. In order not to disclose the sensitive data of SRK S.A., the liquidated mines were given working names in accordance with the decreasing cost of their liquidation, presented as a fraction expressed as a percentage of the total cost of liquidation of all 17 coal mines (**Table 2**). Inflation and changes in labor costs have resulted in incomparability of costs in different years; therefore, a proprietary correction coefficient developed on the basis of data from the Central Statistical Office was used. The liquidation cost converted into the realities of the first quarter of 2021 was analysed.

The liquidation of the mine is always a single case, which results in different costs (**Figure 2**). **Figure 2** shows the numbers of subsequent liquidation processes on the horizontal axis, and the vertical axis shows the percentage of expenditures of individual branches for each of the processes. Cost differences result from the scale of the project. Higher liquidation costs depend on the number of maintained and liquidated facilities. The costs of other processes are in most cases a derivative of running the main processes (1, 2, and 4). This aspect of the liquidation cost structure requires deeper analysis and further research.

The state budget has allocated or will allocate more than EUR 1 billion to the liquidation of the analysed branches, so even a small percentage reduction in the cost of liquidation means measurable financial benefits. Most of component processes of the liquidation of coal mines have potential for optimisation and rationalisation. The variation

Table 2: The costs of liquidated branches of SRK S.A. subjected to statistical analysis.

Branch	B1	B2	B3	B4	B5	B6	B7	B8	B9
	16.16%	12.75%	10.27%	9.98%	8.94%	6.93%	6.19%	5.88%	5.43%
Branch	B10	B11	B12	B13	B14	B15	B16	B17	
	4.30%	3.00%	2.78%	2.24%	1.88%	1.62%	1.34%	0.32%	

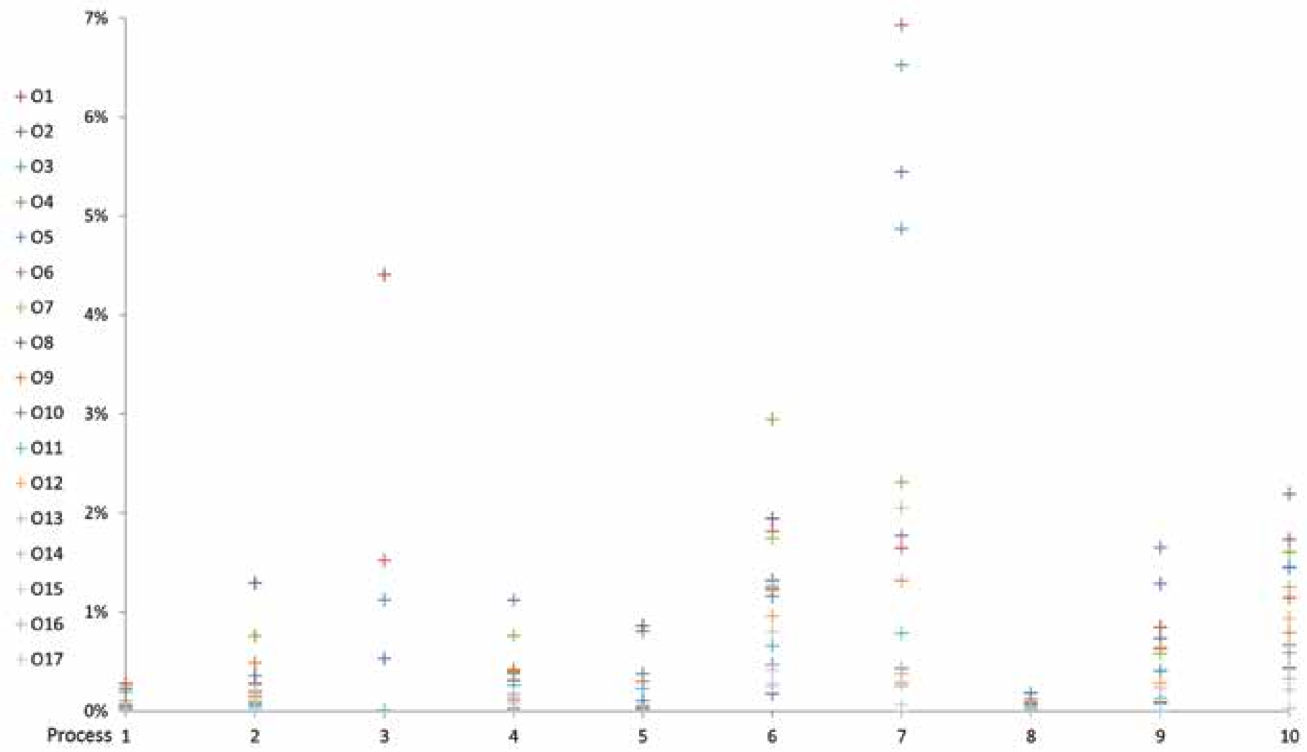

Figure 2: The distribution of the liquidation processes costs of branches of SRK S.A.

of the size of liquidation costs was analysed using the compliance factor according to the Equation (1).

