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Ground support for development in mine fill

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Abstract

Ground support design for development in mine fill remains a common yet technically challenging requirement in underground mining. Development in cemented rockfill (CRF), cemented aggregate fill (CAF), and paste fill (CPF) is often undertaken for short-life access drives, sometimes within complex stope geometries, or for permanent infrastructure, with performance influenced by variable fill material properties.

This paper presents learnings to assist with design and implementation of ground support when developing in mine fill, especially when using fibrecrete liners, mesh and friction bolts as the support system.

Two case studies are presented. The first case study is from Olympic Dam, Australia, detailing the evolution of ground support design for development in CAF. The second is from Cannington, Australia, which has many years of development in CPF. The case studies highlight practical learnings from long-term operational experience and demonstrate how design practices have been refined to align with current standards and improved understanding of cemented fill behaviour.

Keywords: *cemented rockfill, cemented aggregate fill, paste fill, ground support, underground development*

1 Introduction

Development in mine fill has become an increasingly common requirement in underground mining operations, particularly when access through previously filled stopes is required to recover adjacent ore zones. Excavations in mine fill are often required in differing stope geometries, variable curing conditions, and changing mining sequences. This creates ground control conditions that differ substantially from conventional development in rock.

Mine fill behaves, to varying extents, as an engineered material. The geotechnical behaviour of fill can vary significantly depending on fill type, binder content, curing time, placement method, exposure conditions, and interaction with the surrounding rock mass. Variability within the fill itself, including segregation, cold joints, and locally weak zones influence excavation stability. These factors can result in failure mechanisms that are not typically encountered in conventional underground development.

Development in fill has historically been approached using modified versions of conventional rock support standards, or by benchmarking and copying common support practice from other mines. In practice, this can result in support systems that do not adequately address the expected loading conditions, deformation mechanisms, excavation life, or operational requirements associated with development in fill.

Although development in cemented fill is now common practice at many underground mines, published guidance on ground support design remains limited. Consequently, support systems are often developed from operational experience rather than engineering methods that explicitly consider fill behaviour,

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excavation life and mining sequence. This paper presents practical learnings from 2 long-term operations to assist the design and implementation of ground support for development in cemented fill.

2 Development in mine fill: ground support learnings

2.1 Do we need to install friction bolts in mine fill development?

There is conjecture among geotechnical mine site professionals regarding the effectiveness and need for friction bolts in a homogeneous cemented fill mass. In the case of cemented paste fill (CPF), friction bolts are hammered in to provide resistance and retain isolated slabs of paste created by potential cold/flow joints. They also help retain the mesh/fibrecrete surface support in the case of potential delamination. Friction bolts in cemented rockfill (CRF) are used for similar reasons, but due to rock fragments within the fill they are usually installed into full length pre-drilled holes.

Pull testing was conducted on a number of 0.9 m long friction bolts (effective length of 0.75 m) as well as several 39.8 mm friction bolts which were cut to 1 m length and installed in CPF at the Cannington mine (Li et al. 2011). The test results suggest that the friction bolts installed in the CPF could generate a pull-out capacity of 60 kN/m (6 t/m), depending on the cement content and curing age.

Several trials of various types of rockbolts installed in CPF were conducted at the Lanfranchi mine (Foster et al. 2011). The outcome of these trials was the use of a 2.4 m galvanised friction bolt without the tapered end as the first pass support requirement. The jumbo would drill the hole approximately 1 m into the paste fill and then install the untapered bolt into the paste fill using conventional percussion and rotation. The pull test results typically achieved 7–8 tonnes (~3 t/m) before slippage. In some instances where the cement content was lowered to achieve a lower strength CPF, the need for the collar hole became unnecessary with the bolt being pushed directly into the paste.

Friction bolts can be explicitly simulated in the numerical modelling code FLAC3D (Itasca 2023). A series of analyses were conducted on a CPF filled stope to understand the impact of fill strength, cold jointing and friction bolt support effectiveness (1.5 × 1.5m spacing) on CPF development stability. Figure 1 presents the numerical model geometry. The CPF development was modelled with short cuts and cold jointing was explicitly simulated with Mohr–Coulomb sliding interfaces. The shear strength of the cold joints was conservatively represented with zero cohesion, friction angle of 15° and zero tensile strength.

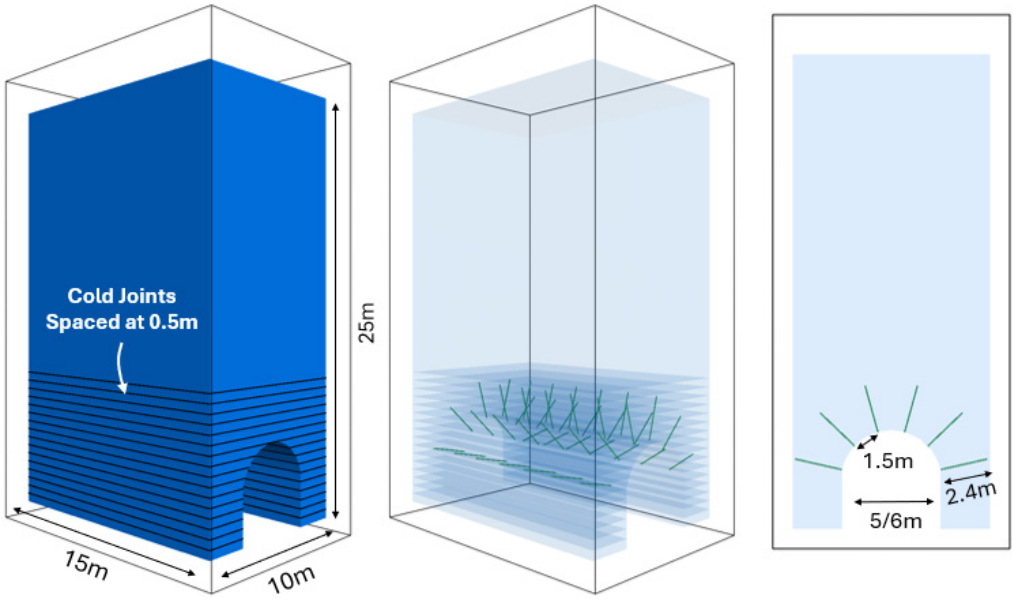


Figure 1 Paste development model with friction bolts

Figure 2 presents the effectiveness of friction bolts in 150 kPa CPF with 0.5 m spaced cold joints. Without friction bolts, collapse of the thin 0.5 m paste beams is predicted. Friction bolts simulated with 4 t/m capacity are observed to stabilise the CPF development and undergo very minor slip. Friction bolts simulated with 2 t/m capacity are observed to stabilise the CPF development, however significant slippage of the friction bolts is predicted.

