AFRIROCK 2025

PIONEERING PROGRESS : THE FUTURE OF ROCK ENGINEERING

The Art of Rock Engineering Design and the Need for Research

Francois Malan – University of Pretoria

SANIRE SOUTH AFRICAN NATIONAL INSTITUTE OF ROCK ENGINEERING

UNIVERSITEIT VAN PRETORIA UNIVERSITY OF PRETORIA YUNIBESITHI YA PRETORIA

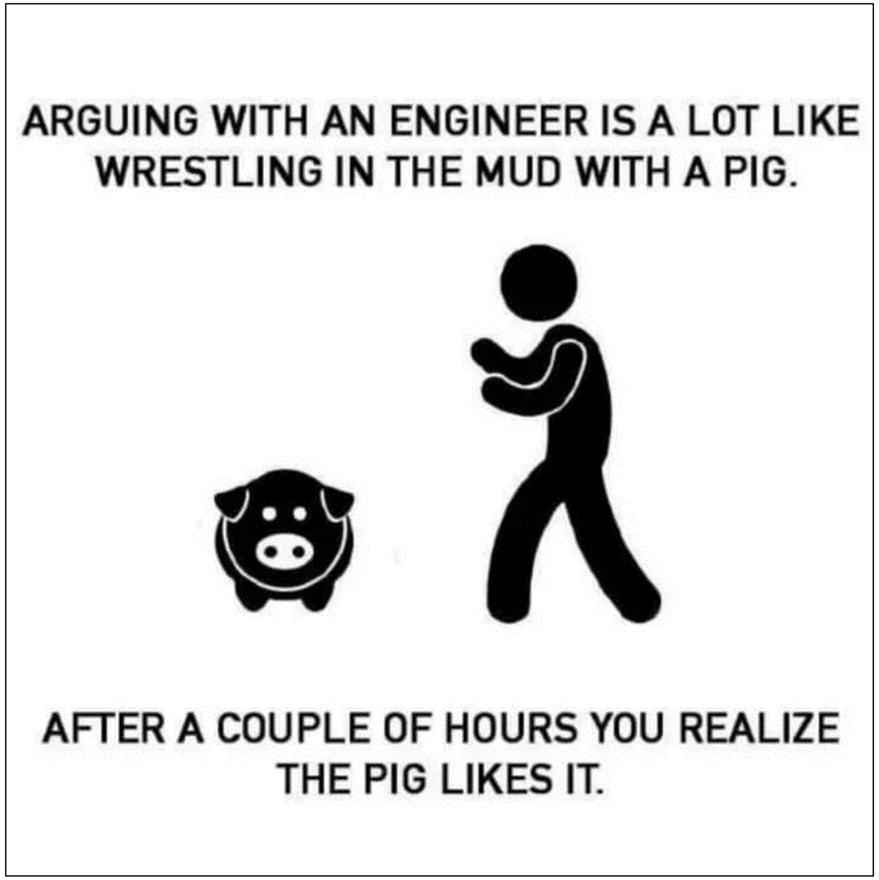
Faculty of Engineering, Built Environment and Information Technology

Fakulteit Ingenieurswese, Bou-omgewing en Inligtingtegnologie / Lefapha la Boetšenere, Tikologo ya Kago le Theknolotši ya Tshedimošo

SAIMM THE SOUTHERN AFRICAN INSTITUTE OF MINING AND METALLURGY

Why do Rock Engineers frequently disagree on design aspects?

- Number of opinions ≡ Number of rock engineers
- Disagreements can lead to poor designs or failures
- Can we learn from these disagreements and improve?
- Philosophy offers the opportunity to adopt a reflective learning approach



Contents

1. Introduction and a bit on Philosophy
2. Case study 1: Elastic modelling versus complex inelastic modelling
3. Case study 2: Pillar design
4. Conclusions and the way forward

ChatGPT and Rock Engineering Design – Is it an art or a science?

Rock engineering design is best described as a **science-based art**.

🔬 Science in Rock Engineering Design

The **science** provides the foundation. Design is based on:

- **Rock mechanics principles** (e.g., stress-strain behavior, failure criteria).
- **Empirical methods** (e.g., Q-system, RMR).
- **Numerical modelling** (e.g., finite element, distinct element, boundary element methods).
- **Monitoring and instrumentation** (e.g., extensometers, stress cells).
- **Geological and geotechnical data** (e.g., boreholes, core logging, lab tests).

🎨 Art in Rock Engineering Design

Other engineering disciplines are more exact!

Design is never purely scientific, because:

- **Natural variability**: No rock mass is fully predictable—geology is complex and discontinuous.
- **Uncertainty**: Even the best data is incomplete or generalized; lab samples rarely represent full in-situ behaviour.
- **Engineering judgment**: Decisions must often be made with partial information.
- **Design adaptation**: As conditions change during excavation, designs must evolve.
- **Risk management**: Balancing performance, cost, and safety is not purely technical.

Some previous thoughts by researchers on this topic

- Rock masses are so complex - realistic modelling, even with sophisticated methods, is impossible. (Stacey, 2003)
- Good rock engineering - must involve both good design and good judgement.

- Bieniawski (1991,1992) design principles
  1. Clarity of design objectives and functional requirements
  2. Minimum uncertainty of geological conditions
  3. Simplicity of design components
  4. State-of-the-art practice
  5. Optimization
  6. Constructibility

Presidential Address: Rock engineering—good design or good judgement?

by T.R. Stacey*

Rock Engineering Design and Philosophy

geosciences

MDPI

Article

Examining Rock Engineering Knowledge through a Philosophical Lens

Davide Elmo [1,*], Amichai Mitelman [2] and Beverly Yang [1]

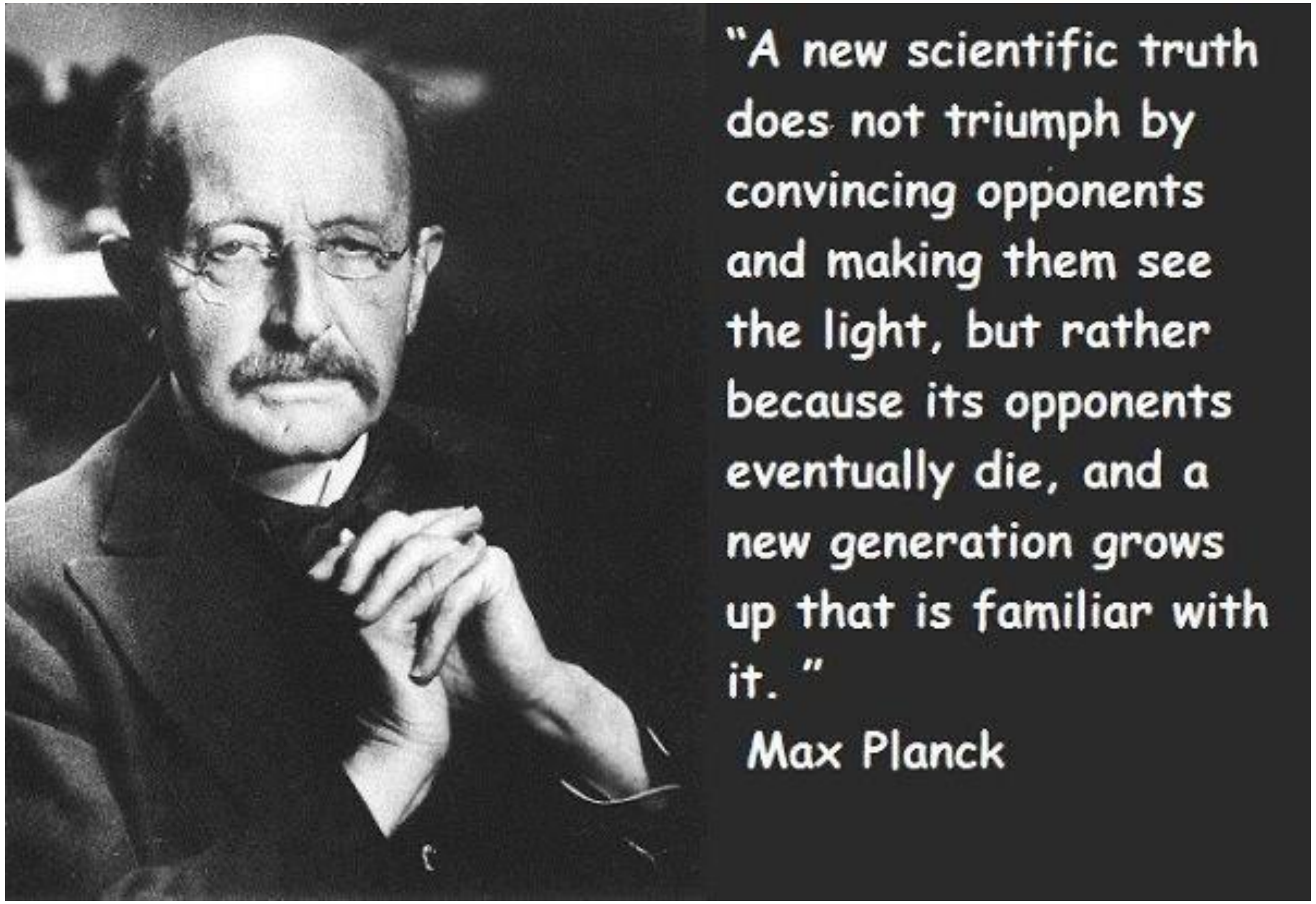
1 Norman B. Keevil Institute of Mining Engineering, University of British Columbia, Vancouver, BC V6T 1Z4, Canada; beverly.yang8@gmail.com
2 Department of Civil Engineering, Ariel University, Ariel 40700, Israel; mamichai@gmail.com
* Correspondence: delmo@mining.ubc.ca

Abstract: This paper presents a philosophical examination of classical rock engineering problems as the basis to move from traditional knowledge to radical (innovative) knowledge. While this paper may appear abstract to engineers and geoscientists more accustomed to case studies and practical design methods, the aim is to demonstrate how the analysis of what constitutes engineering knowledge (*what rock engineers know and how they know it*) should always precede the integration of

