International Society for Rock Mechanics and Rock Engineering
Norwegian Group for Rock Mechanics

ISRM International Symposium
Eurock 2025 – Expanding the Underground Space
Trondheim, Norway, 16-20 June
ISBN 978-82-8208-079-8

Are we in the Golden Age of numerical modelling?

J. Vatcher
Sweco Sverige AB, Sweden
jessa.vatcher@sweco.se

Abstract

A Golden Age is often defined as time of prosperity, production, achievement, creativity, and political stability. Can we describe the current state of numerical modelling in rock mechanics as a Golden Age? The art of numerical modelling has seen many advancements and innovation in recent times. Modellers are now able to look deeper at questions the branch has long posed, moving our fundamental understanding of rock mechanics forward. A review of state-of-the-art modelling tools, techniques, and frameworks shows how complex situations are being investigated by engineers and researchers, leading us to well-suited solutions. From microscopic to mine scale, modellers are pushing the boundaries of modern rock engineering. Case studies are presented to highlight successful applications of these innovations in mining, tunnelling, and geomechanical engineering. By examining current trends and future directions, let us discuss the potential of numerical modelling as a cornerstone for solving contemporary challenges in rock mechanics. Ultimately, readers are invited to ponder whether we are indeed in a Golden Age of numerical modelling, characterized by unparalleled opportunities for research and practical applications in rock engineering.

Keywords

Numerical modelling, innovation, trends

ISRM

NBG

1 Introduction

The field of numerical modelling in rock engineering has evolved rapidly over the past decade. But have we truly entered the 'Golden Age' of this transformative technology? A Golden Age is defined as time of prosperity, production, achievement, creativity, and political stability. Rock engineering is a fantastic field, with many challenges and opportunities to push the boundaries of our knowledge. Empirical and analytical design techniques are well developed, and very useful for problems that are suited to the underlying data set and methods. Within the field of rock engineering, we are, however, pushing the boundaries of these design methods. We are seeing deeper mines, more seismic behaviour, wider spans in underground infrastructure, underground infrastructure that is being fit into small spaces near existing infrastructure, and underground spaces that are designed to last for centuries with very specific design criteria (such as transmissivity restrictions). Simultaneously, we are in the exciting age of generative AI, a new release of Eurocode that focuses heavily upon probabilistic analyses and defining risk, and ever-increasing computational capability. Arguably perfect conditions for innovation within numerical modelling.

Rock engineering is an important discipline for our future, and we need to have a good understanding of our toolkit and what trends are happening so we as practitioners can offer great solutions. Solutions that will help us address complex rock engineering challenges, meet and exceed new design criteria, and are safe and contribute to a more sustainable world. This paper explores the question of being in the Golden Age of numerical modelling in rock engineering by lifting some of the recent innovative work of practitioners in the field and by looking at recent trends in publications.

2 What is numerical modelling?

Before we discuss innovation in numerical modelling, let us go back to basics. What is a numerical model? It’s quite possible, perhaps even likely, that asking that deceptively complex question to *n* practitioners would result in at least *n + 1* answers. I’ve had the privilege of working with many beautiful minds on the subject, and would offer the following considerations about what numerical models are:

- A representation of reality
- A simplification of reality
- One of many tools in our toolbox
- A place to test assumptions and hypotheses
- A tool to help us understand rock behaviour
- A tool to help us push boundaries of knowledge and design

Numerical methods have been used in rock engineering for decades. For an excellent overview of numerical methods in rock engineering, see Starfield and Cundall (1988) and Jing and Hudson (2002). But in essence, while the algorithms differ and each method has its benefits and drawbacks, the modelling process is the same.

The definition of numerical models as a simplification of reality and a place to test assumptions and hypotheses are, in the author’s opinion, integral to the numerical modelling process. Practitioners need to have an idea of what behaviour to expect from the rock to make decisions in the numerical modelling process that will result in representative behaviour. There are many decisions that practitioners must make during the numerical modelling process that significantly influence results, including:

- Numerical method
- Continuum or discontinuum
- Balance between explicit and implicit representation of damage
- Geomechanical domains to include in the model
- Selection of constitutive models that are representative
- Selection of representative rock(mass) properties
- Selection of representative initial stress field(s)
- Excavation geometries to include and their level of detail
- Zone sizes and gradients

With so much influence over the end result, it is reasonable to ask, why use numerical modelling if we as practitioners are steering the result so much? The answer lies in complexity and testing hypotheses. While we need to made decisions during the modelling process to get representative rock(mass) behaviour, interactions of system components are often too complex to understand *a priori*. Using numerical modelling as a tool to test hypotheses enables better system understanding and enables the art of engineering with informed design decisions. Numerical modelling is particularly well suited to questions such as, *"What's influencing rock behaviour here?"* and *"What happens if…"*

3 External trends: favourable for numerical modelling?

To answer the question, *"are we in the Golden Age of numerical modelling?"* we need to understand the external trends that can create a favourable environment for innovation and growth.

The mining industry has long lead times between deposit discovery and production, and new deposits have a conversion rate (from discovery to mine) of approximately 50 - 80%. It is becoming increasingly difficult to open new mines. (Manalo 2023; Schodde 2017) Demand for mined products is increasing, and many mines are resulting to increasing production. There is a preference towards bulk mining, with high production rates and low tonnage costs. This larger volume of ore being produced means greater rock engineering challenges in the form of deeper mines with greater demand for larger stopes and long-lasting infrastructure (in the case of bulk mining). Mines are also located in geologically complex environments. These trends lead to challenging rock behaviour, including seismicity, rockbursting, and squeezing. All of which have significant gaps in the literature linking measurable properties, constitutive models, numerical modelling techniques, and post-processing of numerical modelling results to behaviour. A Google Scholar search for *"seismic* + mine"* from 2024 to today results in 17 000 publications; "*rockburst* + mine*" during the same time period in almost 3 500 publications. There is both the need and opportunity for great innovation and growth of numerical modelling in the mining industry.

Rock engineering infrastructure projects, such as tunnels, are becoming more complex. Many urban centres have a pre-existing abundance of underground infrastructure, often used for public transportation. With increased urban population growth in combination with the increased understanding of the importance of sustainability, the demand for underground city infrastructure is increasing. We are seeing more projects being undertaken where rock infrastructure is near other tunnels or buildings, where we need to quantify and control the influence of the new excavations. We are also seeing underground infrastructure projects that have extreme spans, such as Västlänken project in Göteborg, Sweden. Since these types of challenges are new and very dependent upon the 3D geometry in relation to the geomechanical environment, empirical design applicability is limited. Gaps in the literature exist concerning rock fracturing and damage and even the interaction of rock support, which are important questions in these relatively low-stress environments with these specific challenges. There is a need for numerical modelling, and innovation will be important to understand and solve these challenges.

