Ground Support 2026 - D Cumming-Potvin & J Wesseloo (eds.)
© 2026 Australian Centre for Geomechanics, Perth
doi:10.36487/ACG_repo/2625_13

Assessment of temporary yielding slender sandstone pillars using staged FLAC3D modelling

Zhongyu Xu [a], Hang Xu [b,*], Douglas Tun [c]

[a] *Equilibrium, Australia*

[b] *SRK Consulting, Canada*

[c] *WSP, Australia*

Abstract

The design of slender rock pillars (width-to-height ratio <1.0) and their associated rockbolt support systems remains challenging because of reduced confinement, elevated stress concentrations and sensitivity to geological variability. This paper builds upon a previously published case study on the design of a temporary yielding pillar in massive sandstone by advancing the numerical assessment from a general stability evaluation to a detailed staged FLAC3D model that explicitly simulates the excavation sequence and installation of pattern glass-fibre rockbolts. The case study involves a temporary slender pillar located at the base of a shaft excavation approximately 100 m below ground level, where controlled yielding was adopted as the design philosophy to maintain excavation stability during construction.

The staged numerical model provides improved insight into the progressive development of pillar deformation, stress redistribution, plastic strain localisation and bolt load mobilisation throughout the excavation sequence. Unlike the previous study, the modelling framework explicitly captures the interaction between the yielding pillar and the installed support, enabling assessment of bolt capacity utilisation and support performance under realistic construction conditions. The results identify localised zones of elevated strain and evaluate the effectiveness of the installed rockbolts in providing confinement and enhancing the residual load-bearing capacity of the temporary pillar. Based on these findings, the support layout is optimised to improve pillar performance and maximise the efficiency of the ground support system.

Keywords: *slender pillar, yielding pillar, glass-fibre bolt, FLAC3D*

1 Introduction

Pillar behaviour is strongly influenced by its width-to-height (W/H) ratio, although rock mass quality, in situ stress, excavation sequence and the confinement provided by ground support also play important roles. General guidance on pillar behaviour based on underground mining observations and authors' field experience is summarised in Table 1.

Temporary slender pillars (W/H < 1.0) are occasionally adopted in large underground caverns where construction constraints or excavation sequencing prevent immediate full-span excavation. Compared with squat pillars, slender pillars experience lower confinement and are therefore more susceptible to stress concentration, brittle axial splitting and/or shear failure and excessive deformation. Consequently, their design requires careful consideration of both pillar stability and the interaction between the pillar and the ground support system.

Rather than preventing all post-peak deformation, slender pillars may be intentionally designed as yielding pillars, allowing controlled post-peak deformation while maintaining sufficient residual load-bearing capacity to support the excavation throughout its temporary service life. In this study, yielding refers to the

* Corresponding author. Email address: hxu@srk.com

development of plastic deformation and associated stress redistribution within the pillar and does not necessarily imply pillar failure or instability. The yielding pillar concept promotes stable stress redistribution and reduces the likelihood of sudden brittle failure of the pillar (i.e. loss of loading capacity), enabling adjacent excavation to proceed safely. This design philosophy has been successfully applied in deep hard rock mines in the Canadian Shield (Hedley 1992) and South African gold mines (Ortlepp 1997). In these applications, reinforcement provides lateral confinement to fractured rock, suppresses brittle failure and promotes progressive yielding, thereby enhancing the residual load-bearing capacity of the pillar.

Accordingly, the objective of ground support design for yielding slender pillars is not to eliminate yielding, but to control the deformation process by providing adequate confinement. An effective reinforcement system should maintain pillar integrity, increase residual load-bearing capacity and ensure excavation stability throughout the design life of the temporary excavation.

Table 1 General relationship between pillar width-to-height (W/H) ratio and pillar behaviour (adapted from Xu et al. 2026)

W/H	Typical pillar behaviour	Design implication
<0.5	Very slender pillar	Low confinement; prone to brittle splitting, shear, buckling or unstable failure
0.5–1.0	Slender yielding pillar	Rapid yielding may occur. With adequate confinement from rockbolts or other support, controlled yielding and progressive crushing can be achieved while maintaining residual capacity
1.0–2.0	Intermediate pillar	High peak strength but may exhibit significant energy release during post-peak yielding. Yielding pillars within this range should be used with caution where extraction ratios are high or the local mine stiffness is low
>2.0	Squat pillar	High confinement and stiffness. Failure is generally dominated by progressive compressive crushing rather than brittle instability. Sudden pillar failures become increasingly uncommon as W/H increases
4.0–5.0	Regional support pillar	Commonly adopted for permanent regional stability. The large pillar width also reduces the likelihood that major geological structures completely intersect the pillar