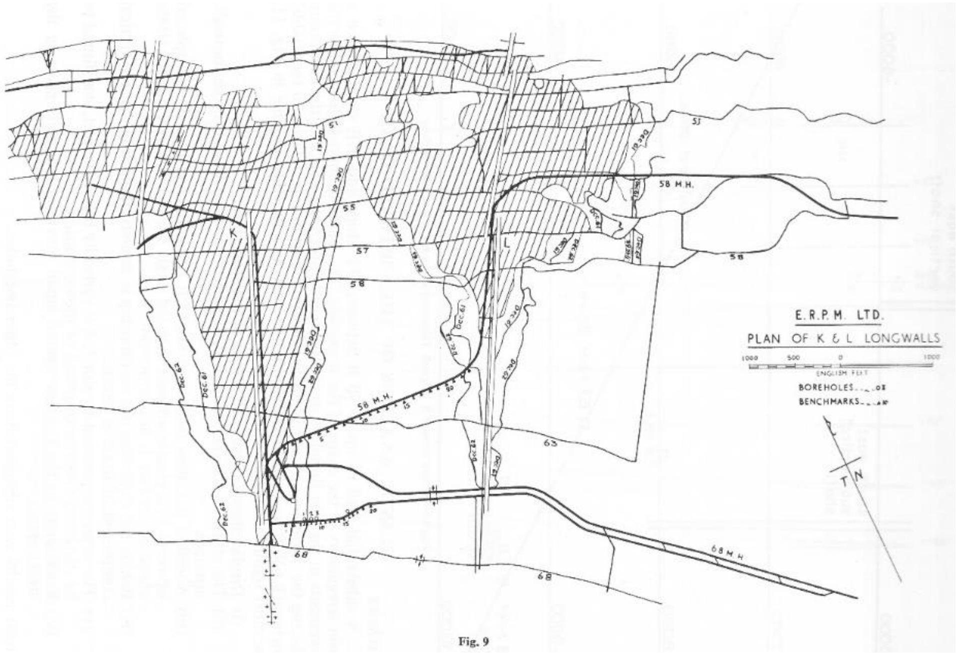
Rock engineering knowledge is shaped by cognitive biases, which over the years have created a sort of dogmatic barrier to innovation.

Little attention has been given to the impact that subjectivity, human factors, and lack of scientific replicability have on the empirical methods used in rock engineering design.

Generational turnover as a force for progress

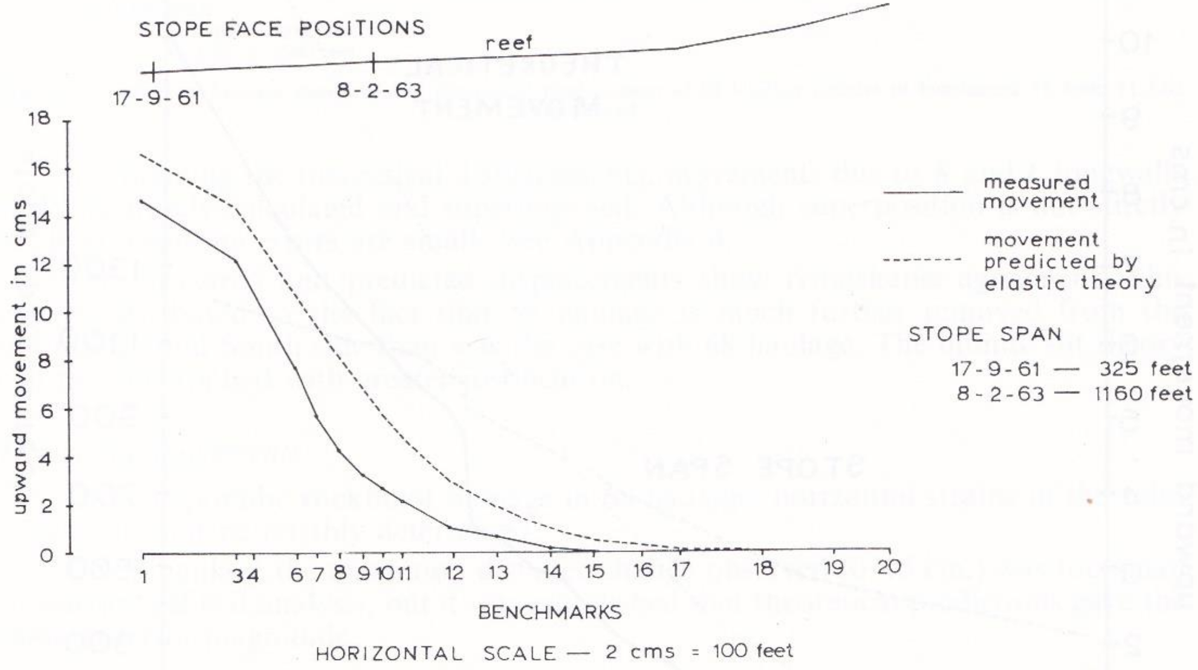


Major breakthrough in gold mine layout design 1960's – Elastic theory adopted

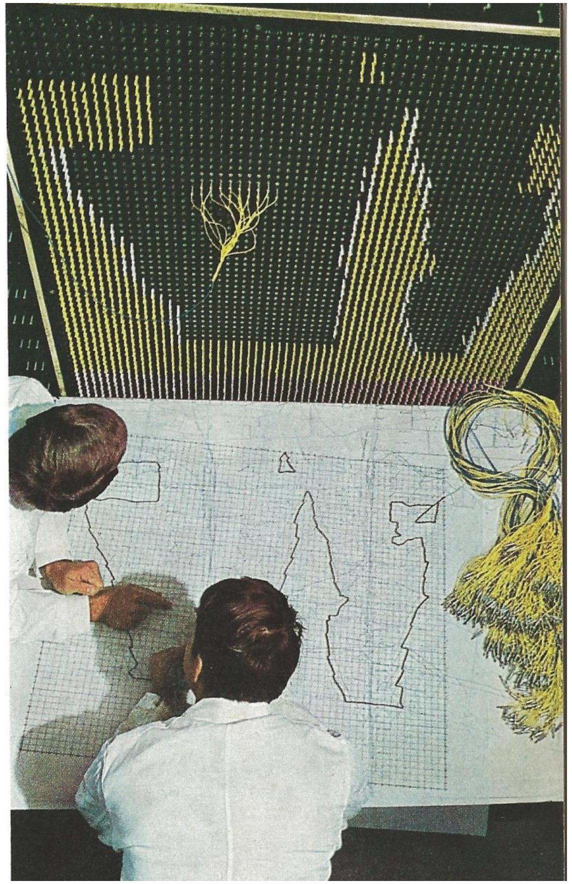


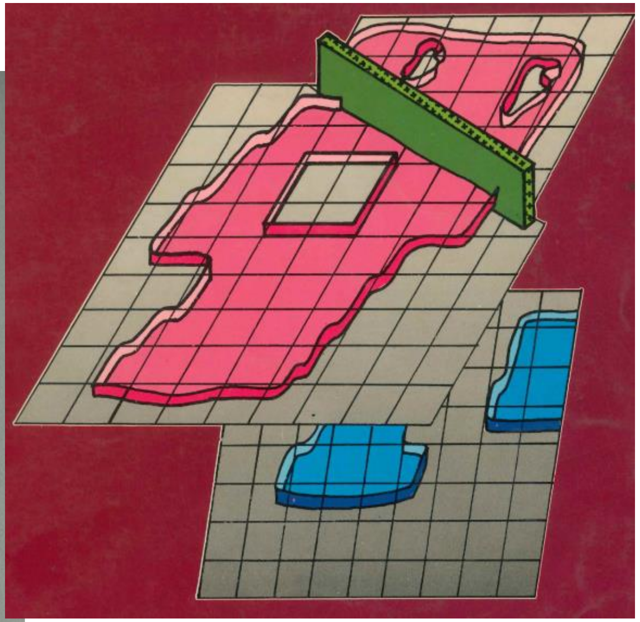
Displacements in hangingwall and footwall tunnel were measured for a period of a year while longwalls below it advanced

Measured movement agree well with elastic theory



Case study 1: Elastic theory made stress simulation possible





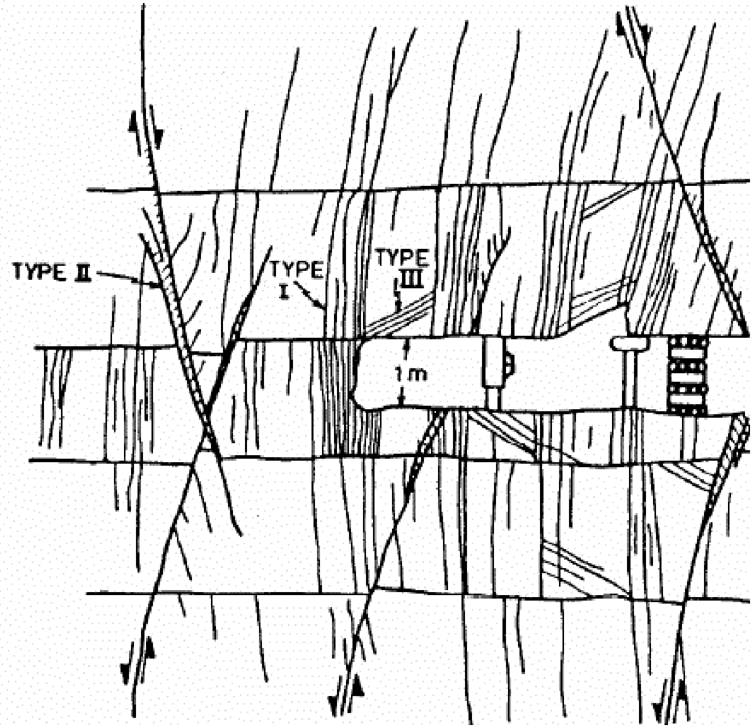
Coded by Prof John Napier

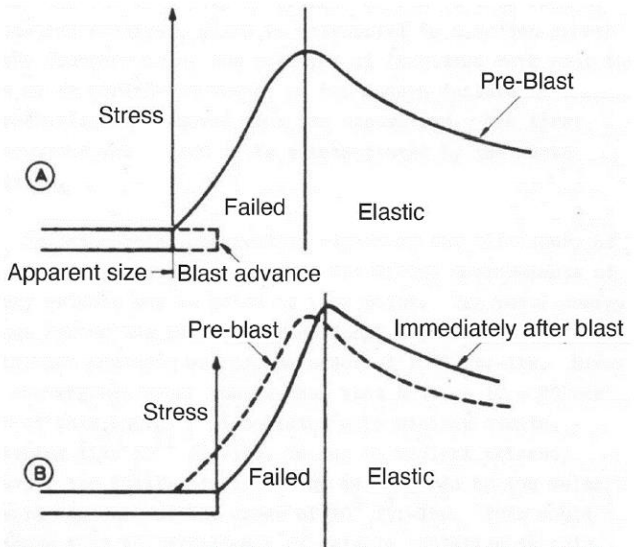
Electrical analogue and early MINSIM simulations in 1970s and 1980s

And the popular design concepts of **APS** and **ERR** were born!