We as rock engineers live in a very exciting time. We have the opportunity to lead the development of underground storage facilities for spent nuclear fuel, where the design life of facilities is thousands of years. This is an important part of contributing to a more sustainable future. There are multiple organizations across the world leading this work, where Svensk Kärnbränslehantering AB (SKB) is one of them. Rock engineering challenges include rock damage and transmissivity, quantifying the effects of data uncertainty and variability, and the long design life. These challenges are outside of empirical and analytical design techniques and require innovation in numerical modelling to solve them.

The explosion of artificial intelligence (AI) into our daily lives has forever changed the way we work, play, and live. Significant AI market growth is expected in 2025 with 83% of businesses surveyed saying that AI is a top priority. (AI Statistics 2025) The importance of AI to the future rock engineering and numerical modelling cannot be understated.

The rock engineering challenges we face in combination with technological advancements (specifically AI) provide an environment that will stimulate innovation in numerical modelling. Considering the definition of a Golden Age, production, achievement, and creativity will be required to solve the challenges ahead of us.

4 Recent publication trends

Trends in publications have the potential to give us insight on the evolution, priorities and directions of numerical modelling in rock mechanics. Publications from approximately the past 5 years have been used in this analysis. Google Scholar was used to evaluate general publication trends. Specific conferences within our field were selected, and trends between numerical modelling the latest proceedings and the previous proceedings were evaluated.

The author considers this to be an initial analysis, with much room for future expansion. Additionally, the analysis leans more heavily on publications in rock mechanics from the mining industry, due to the author's personal background and availability of conference publications. Search terms were evaluated for relevancy to the intended topic.

During the past five years, the number of publications on numerical modelling in rock mechanics peaked in 2022 using the search term *"+numerical +model* +rock +stress"* (see bars in Fig. 1). The scope of these publications is quite broad, including large scale models, small scale models, fracture and damage mechanics, dynamic models, coupled models, and even flow models (thermal and water). 2025 data offers preliminary trends for the year, as data was collected in late February.

Specific search terms were added to *"+numerical +model* +rock +stress"* to evaluate trends in topics. The trend in the topic was evaluated as a percentage of the total number of publications in numerical modelling in rock mechanics (see bars in Fig. 1). Overlaid as lines in Fig. 1 are the recent trends for the terms artificial intelligence and sustainability. Numerical modelling publications mentioning sustainability have been steadily increasing since 2020. From 2022 the number of publications that discuss artificial intelligence has skyrocketed, with 42% of publications in 2024 mentioning AI.

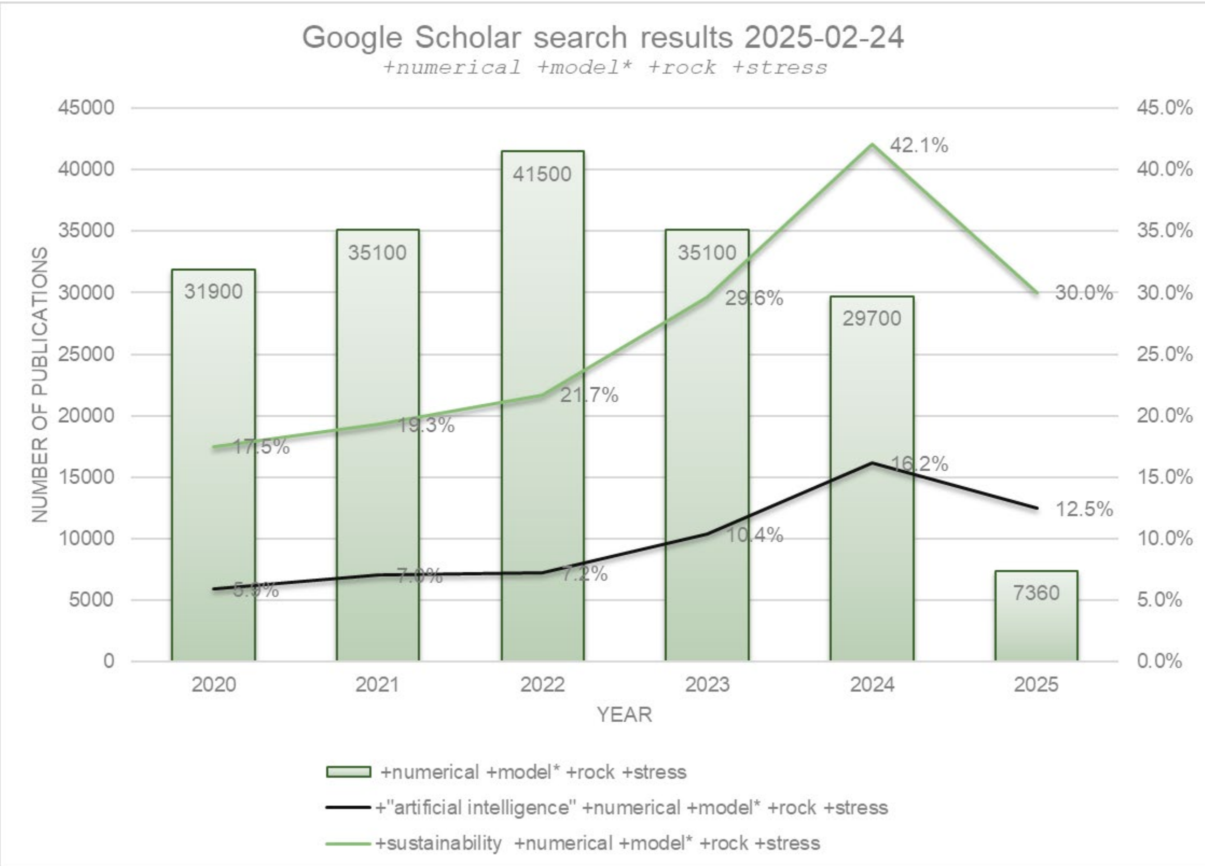

Fig. 1 Number of publications by year from Google Scholar search 2025-02-24.

Interestingly, the number of publications that speak about mines, tunnels or slopes increases at approximately the same rate, with maximus in 2024 (see Fig. 2 left). Trends of the words "validated" and "calibrated" are presented in Fig. 2 right. As a practitioner who values models as a representation of reality, I am pleased to see the strong increase in model validation discussions since 2022. The word validation implies that models were compared to actual behaviour. Calibration has also seen an increase in publications since 2022. Calibration tends to imply a more iterative approach and is often used when speaking of material properties and experimental results. The author interprets these trends as an increase in publications attempting to solve practical problems.

