Lessons Learned from Tight or Blind Filling Induced Barricade Failures

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Abstract
'Tight' backfilling of stopes can be required for geotechnical reasons, and 'blind' filling can be required for logistical placement reasons, potentially resulting in an overall tight-filled condition. Such practices present elevated levels of risk for containment barricade failure in comparison to standard (ie, non-tight) backfilling. Barricade failures can result in high-energy release of backfill into underground workings posing significant hazards where risks are not mitigated. Challenges relating to tight-filling deserve more scrutiny as, to our knowledge, this practice has resulted in most of the barricade failures during the past decade. Increasing awareness of a specific risk is a critical (and potentially overlooked) tool in improving industry safety. In 2007, researchers documented several barricade failures and provided valuable contributions to increasing safety and best practice awareness. Here, this record is updated with the inclusion of seven tight-fill related barricade failures that have occurred at well-respected mines within North America and Australia since 2017.

While the causes of failures are varied, the common trend is that tight backfilling induced elevated pressures within backfilling stopes which have exploited weakness in barricade construction or simply caused apparently sound barricades to fail. Best practices resulting from lessons learned include maintaining adequate ventilation in terms of positioning, size, and construction of breather pipes in stopes and 'spill holes' in barricades, and in tracking and reconciling as-placed fill volumes versus predicted volumes. The use of on-barricade pressure instrumentation may provide useful information. Further, there is opportunity for novel instrumentation approaches to mitigate human error in the potentially unreliable practice of observing continued air flow via breather hole 'flags'. Tight-filling poses a potentially inherent risk of elevated barricade pressures; thus, mitigation factors such as limiting 'fluid' portions of fill, and providing and enforcing conservatively designed exclusion zones are operational requirements.

Key words: backfilling, tight-filling, barricade failure, instrumentation, safe mining

Introduction
Backfilling is an integral component of the mining cycle, with the aim of safely maximizing resource extraction. Backfill placement requires careful management to ensure operational safety as fluid backfill must be contained within underground openings until strength gain within the backfill mitigates concern that fluid pressures may over-pressurize containment structures.

This paper discusses both cemented paste (paste, or CPB) and cemented hydraulic fill (CHF) backfills and focuses on experiences within North American and Australian mines. Within these regions, shotcrete arched barricades (barricades) and consolidated waste rock berms (WRBs) comprise structures typically deemed acceptable for backfill confinement within stopes. Typically, backfilling placement strategies are limited in that the structural designs assume design loads equivalent to fluid pressure of a limited height 'plug' pressure, as described by Grabinsky et al. (2021), and Potvin et al. (2005). Such an approach assumes this initially poured and cured plug volume will isolate the barricade from additional pressures induced by placement of the main pour volume. This results in a two-stage pouring strategy which requires a plug cure period (Figure 1).

Most operations define a specific plug strength requirement correlating to a specific cure time for which this assumption of adequate plug strength is valid. It is notable that some operations rely on an arbitrary plug cure time without reference to a specific strength (or indeed a specific binder content) which introduces an additional element of risk into the backfill management system. Practical considerations regarding the feasibility of continuously backfilling without need for a plug cure period are described by Thompson et al. (2023).