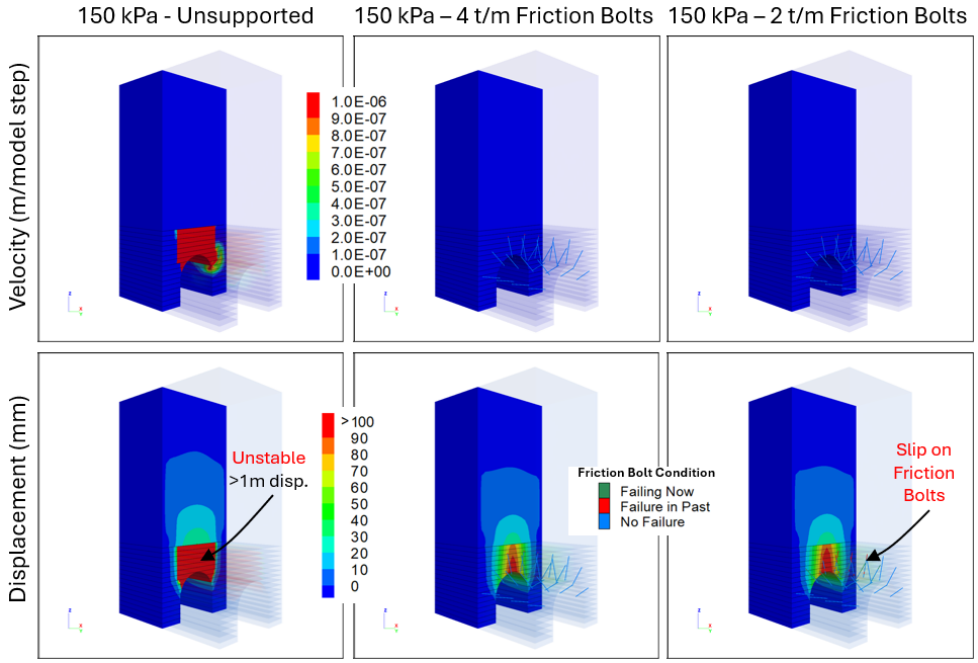


Figure 2 Effectiveness of friction bolt capacity in cemented paste fill

2.2 Behaviour of fibrecrete liners in cemented fill: do we need mesh as well?

The behaviour of fibrecrete linings depends on the age of the lining, geometric aspects of design, ductility of the fibre-concrete composite, and interaction with the mine fill surface. Fibres are critical to ductility, which indirectly affects the interaction between the lining and the mine fill surface by facilitating a redistribution of load away from cracked regions toward more structurally competent regions.

Barrett & McCreath (1995) showed that the critical failure mode of fibrecrete liners is the loss of adhesion to the substrate. Due to the inherent weak and friable nature of cemented fill surfaces, it can be difficult for a freshly sprayed fibrecrete lining to stay in place as it hydrates. Trials of fibrecrete applied to the CPF backs of an underhand drive were conducted at the Lanfranchi mine (Foster et al. 2011). The results of these trials indicated that the fibrecrete was not effectively adhering to the CPF as it does with rock. As such, installation of mesh is typically required to act as additional support to prevent falling out before the fibrecrete had gained sufficient strength.

Due to the significant stiffness contrast between fibrecrete and cemented backfill materials, in long-term backfill development scenarios, whereby adjacent mining causes stress redistribution and relatively minor deformation within the fill mass, a fibrecrete liner that is intended as surface support can become the primary fall-of-ground hazard due to delamination and cracking of the fibrecrete. Fibrecrete linings with friction bolts may be suitable as a standalone support system in some short-term applications. At operations where excavations are required to remain serviceable for longer periods, or where progressive deterioration is anticipated, the more common liner practice is to install mesh within or over the fibrecrete lining in combination with friction bolts to provide additional reinforcement and long-term support capacity.

2.3 Fibrecrete strength and deformation characterisation

Fibrecrete quality control in underground operations is typically specified to achieve 40 MPa uniaxial compressive strength (UCS) after 28 days curing, while round determinant panel (RDP) tests (ASTM International 2004) are specified to achieve an energy absorption of 350 to 400 Joules at 40 mm deflection. In many mines, testing of cast fibrecrete cylinders indicates that the actual fibrecrete strength achieved is generally between 50 and 60 MPa, as illustrated in Figure 3. Typically, the stress-strain response of routine UCS testing is not recorded and therefore the Young's modulus of the fibrecrete, which is a fundamental design parameter, is often required to be estimated from established relationships. When developing in mine fill, or expecting to do so in the future, building a database of modulus testing is recommended, to capture the modulus on approximately 10% of scheduled UCS tests.

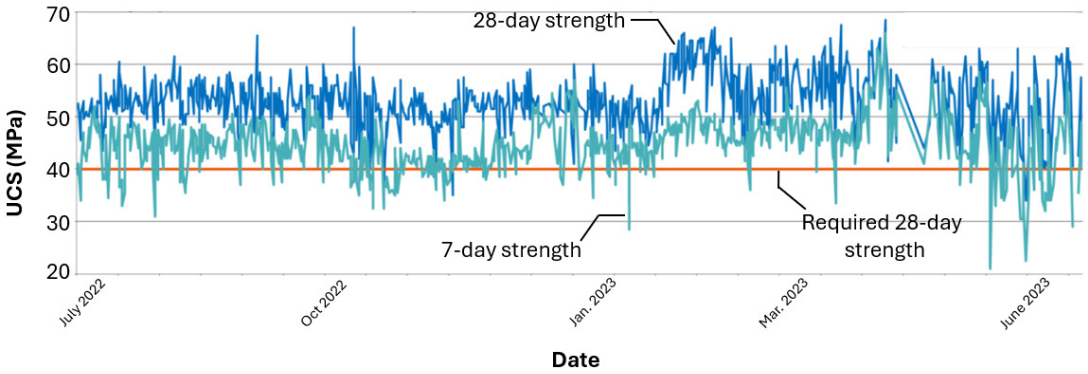


Figure 3 Olympic Dam fibrecrete cylinder strengths July 2022–June 2023

During routine quality control tests, the load-deflection curve from RDP tests may not be recorded, which prevents detailed analysis of the fibrecrete flexural response for design purposes. Ensuring the load-deflection curve is recorded and presented ensures that data is available for model back-analysis or for accurately selecting residual fibrecrete strength ranges.

While extensive literature exists on the compressive and flexural strength of fibrecrete material, the authors are unaware of any published research regarding the adhesion behaviour between sprayed fibrecrete and paste fill surfaces. Bertuzzi & Pells (2002) suggest 1 MPa adhesion is readily achieved in good quality sandstone, while Seymour et al. (2010) report that typical adhesion values in underground mines range from about 0.2 to 1.5 MPa. In lieu of actual adhesion test results with cemented backfill substrates, 0.2 MPa has been adopted for CPF and 0.4 MPa for cemented aggregate fill (CAF) and CRF materials.