Salari et al. (2025) demonstrated the feasibility of adopting yielding slender pillars in a temporary deep cavern excavated in low-strength sandstone using a combination of empirical pillar assessment and numerical modelling. While the study confirmed the effectiveness of the yielding pillar concept, the assessment focused primarily on overall pillar stability and provided limited insight into the interaction between the yielding pillar and the installed ground support throughout the excavation sequence. Consequently, the evolution of strain localisation, support mobilisation and reinforcement demand during construction remained largely unexplored.

This paper extends the work of Salari et al. (2025) by investigating the interaction between temporary yielding pillars and ground support throughout the excavation sequence. Particular emphasis is placed on the evolution of pillar deformation, strain localisation, bolt mobilisation and support performance, with the aim of providing a more comprehensive understanding of yielding pillar behaviour and informing the design of temporary ground support systems.

2 Proposed framework

Salari et al. (2025) proposed a design methodology for temporary yielding slender pillars in massive sandstone by integrating empirical pillar strength assessment with numerical modelling. The methodology comprised three principal components:

1. Empirical estimation of pillar strength using the approaches proposed by Martin & Maybee (2000) and Esterhuizen et al. (2011).
2. Estimation of average pillar stress using an elastic FLAC3D model of the fully excavated cavern to determine the Factor of Safety (FoS).
3. Displacement-controlled single-pillar strength analyses to evaluate the influence of glass-fibre-reinforced polymer (GFRP) bolt reinforcement on the pillar failure mechanism. In the displacement-controlled single-pillar analyses, prescribed displacement was applied to progressively load the pillar and evaluate its load–deformation response and failure mechanism.

The analyses indicated that GFRP reinforcement promoted a more progressive post-peak response and increased the energy absorption capacity of the pillar. The previous study demonstrated that GFRP bolts provide confinement, suppress inclined shear failure and promote progressive crushing, enabling the slender pillar to behave as a yielding pillar throughout the temporary excavation period. While this approach provided an effective basis for assessing overall pillar stability, the cavern-scale model only represented the fully excavated geometry and did not explicitly simulate the staged excavation sequence or installation of reinforcement. Consequently, the progressive redistribution of pillar stress and the pillar–support interaction and reinforcement performance were not captured.

Building upon this methodology, the present study develops a staged three-dimensional FLAC3D modelling framework that explicitly simulates the excavation sequence and installation of pattern GFRP bolts. Unlike the displacement-controlled single-pillar analyses, the staged model explicitly simulates the actual excavation sequence and progressive installation of GFRP reinforcement, enabling the evolution of pillar stress, deformation and support mobilisation during excavation to be evaluated. Two numerical models were developed:

1. An unsupported pillar model
2. A reinforced pillar model incorporating the actual construction sequence.

Unlike the previous assessment, the staged analyses capture the progressive interaction between excavation, pillar response and ground support throughout construction. The framework enables evaluation of pillar deformation, plastic strain localisation and bolt capacity utilisation, providing a rational basis for assessing support performance and optimising the rockbolt layout by targeting zones of concentrated strain. The overall methodology adopted in this study is summarised in Figure 1.

