Consideration of asymmetric drive geometry and conditions on the loading capacity of pastefill barricades

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ABSTRACT

This paper extends the existing knowledge associated with the design and placement of prefabricated pastefill barricades through a consideration of asymmetric drive geometry and conditions. The load capacity of prefabricated barricades and their failure modes are considered in relation to abutment geology and barricade geometry that includes curvature and span and drive geometry that includes abutment angles, haunch angles and misalignment. Design charts are provided for typical barricade sizes to provide general guidance for design capacities and optimising location placement based on asymmetric drive geometry. A recent barricade failure is considered in relation to the drive geometry and the potential impact it had on the installed capacity.

INTRODUCTION

Pastefill is used in underground mining operations to provide passive support to the surrounding rock mass during adjacent excavation. Pastefill is used in preference to hydraulic fill due to its non-segregating nature during placement (Dalcé, Li and Yang, 2019).

Cemented pastefill is mixed in a backfill-plant on the surface and transported underground through pipelines (Sivakugan, Veenstra and Naguleswaran, 2015). Pastefill is contained within the stope typically by impermeable bulkheads. This compares to historical permeable barricades employed to contain draining hydraulic fill within stopes. It is highlighted that in industry many operations refer to the paste containing structures as barricades. Upon hydration of the cement within the pastefill mass, stress arching of the fill into the stope and drive walls reduces the active pressure applied to bulkheads at the base of a stope (Fahey, Helinski and Fourie, 2009).

The typical geometry of a paste bulkhead and its placement in relation to a backfilled stope is presented in Figure 1.