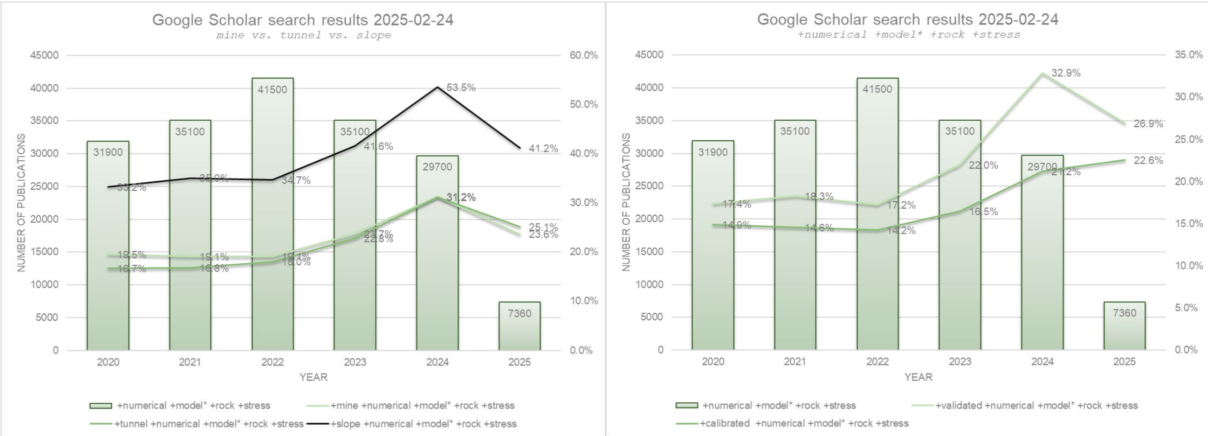

Fig. 2 Publication trends mines, tunnels, and slopes (left) and publication trends validated and calibrated (right).

Popular technical trends include damage and support. Many of the articles discuss both topics, and their presence is increasing (see Fig. 3 left). Fig. 3 right illustrates the trends of more specific technical topics, which, in the opinion of the author, will become more important in the future. These include discrete fracture networks (DFNs), hydraulic fracturing, bonded block modelling (BBM), and mine seismicity. While hydraulic fracturing is clearly the most popular of these niche topics, all of them have seen slight increases in the past two years. These niche topics require much innovation in numerical modelling.

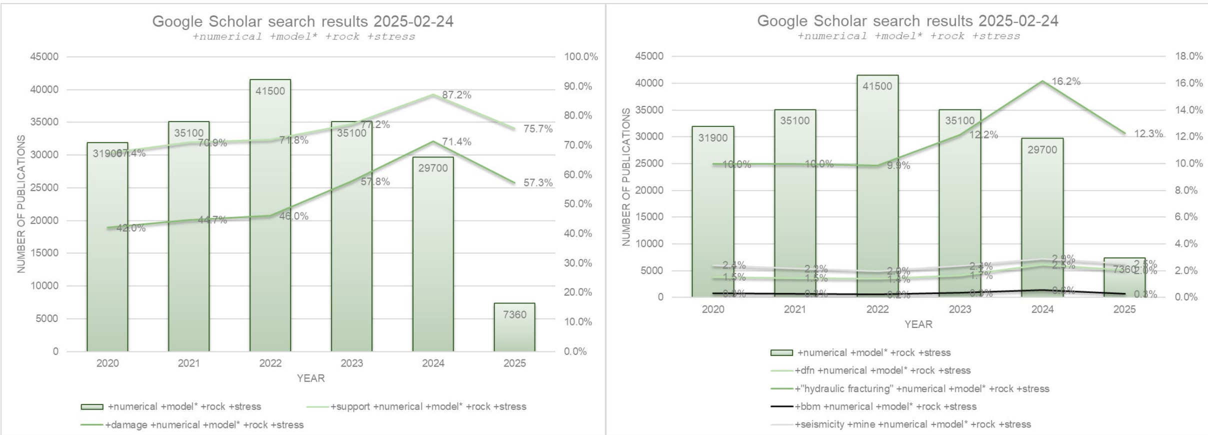

Fig. 3 Publication trends damage and support (left) and publication trends DFN, hydraulic fracturing, BBM and mine seismicity (right).

Conferences are an important source of information for numerical modelling in rock mechanics, as it is often the venue where practical yet innovative work is published. Numerical modelling in rock mechanics is lucky to have two major software companies which hold symposia, Itasca and Rocscience. Proceedings from the most recent (Jim Hazzard et al. 2024; Reginald E. Hammah et al. 2023) and the previous conference (Daniel Billaux et al. 2020; Hammah et al. 2022) were evaluated to identify trends. Additionally, conference proceedings from some relevant mining conferences were used, where articles on numerical modelling articles were extracted from the proceedings. Conferences evaluated include Deep Mining (Patrick Andrieux and Daniel Cumming-Potvin 2024; The Southern African Institute of Mining and Metallurgy 2019), Ground Support (Hadjigeorgiou and Hudyma 2019; Wesseloo 2023), MassMin (Castro et al. 2020; Johansson and Schunnesson 2024), and Slope Stability (Dight 2023; 2021). These were selected as the mining branch is one that often publishes interesting work in conference proceedings, and proceedings are readily available online. Fig. 4 shows a world cloud for the conference proceedings. Words of note include: stress, strength, shear, strain, fracture, soil, seismic, and time.

Fig. 4 Word cloud representing frequency of words in the numerical modelling conference papers.

Text analysis was completed using Voyant Tools (Sinclair and Rockwell 2025) on the numerical modelling articles from the previous and latest proceedings to identify trends. Key words evaluated are grouped into major topics to illuminate changes to the focus of publications. Images show the relative frequency of keywords between the two sets of proceedings. The proceedings are mining skewed (see Fig. 5 left). Evaluation of the types of mining infrastructure mentioned shows that we are most often modelling stopes, and that stopes, shafts, and intersections have become more problematic (since they are mentioned more often).