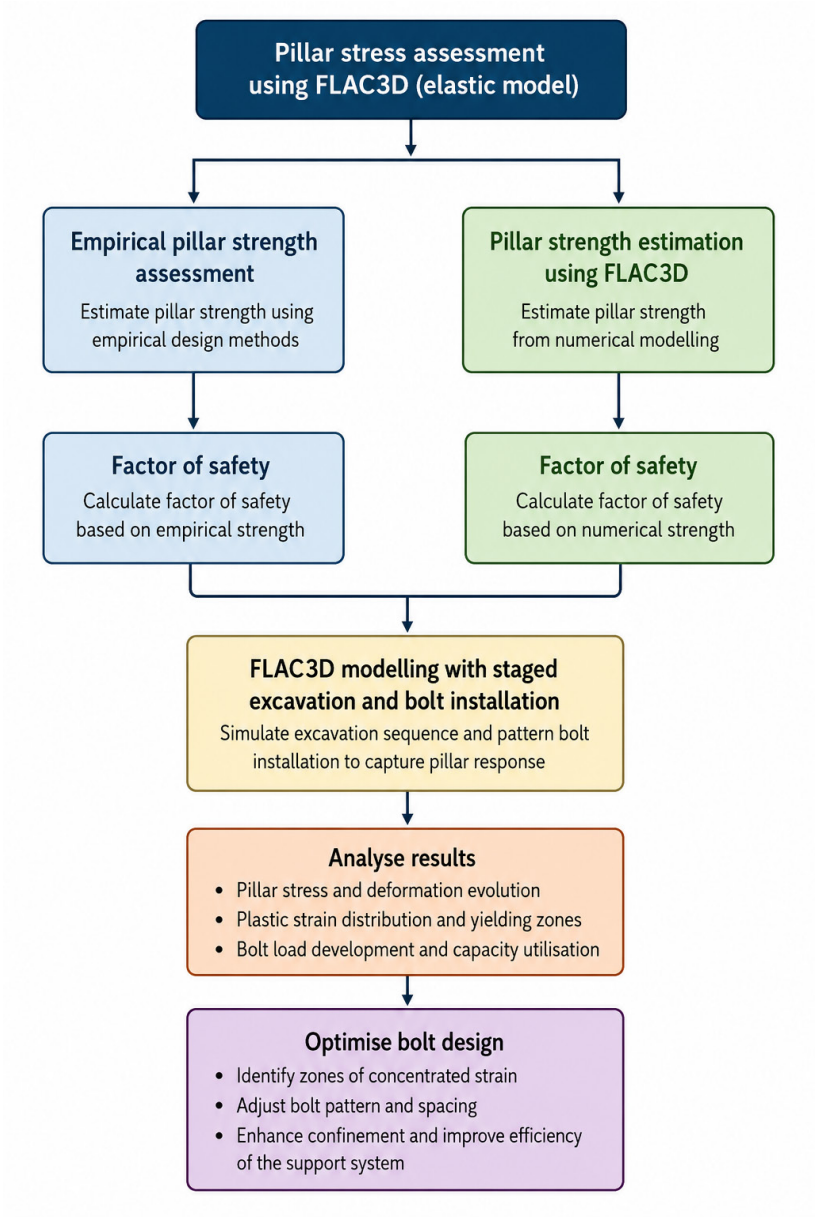


Figure 1 Proposed methodology for the assessment and optimisation of temporary yielding slender pillars using staged FLAC3D modelling

3 Modelling methodology

The design parameters reported by Salari et al. (2025) form the basis of the present study. The adopted geometry, material properties and staged excavation sequence are described in the following sections.

3.1 Cavern dimension and parameters

The case study is based on the temporary deep cavern presented by Salari et al. (2025), located approximately 100 m below ground level at the base of a shaft excavation. The cavern is excavated within a massive, sub-horizontally bedded sandstone formation and is temporarily supported by 2 slender rock pillars during the construction sequence. The pillar geometry, cavern dimensions (as shown in Table 2) and excavation sequence adopted in the numerical model are consistent with the original design.

Table 2 Temporary pillar dimensions and width-to-height ratios adopted from Salari et al. (2025)

Pillar no.	Pillar width, W (m)	Pillar length, L (m)	Pillar height, H (m)	Width-to-height ratio (W/H)
1	3.5	4.25	7.5	0.47
2	4.0	5.5	7.5	0.53

Note: W/H is calculated using the pillar width (W) consistent with the pillar strength assessment adopted from Salari et al. (2025). Pillar length (L) is not included in the W/H calculation

For the numerical modelling undertaken in the previous study presented by Salari et al. (2025), equivalent Mohr–Coulomb strength parameters with strain softening were adopted. The equivalent Mohr–Coulomb strain softening parameters adopted from Salari et al. (2025) are summarised in Table 3. The Hoek–Brown input parameters and derivation of the strain softening relationship are provided in Salari et al. (2025) and are not repeated here.