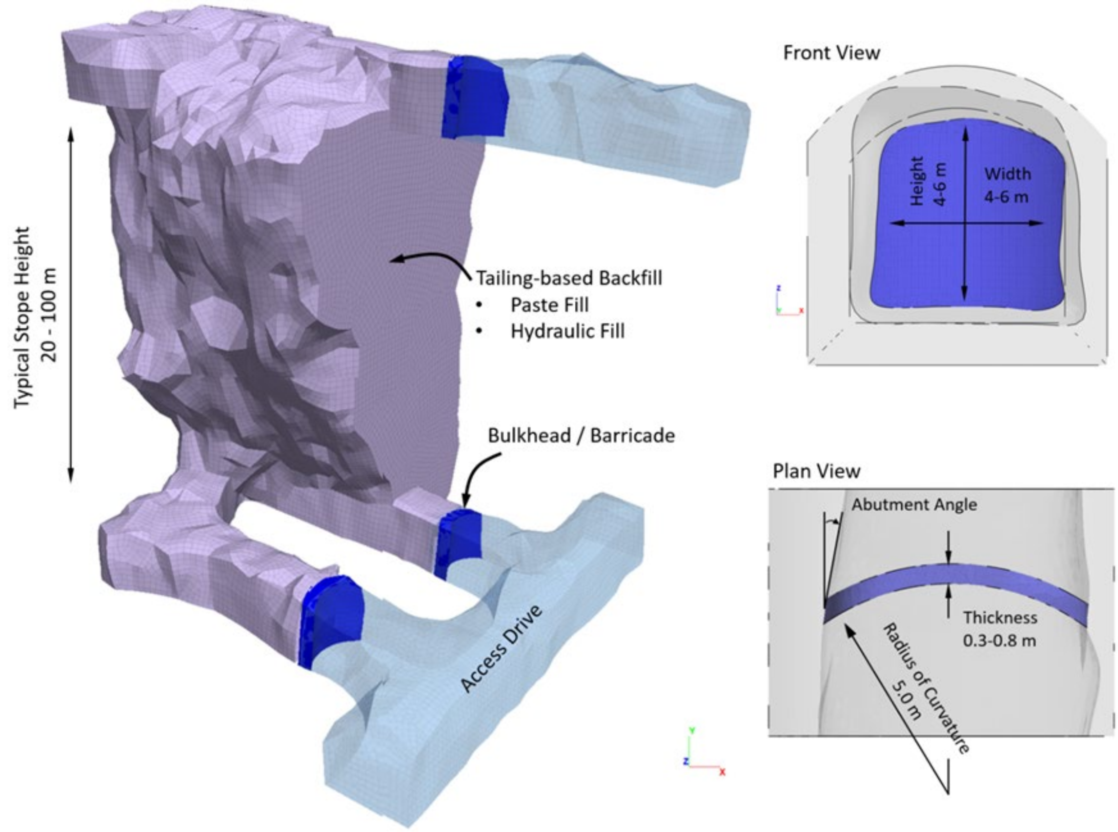

FIG 1 – Typical paste-fill stope profile and location of bulkhead in extraction drives/cross-cuts.

In Australia paste bulkheads are typically constructed using prefabricated arched shaped frames. After erecting the frame, a layer of mesh is attached to the downstream side of the frame which is then covered with hessian and sprayed with approximately 200–400 mm fibrecrete. Figure 2 presents the typical stages of construction for a fibrecrete bulkhead. It is important to note that the prefabricated frames play no role in the bulkhead capacity. They are simply a fast way to erect a backing structure to spray the fibrecrete and they also ensure the arch profile is maintained.

FIG 2 – Formwork and steps of construction of fibrecrete bulkheads (a) pre-fabricated arch placement (b) placement of the mesh and hessian over the arch (c) sprayed fibrecrete.

The cost of erecting a fibrecrete bulkhead in Australian mines is approximately $8000–$12 000. The total construction time is approximately one to two shifts. The bulkhead is usually constructed 'just-in-time' prior to filling the stope. The location of the bulkhead is pre-determined based on operational conditions and standard work procedures (Helinski *et al,* 2011) which are site specific.

RISK OF FAILURE

Bulkhead/barricade failure and the subsequent inrush of paste or hydraulic fill into the underground mining environment is a core risk associated with any hydraulic or paste backfill. Causes of bulkhead/barricade failure have previously been discussed by Grice (1998), Revell and Sainsbury (2007a) and Sheshpari (2015). Contributory causes usually include complex stope geometry, non-ideal filling procedures and lack of real-time data to assess the evolving conditions.

‘In October 2019, two workers at an underground mine were approaching a paste retaining wall during pastefilling, when the wall catastrophically failed. An inrush of fluidised paste entered the drive inundating the workers…’. An investigation into the incident found that the ‘wall failed due to excessive hydraulic pressure being exerted from the pastefill’ (Department of Mines, 2020). A photograph of the failed barricade is presented in Figure 3.

FIG 3 – Drive side of failed paste wall with fill pipe through wall (after Department of Mines, 2020).

Contributory causes of the failure included (a) no effective means of pressure relief in place (b) the pressure of the paste mass exceeded the wall’s capacity (c) the paste behind the barricade was quite fresh meaning it flowed further than expected once uncontained (Department of Mines, 2020).

Actions recommended to mines using fibrecrete bulkheads for pastefill containment included:

- Conducting a detailed engineering and risk assessment (site investigation) for individual stopes. This is especially important to determine when there are variations to standard layouts and processes.
- Use remote monitoring devices to remove workers from potential danger zones associated with the barricades and enforce exclusion zones during the stope filling process.

Based on the recommendations for a stope-based site-investigation, it can also be suggested that the geometry of the drive may have contributed to the failure. This research addresses the important aspect of drive geometry on the as-built capacity of bulkheads and shows how such failures may occur even under ideal filling conditions.

BARRICADE DESIGN CONSIDERATIONS

Design methodology

The design of pastefill bulkheads has historically relied upon analytical solutions (eg Smith and Mitchell, 1982; Li, Aubertin and Belem, 2005; Li and Aubertin, 2009a, 2009b) and numerical methodologies (Grabinsky, Cheung and Bentz, 2014; Cui and Fall, 2017; Helinski, Fahey and Fourie, 2010) that are limited by the necessary simplification of geometry, the properties of the bulkhead materials and the representation of the wall-bulkhead interface.