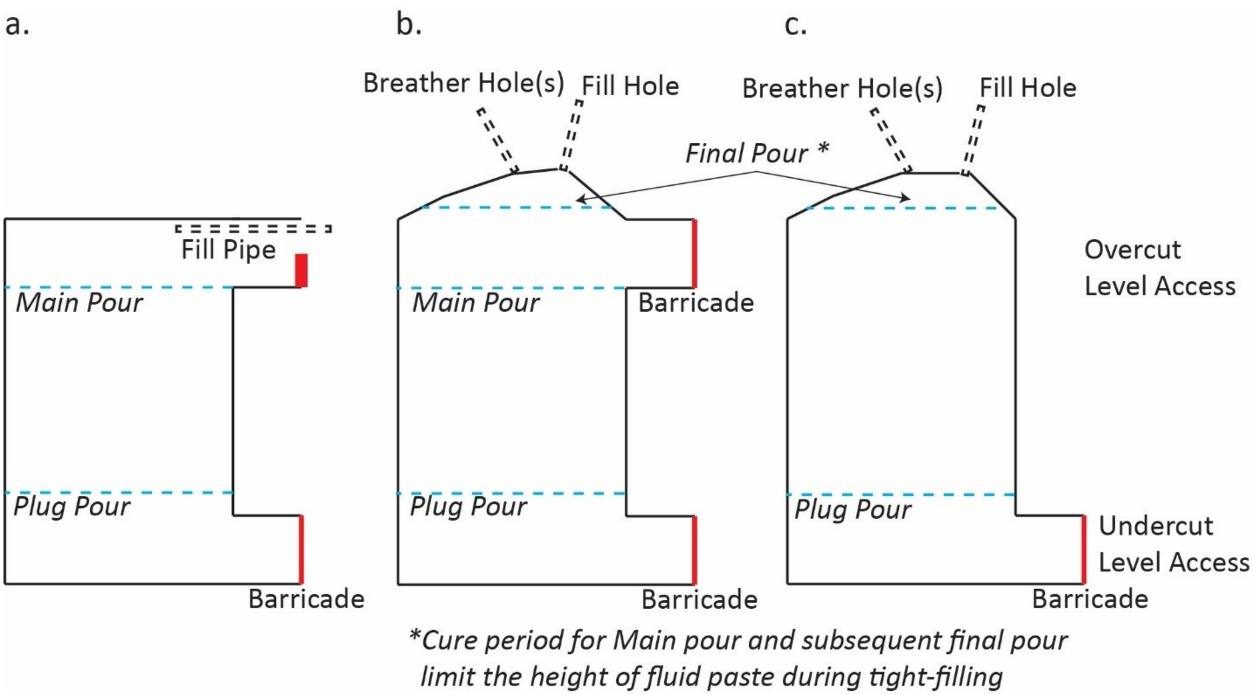

Figure 1. Cross sections through idealized stopes showing: a) typical backfill placement with plug pour and main pour volumes indicated, (b) backfilling to achieve tight-fill of a long-hole stope requiring breather holes (as an alternative set up, a fill pipe and breather holes may pass through the overcut barricade), and c) 'blind' filling.

The failure of a backfill containment structure poses a significant risk in terms of potential for fatalities, injuries, damage to equipment and infrastructure, and operational delays. Specifically, failure can result in the escape of a significant volume of still-fluid backfill which constitutes a high energy release into underground workings (Figure 2). Revell and Sainsbury (2007) document a failure causing debris to be transported 270 m from the barricade. Various sources cite 1–2 m 'high water marks' significant distances from failed barricades. While the risks of backfilling are clear, widespread adoption of what can be considered industry standard practices mean that barricade failures are exceedingly rare. In the past decade, several researchers have considered how to optimize best practices for backfill containment design (Helinski et al., 2011, Oke et al., 2018, Veenstra et al., 2021) and how instrumentation can be used to monitor and potentially control loading upon backfill containment structures (as reviewed in Thompson et al., 2023).

Figure 2. Images showing barricade failure. The solid circle shows breather pipes with flags to indicate air flow, and the dashed circle highlights initial movement.

Barricade best practice and lessons learned

A significant factor in improving backfilling related safety has been the willingness of mines to share 'lessons learned'. Case studies presented by Grice (1998), Revell and Sainsbury (2007), and Yumlu and Guresci (2007) have proven extremely valuable. A fundamental aspect of a backfill practitioner's role is to communicate best practice and risks to engineers or underground crews who may lack detailed backfill experience. From a practical perspective for instance, the recommendation to 'ensure adequate plug height' has more weight when an example of a resultant barricade failure can be cited. The following best practices are consistent with lessons learned from the previously cited studies:

- Verify adequate barricade construction; in terms of geometry, and shotcrete thickness and strength (Revell and Sainsbury 2007, Thompson et al., 2023).
- A detailed, justified and regimented sign off process should be part of operational control measures.
- Ensure adequate plug height. (Revell and Sainsbury, 2007).
- Assess the risk of dynamic loading by rock-falls onto fluid paste (Revell and Sainsbury, 2007).
- Caution is required during tight and blind filling, (Yumlu and Guresci 2007; Gray, (2019) as will be further discussed).
- For CHF, ensure good drainage and maintain optimal solid content (Grice, 1998).
- Utilize containment berms and exclusion zones.

Regarding plug height, Revell and Sainsbury (2007) reported a barricade failure occurring when an under-height plug left the top of a barricade exposed to the subsequent main pour. Their example occurred at a multi-level stope; although the correct volume of backfill had been placed, critically, part of the volume was unexpectedly diverted into a mid-height access drift. Other mechanisms for placement of inadequate plug height have been suggested, eg, a fill point horizontally distant from the brow may require consideration of the beach angle/angle of repose of the backfill.

To complete this short section on lessons learned, Thompson et al. (2023) referenced a barricade failure which occurred when instrumentation was being used to limit barricade pressures upon a planar (ie flat, not arched) barricade. System errors setting up instrumentation and inadequate construction were considered root causes. The following key learnings were emphasized:

- Consider the potential for human or system errors when relying on barricade instrumentation.
- Utilize an engineered barricade with multiple safeguards in place (i.e. plug strength, instrumentation, potentially containment / exclusion zones) especially if attempting continuous or accelerated backfilling.

The authors observed that greater awareness in the concept of continuous pouring has led to increased interest from new paste filling operations. However, the fact that the two operations for which relatively detailed, published case studies exist on implementing continuous pouring had reverted to two-stage backfilling should give pause at least to verify that adequate long-term controls are in place.

The present paper is focused on barricades rather than WRB applications. It is noted, however, that a high energy release of paste did result from failure of a WRB as described by Gelinas (2017). Gelinas addresses key differences between design assumptions and as-built construction of WRBs which emphasizes the cautious approach necessary when WRBs are used for backfill containment.

Previously cited reviews of barricade failures typically involved structures or materials that arguably are not consistent with current practice. The lack of published failures of arched shotcrete barricades under non-tight or blind filling conditions since 2007 would indicate the risks of backfill containment can be successfully managed. However, since 2012 we are aware of eight barricade failures, five of which have resulted in significant or potentially significant releases of fluid backfill. It is notable that seven of the eight failures resulted from tight or blind filling, emphasizing a clear need to raise awareness of lessons learned and best practices specific to this backfilling strategy.

It should be acknowledged the alternative to the above lack of published failures is that barricade failures have occurred but have not been well reported. Some jurisdictions do provide good resources (eg, the barricade failure incident report by the Government of Western Australia, [2020]) and broader adoption of such a notable incident reporting system would provide widespread benefits.