2.4 Design of fibrecrete liners

Many fibrecrete lined tunnels in rock are designed using empirical methods (Barton et al.1974; Barton & Grimstad 2004; Norwegian Geotechnical Institute 2013) or by relatively simple analytical methods (Thomas 2009, 2014) that only consider the gravity loading of isolated rock blocks.

When designing fibrecrete ground support for development in cemented fill, simple numerical models are typically used. There are significant issues to acknowledge if this is the chosen approach, with the main issue being that the methods are unable to account for the actual failure mechanisms. For thin fibrecrete liners (<200 mm), the lining is commonly modelled using linear-elastic beam or plate elements so the post-peak ductile capacity of the fibrecrete is not considered. In most analysis cases the simulated fibrecrete elements are rigidly connected to the ground surface, completely ignoring adhesion. This means that the re-distributive capacity associated with fibre reinforcement is not simulated directly in the models to account for possible interaction and redistribution of load between the lining and ground. The results are typically plotted on an N-M (axial force-bending moment) interaction diagram and compared to available capacity prescribed in international design standards that most commonly reveal only the peak moment-axial load. Figure 4 presents an example N-M diagram for fibrecrete liner design in CRF development based on rigidly attached elastic liner forces and 2D analytical capacity curves defined by Carranza-Torres & Diederichs (2009).

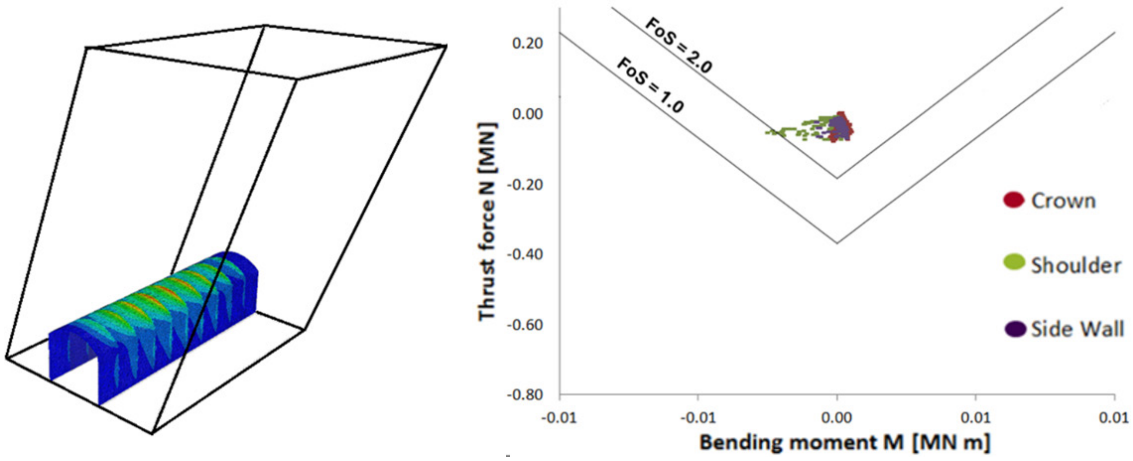


Figure 4 Example of an N-M interaction diagram for a fibrecrete design in cemented rockfill development

Burman et al. (2018) reports that the design of fibrecrete liners based solely on elastic behaviour was judged as unacceptable in any realistic model of tunnel collapse during litigation proceedings into the Lane Cove Tunnel collapse in 2005. Furthermore, the restriction of analytical capacity analysis based solely in the 2D radial (or hoop) section of a tunnel is fundamentally flawed as this completely ignores the often complex out-of-plane (or longitudinal) forces that develop during the initial placement and subsequent loading of fibrecrete liners.

To overcome these fundamental fibrecrete liner design and analysis issues, the recently developed plastic liner element logic in the numerical modelling code FLAC3D Version 9.0 (Itasca 2023) can be used to calibrate the ductile tensile and shear softening behaviour of fibrecrete material. Figure 5 presents the response of a simulated RDP calibrated to match the typical load-deflection response of an RDP test with a UCS of 40 MPa.

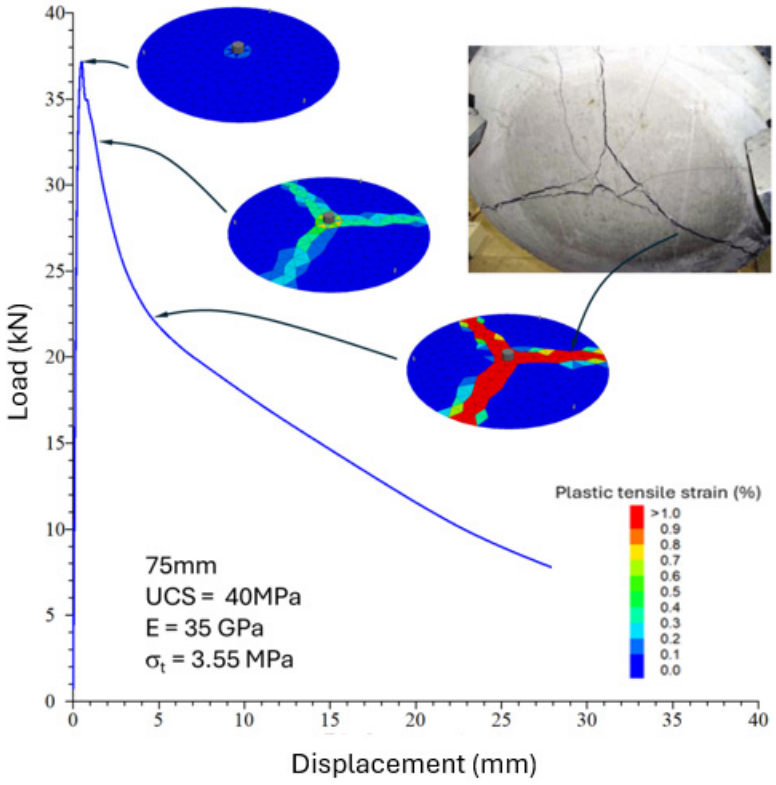


Figure 5 Response of simulated round determinant panel with liner elements in FLAC3D

Plastic tensile strain of less than 1% in the numerical simulation is interpreted to represent hairline cracking of the cementitious material, with tensile capacity retained by the embedded fibres. Plastic tensile strain greater than 1% is interpreted as cracking greater than 5 mm with minimal tensile capacity.