A calibrated 3D numerical modelling approach has been proposed as the most appropriate method of bulkhead design (Bridges, 2003) and FLAC3D has been used to accurately model the non-linear loading behaviour of shotcrete barricade structures since 2007 (Sainsbury and Revell ,2007). The FLAC3D methodology, and its validation, has been described in detail in Sainsbury and Revell (2007) and allows the specification of complex strain-softening material models to simulate the brittle shotcrete behaviour, together with sliding interfaces to represent the shotcrete–wall rock interface. The explicit large-strain formulation allows the full failure mechanism of a bulkhead to be analysed.

However, since the original models that considered rigid drive sidewalls (Sainsbury and Revell, 2007) the modelling methodology has been updated to reflect deformable (not rigid) sidewalls. Grabinsky, Cheung and Bentz (2014) show through a sensitivity study that assuming fully rigid boundary conditions can provide bulkhead results that may overestimate the strength and underestimate of ductility. Within the modelling procedure, the sidewalls are represented with an elastic material model. Based on the results of Grabinsky, Cheung and Bentz (2014) the inclusion of deformable sidewalls may impact the predicted capacity of the bulkhead by 150 per cent.

It is also important to note that the consideration of reinforcing bars and weld wire mesh as identified by (Grabinsky, Cheung and Bentz, 2014) has not been considered with the numerical modelling technique. Although significant advances have been made to explicitly simulate the behaviour of wire mesh, (Karampinos, Baek and Hadjigeorgiou, 2018) the inclusion of this in the bulkhead model is not considered necessary. It is not necessary since the wire mesh is not considered as a structural element in the bulkhead – it is included as formwork to hang the mesh and spray the shotcrete onto. In addition, the mesh is not installed on the free face of the bulkhead, and the additional tensile capacity at the submerged faced is unlikely to prevent failure. From the observed bulkhead failure photos (Figure 3) it is evident that the mesh does not prevent the failure.

Asymmetric drive geometry

Previous research conducted by Revell and Sainsbury (2007b) was able to show that the construction of arch-shape bulkheads significantly increases the ultimate failure pressure (up to 300 per cent) – when compared to flat bulkheads. This outcome is also confirmed by Cheung (2012) who showed that even with only a moderate curvature, arch bulkheads provide a doubling in loading capacity. This increased loading capacity is a direct result of the arched bulkhead shape being able to remain in compression (eg no tensile failure) and a greater thrust/normal force being generated at the wall abutment as shown in Figure 4.

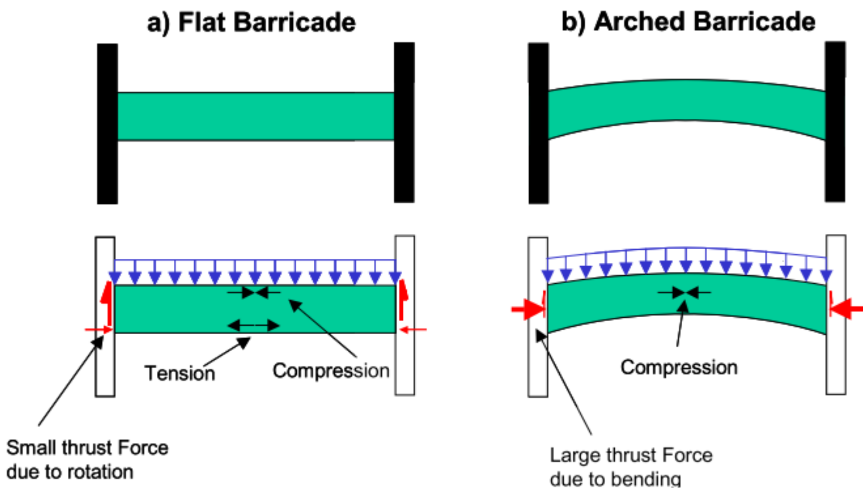

FIG 4 – Forces within a flat and arched bulkhead (after Revell and Sainsbury, 2007b).