Tight-filling and blind-filling

Most stopes within a long-hole (LH) stoping context have both undercut and overcut access. In these cases, fill pipes are installed via the overcut access and there is clear visual ability to define when a stope is full (eg, Figure 1a). There are occasions when backfill placement is required with elevation to the top (back) of the stope, ie, 'tight filling'. As shown in Figure 1b and c, this may be achieved via drilling into a stope so paste can be poured via a bore hole. Figure c shows a 'blind' pour where no overcut access is available. Filling may be achieved through the overcut barricade (eg, Figure 1b), if logistically it is easier; achieving the tight filled condition will be more difficult when the fill point does not intersect the high point of the stope, as consistent with the recommendations of Bloss (2014) and others.

There is a critical requirement to enable air and potentially backfill to escape from a stope during backfilling in order that: i) air is not pressurized within a confined space, and ii) over-filling with backfill does not occur. In either case, very high pressures can be induced within a stope potentially greatly exceeding a typical barricade’s assumed design conditions. The cause of tight-fill induced barricade failures is sometimes hypothesized as a sudden increase in head pressure, as the fully backfilled stope is hydraulically connected to the (full) fill bore hole. With additional paste being pumped into the stope, a highly pressurized system results and in several cases failure of barricades has occurred. Therefore, to enable safe backfilling egress of air (and potentially backfill) is required which is typically enabled via an open overcut (eg, Figure 1a) during conventional backfilling.

For tight or blind filling (Figure 1b and c), there is a need to drill into the open stope or place breather pipes through an overcut barricade to allow venting of air (and potentially backfill) as a stope is backfilled. Experience shows the requirement for potentially more than one breather hole or pipe (for redundancy) given the consequences of blockage, as illustrated by Yumlu and Guresci (2007) who described three blind fill failures. Staged backfilling is also recommended in the LH context at least, (Yumlu and Gurecsci, 2007; Gray, 2019) to allow fill to gain strength and so reduce the volume of fluid paste that could release in the case of a barricade failure, as will be further discussed. Yumlu and Guresci reported that paste line pressures consistently increased prior to barricade failures such that pipe pressure monitoring was adopted in their tight-fill control process.

In the cut and fill (C&F) mining context, fill pipes are installed prior to barricade construction with potentially multiple fill points (Figure 1), and are built through the barricade structure. Breather pipes are also pre-installed, ideally slightly above the respective fill points so that as the drift fills, air and potentially fill can exit the confined void. If the breather pipe becomes blocked then there is potential for high barricade pressures to occur, as previously described. Some mines use barricades that feature a gap (ie, not completely shotcreted) at the top to allow air and backfill to escape. In terms of achieving 'good' tight filling, multiple fill points and breathers may be required, depending on site specific variables, eg, gradient of drift, geometry of the drift (including filling "Y" intersections), angle of deposition of fill. Filling down-grade is preferred if the objective is to minimize tight-fill risks to barricades.

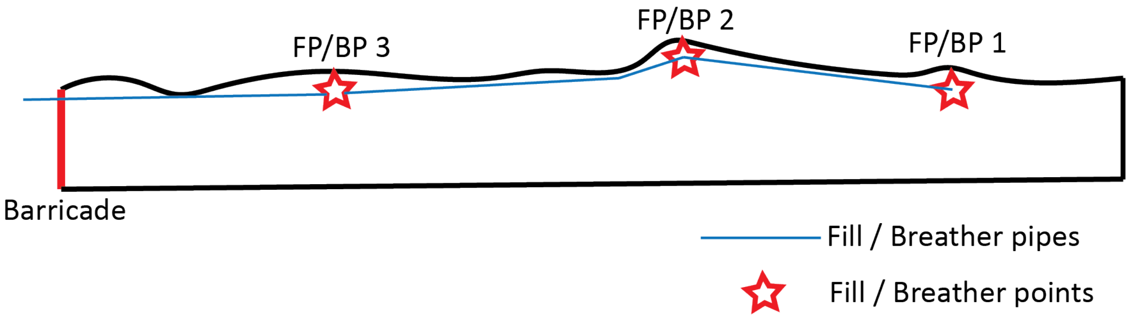

Figure 2. Schematic showing an approach to C&F tight-filling

Mines must determine site specific filling strategies to accommodate variables in terms of the number and order of fillingfrom specific fill points. It is outside the scope of this paper to provide specific guidance on such fill management; rather, the aim here is to raise awareness of risks and share lessons learned. To that end, seven examples of barricade failures are described using a common reporting format of Consequence (of failure), Contributory/Situational Factors, and Key Learnings.

Case Studies Documenting Tight-Fill Induced Barricade Failure

Case Study 1: C&F backfilling

Consequence

Tight-filling at a relatively new-to-CPB filling operation caused a breach of a shotcrete arched barricade in a C&Fdrift. The outflow of paste did not reach the exclusion zone limits.

Contributory/Situational Factors

Excess volume was placed (1100 m^3 vs ~ 900 m^3) and the barricade failed prior to any material flowing through the breather pipes (Figure 2). A contribution to the barricade failure may have been vibration of the paste pour pipe which was chained to back. Three breather pipes of diameter 10 cm were installed; an investigation suggested they had been crushed.