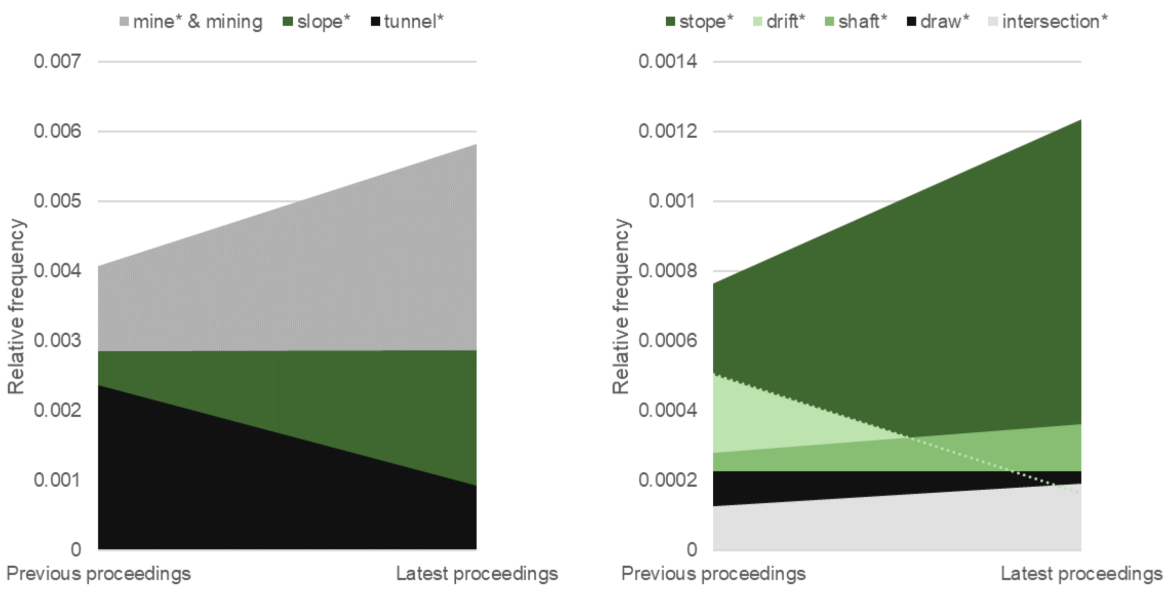

Fig. 5 Relative frequence of keywords from the previous to the latest proceedings analysed. Left shows type of design (mining, slopes, tunnels), where the publications are significantly mining skewed. Right shows what type of mining infrastructure is mentioned most frequently in the publications.

The relative frequency of stress and strength remains essentially constant between the two points in time. Interestingly, stress is mentioned more than strength (see Fig. 6 left). What are we discussing about strength then? Fig. 6 right shows that the focus of the geomechanical and geological understanding of the rock (mass) is changing. The relative frequency of structures and geology is increasing at a high rate. GSI and classification are being mentioned slightly more in the latest conference proceedings. Laboratory and DFN are mentioned significantly less in the latest conference proceedings than the previous proceedings.

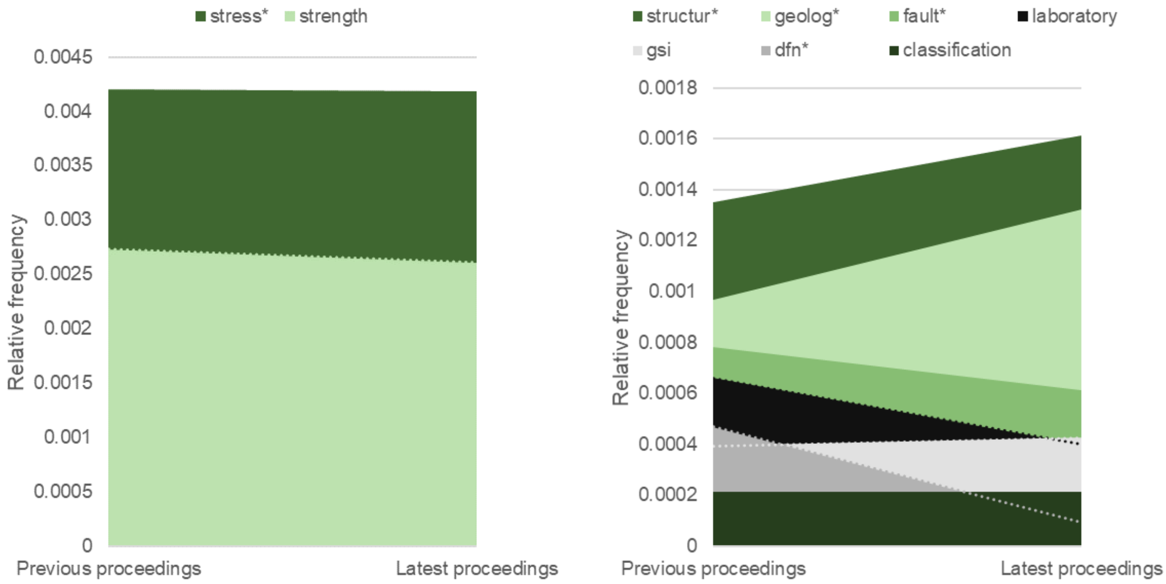

Fig. 6 Relative frequence of keywords from the previous to the latest proceedings analysed. Left shows frequencies of stress and strength. Right shows changes to data related to rock mass strength.

The keywords shown in Fig. 7 are related to two problem areas in rock mechanics: 1. Seismicity and brittle behaviour (left), and 2. Fracture mechanics and damage (right). Seismicity is of significant more focus in the latest proceedings than in the previous proceedings. Interestingly, in the time between the two sets of proceedings the numerical analysis focus about how to solve this problem may have changed. In the previous proceedings, plasticity was mentioned more often than energy. However, in the latest proceedings, energy is the clear focus.

While words related to damage have gained slightly more focus, words related to fracturing have significantly decreased (see Fig. 7 right). One of the most popular particle modelling codes in rock mechanics (Itasca's PFC) declined in popularity in the latest proceedings, while another technique to model fracturing processes (BBM) increased. BBM can be applied using Itasca's PFC or Itasca's 3DEC. Mentions of BBM increased so much that it's relative frequency in the latest proceedings was higher than that of PFC.