Equation 1:

$$V = \frac{s}{\bar{x}} \cdot 100$$

where: V is the compliance coefficient, s is the standard deviation, and x is the arithmetic average. The standard deviation is estimation by applying Equation (2). xi is the successive characteristics of the population, N is the number of observations in the population and μ is the expected value.

Equation 2:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \mu)^2}{N}}$$

If the coefficient of variation is in the range of 0-20%, then the diversity of the population is small, when it is in the range of 2040%, it proves the average diversity of the population, and in the range of 4060% it is highly differentiated. When the coefficient of variation exceeds 60%, it means a great diversity of the population.

Table 3: The analysis of the branches of SRK S.A. as a one group.

Branches Included in the Group			All
CV	The coefficient of variation of total liquidation costs		75.92%
MA	The coefficient of variation in multi-criteria analysis		153.89%
Average CV	75.92%	Average CV and MA	114.91%

Table 4: The analysis of the branches of SRK S.A. as a one group.

Branches / Cost	LB (above 9%)	MLB (from 6% to 9%)	MSB (from 3% to 6%)	SB (to 3%)
CV	23.29%	19.4%	27.62%	49.66%
MA	6.66%	9.75%	39.17%	104.85%
Average CV		29.67%	Average CV and MA	35.05%

Table 5: Multi-criteria analysis of liquidation processes costs “costs minimisation”.

Branches	LB (to 1.0)	MLB (1.0 to 2.5)	MSB (2.5 to 4.0)	SB (above 4.0)
CV	55.2%	28.90%	47.06%	89.83%
MA	51.81%	15.98%	11.86%	32.55%
Average CV		55.25%	Average CV and MA	41.65%

Table 6: Multi-criteria analysis of liquidation processes costs "costs maximisation".

Branches	LB (above 4.0)	MLB (1.25 to 4.0)	MSB (1.25 to 2.5)	SB (to 1.25)
CV	21.43%	22.15%	22.62%	49.35%
MA	1.41%	13.38%	19.16%	100.96%
Average CV		28.89%	Average CV and MA	32.07%

The coefficient of variation of components of costs of liquidation processes of the entire research group amounted to 119.41%, which proves a very high variability of results. It has been found that this indicator is not reliable. Underground coal mines are liquidated according to three liquidation models, and this causes costs replacement in various component liquidation processes. Increasing the outlays in one process may reduce the capital intensity of another. For this reason, a better indicator of the differentiation of analysed examples of liquidation is the analysis of the coefficient of differentiation of the total expenditures on the branch liquidation (CV), which, for all liquidated branches, amounted to 75.92% (**Table 3**).

In order to increase cost consistency, it was proposed to divide the liquidated mines according to their total liquidation costs. As shown in **Table 4**, the division into 4 groups of branches was proposed – Large Branches (LB), Medium Larger Branches (MLB), Medium Smaller Branches (MSB), and Small Branches (SB).

The proposed division significantly improved the coefficient of variability of the liquidation costs of branches in groups (**Table 5**). The average coefficient of variation was 29.67%. In individual groups, the amount of liquidation costs was actually satisfactory, except from the group of Small Branches (SB), and therefore the sorting criteria ought to be changed again.

In the next stage of the research, the branches were sorted according to the indicator obtained in the multi-criteria analysis of the costs of the components of the liquidation processes. This indicator shows the distance of the analysed branch from the hypothetical branch with the most optimal parameters from the examined group of 17 branches. In the applied transformation, the analysed parameters should be classified into groups according to their nature. In this method, the analysed parameters were divided into "stimulant – the increase in value of which is perceived positively, "destimulant" – the increase in value of which is perceived negatively, and "nominant – the increase in value is perceived positively or negatively. In the examined example, all tested parameters are costs for which the increase is perceived negatively; therefore, the costs are assigned as the character of the "destimulant". In the multi-criteria analysis, each of the examined parameters is assigned as the weight that influences the overall result. In this case, it was assumed that each of the examined costs is equally significant and all costs were given a factor of one. Moreover, it was also found that further research will require assigning an appropriate weight to each of the costs. However, this will not affect the principle of operation of the method of the estimation of mining plant liquidation costs.