Table 3 Equivalent Mohr–Coulomb parameters for strain softening model adopted from Salari et al. (2025)

Plastic strain	0	0.005	0.0051	1
Cohesion (kPa)	619	619	61	61
Friction angle (°)	50	50	35	35
Tensile strength	100	100	10	10

3.2 Staged excavation and support installation

A three-dimensional FLAC3D model was developed to reproduce the project geometry and simulate the staged excavation sequence adopted during construction. A characteristic zone size of approximately 0.5 m was adopted within the pillar region. Excavation was modelled in accordance with the construction methodology, with pattern GFRP rockbolts installed at the corresponding excavation stages. Explicit simulation of the excavation and support installation sequence enables realistic representation of the interaction between the temporary yielding pillars and the ground support system throughout construction. Excavation was simulated by assigning a null constitutive model to the zones corresponding to each excavation stage. Following each excavation and support installation stage, the model was solved to equilibrium using a convergence ratio criterion of 1×10^{-5} before proceeding to the subsequent stage

The geometry and dimensions of the temporary cavern and slender pillars are illustrated in Figure 2. Excavation progressed horizontally following the sequence shown in Figure 2, with the temporary pillars retained to provide intermediate support during cavern development. The final cavern height of 7.5 m was achieved in 2 excavation lifts. The upper 4.0 m heading was excavated using a roadheader, followed by excavation of the lower 3.5 m bench. In the case with bolt support, pattern GFRP rockbolts were installed immediately after completion of each heading in accordance with the construction sequence before subsequent excavation stages commenced. GFRP reinforcement was adopted for the temporary pillars to provide confinement during controlled yielding while facilitating subsequent excavation through the reinforced pillars. The bolts were therefore intended to maintain pillar integrity and residual load-bearing capacity during the temporary service period, rather than to act as highly deformable yielding support elements. 1.5 m GFRP bolts were installed at 1.0 m horizontal spacing and 2.0 m vertical spacing. The bolt parameters were summarised in Table 3.

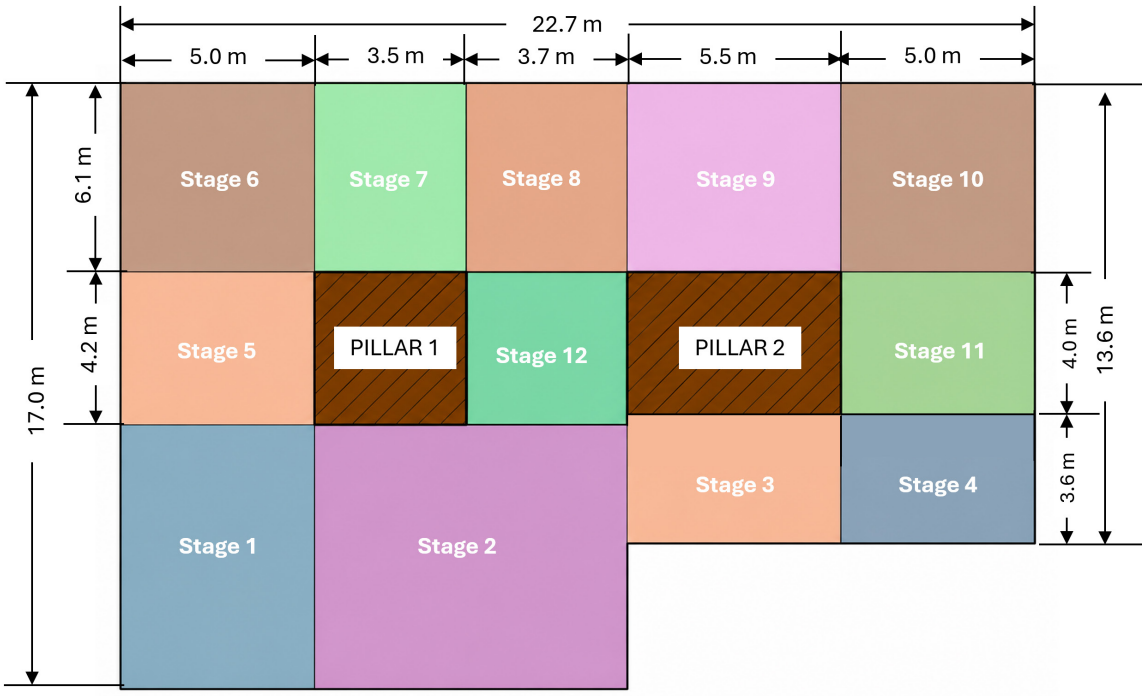


Figure 2 **Plan view of the temporary shaft cavern and staged excavation sequence adopted in the FLAC3D model. The coloured blocks indicate the excavation stages, while the shaded brown regions with hatch represent the temporary slender pillars**

Table 4 **Glass-fibre bolt parameters adopted in FLAC3D models adopted from Salari et al. (2025)**