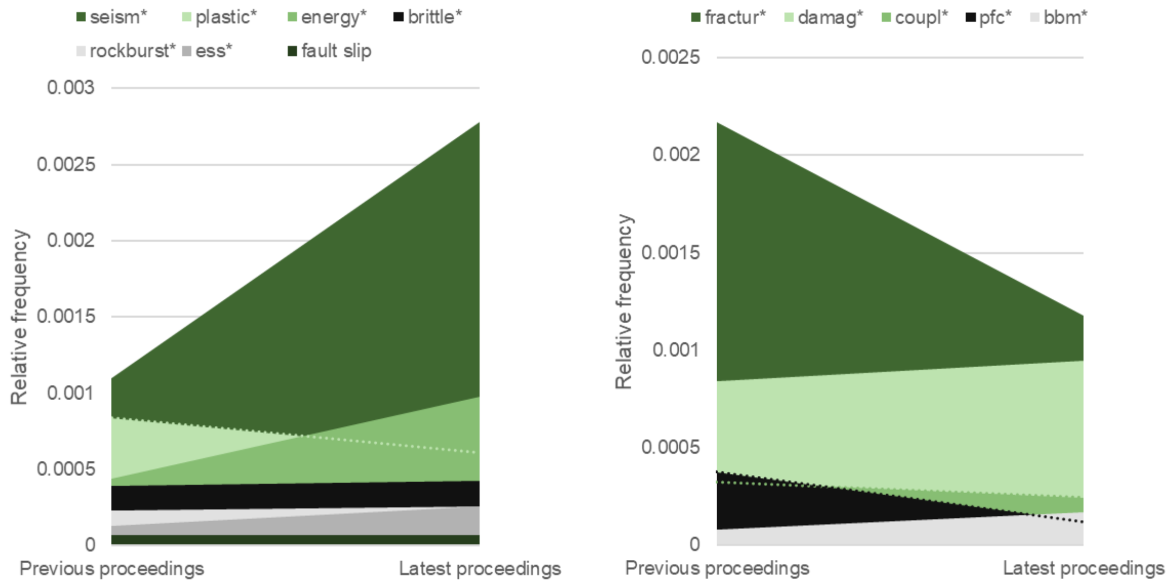

Fig. 7 Relative frequence of keywords from the previous to the latest proceedings analysed. Left shows changes in keywords related to seismicity and brittle behaviour. Right shows keywords related to damage mechanics.

Much like the trends seen using Google Scholar, both AI and sustainability are mentioned more frequently in current proceedings, and AI is gaining more traction than sustainability (see Fig. 8).

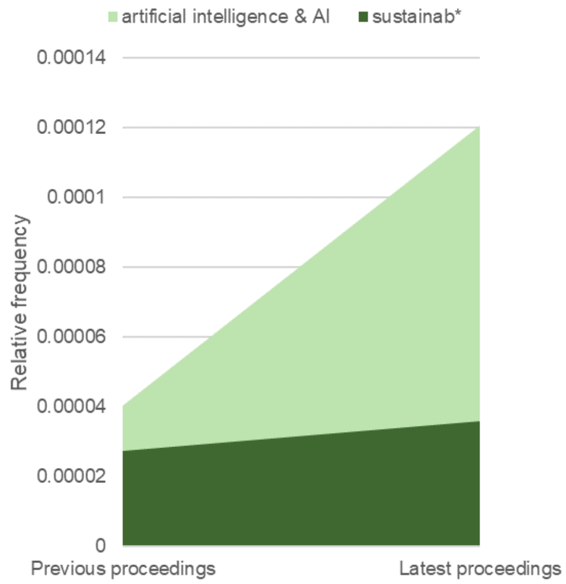

Fig. 8 Relative frequence of keywords from the previous to the latest proceedings analysed. Focus on external trends, AI and sustainability.

There are many interesting trends in recent publications in numerical modelling in rock engineering. General trends from Google Scholar analysis tend to highlight research institutions and universities, whereas the trends from the conference proceedings tend to highlight contributions from academia and industry alike. Text analysis of the articles from proceedings provided interesting insights about changes in focus. Increasing in focus are large scale infrastructure such as stopes, structures and geology, seismicity and energy, BBM, sustainability and AI. Interestingly, DFN's are losing popularity in conference proceedings but gaining slightly in Google Scholar's databases. Trends in publications certainly show development and productivity typical of a Golden Age, and there are plenty of ways in which rock mechanics is developing through time.

5 Innovative examples

There are so many great examples of interesting and useful numerical modelling work. An exhaustive account of innovative examples is beyond the scope of this paper. However, a few inspiring recent examples are offered along with an invitation to read deeper.

Part of what is enabling innovation in numerical modelling are capabilities that have been added to the two major software providers within rock engineering: scripting capabilities. The inclusion of scripting languages, such as python, allowing for automation of model running and pre- and post-processing is integral for our productivity.

A fundamental understanding of fracture mechanics and damage is necessary for practitioners working with numerical modelling. Rock damage is of interest within different fields, for potential correlation with many of the trends gaining popularity in publications, such as stability, seismicity, hydraulic fracturing, spalling, and transmissivity. While small-scale damage mechanics is not a solution to every problem, work in this field increases our understanding, helping us build simplified models that capture realistic behaviour. For purposes of this paper, small scale is defined as modelling typical lab tests.

Many excellent practitioners are working with fundamentals at the grain scale such as the effect of grain shape (Bai, Zhang, and Konietzky 2024) and the effects of hetereogenetiy in grain boundaries (X. Hu et al. 2024) with bonded particle models. The use of rigid, breakable Voronoi-shaped grains connected by a Subspring Network has shown very promising results when representing laboratory scale behaviour in 3D, with the intention of representing brittle behaviour such as spalling (see Fig. 9). (D. Potyondy and Fu 2024; D. Potyondy and Purvance 2024) Grain scale modelling of dynamic laboratory tests has shown interesting results for dynamic rupture and acoustic emissions. (W. R. Hu et al. 2023) Parallel to these bonded particle model techniques is exciting research using BBMs, where grain (block) contacts are explicitly modelled. BBM work at the laboratory scale is also exploring grain shape and fundamental controlling factors. (West and Walton 2023; Inga et al. 2023) West et al. (2024) present one interesting application of BBM, where models were used as to test the effect of joints and properties on specimen behaviour. These techniques and the exploration of the fundamentals will be critical to modelling complex rock behaviour at larger scales.

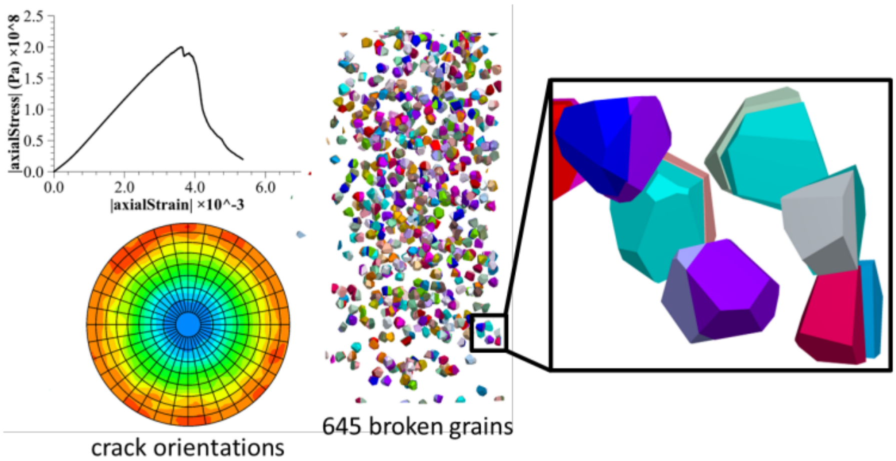

Fig. 9 Image with Subspring Network Breakable Voronoi grain (bonded particle model) numerical model's stress-strain curve, broken grains and crack orientations on a stereonet. From (D. O. Potyondy and Purvance 2024).