2.5 Ground support design for cemented rockfill development

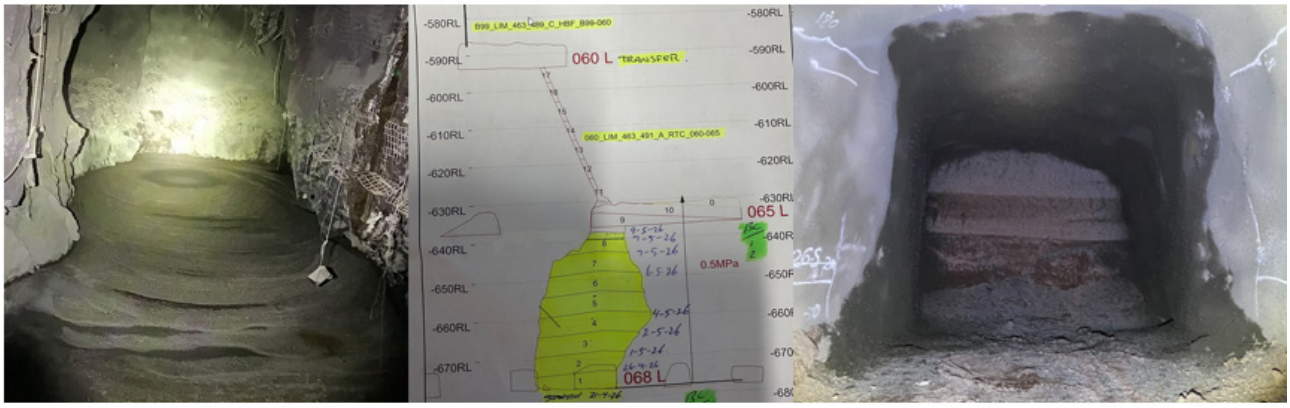
Ground support design for development in CRF differs from CPF and some CAF applications. CRF generally involves limited screening and control during preparation, with the fill comprising of variable size rock fragments mixed with cement slurry in a sump near the stope void. As a result, some variability in the placed fill and its engineering properties is unavoidable.

Inconsistent ground support performance in CRF is often associated with variability in CRF constituents, mixing and placement, rather than deficiencies in the support design itself. Inadequate plans, supervision and quality control during CRF placement can result in poorly consolidated fill and uncemented zones that significantly influence excavation stability. Successful ground support performance in CRF relies not only on an appropriate design, but most importantly on consistent fill preparation, placement practices, supervision and quality control.

3 Olympic Dam: cemented aggregate fill development

3.1 Cemented aggregate fill background at Olympic Dam

Olympic Dam is an iron oxide-copper-gold deposit mine, situated in South Australia, producing approximately 11 MT per annum. It undertakes a sublevel open stoping mining method where stopes range from single lift (30 m tall) to multi-lift (up to 260 m tall), with an average footprint of 30 × 30 m. Approximately 50 mined stopes per annum are backfilled using CAF (Figure 6a shows placed CAF within a stope). The CAF plant produces 2.4–2.5 Mm^3 of CAF per year, with CAF transferred to stopes from surface via a borehole network. Olympic Dam CAF consists of either deslimed tailings or dune sand, 40 mm limestone aggregate, water and cement.



a. Recently placed CAF b. Fill plan c. CAF supported drive

Figure 6 (a) Recently placed cemented aggregate fill (CAF) within a stope, (b) Fill plan (c) CAF drive fully supported

CAF strength is designed and monitored to ensure that fill masses are stable under the following conditions:

- during the mining of future adjacent stopes with vertical face exposures
- during the mining of access drives through the stope
- during the undercutting when mining a stope below the CAF filled stope.

Due to ventilation and scheduling constraints, development of access drives in CAF filled stopes is common practice. Olympic Dam develop approximately 5 km per annum through CAF and CAF filled drives. Strength guidelines for development in CAF are described in Table 1. CAF drives are typically 5 × 5 m semi-arch profile.

Drives are mined in 3 to 4 m cuts using drill and blast methods with controlled blast and perimeter holes. No intersections are formed within CAF development.

Table 1 Strength guidelines for the development in cemented aggregate fill (CAF)

Development type	Vertical location of development in CAF filled stope	Required CAF strength
Full development in CAF	Bottom 20 m of stope	2.0 MPa
	Top of stope to 30 m below the top	1.5 MPa
	Elsewhere in stope	1.0 MPa
Development stubbing into CAF	Anywhere in stope	1.0 MPa

Ground support for CAF development consists of 75 mm fibrecrete installed floor to floor, shown in Figure 6c. In poorer CAF masses, the thickness is increased to between 150 and 200 mm to prevent localised failures. Anecdotally, the increased surface roughness of CAF achieves a higher adhesion strength compared to CPF, as well as forming a full arch lining from floor to floor, negating the need for mesh reinforcement.

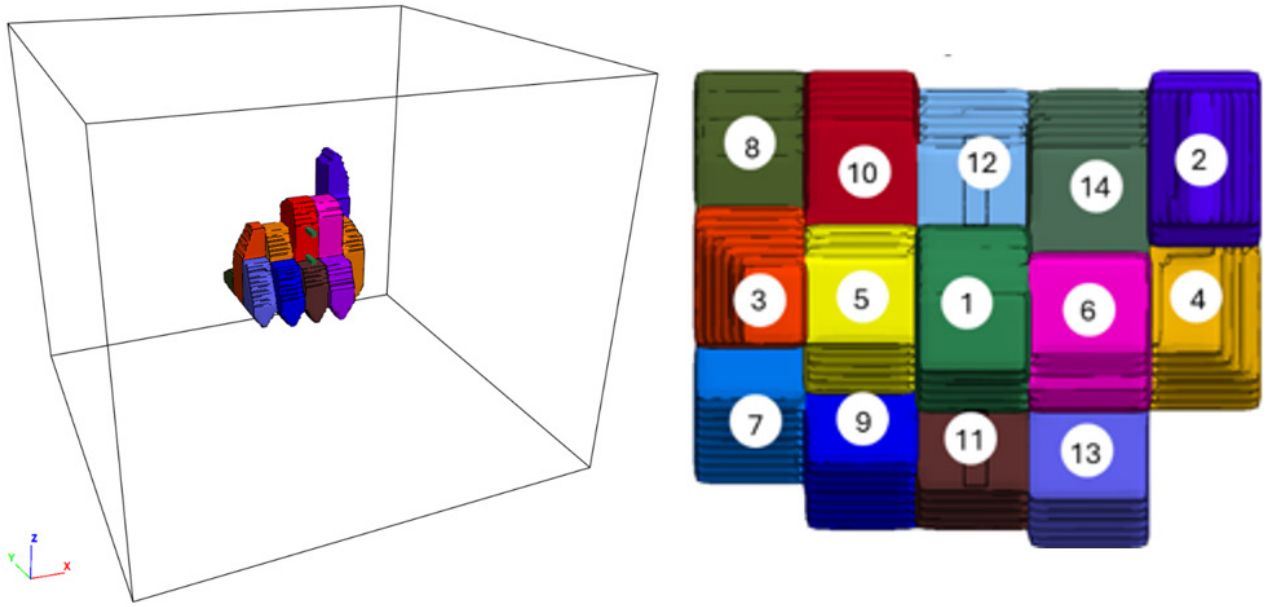
3.2 Cemented aggregate fill development fibrecrete cracking: 048_VIO_361_621 stope