Properties	Value
Bolt Young's modulus (GPa)	61
Bolt tensile yield strength (N)	315
Bolt diameter (mm)	32
Grout cohesion (N/m)	125.66
Grout friction (°)	35
Grout stiffness (N/m/m)	12.67×10^9
Grout perimeter (m)	0.157

4 Analysis results

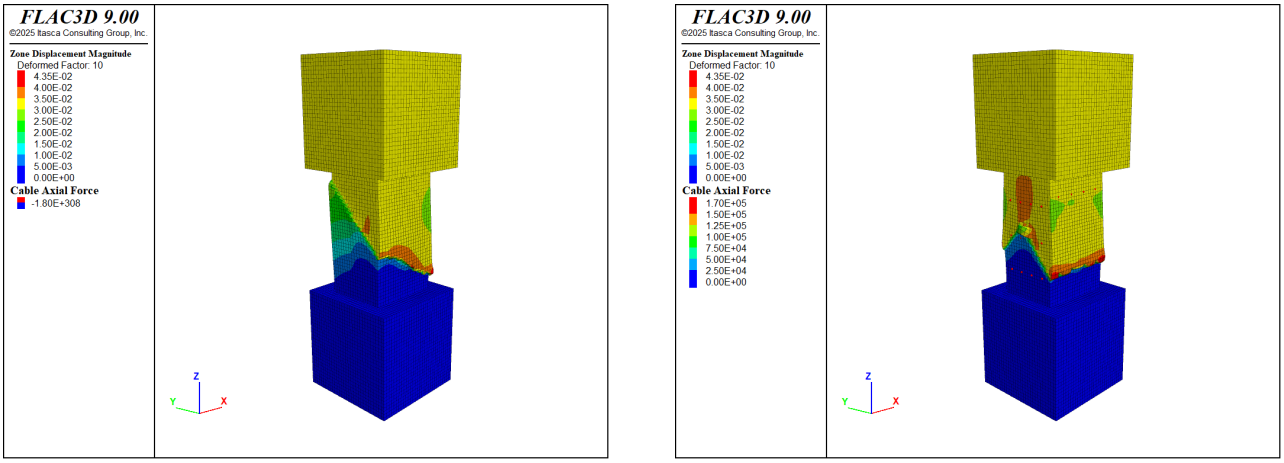
The FoS calculated using the empirical methods are summarised in Table 5. The displacement-controlled single-pillar analyses of Pillar 1, previously presented by Salari et al. (2025), are reproduced in Figure 3 to illustrate the influence of GFRP reinforcement on the predicted post-peak pillar response. These analyses are independent of the staged cavern excavation sequence presented in the current study. The unsupported pillar (Figure 3a) exhibited more localised deformation, whereas the reinforced pillar (Figure 3b) developed a more distributed progressive crushing mechanism. These previous results provide a reference for interpreting the behaviour of the reinforced pillars in the staged cavern-scale analyses presented below.

The response the of unsupported pillar is characteristic of slender pillars with limited lateral confinement, where stress concentrations promote localised shear failure as yielding develops. In contrast, the pattern GFRP reinforcement provides additional lateral confinement and promotes a more distributed progressive crushing mechanism, consistent with the intended yielding pillar design philosophy. This controlled yielding enables the pillar to continue carrying load beyond the onset of plastic deformation, thereby maintaining

sufficient residual load-bearing capacity throughout the temporary service life of the shaft excavation. Salari et al. (2025) reported that the GFRP bolt reinforcement increased the pillar toughness (energy absorption capacity) by approximately 22%. Although the reinforced pillar strength remained lower than the estimated pillar stress, indicating that yielding still occurred, the additional confinement provided by the GFRP bolts delayed failure and enabled the pillar to sustain larger deformations while maintaining stability.

Table 5 Results of temporary pillar stability assessment (Salari et al. 2025)

Pillar no.	Pillar width (m)	Pillar height (m)	UCS (MPa)	Average pillar stress (MPa)	Martin & Maybee (2020)		Esterhuizen et al. (2011)	
					Pillar strength (MPa)	FOS	Pillar strength (MPa)	FOS
1	3.5	7.5	12	4.3	3.8	0.90	3.5	0.80
2	4.0	7.5	12	4.0	3.8	0.95	3.6	0.9



(a) (b)

Figure 3 Comparison of the failure mechanisms from the displacement-controlled single-pillar analyses of Pillar 1 presented by Salari et al. (2025) (Deformation factor = 10). (a) The unsupported pillar; (b) The pillar reinforced with pattern glass-fibre-reinforced polymer bolts. Reproduced from Salari et al. (2025)

In the staged excavation analyses, the average vertical stress within the pillar increased slightly from 4.08 MPa in the unsupported case to 4.18 MPa in the GFRP bolt-supported case. This difference is relatively small but indicates that the reinforced pillar retained marginally greater load-bearing capacity after excavation. The installed GFRP bolts provided confinement, suppressed localised shear failure and promoted a more distributed yielding mechanism.