An example of an arched and flat bulkhead failure mode is presented in Figure 5.

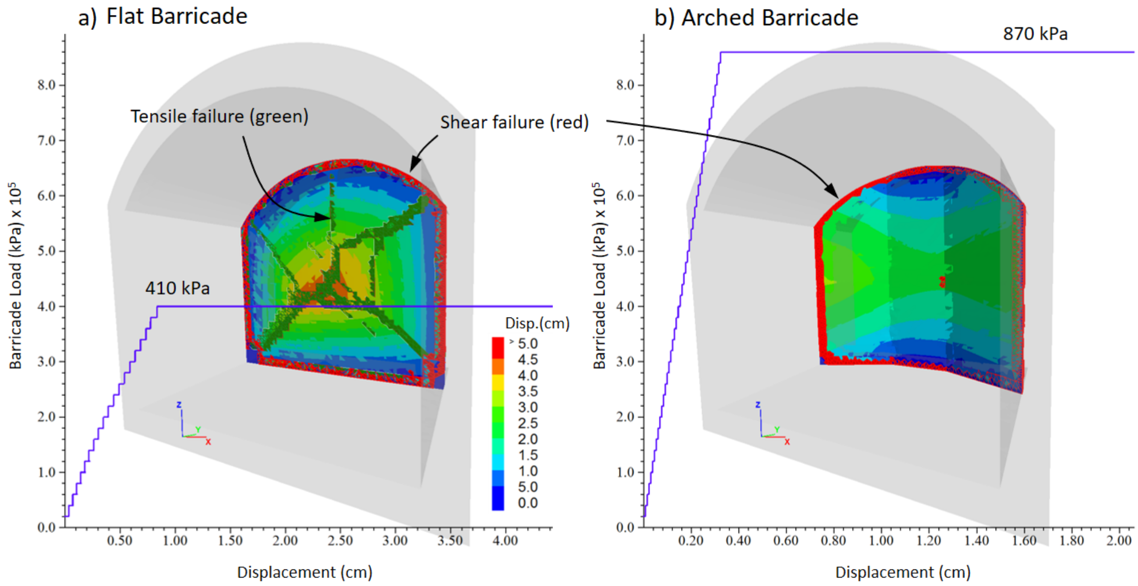

FIG 5 – Comparison of arched and flat bulkhead failure mechanism.

As such, it is usual to design and construct bulkheads with an arched shape. However, numerical models used to do this, up to this point (eg Helinski *et al,* 2011; Revell and Sainsbury, 2007b) have only considered that the drive walls are parallel or symmetric in nature. This is rarely the case. To study the effect of asymmetric drive geometry a series of simulations have been conducted that consider asymmetry in the sidewalls and back, together and separately. Figure 6 presents the results of a drive geometry that is telescopic on one side only and the back (drive roof).