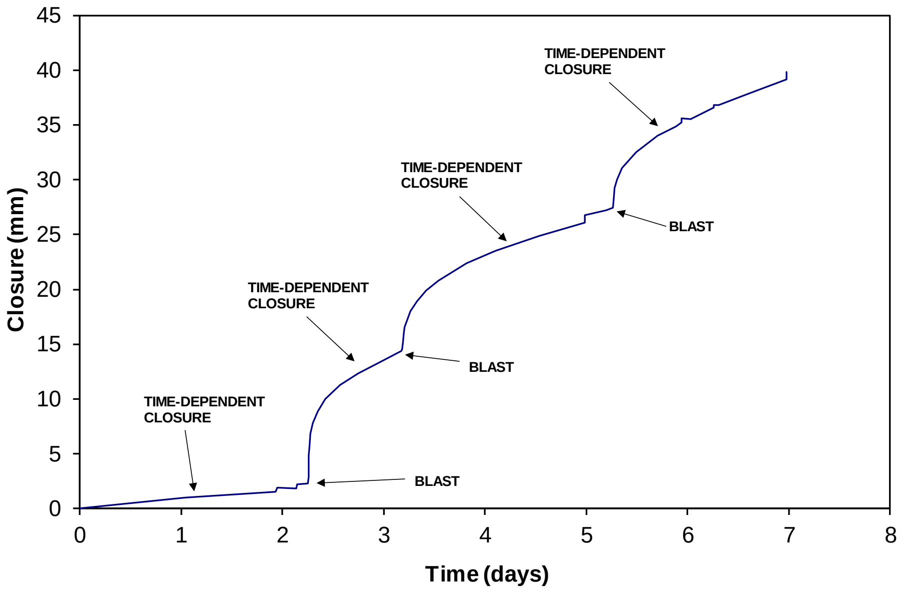
Case study 1: Drawback of elastic theory

- Cannot simulate the fracture zone
- Cannot simulate the time-dependent response of the rock mass and mining rate



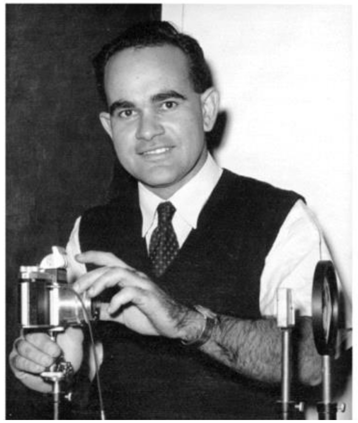


Recognized by Hodgson (1967)

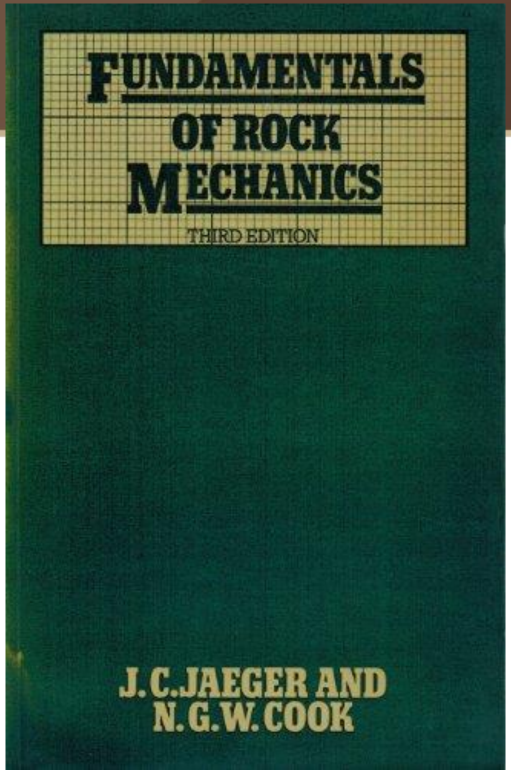


Time-dependent closure measurements by in the 1990s

Case study 1: Ignoring the fracture zone for the sake of convenience



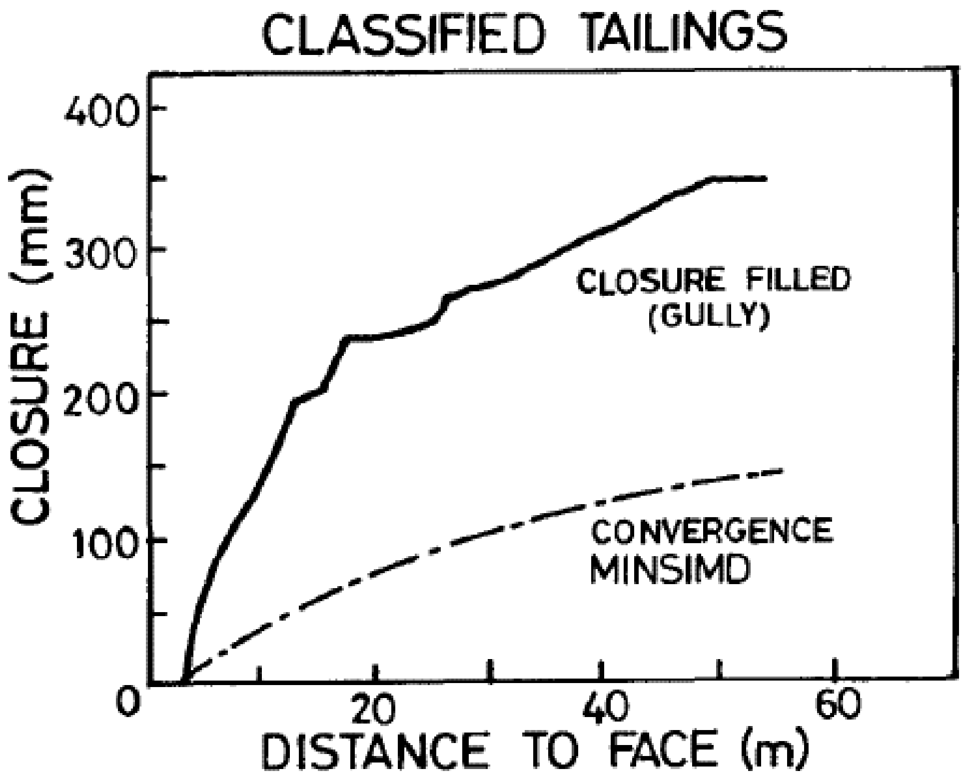
(cognitive biases - dogmatic barrier to innovation)



In the first edition of Jaeger and Cook's book, Fundamentals of Rock Mechanics (1969), mention of structural discontinuities occurs on about a dozen of the 500 pages of the book. This comment does not imply criticism of this outstanding book but it illustrates the dominance of elastic theory in the approach to rock mechanics associated with deep-level mining problems

Hoek (2006)

Case study 1: Disagreements how to account for stope closure recorded underground



Gurtunca and Adams (1991)

The use of an in situ modulus provides an effective interim solution…

Gurtunca and Adams (1991)

…the recommendation that such an in situ modulus should be used for calculations of energy release rate (ERR), are viewed with some concern.
It is recommended that the interim solution suggested by the authors should not be used.

Comments published by other authors in JSAIMM

Case study 1: New model combining a limit equilibrium face crush model and a bulking model

Contents lists available at ScienceDirect

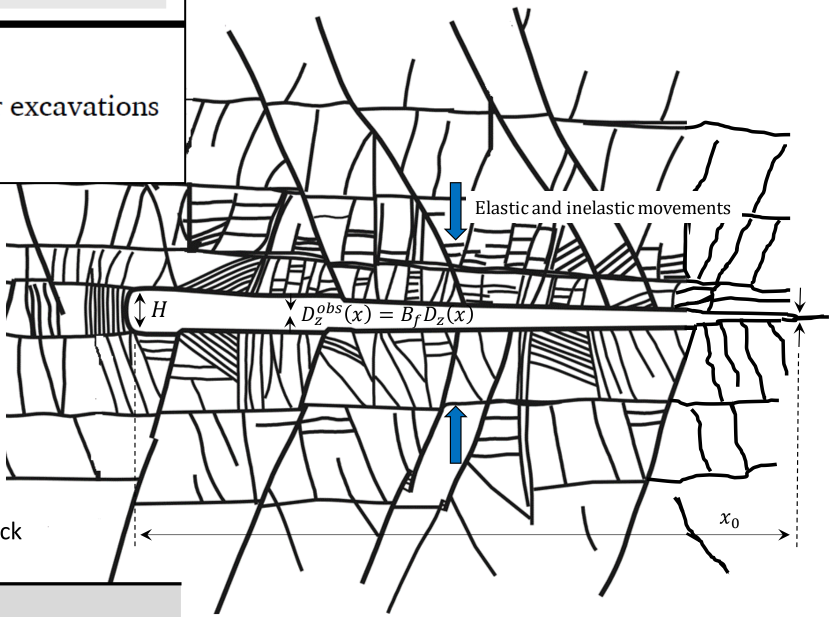
International Journal of Rock Mechanics and Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