In fact, both bonded particle models and BBM techniques are already being applied and tested on larger scale problems. Hamediazad and Bahrani (2024) present interesting BBM models for brittle mine pillars, where they used combinations of different block and contact constiutitve models calibrated to pillar behaviour (see Fig. 10). From there they investigated rock mass strength. This technique could be particularly powerful to speed up future modelling of the rock mass, by improving the quality and reliability of continuum modelling. Ghazvinian et al. (2023) published very interesting BBM work where forecasting complex 3D interaction between block caving draw points.

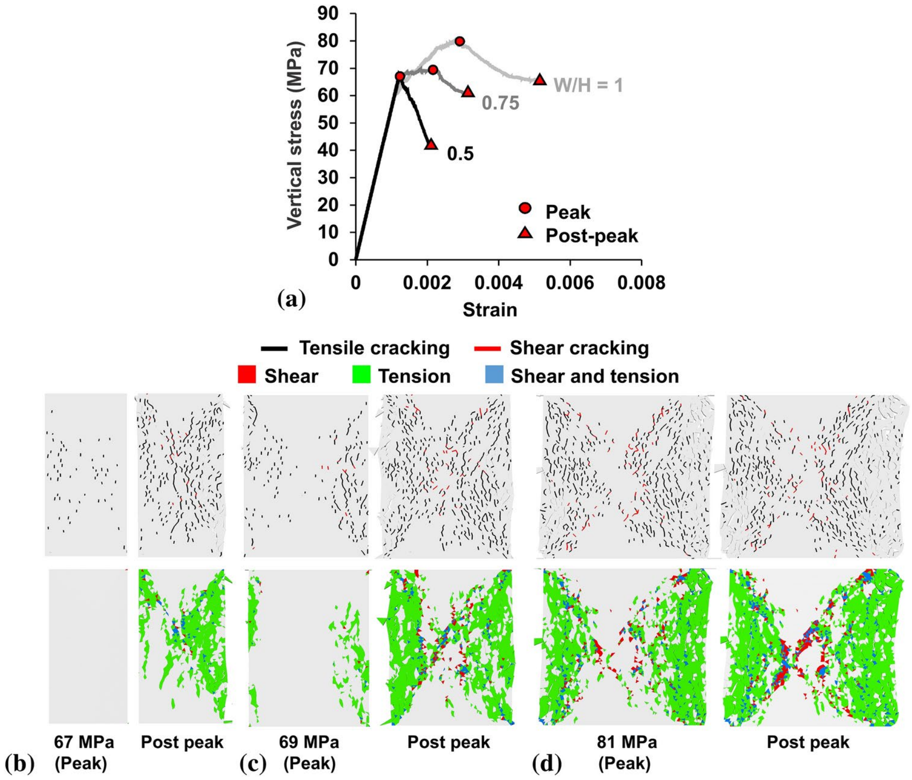

Fig. 10 BBM model focusing on pillar behaviour, from (Hamediazad and Bahrani 2024).

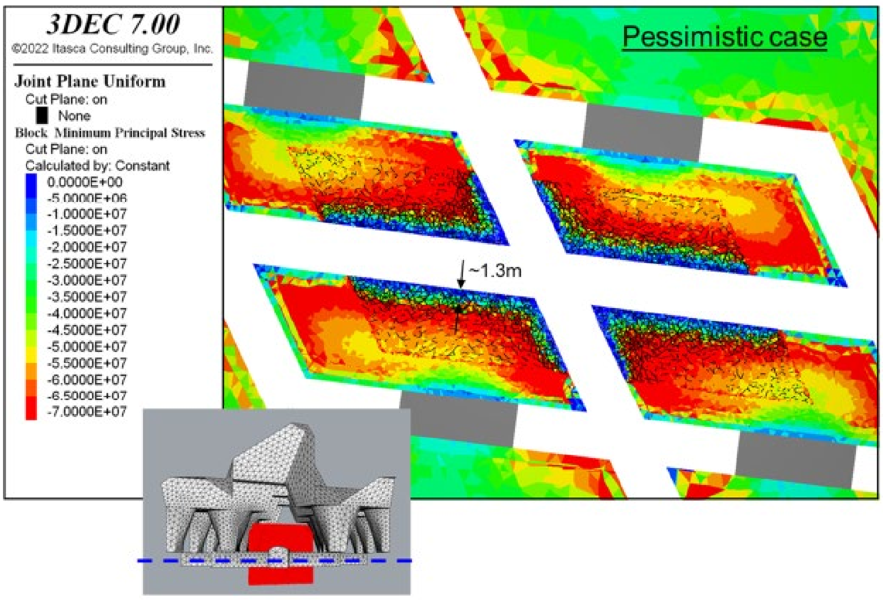

Fig. 11 BBM model showing forecasted damage in intersections near drawbells, from (Ghazvinian et al. 2023).

Although showing signs of less popularity in current conference proceedings, it is the opinion of the author that DFNs are very important to the future of rock mechanics. Fracture networks at different scales often control rock behaviour. The importance of the DFN parameters on the stress field was shown very clearly by Lavoine et al. (2024). If we expect to model realistic rock mass behaviour and understand the possible futures we might encounter, we likely need to model realisations of the fracture network.

Trends showed an increase in publication about seismicity and numerical modelling. One particularly innovative idea is presented by Lachenicht et al. (2024). Plastic work was calculated using numerical models for the rock mass and discontinuities, representing progressive degradation. The system strength was evaluated by progressively reducing the strength. Spatial and temporal correlations of the progressive degradation, system strength and observed seismic events were used to identify zones of seismic potential. Lachenicht et al. (2024) published work have many innovative and promising ideas about relating model behaviour to seismicity (see Fig. 12 for example results).

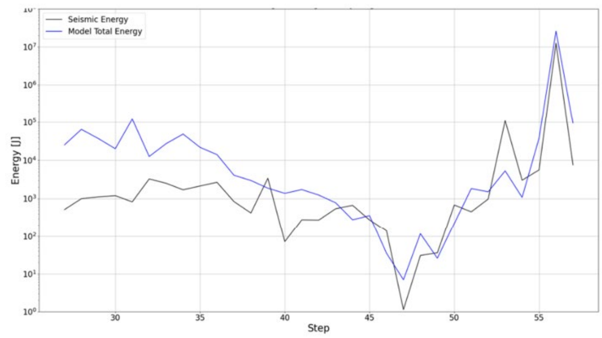

Fig. 12 Modelled seismic energy release and observed seismic energy release during production for a mine, from (Lachenicht et al. 2024)

Another innovative idea concerning mine seismicity is presented by Séguineau de Préval et al. (2024). Here, numerical indicators are derived from 3D inelastic continuum models, including plastic work (total, shear and volumetric), softening variation, and deviatoric strength ratio. Parameters from actual mine seismicity are used in regression analyses, comparing the seismic data with the numerical modelling data.