Key Learnings

- Establish placement volume limits.
- Tightly secure the fill pipe through the barricade.
- Use breather pipes made from competent material to resist crushing with minimum 15 cm diameter.
- Use a minimum of three breather pipes, staggered within a drift, and ensure the point of highest elevation is identified in stope design packages as a potential fill/breather point.
- Tightly secure fill and breather pipes to the back (as in-stope videos from an earlier stope showed paste moved the pipes during filling).
- Place flags on the ends of breather pipes to indicate air flow.

Figure 2. View within the drift showing volume of remnant backfill and bent breather pipes (left); the barricade failed on one side (right).

Case study 2: C&F backfilling

Consequence

Tight-filling caused the dynamic failure of a shotcrete barricade causing a high energy release of paste which flowed over the nearby 2 m height catchment berm and with > 1 m height along an adjacent access drift (Figure 3). Workers were not in the area but this could constitute a near miss incident.

Contributory/Situational Factors:

This event subsequently occurred at the mine described in Case Study 1. The C&F drift was estimated to have a volume of 1050 m^3 paste, with a shotcrete barricade located at the intersection of the access drive. A volume of 930 m^3 was placed at failure. The barricade failure occurred due to overfilling of paste or pressurized confined air. Breather pipes with flags attached to the ends were installed but no movement of the flags was visible (on remote camera footage) prior to failure. Barricade capacity may have been lower than standard due to siting location (at a cross cut) and variable quality rock comprising the barricade abutment. Failure occurred at the paste-pipe side, although this is also the 'worst case' abutment side of the structure in terms of barricade siting.

Key Learnings:

- An alternative backfill containment design was used with revised pressure limits.
- Exclusion/Catchment berm location strategies were re-assessed for future filling.

In follow-up discussions, the mine has reported no further failures.

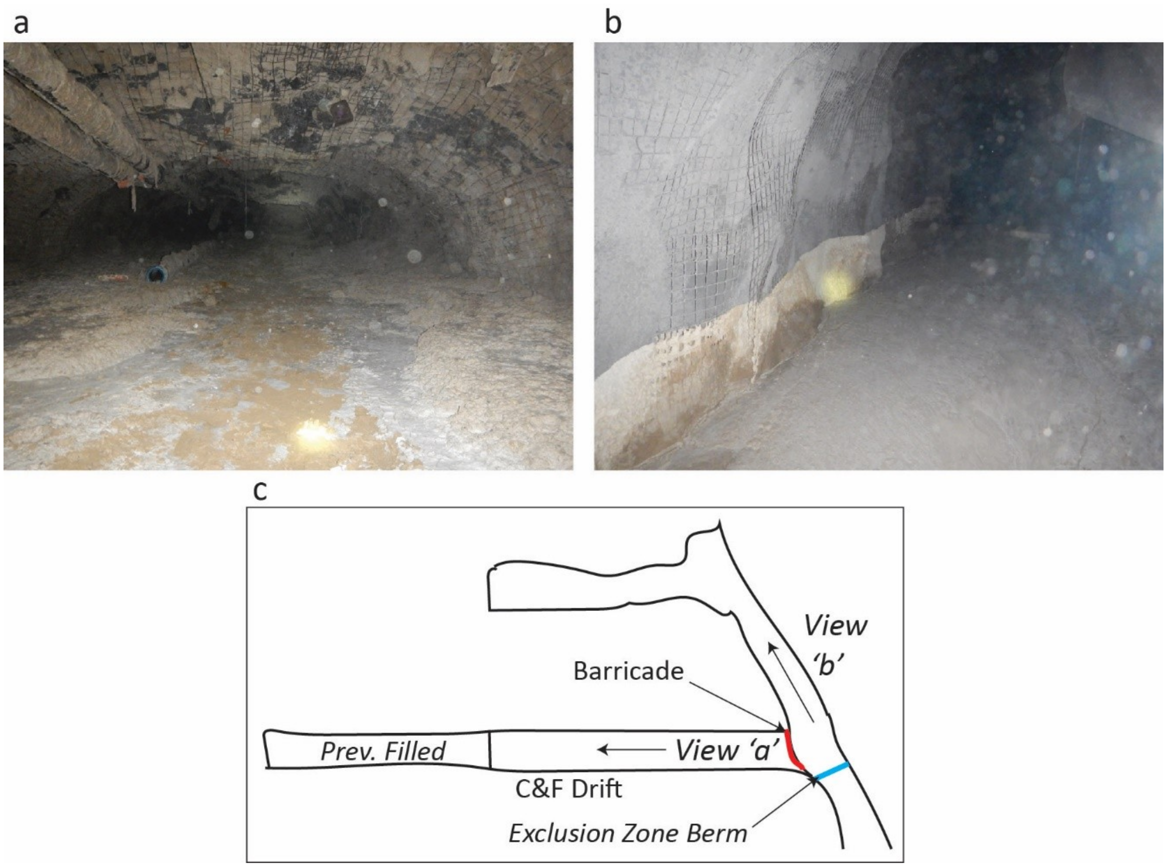

Figure 3. a) View of remaining backfill within the C&F drift, b) view along the access drift showing "high flow mark" and c), plan view and orientation information of photos.

Case Study 3: C&F backfilling

Publicly available reports indicate two workers were in the vicinity of a 'release of material' from a backfill barricade at a Canadian mine, one of whom sustained non-critical injuries. A barricade failure is understood to have occurred due to tight-filling within a C&F drift. The root cause is thought to be breather hole issues.

Case Study 4: Drift filling

The operation was filling a drive with CPB between two barricades when the downstream barricade failed and released backfill into the level (Figure 4).