The applied transformation quotient method eliminates the problem of possible difference between the units of the analysed parameters and the absolute size of the numbers describing individual parameters by locating the obtained values of individual parameters as a dimensionless number in the range from 0 to 1. The value of the liquidation cost of a branch in the multi-criteria analysis for all the "destimulant" features, and assuming that the weights for all costs are equal to one, can be calculated according to the Equation (3):

Equation 3:

$$FC_{j\ min} = \sum_{i=1}^{10} \frac{h_{i\ min}}{h_{ij}}$$

where: $FC_{j\ min}$ is the liquidation cost of the branch *"j"* in a multi-criteria approach, *i* is the number of the mine liquidation component process, *j* is the number of analysed branch, $h_{i\ min}$ the lowest cost value in the process "i", and h_{ij} is the liquidation cost in the process *"i"* for the branch *"j"*. Sorting branches according to the multi-criteria "cost minimisation" gave much worse results than the previous sorting according to the amount of the total liquidation cost. The average coefficient of cost variation was as high as 55.25% (**Table 5**).

For checking purposes, calculations were made where the costs were treated as "stimulants" and the branches were sorted according to the "cost maximisation". This method of sorting revealed the optimal variant of grouping branches. When all parameters are "stimulants" and assuming that the weights for all costs are equal to one, the multicriteria evaluation using the quotient transformation is Equation (4):

Equation 4:

$$FC_{j\ max} = \sum_{i=1}^{10} \frac{h_{ij}}{h_{i\ max}}$$

where: $FC_{j\ max}$ is the liquidation cost of the branch *"j"* in a multi-criteria approach, *i* is the number of the mine liquidation component process, j is the number of analysed branch, $h_{i\ max}$ the highest cost value in the process *"i"*, and hij is the liquidation cost in the process *"i"* for the branch *"j"*.

In the proposed division into four groups (**Table 6**), the average coefficient of variation is 28.89% and only the group of Small Branches differs significantly from the other groups. It was found that B17 differs from the rest of the group of Small Branches (SB) by more than three times of the amount of standard deviation. Because of that fact a Micro Branch (Micro B) was created as an additional fifth group that includes only one branch. After the exclusion of Branch 17 from the group of Small Branches (SB), the average coefficient of variability of the costs of the liquidation of branches in the analysed groups decreased to 21.99%. On the basis of the conducted analysis, it was found that when selecting the method of sorting branches, the average coefficient of variation of total costs and the average coefficient of variation of the multi-criteria value of costs, calculated as the average value of these values, should be taken into account. This allows for the combination of optimisation of costs and the structure of these costs. The calculated average variation index for the previous divisions confirmed that the optimal variant of the division is the division into five groups in accordance with the "cost maximisation" (**Table 7**).

Table 7: Multi-criteria analysis "costs maximisation" (5 groups).

Branches	LB (above 4.0)	MLB 1.25 to 4.0)	MSB (1.25 to 2.5)	SB (0.6 to 1.25)	Micro B (to 0.6)
CV	21.43%	22.15%	22.62%	21.75%	
MA	1.41%	13.38%	19.16%	14.07%	
Average CV		21.99%	Average CV and MA		17.76%