The influence of GFRP reinforcement on strain localisation was further examined using the maximum principal strain increment, as shown in Figure 4. In both the unsupported and reinforced cases, strain localisation is concentrated within the upper portion (heading level) of the pillar, reflecting the adopted excavation sequence. The upper 4.0 m heading was excavated before the lower 3.5 m bench, resulting in earlier exposure, stress redistribution and deformation within the upper section of the pillar. Consequently, greater strain accumulation occurs in the upper portion of the pillar than in the lower bench, which was excavated at a later stage. Compared with the unsupported pillar (Figure 4a), the installation of pattern GFRP bolts (Figure 4b) reduces the degree of strain localisation by providing additional confinement to the fractured rock mass.

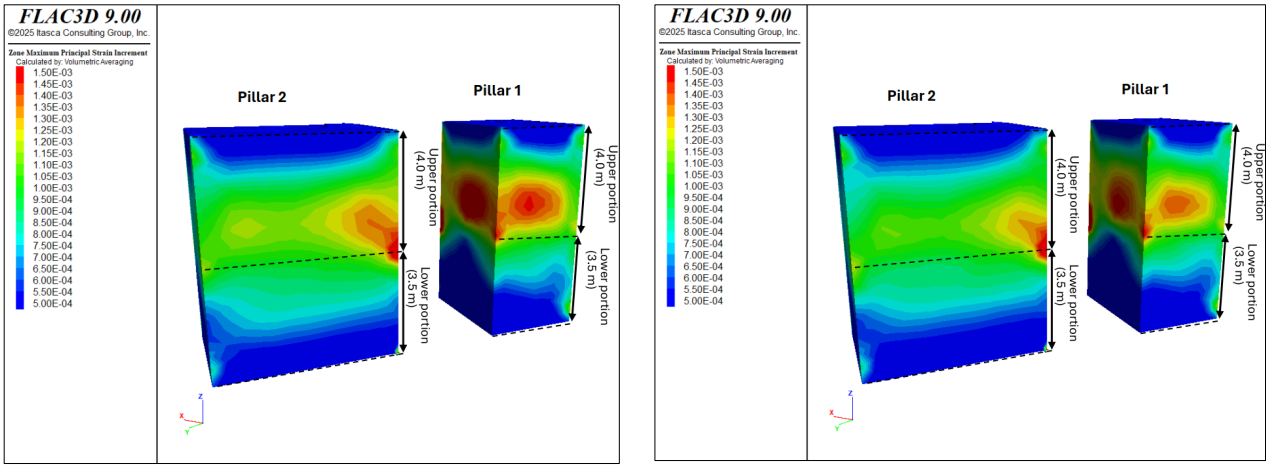


Figure 4 Distribution of maximum principal strain increment in Pillars 1 and 2 at the end of the staged excavation sequence. (a) The unsupported pillar; (b) The pillar reinforced with pattern glass-fibre-reinforced polymer bolts. The reinforced pillar undergoes less localised strain

The concentration of strain within the upper portion (heading level) of the pillar has important implications for ground support design. As this region experiences the earliest and greatest deformation during the excavation sequence, it represents the critical zone for support mobilisation. This behaviour is reflected in the axial force distribution of the GFRP bolts shown in Figure 5, where the highest bolt loads are concentrated within the heading level portion of the pillar. The staged numerical model therefore provides a rational basis for assessing bolt demand and optimising the support layout by targeting reinforcement in regions of concentrated strain, rather than adopting a uniform bolt pattern throughout the pillar.