Consequence:

The exclusion zone volume and/or catchment berm height was inadequate resulting in significant backfill runout through the level. Two underground operators were within the runout area when the failure occurred but were able to evacuate without negative consequence. Two underground vehicles were inundated with backfill.

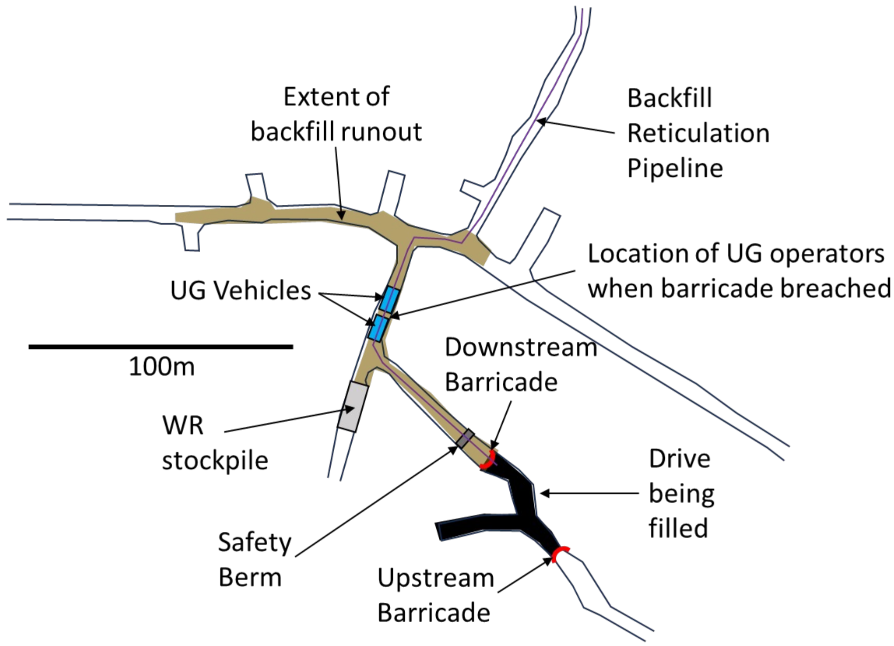

Figure 4. Schematic of filling level geometry with location of drive being filled, various UG features, and the approximate extent of the backfill runout post barricade breach.

Contributory/Situational Factors:
The operation utilizes LH open stoping and has little experience with filling drives; as such, risks were not understood fully. Both barricades had pressure release valving installed. The downstream barricade's valve was closed to allow more backfill placement. The wall drainage system did not have caps removed. Pipeline pressure instrumentation analysis indicated that the reticulation pipeline was allowed to connect to the fill mass and overpressure the barricade (ie, a tight-fill failure). The barricade had a pressure sensor installed but this was not plugged into a datalogger.

Key Learnings

- Future drive filling operations needed to be properly assessed in terms of risk and mitigation.
- The exclusion zone volume and/or catchment berm design was not adequate for this type of filling.
- Ensure barricade instrumentation is plugged in and can be monitored.

Case Study 5: Tight-filling at the overcut of a long hole stope
Consequence:
Tight-filling caused the detachment of a barricade from a sidewall abutment. High energy paste release did not occur but significant clean-up was needed as the leak was not immediately detected.

Situational Factors:
Filling is limited to 1 m below the overcut floor, after which the overcut barricade is constructed. A relatively high binder content paste is used for the overcut 'tight' volume, as previous instrumentation and lab work had defined an initial set time for this mix design with which exclusion zones can be planned.

Volumes are scanned before the barricade is constructed to establish pour volume limits (which are used to set plant run-time limits).

Contributory Factors:
A barricade was constructed at the overcut access of a stope with similar configuration to Figure 1b. The barricade construction process was non-ideal, with the prefabricated falsework frame suffering mechanical damage, resulting in partial detachment from the (NW) sidewall. This issue was exacerbated by potentially inadequate shotcrete thickness in the location of a reinforcing 'corbel' on this NW sidewall due to the close location of a remote mucking stand which obscured the view of the shotcrete applicator. The barricade failure is assumed to have been caused due to the fill height exceeding 5 m above the barricade and reaching the borehole, resulting in a 40 m fluid head elevation. The total volume of paste released due to the failure event is difficult to determine as excess flushes were conducted to 'weaken' the spilled paste, which itself caused problems during clean up. Paste above the 2/3 height of the 5 m tall barricade was released from the stope. Images of the fractured barricade, and subsequently deconstructed barricade are shown in Figure 5.

Key Learnings
Typically filling is managed at this site with a strong, engineered barricade, instrumentation to verify pressure thresholds during filling, and a higher strength paste plug. Continuous pours are routinely achieved. This is the first barricade failure in over 1000 backfilled stopes at this site. While this failure did not result in a critical event, this re-emphasized the need for good QA/QC and risk mitigation practices. The following points are emphasized:

- Remote access camera and barricade instrumentation would have enabled faster shutdown and easier clean up. These are used at undercut barricades, and are now required at overcut barricades, with an additional pressure sensor at the base of the wall recommended to better define and calibrate fill height versus volumes placed.
- Filling into the stope is via a hopper into the borehole (into the stope), with the hopper providing the disconnect between the pipes to surface to limit potential head pressures.

Ultimately, high binder paste to minimize potential fluid volumes, combined with well designed catchment areas are critical controls to mitigate risk in these relatively rare tight-fill cases.