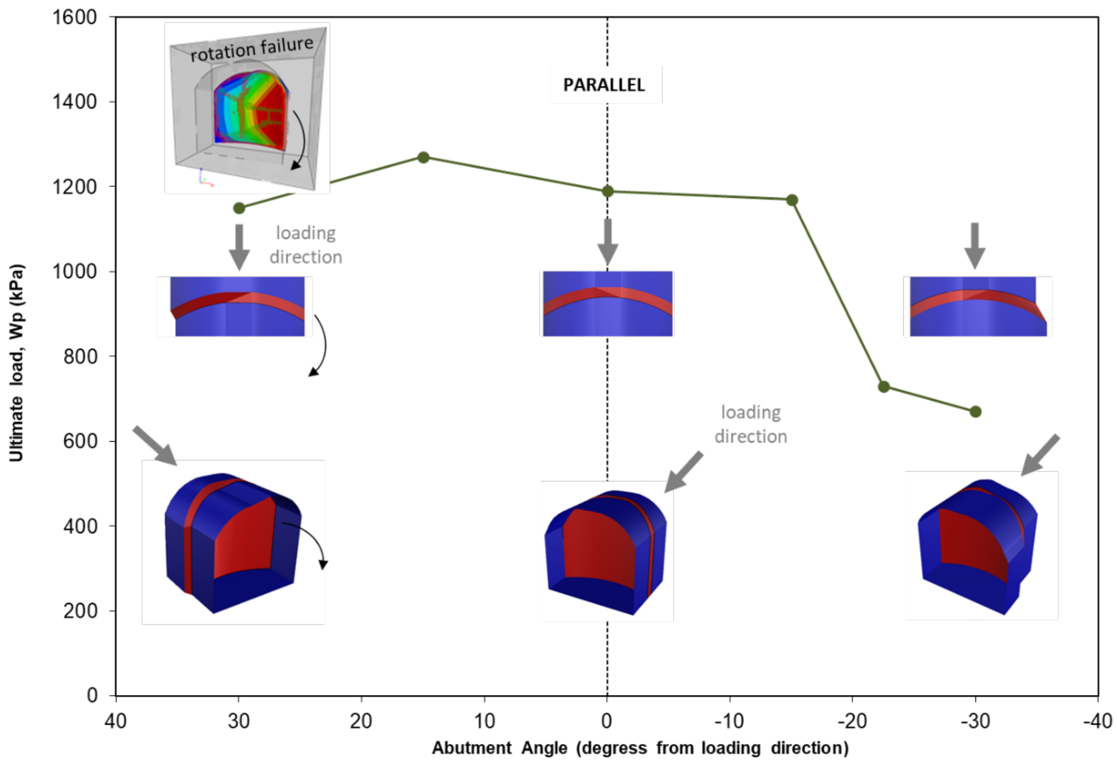

FIG 6 – Consideration of positive and negative sidewall abutment geometry on one sidewall only including the back of the drive.

A significant reduction in capacity is observed (40 per cent reduction) when one-sidewall/back has a negative abutment angle. However, the capacity is little changed when one-sidewall/back has a positive abutment angle. The mode of failure in this case is rotation/shear along the 'straight' sidewall geometry – the positive sidewall abutment is 'locked-in'. When the drive back is not considered in the asymmetry of the drive, the simulation results presented in Figure 7 are observed.