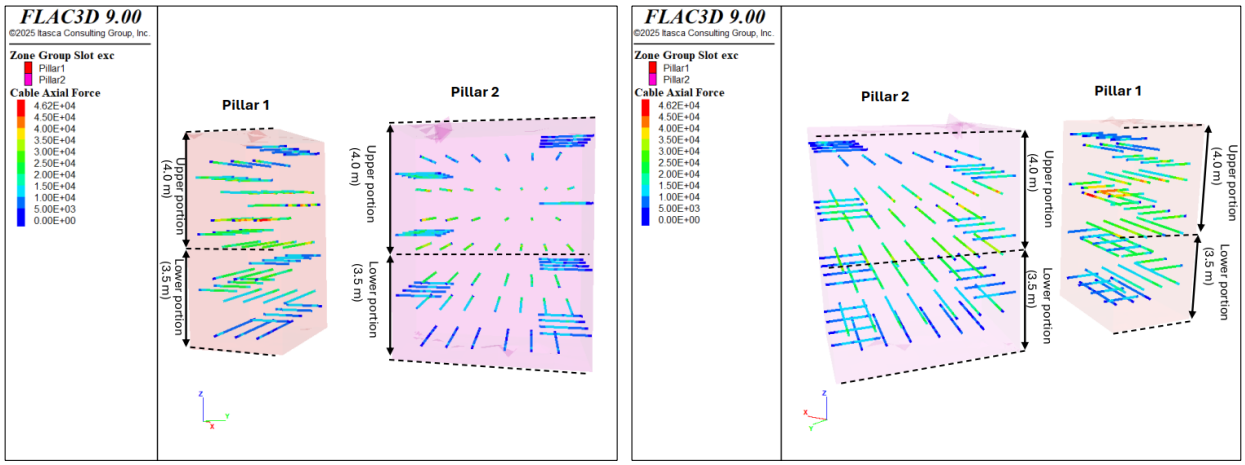


Figure 5 Distribution of axial forces in the pattern glass-fibre-reinforced polymer bolt system at the completion of the staged excavation sequence. Higher bolt forces are concentrated within the upper heading level portion of the pillar, corresponding to the critical yielding zone. (a) Northwest view; (b) Southeast view, corresponding to the same viewpoint as Figure 4

5 Conclusion

This paper extends the temporary slender pillar design methodology proposed by Salari et al. (2025) through the development of a staged three-dimensional FLAC3D modelling framework that explicitly simulates excavation and pattern GFRP bolt installation. The proposed framework captures the progressive evolution of pillar stress redistribution, deformation, plastic strain localisation and bolt mobilisation throughout

construction, providing insight beyond conventional empirical and simplified numerical assessments. The modelling results enable quantitative evaluation of bolt capacity utilisation and identify critical zones requiring additional confinement, providing a rational basis for optimising support layouts and improving the efficiency of temporary ground support systems.

Acknowledgement

The SRK Consulting author acknowledges our colleague William Joughin (SRK Consulting, Johannesburg) for his valuable insights into the yielding pillar concept in South African deep reef mining.

References

Esterhuizen, GS, Dolinar, DR & Ellenberger, JL 2011, 'Pillar strength in underground stone mines in the United States', *International Journal of Rock Mechanics and Mining Sciences*, vol. 48, no. 1, pp. 42–50.

Hedley, DG 1992, *Rockburst handbook for Ontario hardrock mines*, CANMET Special Publication SP92-1E, Canada Centre for Mineral and Energy Technology, Ottawa.

Martin, CD & Maybee, WG 2000, 'The strength of hard-rock pillars', *International Journal of Rock Mechanics and Mining Sciences*, vol. 37, no. 8, pp. 1239–1246.

Ortlepp, WD 1997, *Rock Fracture and Rockbursts: An Illustrative Study*, South African Institute of Mining and Metallurgy, Johannesburg.

Salari, S, De Silva, H, Narayana, M & Xu, C 2025, 'Temporary slender pillar design in low strength sandstone: a theoretical study on enhancing stability of temporary deep caverns', *Proceedings of the 19th Australasian Tunnelling Conference*, Australasian Tunnelling Society, Sydney, pp. 441–448.

Xu, Y-H, Ollila, B, Parsons, J, Joughin, W, Meyer, SG, Jakubec, J & Thomas, A 2026, 'Seismic hazard in deep hard rock mining: a brief comparison of stoping and caving experience', in A van As, D Cumming-Potvin & J Wesseloo (eds), *Caving 2026: Proceedings of the Sixth International Conference on Block and Sublevel Caving*, Australian Centre for Geomechanics, Perth, pp. 1–15, https://doi.org/10.36487/ACG_repo/2645_97