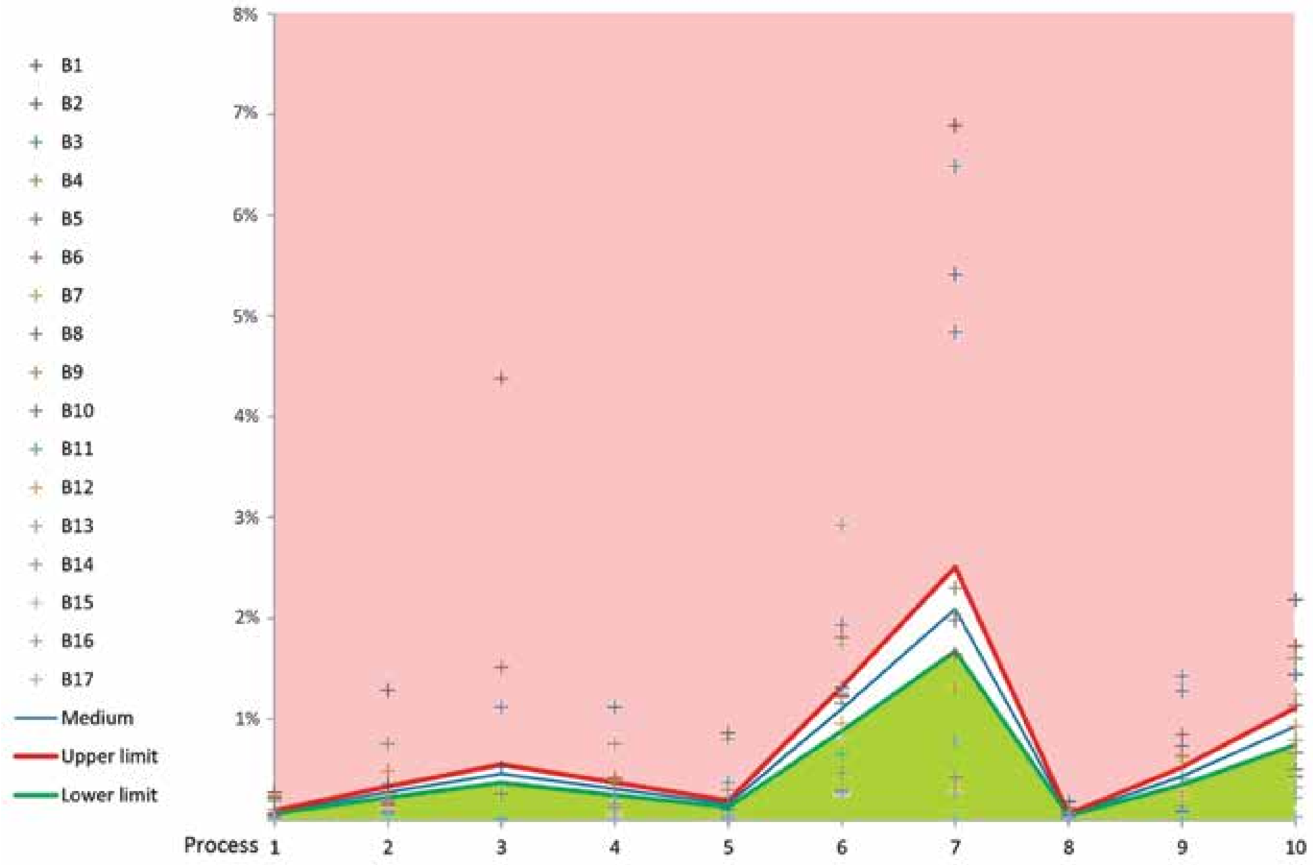

Figure 3: The idea of the assessment method of the correctness of the cost-estimation of mine liquidation processes.

INSERT Compl. Coeff.	INSERT Cost	EVALUATE IN GROUP Processes	ALL	Mikro Branches
20%		Process 1 (liquidation of excavations)	0.000	0.000
20%		Process 2 (liquidation of shafts and pits)	0.000	0.000
20%		Process 3 (securing of neighbouring mines)	0.000	0.000
20%		Process 4 (liquidation of area facilities)	0.000	0.000
20%		Process 5 (land reclamation)	0.000	0.000
20%		Process 6 (maintenance of facilities above)	0.000	0.000
20%		Process 7 (securing of liquidated mine)	0.000	0.000
20%		Process 8 (projects, expertise, etc)	0.000	0.000
20%		Process 9 (mining damage)	0.000	0.000
20%		Process 10 (general management)	0.000	0.000
20%		**Total**	**0.000**	**0.00**

Figure 4: Screenshot of the liquidation costs assessment tool.

On the basis of the obtained division into reference groups of values, a tool for the assessment of the amount of mine liquidation expenditures was proposed. The method signals deviations in the amount of costs for the total cost and the cost division into individual component processes. **Figure 3** presents the idea of the assessment method against the entire population of analysed liquidation examples. Most of the costs are outside the zone of acceptable values (white field between the green and red lines), and therefore the division into reference groups was made. The range of acceptable values results from the coefficient of variation established by the user, for which the standard deviation is calculated. The lower limit (green line) is determined by the mean value decreased by the calculated standard deviation, and the upper limit (red line) is determined by the mean value increased by the same value (**Figure 3**). So as to illustrate the method, it was assumed that the acceptable deviation would result from the adopted variability index equal to 20%. This is the upper limit for a high match population.

