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Best practices in continuously (or not continuously) pouring paste backfill

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Abstract

Cemented paste is established as a widely used backfill material. Mines using this type of backfill initially use conservative pouring strategies whereby a 'plug' is poured to a height exceeding the (containment) barricade and brow. The plug is allowed to cure to an extent that the remainder of the stope can be poured without inducing significant additional pressure on the barricade. In the last decade, more mines are applying engineering principles including engineered barricade designs, barricade pressure monitoring, specific backfill plug strength designs, and quality assurance/quality control (QA/QC) plant-based protocols to evaluate and verify how the efficiency of backfill placement can be safely optimised.

There are several examples within the literature where mines have demonstrated how continuous backfilling can be safely adopted into their respective standard operating procedures. There is, however, an absence of published field data for cases where high or inconsistently low pressures at barricades limit the advisability of continuous pouring. This can create a bias in expectations. We present case study data from mines where a range of barricade pressures leads to, at best, an unproven justification for continuous pouring. Risk profiles are heightened if non-ideal conditions exist (i.e. non-engineered barricades, new operations lacking in site-specific experience). Emphasis on the continual process of safely optimising backfilling efficiency is more helpful than a focus on the potential end result of continuous pouring. Indeed, we cite cases where operations have reverted to more conservative strategies when better appreciation of the risks of continuous pouring evolve with time or changing conditions.

We have previously recommended initially collecting 'baseline' data to assess the range of barricade pressures under normal operating conditions, prior to a recommendation for continuous pour trials. This paper emphasises that although collection of baseline data can be time consuming, given the consequences of barricade failure, it is a necessary task to adequately define risks.

As technology allows the more widespread use of instrumentation to fulfil previous 'use barricade pressure data to verify safe and efficient backfilling' recommendations, it is important to step back and review best practice approaches and, indeed, the context of when it is feasible and when it is not feasible for continuously backfilling or accelerated backfilling to be adopted. Critically, we emphasise that instrumentation is only part of the solution to ensure safe backfilling. Definition of adequate plug strength, proven by QA/QC in terms of early age strength testing, adequate barricade designs and potentially personnel exclusion zones are also necessary.

Keywords: *paste backfill, continuous pouring, accelerated backfilling, instrumentation, backfill pressure, shotcrete barricades*

1 Introduction

Cemented paste (paste) backfilling of longhole stopes involves construction of a containment structure; typically either an arched shotcrete barricade or consolidated waste rock berm at undercut stope accesses. Paste is then deposited into the stope via a pipe from an overcut access, or via drilled holes if no overcut access is available. The conventional approach to backfill placement has been to pour an initial volume of paste to cover the barricade and undercut brow. This initial paste plug is allowed to cure such that the containment structure, which for the purposes of this paper is assumed to be a barricade unless otherwise stated, is isolated from the pressures induced by the placement of the main backfill volume. This two-stage pouring strategy is illustrated in Figure 1. Barricade strengths are typically designed assuming the load applied by the fluid paste plug.

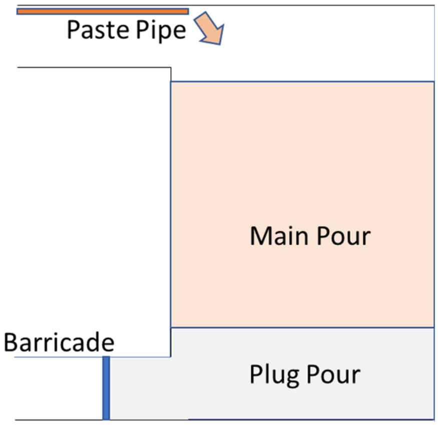

Figure 1 Schematic diagram showing paste volumes for a stope backfilled in two stages: Plug and main pour backfill volumes are annotated. A plug cure period is typically required to allow the plug to gain adequate strength before the main pour is started

A two-stage pour provides a conservative backfilling strategy which is appropriate if either barricade strength or pressures acting upon a barricade are not known. Cure periods, which are required to allow the plug to gain the adequate strength needed to isolate barricades from the load applied by the main pour, are typically between 24 hours and 7 days. Frequently such strengths are not well defined. Mines are increasingly considering the feasibility of continuous backfilling, which is an alternative strategy where stopes are backfilled in one continuous pour, with no requirement for a plug cure period. The benefits of filling stopes more rapidly and with less breaks are widely recognised in terms of a faster mining cycle, less flushes (which improves paste quality), minimised potential cold jointing, and increased efficiency through fewer plant shutdowns and underground switches between backfilling stopes.