Figure 5. Images of the displaced barricade which was subsequently partially dismantled to reveal paste above the 3/4 barricade height had been discharged either during the original displacement, or the subsequent extensive flushing.

Case study 6 – Tight-filling at overcut of long hole stope
(As summarized from Gray, 2019)

Consequence:
A high-energy release of paste occurred due to a tight-fill induced barricade failure. Paste flowed 100 m from the barricade, over a catchment berm 30 m from the barricade, continued 50 m past a right-angle turn, and proceeded another 50 m past another right-angle turn. Approximately 1 m of fill height required removal from the 100 m distant intersection (Figure 6).

Contributory/Situational Factors:
Tight-filling occurred to an approximate height of 5 m above the overcut barricade (analogous to the Figure 1b scenario). Breather holes were installed (vertically) which provided adequate air pressure relief during filling, but once the stope was full pressure within the paste exceeded the barricade capacity. Paste in the fill hole was hypothesized equal to a 30 m paste head equivalent to 700 kPa. Fresh paste behind the barricade was able to flow further than expected.

Key Learnings
For future tight-filling, in addition to breather holes, the following requirements were made:

- Install two 'spill holes' of 10 cm diameter and 0.5 m from the top of overcut (crown) barricades; these positions marked the limit of the initially placed backfill height. This paste volume below the spill holes shoud be allowed to cure to control the potentially flowable volume of paste within tight-filling spaces, and termed a 'stop and cure process'.

- Containment / exclusion zones should be equal to the maximum volume of the potentially fluid paste. There was realization that the potential for high barricade pressures was underestimated as was the potential for paste to flow significant distances. A key take-away was that low likelihood risk should not lead to complacency in design.

Figure 6. Failed barricade and paste excavated from intersecting drift an estimated 100 m from the barricade (From Gray, 2019).

Case Study 7: Tight-filling at overcut of longhole stope

Consequence

During the final stope flush, the lower section of the barricade unexpectedly detached and fell into the overcut drive (Figure 7). There was no significant release of backfill observed related to this barricade failure.

Contributory/Situational Factors

The overcut drive was filled in stages to limit (operationally constrained) exclusion zone size requirement. The penultimate filling stage had therefore been limited to ~ 50% of the barricade height and cured for several weeks prior to the final pour. The barricade had several small diameter 'drain' holes installed vertically along the centerline of the wall and one large diameter 'drain' hole installed at the top of the barricade. Some backfill leaked through cracks in the shotcrete and through the small diameter drain holes, but not through the large diameter drain hole. The right-hand of the barricade cracked, and shotcrete was displaced below this crack (Figure 8). It is assumed hydraulic connection between the fluid backfill and the failed region of barricade was enabled, perhaps by water flow if shrinkage had resulted in a gap between the barricade and the previously placed fill. However this hydraulic connection was not sufficient to enable fluid paste to flow along the cured paste-barricade interface and into the drift.

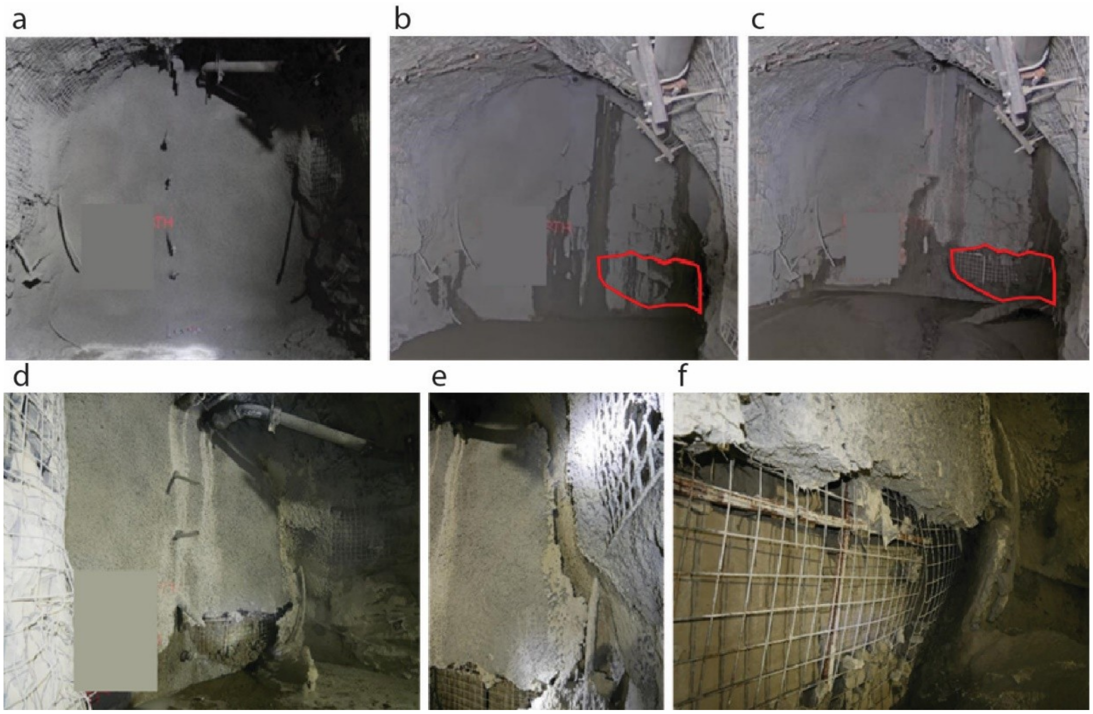

Figure 8. (a) Barricade post-construction, (b) prior to flush, and (c) post-flush. The red outline shows the approximate location of the displaced shotcrete, with additional images showing this detail (d–f). (Identification numbers have been obscured in the images.)