Currently, the work published in understanding mine seismicity from a numerical modelling perspective is heavily focused on back analysis and calibrating model parameters with actual seismicity. Once this is done, models are used to forecast volumes which have a higher risk of seismic events. It is generally agreed upon in the literature that single seismic events are not predictable, due to the stochastic nature of the system. It is unclear how site specific these analyses are, and it is unclear what governing parameters can be applied to other mines.

AI and statistical analyses are becoming more popular in numerical modelling. Monte Carlo frameworks are commonly being applied in the literature, where machine learning uses results from the Monte Carlo simulation to predict future results. (Chen et al. 2025; Mitelman et al. 2023) Accelerated Weight Histogram (AWH) method, which is a Monte-Carlo-based simulation approach, was recently applied to identifying failure probability using numerical modelling. (Lidmar et al. 2023) We can expect more innovation to come in this area.

To the author's delight, there are several recent examples of clever simplifications in numerical modelling. Parsa-Pajouh (2025) discusses the use of generative AI to automate numerical analyses and guide practitioners. Salgado Veliz et al. (2024) present a lovely application of numerical modelling to create design guidelines for cave interaction. Ouellet et al. (2024) uses the regression analysis of seismicity and numerical indicators previously discussed and presents risk profiles for stopes in a simplified form, in ternary plots and bar charts in stoplight colours (see Fig. 13). Innovation in numerical modelling doesn't need to be about complex programming; sometimes it's even in how we post-process and communicate results.

Stress Rating	Count	%
High	130	22.7%
Moderate	151	26.3%
Low	293	51.0%

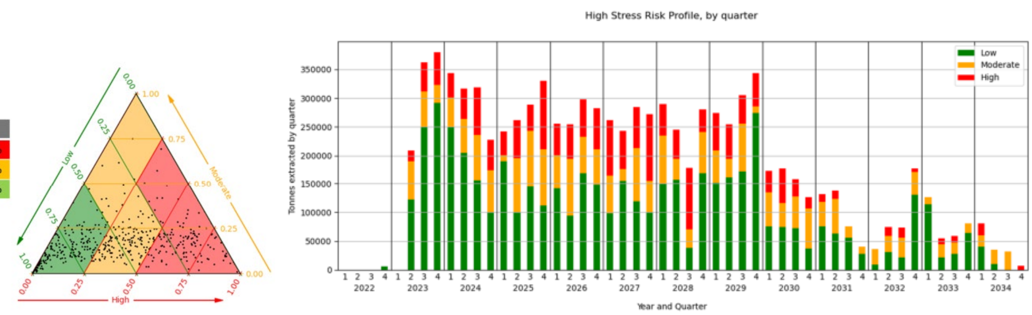

Fig. 13 Communicating seismic risk results in tertiary plot (left) and bar graph (right) for stopes mined, from (Ouellet et al. 2024).

6 Conclusion

There is an extraordinary amount of innovation happen in numerical modelling right now. Trends point towards increased use of AI, advancements in small-scale fracture mechanics and damage understanding, and innovative applications in bonded particle models (BPM) and block-based models (BBM). These developments are enabling more accurate and reliable representations of complex rock behaviors, both at laboratory and larger scales.

Additionally, emerging techniques in discrete fracture networks (DFN) and seismicity analysis are contributing to a deeper understanding of rock mass behavior and seismic potential. The integration of AI and statistical analyses, including Monte Carlo simulations, is also paving the way for more predictive and probabilistic approaches to numerical modelling. Simplifications in numerical modelling, such as generative AI for automation and intuitive presentation of results, are helping practitioners communicate findings more effectively and apply them in practical scenarios.

While it may be premature to definitively declare that we are in the Golden Age of numerical modelling, the current trajectory of innovation, research, and application suggest that we are certainly experiencing a remarkable period of growth and development in this field. The future holds great promise for further advancements that will continue to revolutionize numerical modelling and its applications in rock engineering and beyond. An exciting field to be a part of!

References

AI Statistics (2025) 70 AI Statistics of 2025 (Adoption Rates & Latest Trends). AI Statistics - Artificial Intelligence. https://aistatistics.ai/.

Andrieux P, Cumming-Potvin D (2024) Proceedings of the 10th International Conference on Deep and High Stress Mining. Deep Mining, Montreal, 2024.

Bai Q, Zhang C, Konietzky H (2024) Effects of Particle Shape on Mechanical Responses of Rock Materials Using Bonded-Particle Model. Computers and Geotechnics 176: 106754. https://doi.org/10.1016/j.compgeo.2024.106754.

Castro R, Báez F, Suzuki K (2020) Proceedings of the Eighth International Conference & Exhibition on Mass Mining, Santiago Chile, 2020.

Chen Y, Liu W, Ai D, Zhu H, Du Y (2025) Probabilistic Reliability Assessment Method for Max Ground Settlement Prediction of Subway Tunnel under Uncertain Construction Information. Computers and Geotechnics 177: 106805. https://doi.org/10.1016/j.compgeo.2024.106805.

Daniel B, Hazzard J, Nelson M, Schöpfer M (2020) Proceedings of the 5th International Itasca Symposium, Vienna, 2020. https://www.itascainternational.com/events/applied-numerical-modeling-in-geomechanics-2020.

Dight P (2021) Proceedings of the Second International Slope Stability in Mining Conference. Slope Stability, Perth, Australia, 2021.

Dight P (2023) Proceedings of the Third International Slope Stability in Mining Conference. Slope Stability, Perth, Australia, 2023.

Ghazvinian E, Orrego C, Fuenzalida M, Wesseloo J (2023) Numerical Forecast of Central Access Ground Support Behaviour at Cadia East PC1-2. Australian Centre for Geomechanics, Perth. https://doi.org/10.36487/ACG_repo/2325_35.

Hadjigeorgiou J, Hudyma M (2019) Proceedings of the Ninth International Symposium on Ground Support in Mining and Underground Construction. Ground Support, Perth, 2019.

Hamediazad F, Bahrani N (2024) Evaluation of the Rock Mass Strength for Hard Rock Pillar Design Using Bonded Block Models. Rock Mechanics and Rock Engineering 57 (5): 3659–80. https://doi.org/10.1007/s00603-023-03718-0.

Hammah R, Yacoub T, McQuillan A, Curran J (2022) The Evolution of Geotech - 25 Years of Innovation. Rocscience Symposium, London, 2022. https://doi.org/10.1201/9781003188339.

Hammah RE, Javankhoshdel S, Yacoub T, Azami A, McQuillan A (2023) Proceedings of the Rocscience International Conference. https://www.atlantis-press.com/proceedings/ric-23/publishing.