During late 2022, minor fibrecrete cracking was observed in the 048_VIO_361_621 stope CAF development that had a fibrecrete thickness of 150 mm. Short to medium (2–5 mm) radial and longitudinal cracking was observed predominately along the right wall but was also observed in the left wall and backs (Figure 7a). New cracks were documented at each subsequent inspection. Inspection of the drive during June 2023 documented increased crack openings and the potential for fibrecrete delamination and fall-off (Figure 7b).



Figure 7 Fibrecrete cracking in 048_VIO_361_621 stope cemented aggregate fill development

To understand the CAF development fibrecrete cracking, a 3D model was constructed in FLAC3D to simulate typical CAF mining geometry and sequence. Figure 8 illustrates the model geometry and simulated extraction sequence. Within the model sequence, each stope is excavated and subsequently filled in 5 m increments with a filling algorithm that sequentially increases the strength and stiffness of the CAF material to simulate the internal stress distribution prior to CAF development.



a. CAF filling model – perspective view *b. CAF filling sequence – plan view*

Figure 8 FLAC3D cemented aggregate fill (CAF) model geometry

Figure 9 illustrates the response of two 5 × 5 m CAF drives after excavation of an adjacent primary stope (Stope 2) and exposure of 2 adjacent secondary stopes (Stope 6) and complete extraction sequence (Stope 14). Fibrecrete ground support was installed in-cycle within each 4 m advance of CAF development (150 mm thick, 40 MPa UCS, 0.2 MPa adhesion). Deformation at the crown of each drive is predicted to continuously accumulate throughout the excavation sequence as the internal stresses within the fill mass are redistributed during each subsequent fill mass exposure.

Minor (hairline) radial fibrecrete cracking is predicted during excavation of the single adjacent primary stope (Stope 2). After excavation of 2 adjacent secondary stopes (Stope 6) additional radial cracking is predicted to evolve, together with more significant longitudinal cracking in the lower CAF drive. At completion of the extraction sequence (Stope 14), further radial shear failure of the fibrecrete is predicted, primarily along the interface between the CAF and host rock mass.

The CAF development was predicted to remain stable, however the widespread fibrecrete cracking and its interaction poses a hazard for delamination and fall-off, as stoping is conducted around the primary stope containing CAF development. This is consistent with the evolution of fibrecrete cracking in the 048_VIO_361_621 stope CAF development.

This analysis highlights the importance of considering the location of the development within the fill column and the local excavation and filling sequence during ground support design. Ongoing void creation and filling alter the stress distribution within the fill mass, resulting in changing loading conditions that should be considered during design. Olympic Dam incorporated these learnings into the ground support design process.

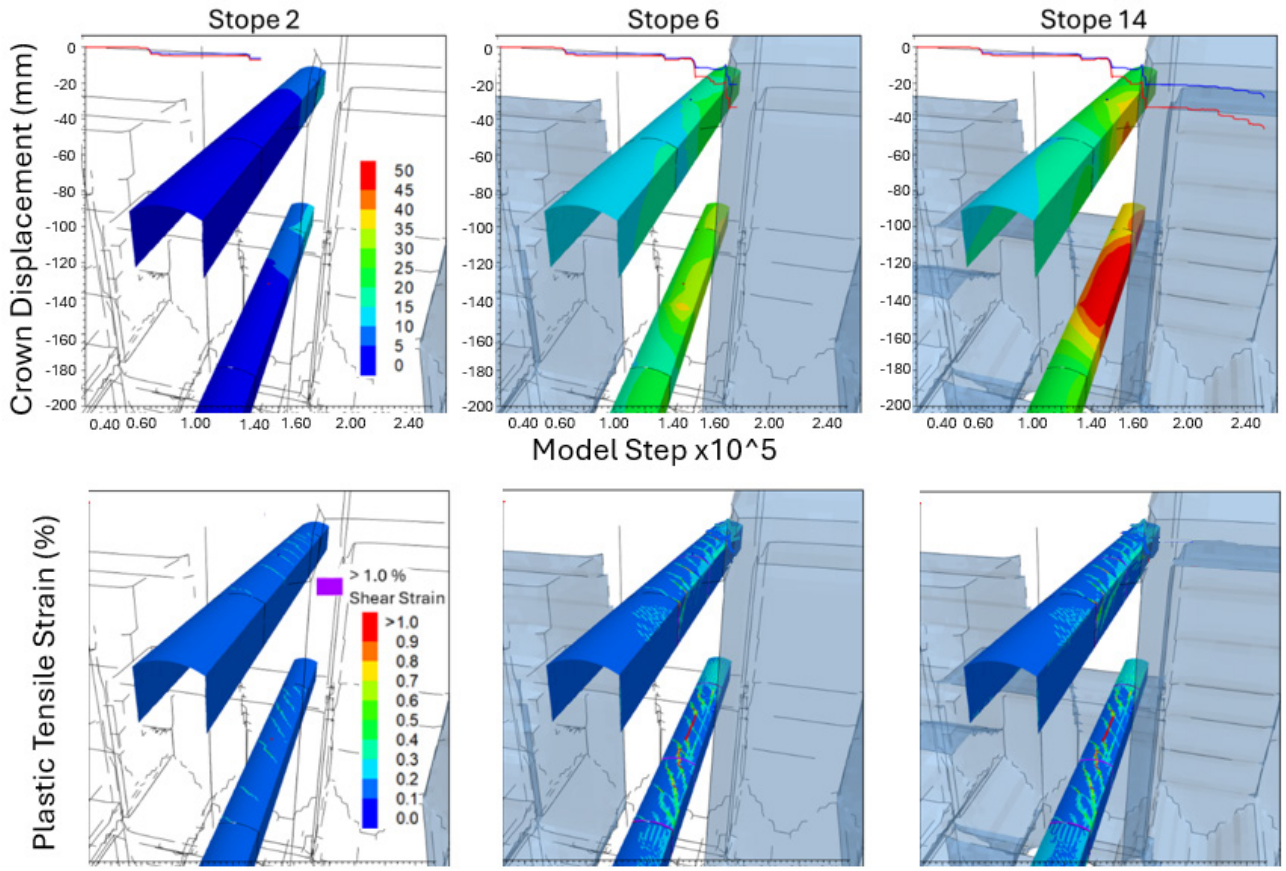


Figure 9 Predicted evolution of fibrecrete cracking throughout simulated extraction/filling sequence

4 Cannington mine: cemented paste fill development

Development in CPF is an essential part of the mining cycle at Cannington, which has been operating as an open stope, silver–lead–zinc mine for over 25 years. Cannington's mining strategy includes full ore extraction, meaning that all stope voids are paste-filled, cured and exposed by adjacent stopes. Rib pillars between stopes to promote stability are typically not included in the mine design. CPF production involves tailings slurry piped to the paste plant from the mill thickener at a solids percentage of 62–68 % solids, and a P80 of between 100–120 microns. The paste plant conditions the slurry to increase the solids percentage to 72–75% solids at which point binder is added in the paste holding hopper and mixed through. After mixing, the CPF is pumped underground via a reticulation system of steel and polypipe to the planned fill location.