EVALUATE IN GROUP	All	Large Branches
Processes	%	%
Process 1 (liquidation of excavations)	0.004	0.004
Process 2 (liquidation of shafts and pits)	0.007	0.007
Process 3 (securing of neighbouring mines)	0.011	0.011
Process 4 (liquidation of area facilities)	0.022	0.022
Process 5 (land reclamation)	0.002	0.002
Process 6 (maintenance of facilities above)	0.026	0.026
Process 7 (securing of liquidated mine)	0.109	0.109
Process 8 (projects, expertise, etc)	0.004	0.004
Process 9 (mining damage)	0.026	0.026
Process 10 (general management)	0.044	0.044
Total	**0.255**	**0.255**

Figure 5: Assessment of the hypothetical branch B18 with twice value of the liquidation cost of branch B2.

EVALUATE IN GROUP	All	Small Branches
Processes	%	%
Process 1 (liquidation of excavations)	0.000	0.000
Process 2 (liquidation of shafts and pits)	0.001	0.001
Process 3 (securing of neighbouring mines)	0.000	0.000
Process 4 (liquidation of area facilities)	0.001	0.001
Process 5 (land reclamation)	0.000	0.000
Process 6 (maintenance of facilities above)	0.005	0.005
Process 7 (securing of liquidated mine)	0.004	0.004
Process 8 (projects, expertise, etc)	0.000	0.000
Process 9 (mining damage)	0.001	0.001
Process 10 (general management)	0.004	0.004
Total	**0.016**	**0.016**

Figure 6: Assessment of the hypothetical branch B19 with minimal value of the liquidation cost of Medium Larger Branches (MLB).

EVALUATE IN GROUP	All	Medium Smaller
Processes	%	%
Process 1 (liquidation of excavations)	0.000	0.000
Process 2 (liquidation of shafts and pits)	0.001	0.001
Process 3 (securing of neighbouring mines)	0.000	0.000
Process 4 (liquidation of area facilities)	0.001	0.001
Process 5 (land reclamation)	0.001	0.001
Process 6 (maintenance of facilities above)	0.006	0.006
Process 7 (securing of liquidated mine)	0.009	0.009
Process 8 (projects, expertise, etc)	0.000	0.000
Process 9 (mining damage)	0.007	0.007
Process 10 (general management)	0.007	0.007
Total	**0.032**	**0.032**

Figure 7: Assessment of the hypothetical branch B20 with average values of the liquidation cost of Medium Smaller Branches (MSB).

DISCUSSION

In the proposed method, the potential user enters the estimated liquidation costs for individual liquidation processes (fields marked as bright green in **Figure 4**) and enters the value of the coefficient of variation for each of the processes and for the total liquidation cost (fields marked pink). The software immediately informs in which reference group the analysed case is. The blue field displays the name of the reference group (**Figure 4**). In this column, the obtained costs are compared to the average for each process and for the total liquidation cost in this reference group. When the entered cost exceeds the upper limit of the acceptable value, the field and digits turn into red. When the cost is below the lower limit of the acceptable value, the field and digits turn into green. Additionally, when the entered cost significantly (by more than three standard deviations) exceeds the lower or upper limit, the adjacent field turns into red. It was also proposed to signal the field in yellow, so as to take into account the fact of not incurring costs in a given process. The signaling of the deviation from the average value does not have to mean an error. Any deviation may result from the specificity of the liquidated branch and it is a place for the user's decision. For comparison, the costs entered by the user are analysed in the same way for the entire population of the liquidated coal mines, which may additionally reassure the

EVALUATE IN GROUP	All	Medium Larger
Processes	%	%
Process 1 (liquidation of excavations)	0.000	0.000
Process 2 (liquidation of shafts and pits)	0.001	0.001
Process 3 (securing of neighbouring mines)	0.011	0.011
Process 4 (liquidation of area facilities)	0.008	0.008
Process 5 (land reclamation)	0.004	0.004
Process 6 (maintenance of facilities above)	0.018	0.018
Process 7 (securing of liquidated mine)	0.021	0.021
Process 8 (projects, expertise, etc)	0.001	0.001
Process 9 (mining damage)	0.001	0.001
Process 10 (general management)	0.016	0.016
Total	**0.081**	**0.081**

Figure 8: Assessment of the hypothetical branch B21 with random values of the liquidation cost of Medium Larger Branches (MLB).

designer to the correctness of the estimated liquidation costs.