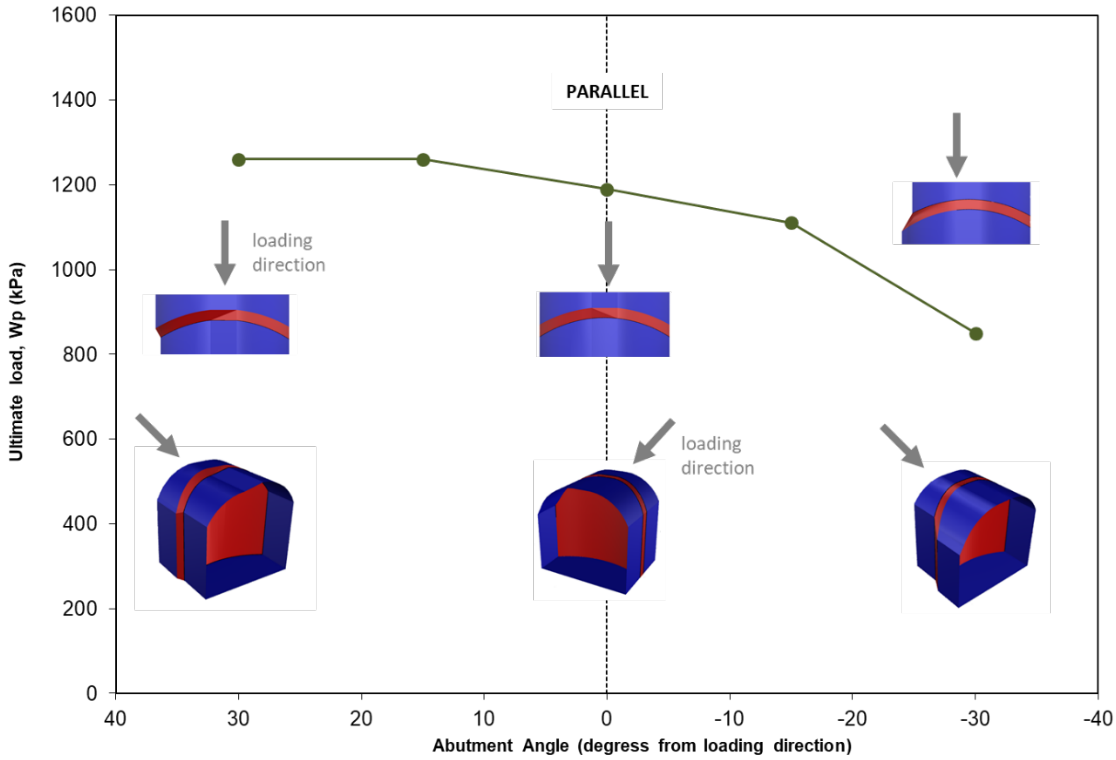

FIG 7 – Consideration of positive and negative sidewall abutment geometry on one side only.

In comparison to Figure 6, the results are less impacted, in relation to the reduction in strength, since the back of the drive provides additional resistance to moving since it can 'lock-in' the barricade.

When the back of the drive is considered only in relation to positive and negative abutment angles (Figure 8) a significant decrease is capacity is observed for the 30° negative abutment angle case.