4.1 Cemented paste fill development design and support considerations

Planned service life of CPF development varies from months in stoping areas to decades in areas where bypasses are required to provide transverse access from one side of the mine to the other. The number and extent of CPF bypasses at Cannington is a significant difference relative to many other underground mines. Figure 10 highlights an example of a paste development bypass on a typical mine level (375mLv).

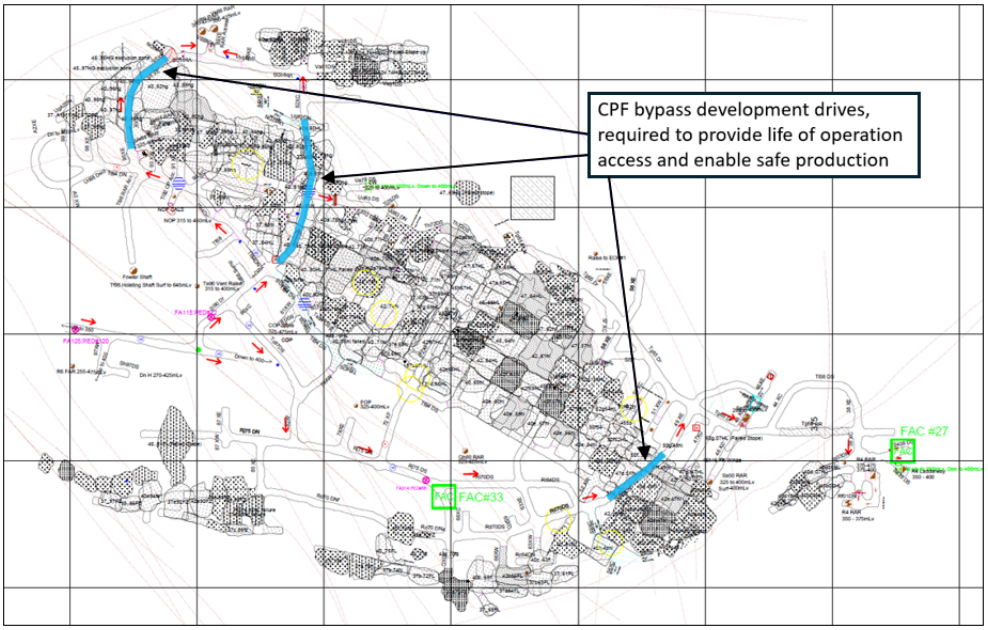


Figure 10 Plan view of 375mLv with cemented paste fill bypass development highlighted

CPF development design assessment during the mine planning process has evolved over time to reference a site-based risk matrix (shown in Figure 11), which considers the orientation of any paste/rock contacts, and the risks associated with the CPF quality, depending on the UCS QAQC data results.

	Low Risk Pastefill (LP)	Mod. Risk Pastefill (MP)	High Risk Pastefill (HP)
High Risk Geometry (HG)	HG/LP*	HG/MP*	HG/HP
Mod. Risk Geometry (MG)	MG/LP	MG/MP	MG/HP
Low Risk Geometry (LG)	LG/LP	LG/MP	LG/HP

Low Risk Minor Risk	Support as per Ground Support Selection Flowchart in UGCMP
Moderate Risk	Refer to RA007101, GE-0139 v4 and PRO-TS0137 Section 4.2.3.7. Additional controls* are likely required. Controls are to be adequate, ALARP and agreed upon amongst the Geotechnical, Mine Design and Operational Teams.
High Risk	Re-design or Further Risk Assessment Required

Figure 11 Cannington risk matrix for cemented paste fill development

4.2 Development advance and ground support implementation

The current CPF development advance cycle largely aligns with the mining-support regime described by Li et al. (2011), which comprises the following:

1. bore (Figure 12 shows a typical face boring pattern in CPF), charge, fire one 4.5 m cut and bog
2. spray the exposed paste with a coat of fibrecrete (50 mm thick) from floor to floor (Figure 13a)
3. wait for the fibrecrete to reach a UCS of 1 MPa, then install mesh over the fibrecrete using 2.4 m friction bolts from gradeline to gradeline
4. bore, charge and fire the next 4.5 m cut
5. bog the next cut; spray the first coat of fibrecrete (50 mm thick) for the existing cut from floor to floor, and then spray the second coat of fibrecrete, (50 mm thick) from floor to floor, over the mesh in the previous cut (Figure 13b).