A continuous pouring strategy should only be considered where barricade strength and pressure conditions are well known. The continuous pour strategy typically assumes the paste in the initial plug region has gained strength sufficiently quickly so that barricade pressures peak before the plug pour is completed, or where pressure thresholds at the barricade are not exceeded during subsequent backfilling. Grabinsky et al. (2021, 2023) presented an analysis approach whereby an initial plug strength condition must be met and, subsequently, the strength gain in the plug must increase more rapidly than the incremental loading increase during the continued pour. Barricade pressures during continuous pours should be measured to ensure a safe loading range is maintained. This additional step of formally defining a plug strength and applying quality assurance/quality control (QA/QC) through unconfined compressive strength testing of early age paste samples provides an important improvement in ensuring accelerated backfilling is performed safely.

To an extent, 'continuous pouring' has become a buzzword within the backfilling community. Increased adoption of continuous pouring has been enabled by advances in, or increased use of, technology allowing real-time barricade pressure monitoring within the challenging underground environment. This has delivered significant advantages and the process of evaluating how to safely optimise backfilling efficiency is recommended for any operation. The aim of this paper is to emphasise that the implementation of such a process is non-trivial and a thorough understanding of site-specific risks is critically important.

It is understandable that case study data available within the literature typically presents successful outcomes (i.e. Thompson et al. 2012; Li et al. 2014; Brown et al. 2019; Oke et al. 2021). However, we caution that cases exist where initial trials have deemed that continuous pouring was not feasible, or mines have discontinued the use of continuous pours, in response to greater awareness of site-specific risks, as will be discussed. In the interest of operational safety, it is essential that lessons learned be shared, and this paper presents case study data which is considered valuable in setting reasonable expectations for other mines. In our experience, mines may be surprised at the extent of initial testwork that is required. As continuous pour trials are conducted more widely, there needs to be greater awareness that, if performed incorrectly, the risks of backfill containment barricades failing and inducing high energy releases of fluid backfill into mine workings are significantly increased. This paper discusses best practice approaches to safely accelerating backfilling within the context of operational experience and case study data.

2 Previously proposed approach to optimising backfilling efficiency

Our earlier work (Thompson et al. 2011, 2012) showed how in situ (stope) pressure data could demonstrate the viability of continuous pouring based on understanding of a mine's typical backfill behaviour, and barricade pressure data could be used to identify and maintain safe operating conditions during continuous pours.

Based on this work, our typical recommendations for mines looking to investigate the feasibility of optimising backfilling efficiency above a basic two-stage pour approach was to conduct:

1. Initial trials during routine backfilling to determine baseline barricade pressure conditions.
2. One or more continuous pour trials utilising barricade and in-stope instruments.
3. Pressure monitoring at barricades at which accelerated backfilling was conducted.

Progression would occur subject to adequate results from baseline and continuous pour trial stages. While these recommendations remain valid, other considerations are required, as will be detailed.

2.1 Type of instruments and typical data

Backfill pressure data has been measured by many practitioners (as reviewed by Thompson et al. 2012, plus Alcott et al. 2019, Oke et al. 2021, and others). Total earth pressure (σ) measured using total earth pressure cells (TEPC), and porewater pressure (u) measured using piezometers, provide very useful data. The combination of these instruments enables calculation of effective stress σ', which is defined as $\sigma' = \sigma - u$.

These instruments typically also measure temperature, which is useful in the context of cemented backfills as the exothermic cement hydration reaction induces temperature changes as backfill cures in situ, providing some indication of the state of this process (i.e. Thompson et al. 2012).

For initial baseline testing and routine monitoring featuring barricade instrumentation, it is often recommended that two instrument clusters, each containing one TEPC and one piezometer, are positioned in the central axis of the barricade at approximately 1/3 and 2/3 of the total barricade height (i.e. Figure 2). In-stope monitoring typically features clusters with three orthogonally configured TEPCs and one piezometer, providing data as shown in Figure 3. One cluster is ideally positioned in the centre of the stope, and one under the undercut stope brow (Figure 2). The open stope cluster provides worst-case data as pressures measured in the centre of the stope are the largest, with pressures reducing towards the stope walls and under the stope brow (Thompson et al. 2011). The under-brow cluster provides useful data as although pressures tend to have lower magnitude than the centre stope, this location is advantageous as instruments and cables are more protected and less vulnerable to damage by falling rocks.