Key Learnings

The causal mechanism of barricade failure is unclear. Images show the barricade started to yield prior to the flush, or at least cracking is demonstrated (noted in Figure 8b). It is assumed the flush induced an additional pressure spike to cause the illustrated shotcrete displacement. Staged pours are a relatively common practice to reduce exclusion zone size and the cure period limited the consequences of the failure.

Discussion

Comparing C&F and LH stope case studies

Based on the case study examples, it is clear that different challenges exist when managing tight-filling for either C&F and LH stoping. For C&F, volumes are markedly smaller, so there is a limited margin of error in overfilling and better awareness of volume requirements in these more easily measured drifts. Some mines include additional, small diameter 'breather holes' through the barricade specifically to indicate fill height, or as already mentioned leave gaps at the top of barricades to avoid over-pressuring. The stope cycle time for C&F is typically much faster than LH, so there is less potential to stop pouring and enable 'stop and cure' processes to minimize potentially fluid or flowable paste volumes.

For LH stopes, while fill volumes are much greater there is also limited ability to define fill heights especially in blind pours. There is inherent uncertainty in terms of when the backfilling process is approaching completion, especially if Cavity Monitoring Surveys and as-placed backfill volumes do not consistently reconcile, as reported by Yumlu and Guresci (2007) and consistent with others. Additional holes drilled into the stope may be necessary with which fill heights, through air flow cessation or leakage of backfill, can be estimated. If a barricade is erected at an overcut (eg, Figure 1b) then additional, small diameter holes can indicate fill height, as per Case Study 6. Lmiting fill heights and allowing stop and cure processes to allow fill to cure, minimizing potential volumes of flowable fill for tight and blind pours, is a key recommendation provided by Yumlu and Guresci (2007), and Gray (2019).

Breather holes and observing filling to completion

As evidenced during the C&F studies if not the LH cases, determination of fill height to indicate close to or genuinely tight status of a backfilling stope is frequently achieved by monitoring the breather holes/lines. 'Flags' are attached to breather pipes (highlighted in Figure 2) to indicate airflow; either a halt in airflow from a stope, or the flow of fill material itself from the breather pipes indicate fill has exceeded the breather point elevation. Such a means of identifying fill height is occasionally problematic, as ventilation outside of the stope may confuse interpretation of a flag showing air-flow patterns from the breather pipe. Alternatively, the root cause in one case study was the observer required fill to flow from the breather pipe prior to stopping the pour. In such a case, blockage (ie, material blockage or crushing/bending) of the pipe creates a dangerous false negative interpretation. Even if an observer can (remotely) determine when a stope is full, through means of air or backfill egress, the volume of material within the lines is still to be deposited and so there is little clarity on how much is too much in terms of excess material placement required to critically overload a barricade.

Realistically, the task of observing tight fill completion via breather hole flags may download unreasonable expectation upon a (remote) observer if human error (eg, a period of inattention) may result in risk of barricade failure. There is a clear need for technological solutions to monitor and alert a backfill plant to changes in airflow from a breather line, given the apparent risks of tight-filling and current human observation based existing controls. An alternative approach has been adopted at one site, where water sensing instruments are used to indicate fill heights which trigger flashing lights that are visible on monitoring cameras when fill height thresholds are attained.

The above discussion raises the question of how much is too much fill in a tight-filling stope. Barricade pressure monitoring is becoming more common during backfilling, and it is unfortunate that such pressure data during tight-filling has not yet (to our knowledge) been published. Specifically, data showing how barricade pressures increase for a range of tight-filling stope geometries would be very useful. Such data are necessary to determine how quickly pressures can rise above critical safe loading thresholds and as such could directly inform best practice debate and plausibly modification to task-specific barricade design.

Operational and research and development efforts to manage tight-filling to minimize the potential for high pressure conditions are strongly recommended. However, the demonstrated potential for tight-filling to cause failure of otherwise competent barricades means that risks apparently cannot be avoided and so must be mitigated. Limiting flowable volumes of fill when approaching the tight-filled condition is a strong recommendation, as per the approach of Gray (2019) with spill holes and stop and cure procedures. Remote camera viewing and pressure instrumentation will also aid immediate understanding of conditions at a specific barricade, and aid in further understanding of the potential tight-fill induced barricade failure process.

Exclusion zones and catchment berms

Exclusion zones are an essential mitigation strategy, as employed at all the operations featured in this paper. The incident shown in Figure 2 resulted in the initial paste wave overtopping the exclusion /

containment berm; he Case Study 6 example also resulted in paste far exceeding the expected bounds implied by their containment berm. The functionality of an exclusion zone may vary from site to site depending on safety culture. An incident report (G.W.A., 2020) noted that "workers were inside an exclusion zone at the time of the incident" and escaped the inrush of paste by climbing up the wall mesh. This emphasizes the need for multiple controls as part of a comprehensive risk management strategy.