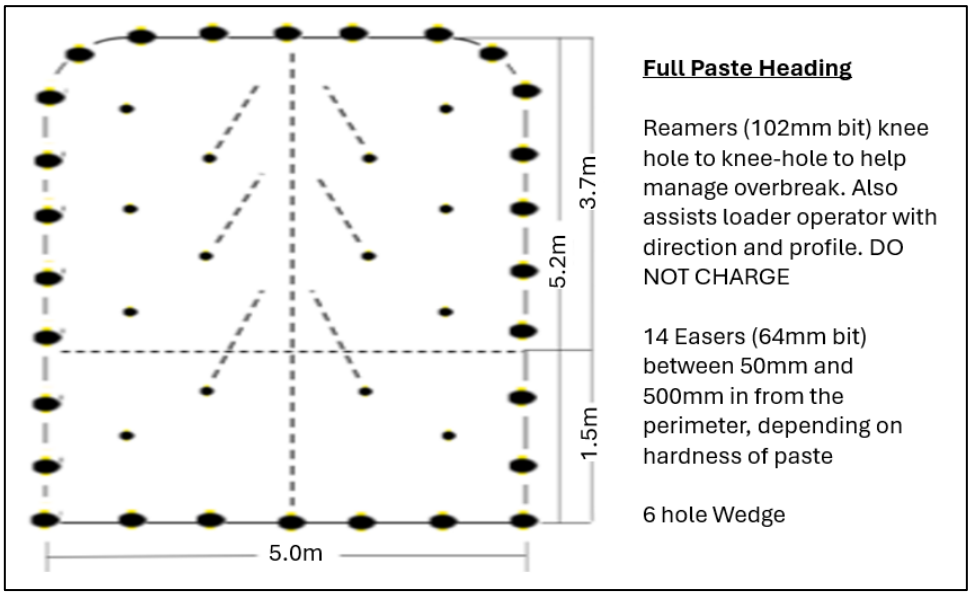
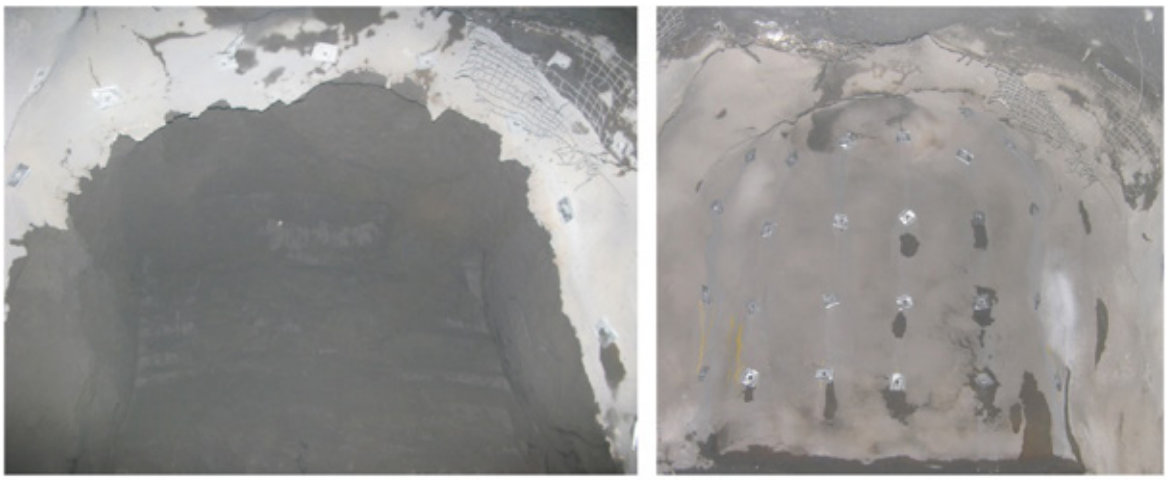


Figure 12 Typical development face boring pattern in cemented paste fill



a. 2 m development cut into 4.0 % CPF after 14 days curing

b. The same heading later fully supported

Figure 13 Ground support process in cemented paste fill development

The most significant departure from the design approach described by Li et al. (2011) was the increase in cut length from 3.0 to 4.5 m. This change followed the adoption of a different binder system and was supported by a risk assessment and a controlled trial program that demonstrated the stability of the increased unsupported CPF exposure. CPF excavation spans are verified as mined to design through the survey memo sign-off process. Additional fibrecrete shell thickness is prescribed and installed as required to account for the additional loading demands placed on the ground support system.

No stability issues have been experienced at the Cannington mine using the CPF development support method described above in short-term development. However, evidence of friction bolt corrosion has been observed in long-term (>2 year) paste fill development. A limited number of fall-of-ground events have been recorded in long-term paste fill development at the Cannington mine. These instances have been influenced by the extraction of multiple adjacent stopes in the mining sequence.

4.3 Cemented paste fill development backs failure

In 2021, re-entry into a CPF development drive identified a section of failed ground support, resulting in 20 t of paste to fall from the backs. Although the area had been physically inaccessible for 6 months due to an active stope blocking access, the failure provided an opportunity to investigate with the intent to better-understand how the failure occurred. Figure 14 shows the scale and damage associated with the 400mLv CPF backs failure.

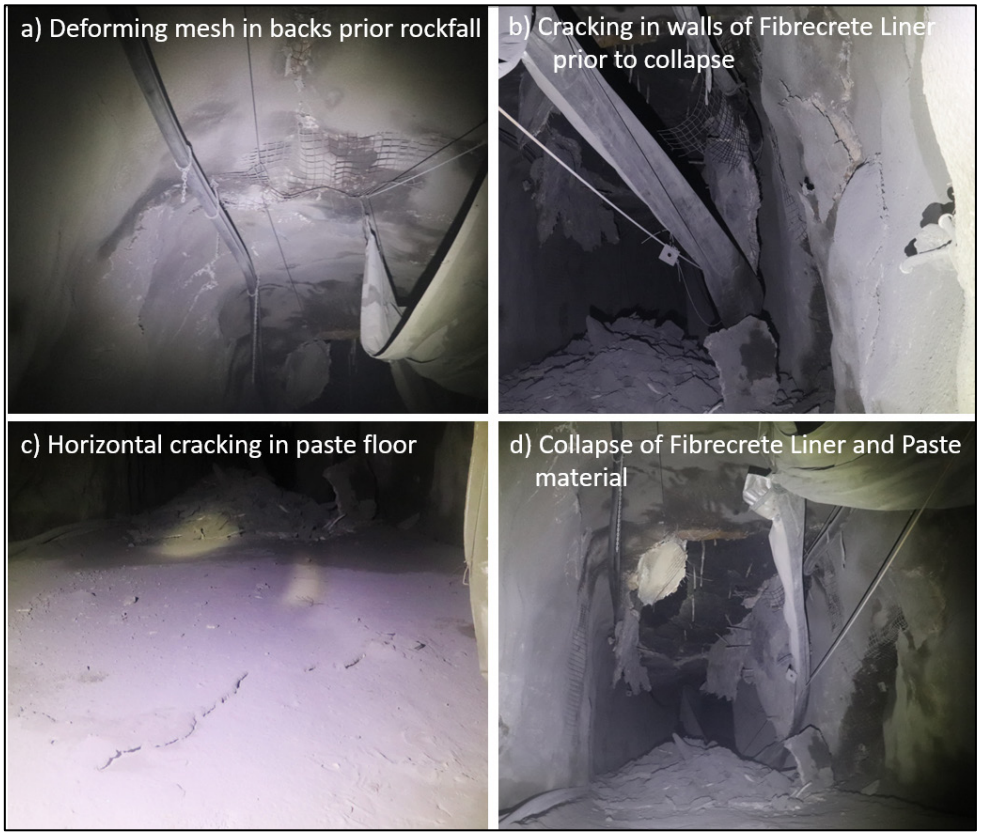


Figure 14 Perspectives of the 400mLv cemented paste fill backs failure

Geotechnical investigation of the CPF failure found:

- CPF backs failure occurred within a paste-filled stope (approximately 7 m from the nearest paste-rock contact)
- CPF was placed during stope fill activities in 2001
- development in the CPF was mined in 2016, exposing a relatively flat back profile in the area
- the backs in the failure vicinity were damp
- CPF fall-out occurred to a maximum depth of 1 to 1.5 m
- some moderate corrosion of the ground support elements was observed, but stress induced damage was identified as the dominant contributing factor of the failure.