A bulking model to simulate stope convergence in deep tabular excavations

Y. Jooste, J.A.L. Napier, D.F. Malan

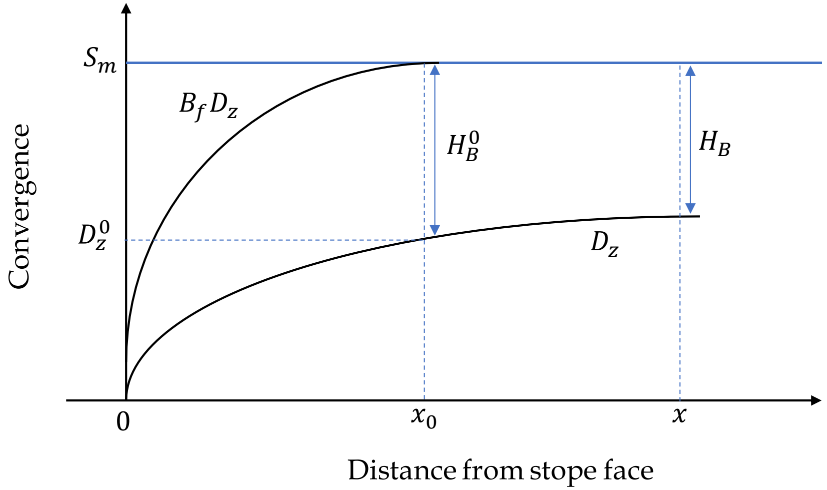
The bulking model combined with a limit equilibrium model seems capable of replicating the underground closure behaviour.



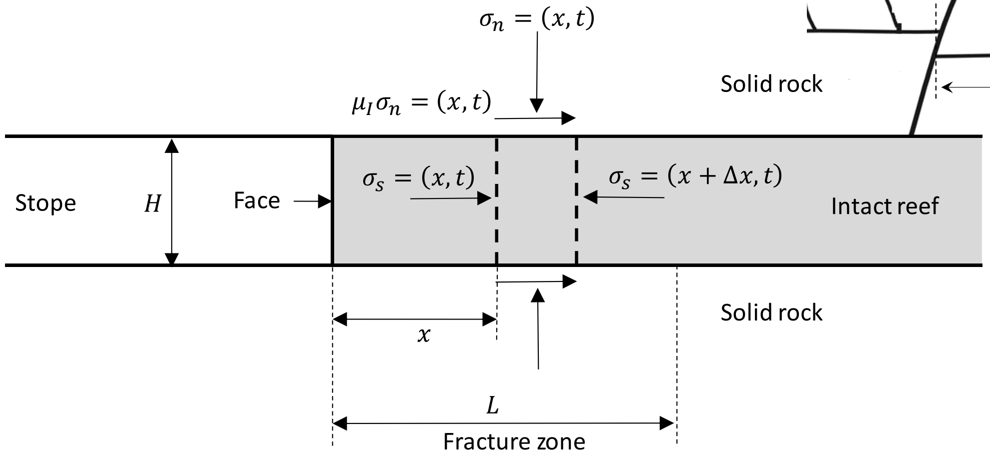
Bulking model

$$D_z^{obs} = B_f D_z$$

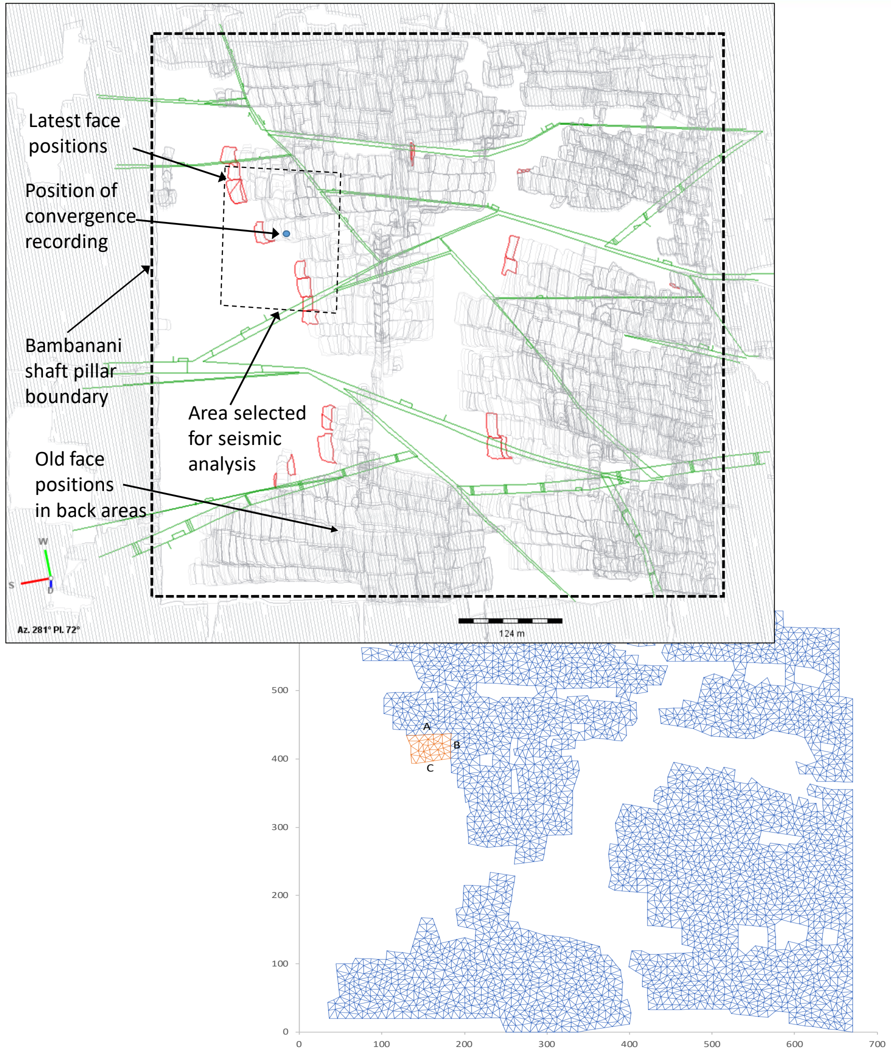
$$B_f = B_f^m - \left(B_f^m - B_f^0\right)\left(\frac{1}{2}\right)^{T/\lambda_B}$$

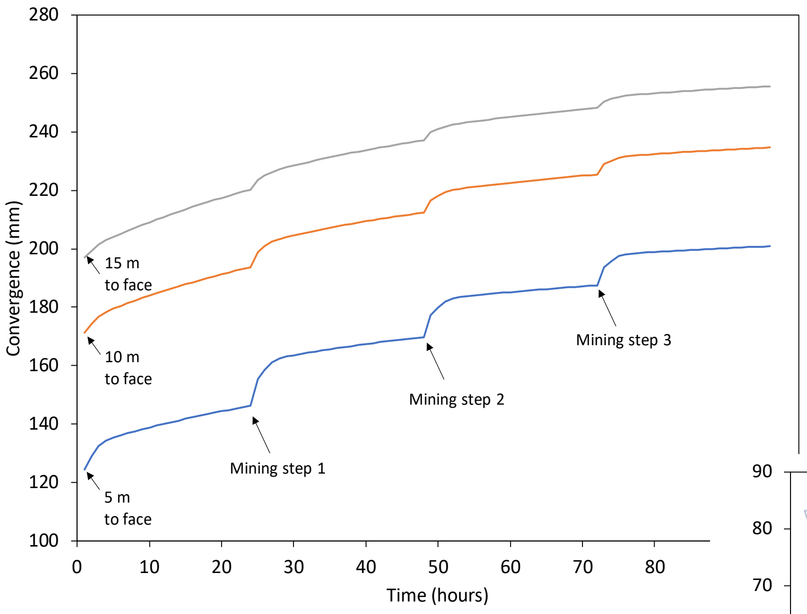


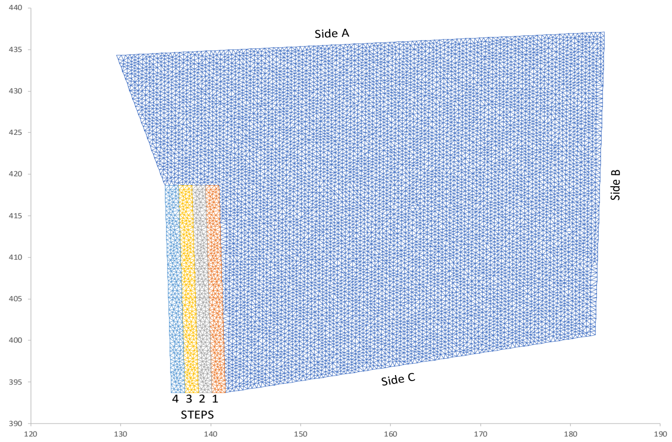
Limit equilibrium model for face crushing

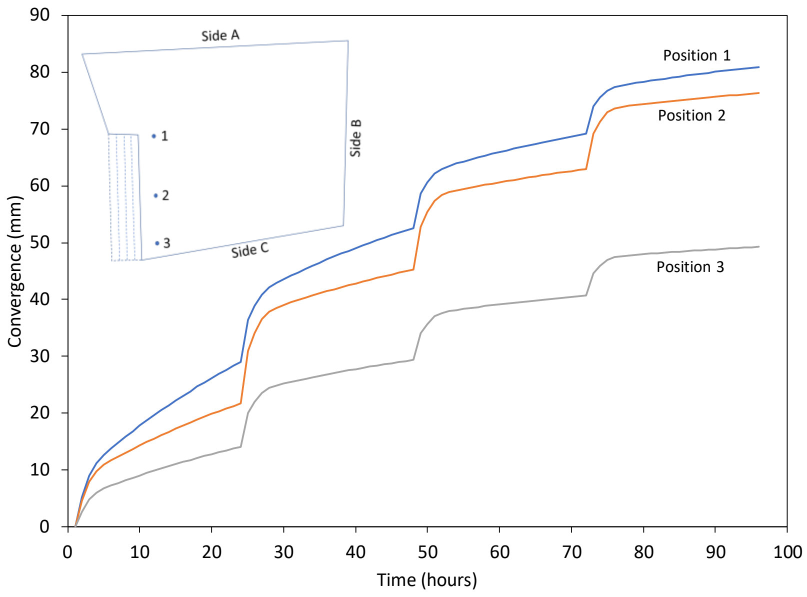


Case study 1: New model combining a limit equilibrium face crush model and a bulking model









Can finally (almost) simulate the closure behaviour!