Currently, there are no actions that are going to provide negotiations so as to take over next branches to liquidate. Therefore, in order to verify the proposed method, a hypothetical takeover of four branches with working names: B18, B19, B20, and B21 was proposed. The first of the proposed branch is B18 with the value of component costs equal to twice of the liquidation costs of B2, with the highest cost in terms of multi-criteria attempt. The estimated cost of liquidation of B18 amounted to as much as 25.51% of the total costs incurred by SRK S.A. for the liquidation of analysed 17 coal mines. B19 is another branch with the estimated amount of liquidation costs (1.64% of the total cost) equal to the minimum values for the group of Medium Larger Branches (MLB). B20 is a branch with costs equal to the average costs for the group of Medium Smaller Branches (3.36% of the total cost). The last of the hypothetical branches is B21 of which the liquidation costs were assumed as random values from the group of Medium Larger Branches (MLB), which amounted to 8.07% of the total cost.

As expected, B18 was analysed in its upper part in the group of Large Branches (LB), in the case of four processes caused the signaling of exceeding the mean value, and in the comparison group, as many as six processes (**Figure 5**). Such reaction of the method was expected because the cost of liquidation of such a branch could be extremely high. In the case of process 3 (securing the neighboring mines) and process 5 (land reclamation), the software signaled an underestimation of expenses for the branch of this size. The prototype of the analysed B18, branch B2 in this respect incurs extremely low expenditures.

The second of the analysed branch is called B19. Despite the fact that the data was collected from the group of Medium Smaller Branches (MSB), it is qualified for the group of Small Branches (SB) in its central part (**Figure 6**). The method showed that processes 7 and 8 are below the average in this reference range, with the cost of process 8 only slightly above the upper limit of the limit. Process 2 showed a slight underestimation, while process 6 was well below the average. Figure 7 shows the analysis of the hypothetical branch B20 with average values of the liquidation costs of Medium Smaller Branches (MSB).

The analysis of costs of B20 also resulted in the expected reaction of the method. In this case, all the fields of liquidation components costs remained unresponsive to the method (**Table 6**), which was a reaction to the analysis of the reference example.

The biggest challenge for the methodology of assessment of liquidation costs was the analysis of the last case of B21 (**Table 7**), which was characterised by costs randomly selected from the group of Medium Larger Branches (MLB). This branch was situated in the upper zone of its reference group. The difficulty in assessing such a "creation" results from a very unbalanced cost structure. Some of them come from the group of more capital-intensive branches, and some from much less, so the amount of costs incurred and the arrangement of the colors of the fields in different colors may be a bit confusing for a practitioner dealing with the liquidation of mines. **Figure 8** indicates the assessment of the hypothetical branch B21 with random values of the liquidation costs of Medium Larger Branches (MLB).

In this case, the method procedure worked properly and the signaling of deviations from the mean value is in line with the experts' opinion. In the second stage of the tool verification, the evaluation of the same variants by practitioners was convergent and the method of response was accepted.

CONCLUSIONS

Coal mine closure processes are being carried out in the European Union due to the current energy transition. A new economic tool has been developed to analyze the coal mine liquidation costs. The proposed method of the assessment of estimated cost of the mine liquidation can be used as a reference point for detailed analysis and multi-criteria cost planning. The system of accounting for the costs of liquidation component processes is typical for SRK S.A. In addition, with some modifications the proposed methodology can also be applied by another entity dealing with liquidation. The presented cost assessment procedure may facilitate the monitoring of conducted activities in terms of rationalisation and minimisation of the costs incurred. The proposed tool may be one of the components introducing the process approach in the field of effective liquidation of coal mines, which is particularly important in a situation where the scientific literature in this area is extremely scarce.

In order to protect the sensitive data at work, the actual costs incurred have been converted into a fraction of the total costs of liquidation. A similar analysis was carried out for the value expressed in money and converted to the total cost of the process, as well as to the maximum cost of liquidation of the branch. Due to the volume of the work, these results have not been included. The same results were obtained in all cases, which may prove the correctness of the proposed method.

Finally, the proposed method for assessing the cost of mine liquidation is understand- able, simple, and easy to use for applications in preliminary design works and ongoing engineering works.

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