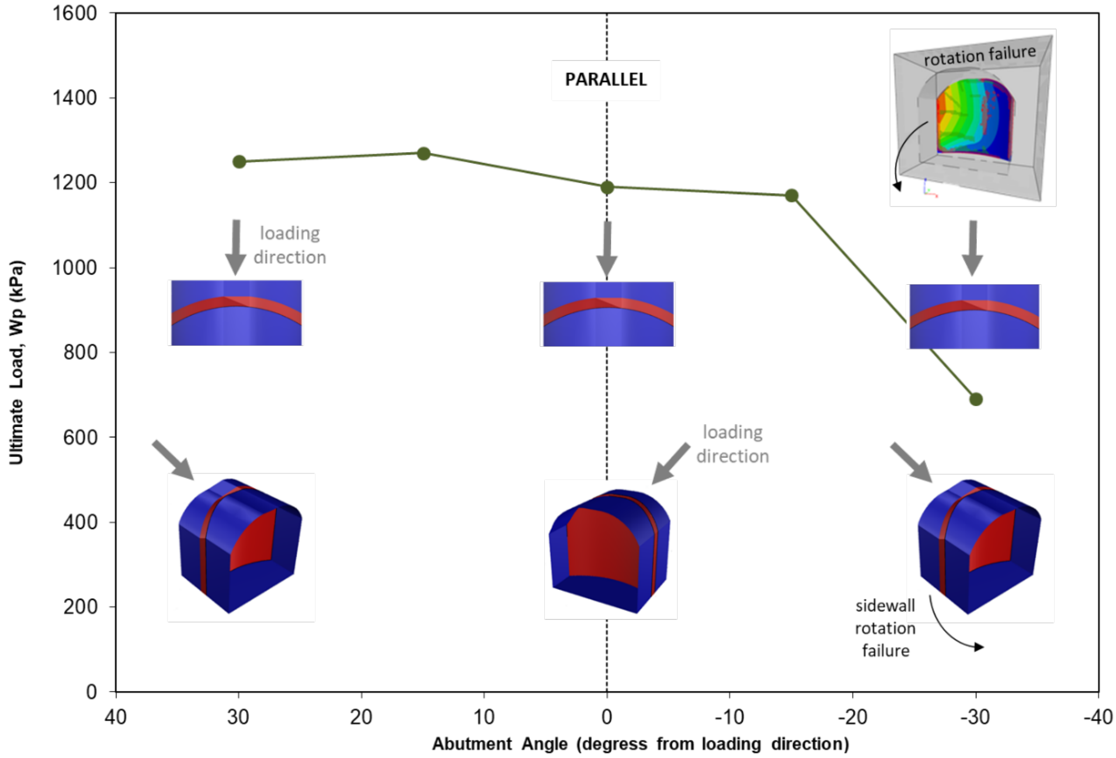

FIG 8 – Consideration of positive and negative back abutment geometry.

This result is similar to the results in Figure 6 which suggests that a negative abutment angle in the back of the drive has the most significant impact on reducing the performance capacity of the barricade.

BARRICADE DESIGN APPLICATION

The design charts provided in Figures 6, 7 and 8 are applied for a case the considers the as-built geometry of the drive. Through the consideration of the sidewall and back angles an optimum barricade location can be selected (Figure 9).

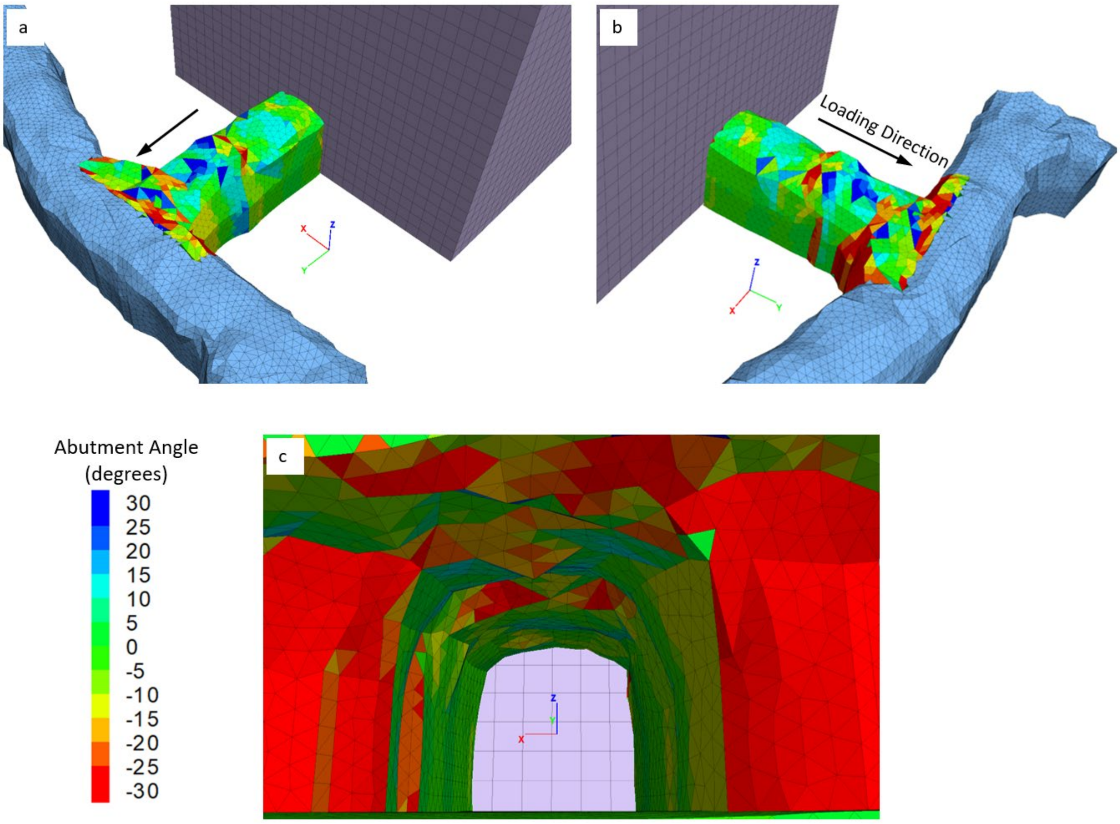

FIG 9 – Consideration of a negative abutment angle at the location of the barricade failure.