Case study 1: Drawback of the new model

Large number of parameters to calibrate
for the limit equilibrium and bulking models!

Parameter	**Value**
Depth	2500 m
Face advance increment	1.5 m
Dip	0°
Young's Modulus, E	70 GPa
Poisson's ratio, ν	0.2
Number of elements in the coarse mesh	7088
Number of elements in the fine mesh	21622
Average grid size – coarse mesh, $\bar{g}$	≈ 34 m^2
Average grid size – fine mesh, $\bar{g}$	≈ 0.089 m^2
Intact strength intercept, σ_c^i	150 MPa
Intact strength slope, m_i	3
Initial residual strength intercept, σ_c^0	150 MPa
Initial residual strength slope, m_0	3
Final residual strength intercept, σ_c^f	15 MPa
Final residual strength slope, m_f	3
Effective mining height, H	1.5 m
Intact seam stiffness modulus, k_s	46 667 MPa/m
Fracture zone interface friction angle, ϕ	35°
Limit equilibrium half-life parameter, λ	0.5 h
Initial bulking factor, B_f^0	2
Final bulking factor, B_f^m	2.5
Bulking half-life parameter, λ_B	28.9 h
Compaction stiffness, E_0	10 000 MPa

Elastic models suddenly seem attractive!

Lesson 1 – Elmo et al (2022)
If older and simpler solutions have a clear advantage in terms of durability and/or efficiency, even if this advantage is restricted to a limited purpose, they continue to exist and evolve.

Case study 2: Hard rock pillar strength in the Bushveld Complex

Coal was the initial driver for pillar research - Coalbrook disaster

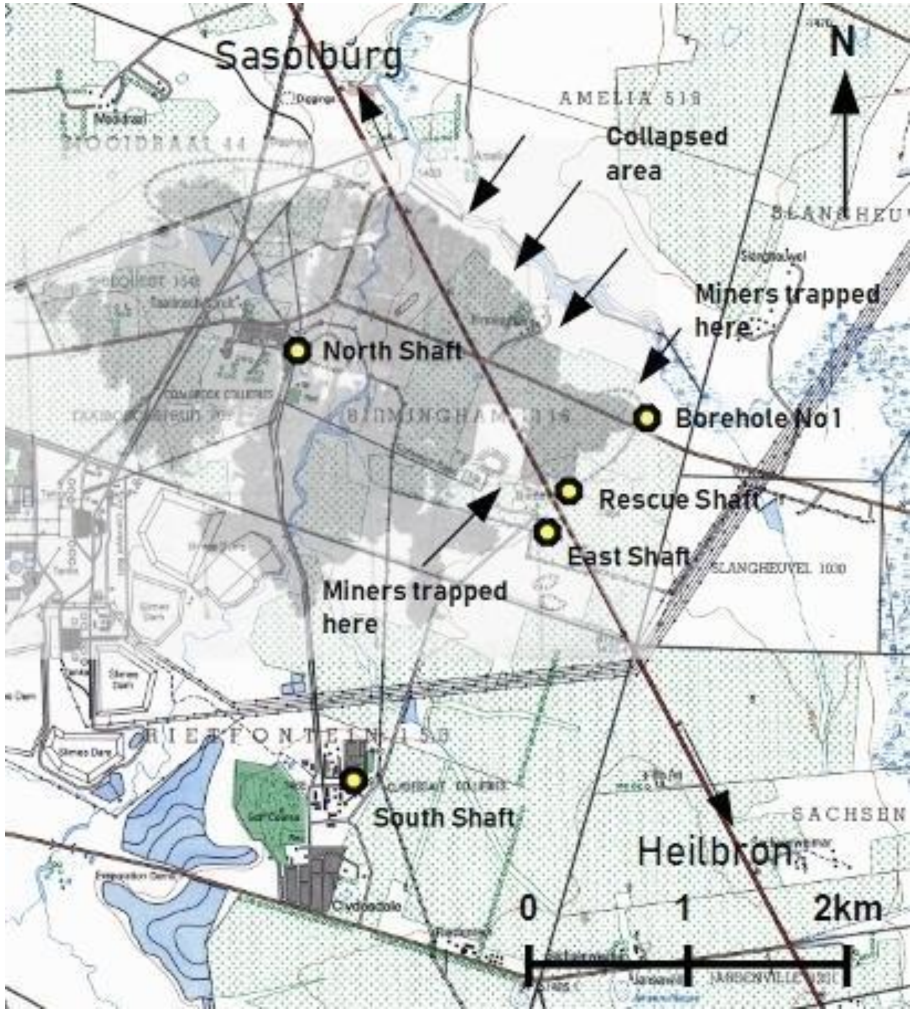

level.
A widow without children draws

Coalbrook: drill breaks down

28/1/60

A new shaft to trapped men

STAFF REPORTER



Case study 2: The aftermath of the Coalbrook disaster

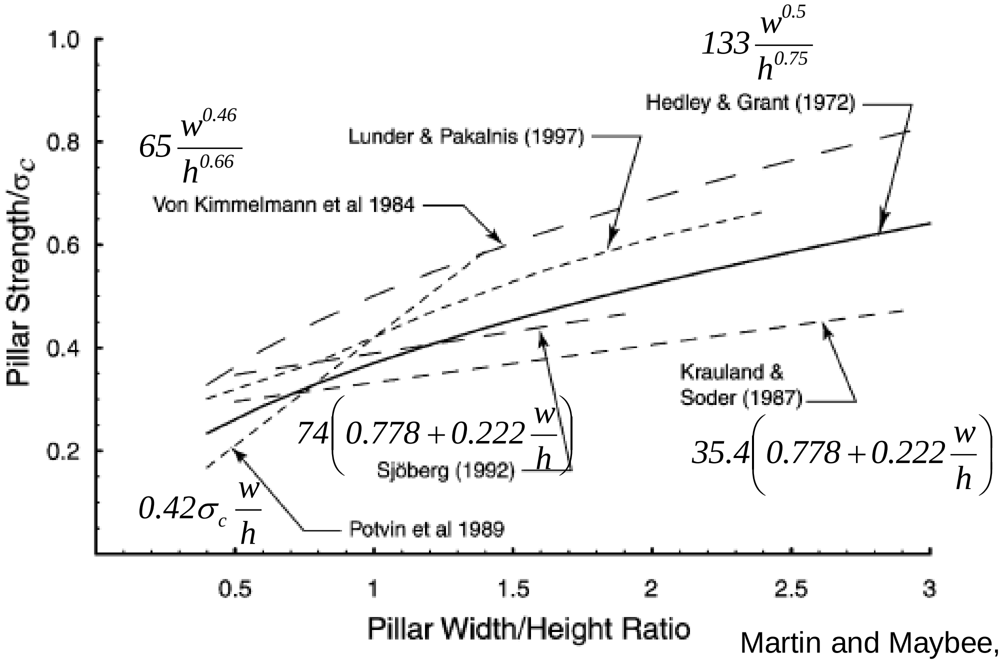
- Pillars over an area of 324 hectares collapsed
- Rock mechanics research to find a method to determine coal pillar strength was given priority
- Salamon and Munro (1967) published their famous *empirical* coal pillar strength formula

$$\sigma_p = 7.176 \frac{w^{0.46}}{h^{0.66}} \; MPa$$

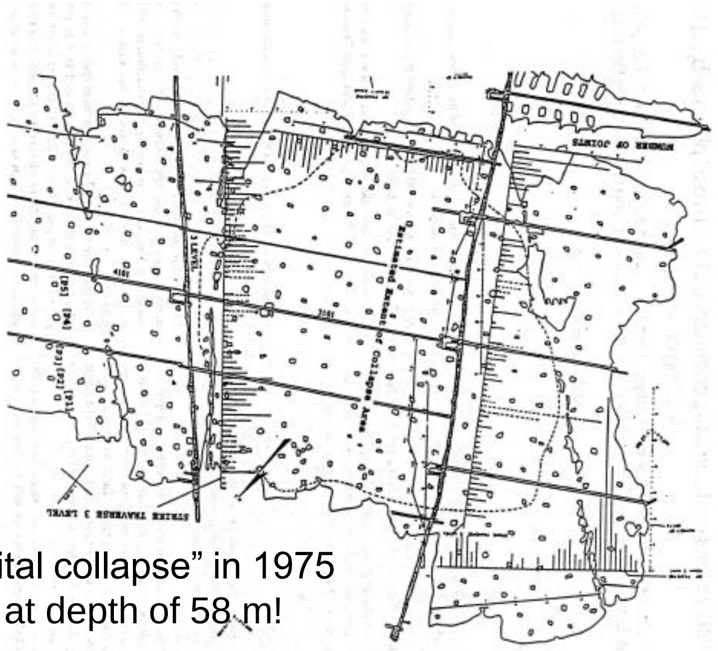
- Widely accepted in coal mining industry up to the present day (Lesson 1)

Case study 2: Hard rock pillar strength in the Bushveld Complex

- Platinum and Chrome mostly ignored by the large research programs in the country
- Had to adopt principles used in other mines – Few large collapses mostly ignored and not used for research
- Canadian Hedley and Grant formula adopted as nothing else was available – Became <u>“industry standard”</u>
- PlatMine formula also developed (Watson et al 2021)