A numerical model was constructed in FLAC3D to simulate changes to the CPF development failure area as surrounding stopes were extracted. The model captured the extensive stoping front, excavation of stopes over time (years) and resulting stress changes on the 400mLv development drive, with the model setup shown in Figure 15. The model results, shown in Figure 16, were generated using the plastic liner element logic in the numerical modelling code FLAC3D (FLAC3D Version 9.0 [Itasca 2023]). The timing of fibrecrete cracking was modelled throughout the sequence and clearly demonstrated the influence of stress redistribution and loading on CPF development within the stoping front.

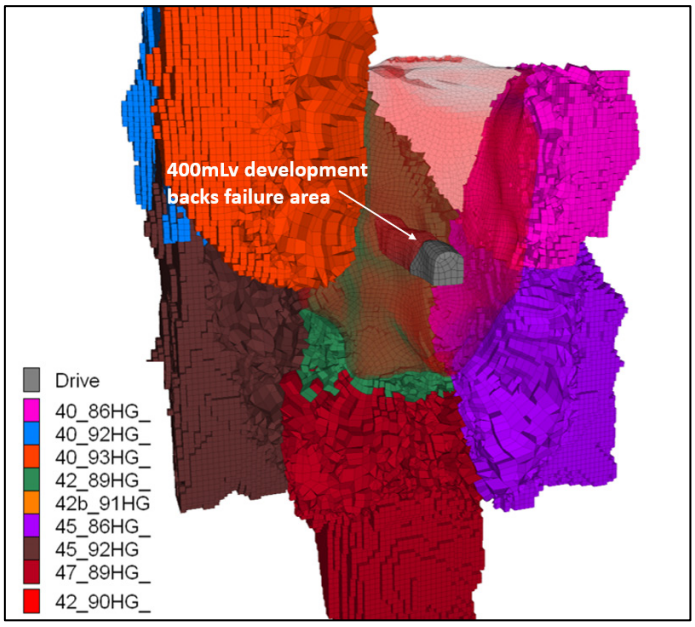


Figure 15 400mLv FLAC3D cemented paste fill model geometry

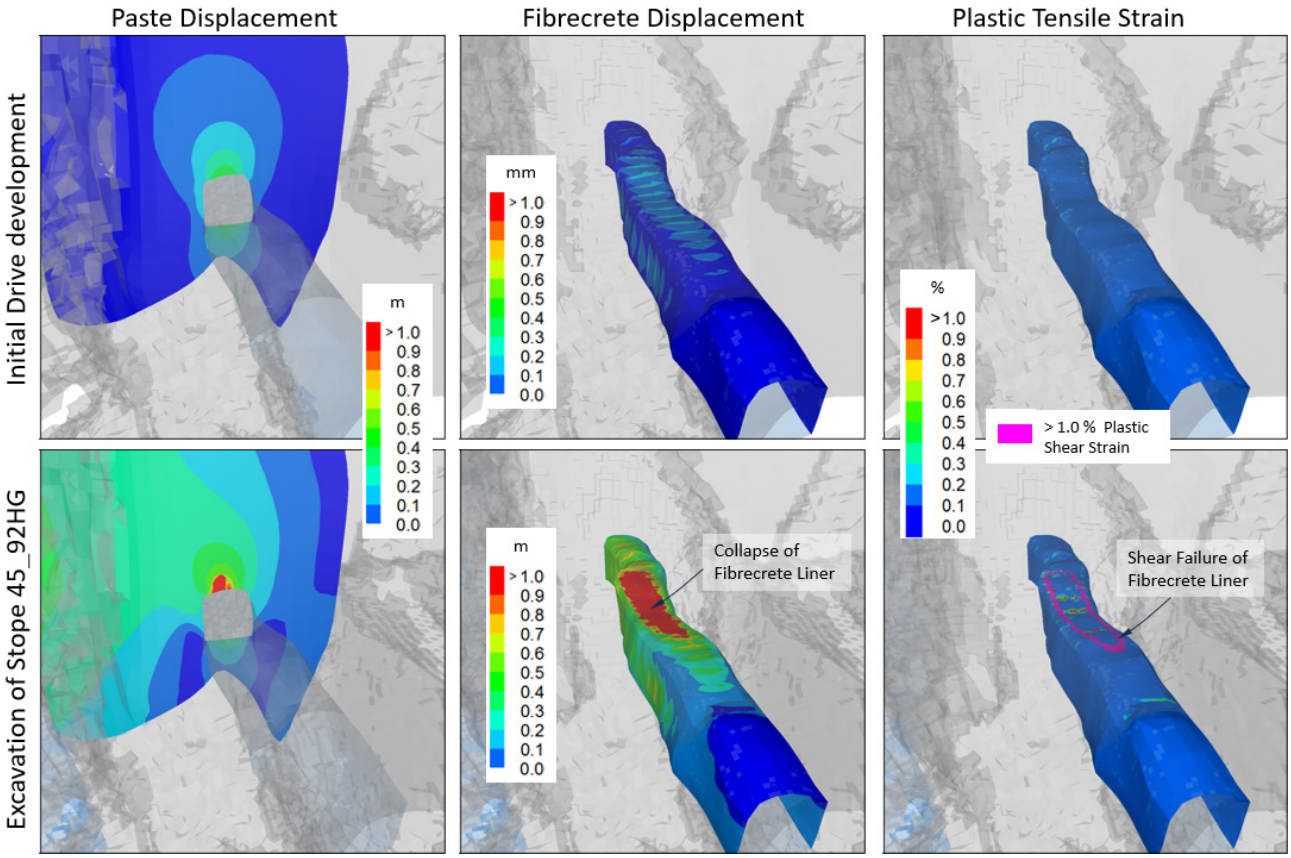


Figure 16 Response of 400mLv cemented paste fill development during simulated extraction sequence

Learnings from in-field observations such as the 2021 CPF backs failure event were included in the CPF management strategy at Cannington. Improved understanding of mine-scale subsidence and its impact has heightened awareness that CPF development drives are not ‘set-and-forget’ excavations.

5 Conclusion

Ground support for development in cemented mine fill requires consideration of factors that differ from conventional development in rock. The presented case studies demonstrate the importance of understanding fill behaviour, excavation life and mining sequence when designing ground support systems. Continued refinement of design methods, supported by operational observations and numerical analysis, will improve the long-term performance of mine fill development.

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