Once the location is selected, it can be accurately located by survey to ensure capacity is achieved. A review of the geometry of the drive in Figure 3 after the barricade failure suggests that a negative abutment angle is observed on the side of the barricade that failed. It is highlighted in red in Figure 10.

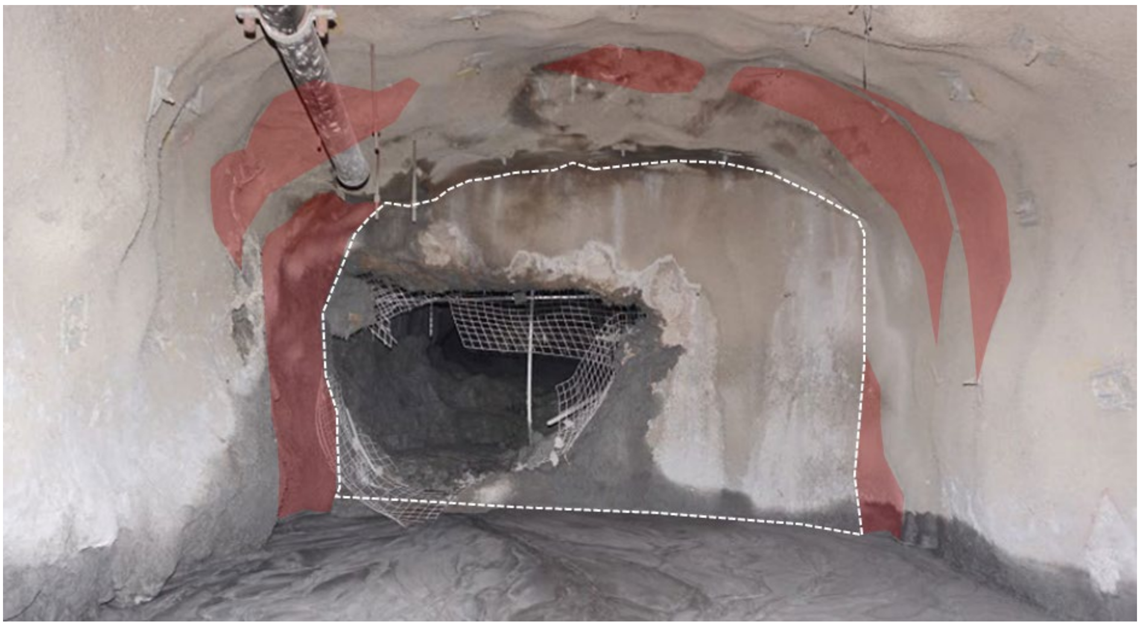

FIG 10 – Consideration of a negative abutment angle at the location of the barricade failure.

SUMMARY AND CONCLUSIONS

Design charts are provided based on a validated numerical modelling methodology to consider the ultimate capacity of prefabricated barricades installed in asymmetric drive geometries. It has been shown that capacity of the fibrecrete barricades can decrease by up to 50 per cent when negative abutment angles are encountered. A review of a recent barricade failure suggests that negative abutment angles may have impacted the ultimate capacity of the installed barricade leading to the failure. Based on the results the modelling the following guidelines are suggested for mining operations using prefabricated barricades:

- Barricade design must consider the location in relation to the as-built drive sidewall and back angles.
- Barricade must be relocated if any quadrant exceeds a negative (outward) angle greater than 30 degrees.
- Increase barricade thickness (capacity) if any quadrant has a negative (outward) angle between 15 and 30 degrees.
- Increase barricade thickness (capacity) if any quadrant has a positive (inward) angle greater than 30 degrees.

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