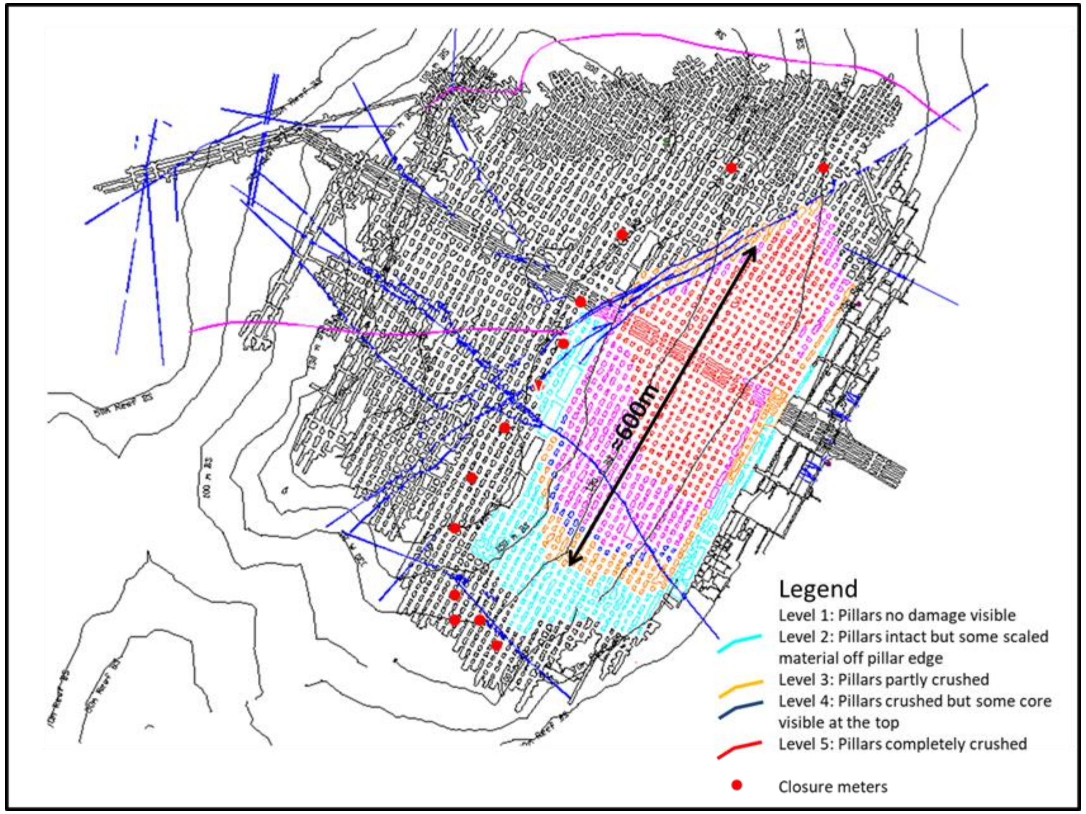
Martin and Maybee, 2000



- The infamous “Hospital collapse” in 1975
- Extraction ratio 97% at depth of 58 m!
- Pillars 5 m square

Case study 2: The risk when using the "industry standard"

- The pillar design for Everest - Hedley and Grant formula and the "industry" conservative assumption of $K = \frac{1}{3}UCS$
- The effect of the weak alteration layer at the pillar/hangingwall contact was ignored



Lesson 2 – Elmo et al (2022)

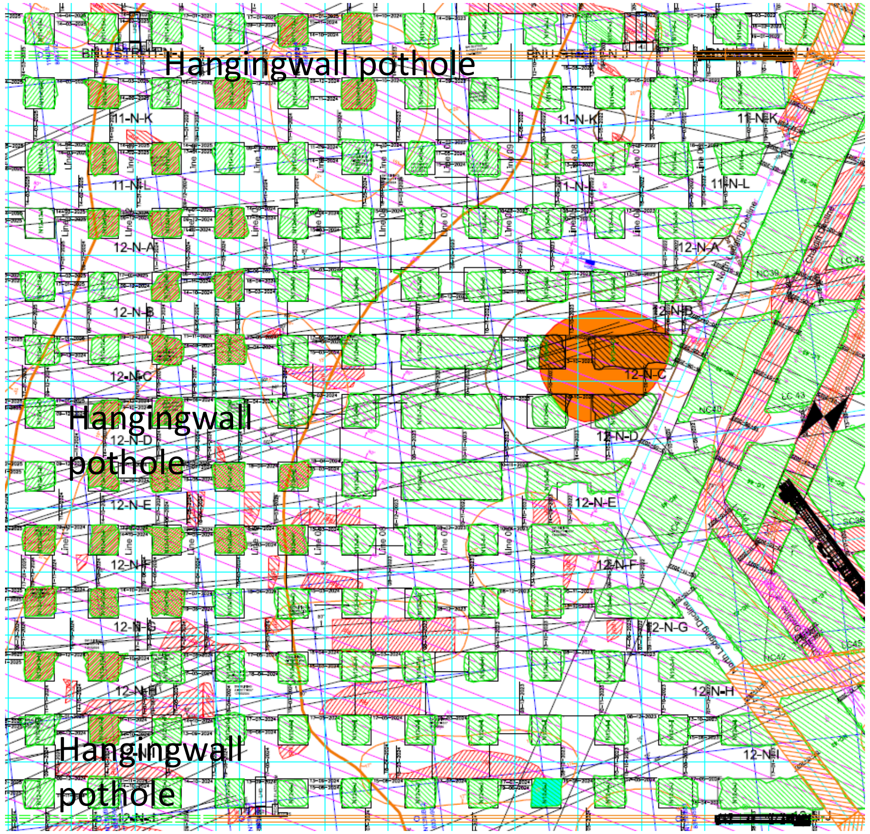
The term "industry standard" refers to criteria generally accepted by industry. However, the definition does not necessarily imply that those criteria are the best technical solutions, nor it does imply those criteria are correct

Case study 2: Another problem with these empirical formulas!

- Mine A adopted an empirical formula that would enable bord and pillar mining beyond 1000 m depth
- Unexpectedly, at 500 m depth there is now excessive spalling in an area of the mine – UG2 may be weaker

Case study 2: Another problem with these empirical formulas!

- Significant spalling of pillars below the hangingwall pothole



Lesson 3 – Elmo et al (2022)
Accept that geological processes are variable and therefore focus our attempts to better characterise variability rather than seeking to describe rock masses through a single numerical input.

Case study 2: A limit equilibrium numerical model as an alternative to simulate pillar stability

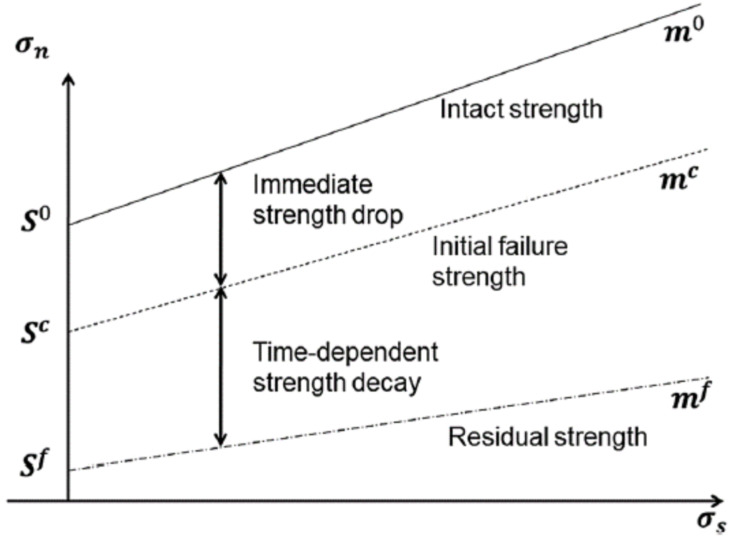
Failure relationship $\sigma_n = m\sigma_s + S$

Time-dependency

$$S(t) = S^f + F\big(t - T(x)\big)\big(S^c - S^f\big)$$

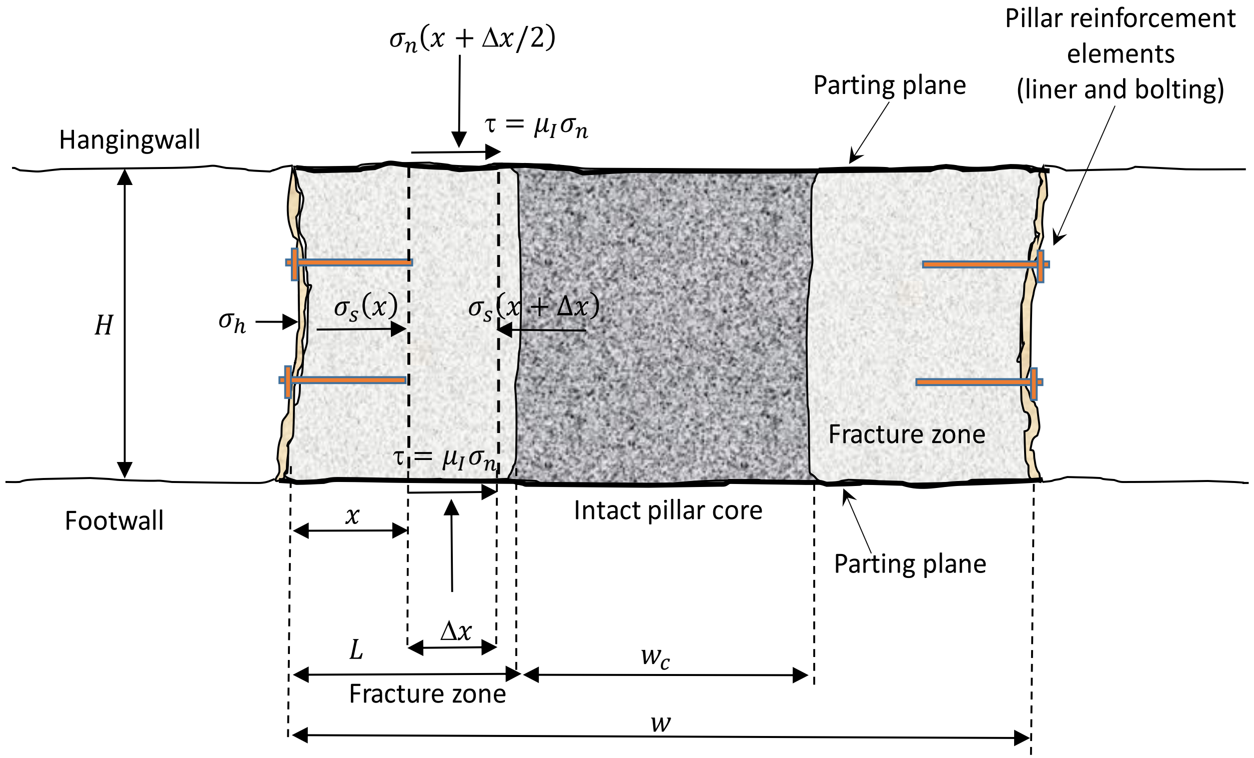
$$m(t) = m^f + F\big(t - T(x)\big)\big(m^c - m^f\big)$$