Hazzard J, Nelson M, Katsaga T, Sanftenberg J (2024) Proceedings of the 6th Itasca Symposium on Applied Numerical Modeling. Toronto, 2024. https://www.itascainternational.com/events/6th-itasca-symposium-on-applied-numerical-modeling.

Hu WR, Liu K, Potyondy DO, Salmi EF, Sellers EJ, Zhang QB (2023) Grain-Based Modelling of Dynamic Shear Rupture of Heterogeneous Rock Using a Coupled Continuum-Discrete Model. International Journal of Impact Engineering 172 (February):104420. https://doi.org/10.1016/j.ijimpeng.2022.104420.

Hu X, Liao D, Hu H, Xie S, Xie N, Gong X (2024) The Influence of Mechanical Heterogeneity of Grain Boundary on Mechanical and Microcracking Behavior of Granite Under Mode I Loading Using a

Grain-Based Model. Rock Mechanics and Rock Engineering 57 (5): 3139–69. https://doi.org/10.1007/s00603-023-03752-y.
Inga CEC, Sinha S, Walton G, Holley E (2023) Modeling Brazilian Tensile Strength Tests on a Brittle Rock Using Deterministic, Semi-Deterministic, and Voronoi Bonded Block Models. Rock Mechanics and Rock Engineering 56 (7): 5293–5313. https://doi.org/10.1007/s00603-023-03329-9.
Jing L, Hudson JA (2002) Numerical Methods in Rock Mechanics. International Journal of Rock Mechanics and Mining Sciences 39 (2002): 409–27.
Johansson D, Schunnesson H (2024) Proceedings of the 9th International Conference and Exhibition on Mass Mining. Kiruna, 2024.
Lachenicht R, Sharrock G, Cumming-Potvin D, Andrieux P (2024) Model Calibration and Seismic Potential Vulnerability Assessment with the Mining Rock Mass Seismicity Model. Australian Centre for Geomechanics. https://doi.org/10.36487/ACG_repo/2465_50.
Lavoine E, Davy P, Darcel C, Mas Ivars D, Kasani HA (2024) Assessing Stress Variability in Fractured Rock Masses with Frictional Properties and Power Law Fracture Size Distributions. Rock Mechanics and Rock Engineering 57 (4): 2407–20. https://doi.org/10.1007/s00603-023-03683-8.
Lidmar J, Edelbro C, Vatcher J, Spross J (2023) Estimation of Small Failure Probabilities Using the Accelerated Weight Histogram Method. Probabilistic Engineering Mechanics 74 (October):103501. https://doi.org/10.1016/j.probengmech.2023.103501.
Manalo P (2023) Discovery to Production Averages 15.7 Years for 127 Mines. S&P Global Market Intelligence (blog). June 5, 2023. https://www.spglobal.com/market-intelligence/en/news-insights/research/discovery-to-production-averages-15-7-years-for-127-mines.
Mitelman A, Ganz A, Urlainis A (2023) Utilizing the Monte-Carlo Capability in RS2 for Machine-Learning Applications. Rocscience International Conference, Toronto, 2023. https://doi.org/10.2991/978-94-6463-258-3_16.
Ouellet A, Séguineau de Préval C, Andrieux P, Cumming-Potvin D, Andrieux P (2024). Establishment of Geomechanical Risk Profiles from Inelastic Continuum Modelling Results. Australian Centre for Geomechanics. https://doi.org/10.36487/ACG_repo/2465_45.
Parsa-Pajouh A (2025) Application of Generative AI to Automate Numerical Analysis and Synthetic Data Generation in Geotechnical Engineering. Machine Learning and Data Science in Geotechnics 1 (1): 46–55. https://doi.org/10.1108/MLAG-09-2024-0008.
Potyondy DO, Fu W (2024) A 3D Subspring Network Breakable Voronoi Model for Rock: Laboratory-Scale Behavior. 58th U.S. Rock Mechanics/Geomechanics Symposium, Golden, 2024. https://doi.org/10.56952/ARMA-2024-0493.
Potyondy DO, Purvance MD (2024) A 3D Subspring Network Breakable Voronoi Model for Rock: Grain-Breakage Scheme. 6th Itasca Symposium on Applied Numerical Modeling, Toronto, 2024.
Salgado Veliz J, Barahona M, Constanzo H, Villarreal M, Cumming-Potvin D, Andrieux P (2024) Back-Analysis and Chart Creation as a Graphical Tool for the Characterisation of Cave Interaction at División El Teniente, Codelco, Chile. Australian Centre for Geomechanics. https://doi.org/10.36487/ACG_repo/2465_13.
Schodde R (2017) Time Delay between Discovery and Development – Is It Getting More Difficult? – MINEX CONSULTING. September 23, 2017. https://minexconsulting.com/time-delay-between-discovery-and-development-is-it-getting-more-difficult/.
Séguineau de Préval C, Ouellet A, Andrieux P, Cumming-Potvin D, Andrieux P (2024) Use of Inelastic Continuum Models to Assess Mine Seismicity Levels. Australian Centre for Geomechanics. https://doi.org/10.36487/ACG_repo/2465_76.
Sinclair S, Rockwell G (2025) Voyant Tools. Voyant Consortium. https://voyant-tools.org/?corpus=c90b62a55303e86d7230a037965ec936&view=cirrus&stopList=keywords-c9323594db1a9ef2ee2fd44aadfb89ee&visible=400.
Starfield AM, Cundall PA (1988) Towards a Methodology for Rock Mechanics Modelling. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts 25 (3): 99–106. https://doi.org/10/bfhrhc.
The Southern African Institute of Mining and Metallurgy (2019) Deep Mining 2019: Ninth International Conference on Deep and High Stress Mining. Johannesburg.
Walton G, Gaines S (2023) Evaluation of Stress Path and Load Rate Effects on Rock Strength Using Compression Testing Data for Stanstead Granite. International Journal of Rock Mechanics and Mining Sciences 169 (September):105455. https://doi.org/10.1016/j.ijrmms.2023.105455.
Wesseloo J (2023) Proceedings of the 10th International Conference on Ground Support in Mining and Underground Construction.
West I, Walton G (2023) Quantitative Evaluation of the Effects of Input Parameter Heterogeneity on Model Behavior for Bonded Block Models of Laboratory Rock Specimens. Rock Mechanics and Rock Engineering 56 (10): 7129–46. https://doi.org/10.1007/s00603-023-03248-9.
West I, Walton G, Diederichs M (2024) Evaluating the Effects of Joint Set Properties on Laboratory Rockmass Analog Specimen Strength Using Bonded Block Models. Rock Mechanics and Rock Engineering, July. https://doi.org/10.1007/s00603-024-04005-2.