There is a natural tendency to underestimate containment berm volume requirements given the limiting consequences on surrounding operational activities, especially given the inherent low probability of this risk. In terms of defining the exclusion zone limits, consideration of the grade of development and run out paths are required. A standard exclusion berm design is recommended. The volume defined as being above the stop and cure zone is a logical estimate for catchment purposes, although defining an appropriate strength for which the stop and cure zone must attain is more contentious. A liquefaction-resistant unconfined compressive strength (UCS), commonly assumed as 100 kPa, would be one approach. However, it is not clear that 100 kPa would be attained within three days; this represents the cure period subsequently adopted by Gray (2019) for many mines, unless relatively high strength mix designs were assumed. Others have suggested lower UCS thresholds may be valid for liquefaction resistance but ultimately such a threshold would likely be site specific and very limited data exists to support interpretations; Suazo (2016) provides a useful review. Review of images from C&F failures (Figures 2 and 3) indicate relatively flat paste exposures left within the C&F drifts. In comparison, the image into the LH stope (Figure 5) infers more topography within remnant paste, so potentially some liquefaction occurred through contact with flows of paste. Closer review of remnant paste surfaces would be useful.

Site specific assessment should quantify if the purpose of containment berms is to prevent a significant depth accumulation of paste outside of an exclusion zone or more conservatively, prevent any potential over-flow of paste. Typically, exclusion zones are designed assuming the catchment volume available between the barricade and berm, and below the crest height of the berm. With this assumption in mind, the observed high amplitude outflow resulting from barricade rupture (Figure 2) may not prevent some limited paste flow over a berm.

Geotechnical needs

Given elevated backfilling risks of tight-backfilling, it may be beneficial to consider site-specific geotechnical requirements for tight-filling. There may be viable trade-offs regarding increased fill management requirements and risks of barricade failure to achieve high degrees of tight-filling vs geotechnical consequences of tolerating less than complete tight-filling.

Geotechnical consideration of breather and fill hole breakthrough positions has also been recommended by one site in this study; over-break within the stope was experiende that changed the breakthrough elevation of the holes to the extent that the fill point was above the breather hole. This was contrary to design intention. In some cases, measuring these hole lengths prior to backfilling or controlling positions by using fixed lengths of HDPE pipes were proposed.

Worst case consideration

While there are differences in the fill management process for C&F and LH tight-filling, the potential volume of fluid paste that escaped in the various case studies appears relatively similar. This is primarily due to the LH barricade failures occurring at overcut horizons with minimal height of paste above. Certainly, the worst-case scenario would be failure of an undercut barricade, which was induced by blind-filling as reported by Yumlu and Guresci (2007). This would be a feasible occurrence if, as can occur, a mine had placed a relatively low strength fill without the realization the paste could remain in a fluid state for a period exceeding 24 hours. In relation to tight-filling, Gray (2019) posed the question "Where are you relying on low likelihood to prevent a serious incident at your operation?" In light of the consequences of failure, especially of an undercut barricade, consideration of fill strengths and stop and cure processes to limit fluid volumes of fill should be a requirement for all tight-filling applications.

Best practice recommendations

In summary, best practice recommendations are as follows:

- Ensure an engineered barricade design is used, and if feasible, include an unsealed (shotcrete) gap to allow backfill to escape and so prevent tight-fill pressure accumulation. (C&F).
- Verify required fill volumes using Cavity Monitoring Surveys (CMS) and manage filling accordingly (C&F).
- Manage placed volumes (as above) but physically limit flowable volumes using spill holes within barricades, and consider strength requirements for backfill under the stop and cure fill horizon prior to tight-filling. (LH)
- Install breather holes as consistent with drift (C&F) or stope geometry (LH) requirements; ensure an adequate number of breather holes/pipes to allow redundancy, with adequate size and material for operational function.
- Use remote video cameras to verify barricade condition and 'active' breather hole status if flags are used, plus backfill pressure instruments to monitor barricade pressures.
- Consider if pour line pressures can be included in placement management controls.
- Require a conservative provision of catchment and exclusion zone volume.
- Conduct a thorough risk assessment with consideration of hazard mitigation as required. Operations with little previous experience may require more conservative controls until there is better awareness of site-specific risks.

Conclusion

Seven case studies of tight or blind fill induced barricade failure have been presented varying in severity and consequence, but with a common theme which emphasizes that safe tight-backfilling requires continued operational focus. Clearly, the issue of barricade failures has not been 'solved' since (to our knowledge) the last well-documented case study examples were published in 2007.

It has been commented that "We should be more comfortable and willing to share our mistakes, so others can learn from them and hopefully we contribute to safer mining practices" (Guresci, pers. comm. 2023). This philosophy is extremely welcome in the mining industry, and its benefits are widely acknowledged in other industries (Syed, 2015). While considerations in Thompson et al. (2023) and associated discussion around continuous pouring is extremely valid, it should be acknowledged that the main operational risk of backfilling placement, based on known barricade failures reported in the last decade, is in the safe management of tight backfilling.

The recommendations and discussions contained within this paper are based on the authors' or featured mines collective experiences and it is important to acknowledge that site-specific needs are present within every operation. As such, localized assessment of risk should be made by qualified persons when considering backfill placement at any operation. This paper is provided to share experiences and promote discussion as part of that process.

Acknowledgements
The principal contribution of the authors has been to collate case study information and key learnings; all credit is attributed to mine staff from the featured mines who have provided information and images, and significantly supported this effort to increase awareness. The authors would be happy to support, advise, or collaborate in future efforts to respectfully, and confidentially communicate more lessons learned on barricade or other backfill safety related issues. The input of several reviewers is gratefully acknowledged in the preparation of this paper.

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