$$F(\tau) = \left(\frac{1}{2}\right)^{\frac{\tau}{\lambda}} = e^{-\alpha\tau}$$

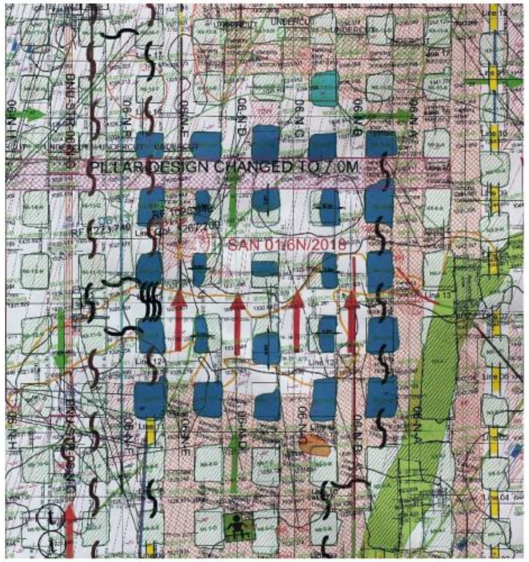


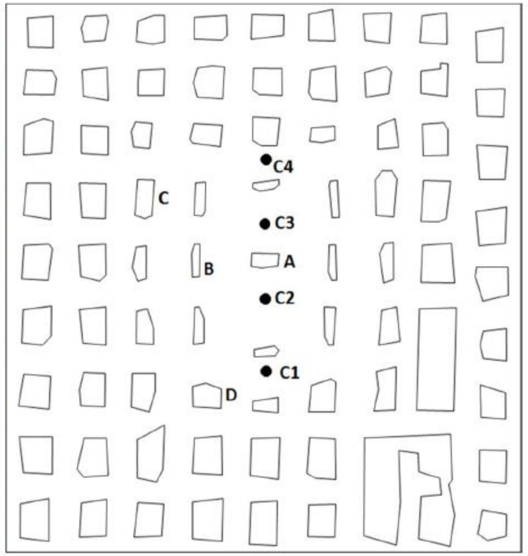
Built into displacement discontinuity code TEXAN

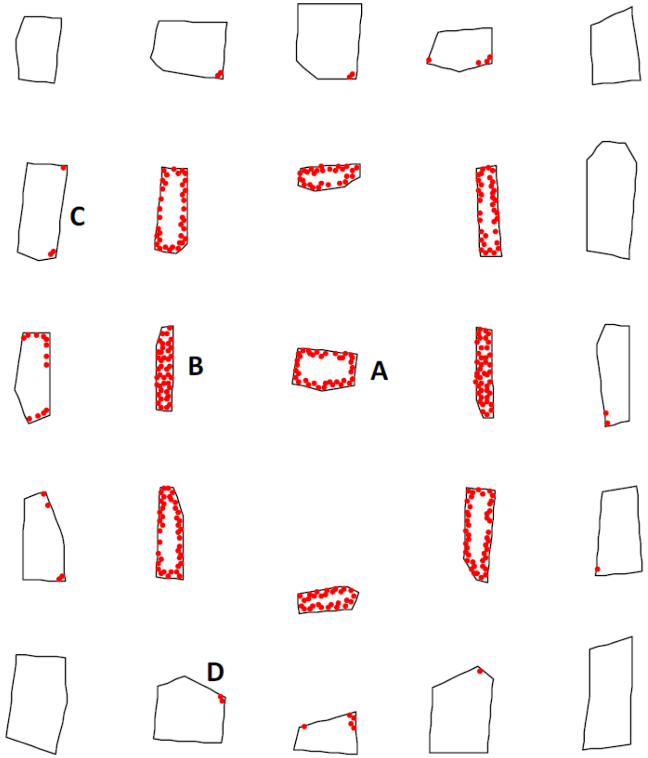
$$\sigma_n = Se^{2mx\tan\phi/H}$$



Case study 2: Use of the famous pillar mining experiment to calibrate the model







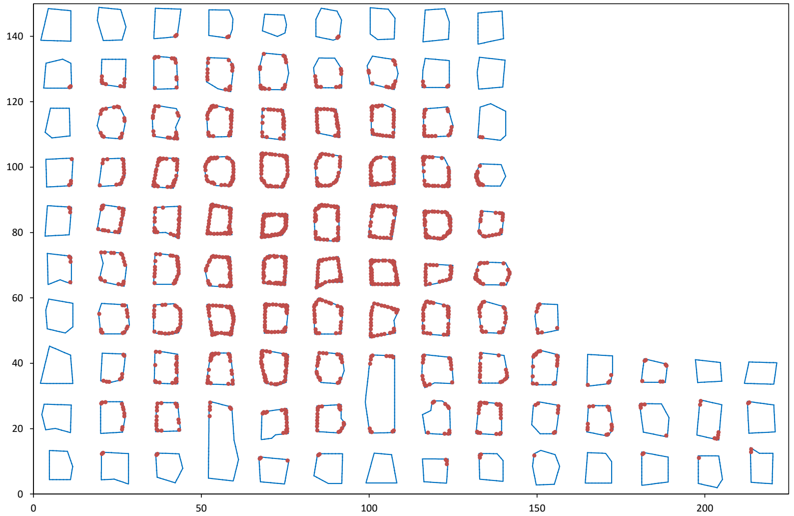
Rock Mechanics and Rock Engineering
https://doi.org/10.1007/s00603-020-02265-2

ORIGINAL PAPER

A Limit Equilibrium Model of Tabular Mine Pillar Failure

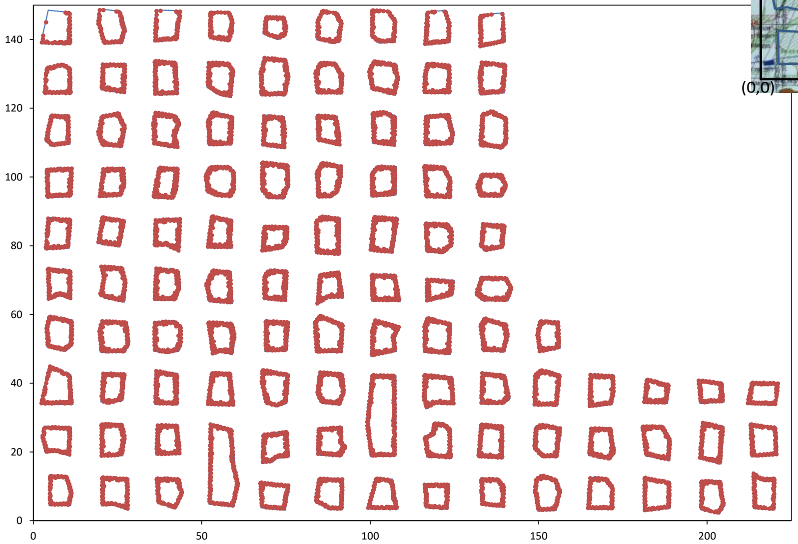
J. A. L. Napier[1] · D. F. Malan[1]

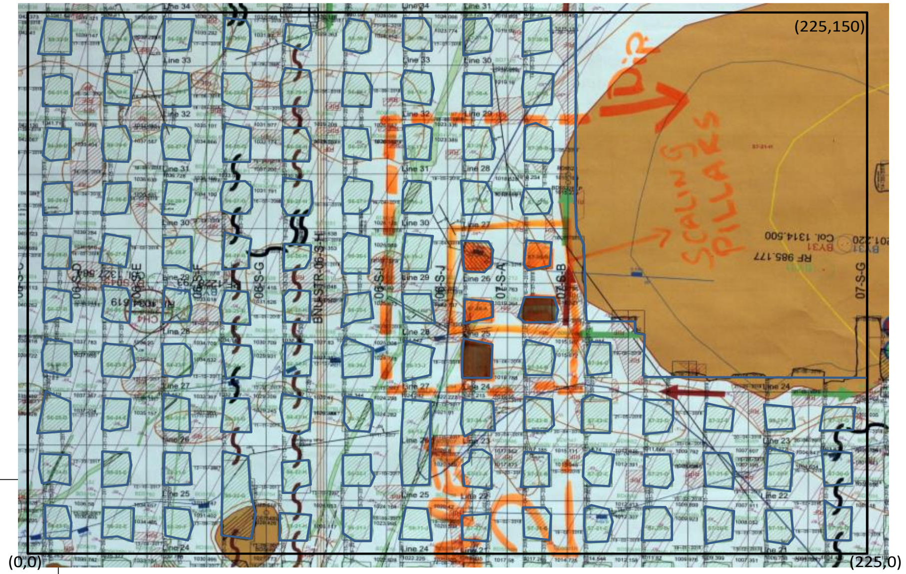
Case study 2: Simulate the deeper layouts with the model



400 m

800 m





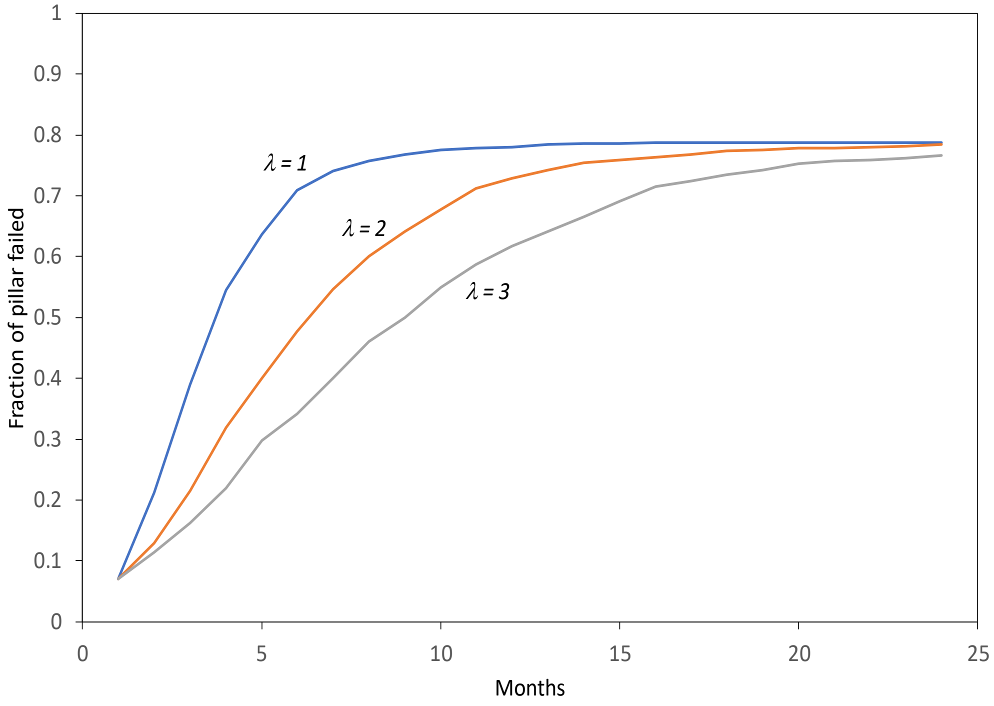
Case study 2: Simulate time-dependent pillar scaling

Rock Mechanics and Rock Engineering (2023) 56:3773–3786
https://doi.org/10.1007/s00603-023-03239-w

ORIGINAL PAPER

A Limit Equilibrium Model to Simulate Time-Dependent Pillar Scaling in Hard Rock Bord and Pillar Mines

D. G. Wessels[1] · D. F. Malan[1]



Case study 2: The difficulty with inelastic modelling codes to simulate pillar behaviour

Need to calibrate these many parameters!

Parameter	Value
Intact strength intercept, S^0	50 MPa
Intact strength slope, m^0	7
Initial residual strength intercept, S^c	30 MPa and 50 MPa
Initial residual strength slope, m^c	7
Final residual strength intercept, S^f	20 MPa
Final residual strength slope, m^f	7
Effective seam height, H	5.5 m
Intact rock Young's modulus, E	90 GPa
Intact rock Poisson's ratio, ν	0.2
Intact seam stiffness modulus, k_s	16,363 MPa/m
Fracture zone interface friction angle	30°
Half-life, λ	12 months

Also applicable to complex finite difference and discrete element modelling

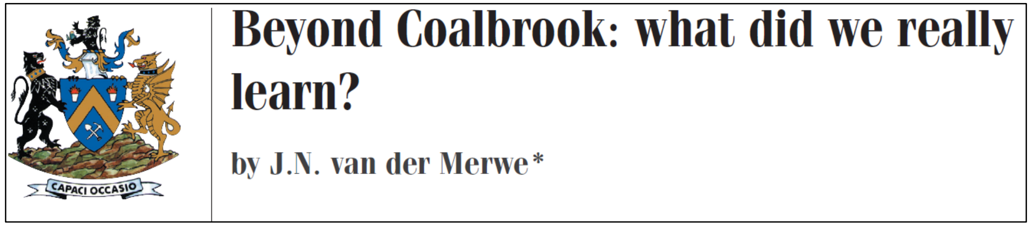
Lesson 4 – Elmo et al (2022)

Models are constrained by the impossibility to reduce the uncertainty associated with data collection (geological uncertainty), modelling (parameter and model uncertainty), and persons (human uncertainty).

A complex numerical model does not necessarily provide more accurate predictions than a simple one

The way forward and the need for research

- Very little rock engineering research done in country compared to the 1960s and 1970s
- *“Is it conceivable that the most important lesson from Coalbrook, namely that in order to be effective at all, knowledge has to be generated before it is needed, was not learnt?”*


Beyond Coalbrook: what did we really learn?

by J.N. van der Merwe*

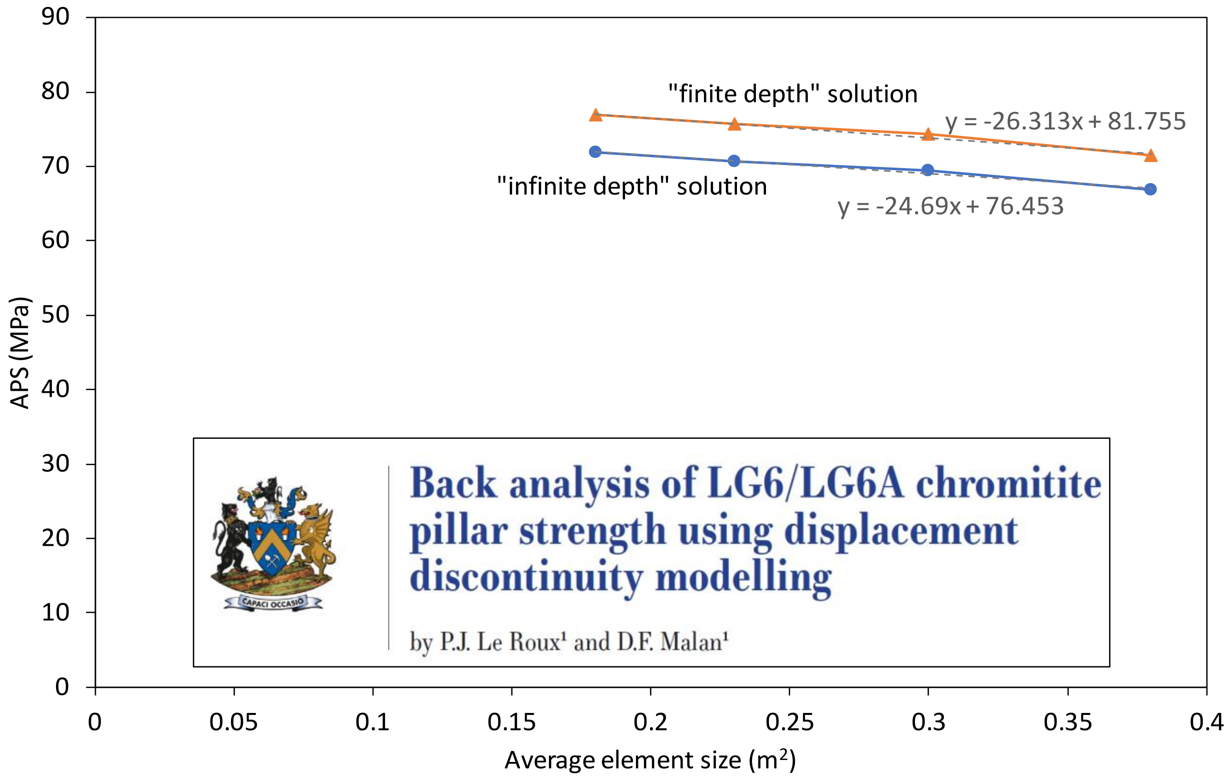
- Need to energise rock engineering research efforts in the country!

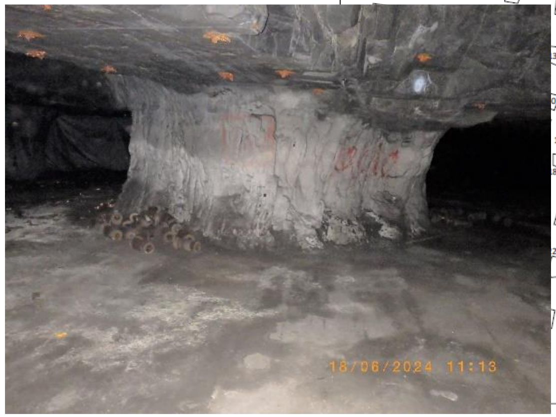
Lesson 5 – Elmo et al (2022)

- For research, apply critical thinking and question the foundations of rock engineering as an empirical science
- Conduct “replication” research as a more rigorous form of review compared to the traditional peer review
  - The original researchers provide full information to allow others to replicate their work

The value of replication research

- Used both TEXAN and MAP3D to simulate APS on small pillars
- Complex, large-scale geometry close to surface - Studied the effect of element size
- Identical results, but had to work very closely to understand assumptions and modelling methodology





Why do Rock Engineers frequently disagree on aspects of design?

Rock engineers frequently disagree about aspects of design because rock engineering inherently involves **high uncertainty**, **site-specific variability**, and often **limited data**, all of which demand judgment calls that differ based on experience, interpretation, and risk tolerance.

Disagreement in rock engineering is not a flaw — a reflection of the **complex, uncertain nature** of the rock mass and the **judgment-based** aspect of the discipline.

Good design often emerges from **critical debate**, multiple perspectives, and iterative refinement.

(Own addition) This high uncertainty in rock engineering requires ongoing monitoring of designs and a new approach to research

(Own addition) A case for incorporating philosophy in rock engineering practice and education

THANK YOU