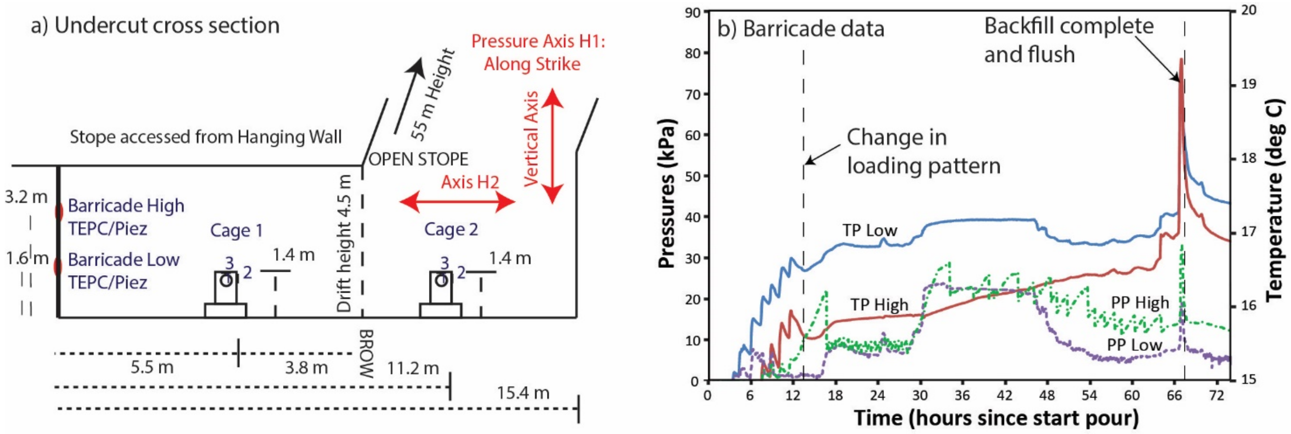

Figure 2 Instrument configuration, total earth pressure, (TP) and pore pressure (PP) data from high and low positioned barricade instruments during a continuous pour (Thompson et al. 2011)

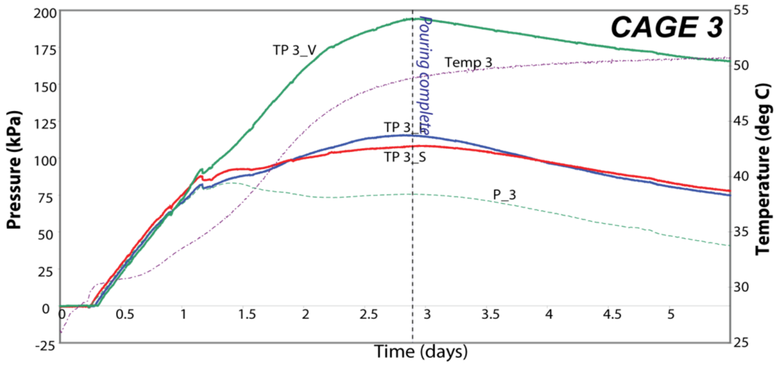

Figure 3 Representative in-stope pressure and temperature data (from Thompson et al. 2012) showing total earth pressure (TP) measured in vertical (V), horizontal long (L) and horizontal short (S) stope axes, and pore pressure (P)

The orthogonally configured clusters are valuable in providing a more complete, or easier interpretation of the fluid to soil-like material transition when compared with the TEPC and piezometer configuration at a barricade location. Initially for a fluid backfill, TEPCs oriented to measure pressure in two horizontal and one vertical axes will measure equal pressures (i.e. Figure 3). A deviation from this hydrostatic loading regime then occurs which signifies the beginning of the transition from a fluid to soil-like material and the development of effective stress. During the hydrostatic loading period, barricade pressures are primarily controlled by the rise rate of CPB and so are dependent on stope geometry and plant output rate. Within a specific tailings stream, the timing of transition from hydrostatic loading is significantly controlled by binder content and, as such, binder content is a significant variable in controlling the magnitude of pressures (Thompson et al. 2012).

2.2 Baseline testing

Baseline testing case study data will be presented. This site-specific work is necessary to provide background information on the range of pressures that can be expected during routine two-stage pour backfilling. This can provide initial guidance on how close barricade pressures typically are to safe barricade working limits during routine pouring and the potential range of pressures that may be experienced for specific stope geometries or paste recipes. Such information is important firstly in planning the logistics of a continuous pour trial and secondly in assessing the feasibility of future strategies to safely accelerate backfilling.

Positive results during baseline testing would feature barricade pressures peaking and then falling during the plug pour, with peak pressures being relatively low in comparison with safe barricade loading limits. Less favourable results tend to show pressures continuing to increase at a relatively constant rate during the plug pour, with pressures no longer considered low with respect to allowable pressure thresholds.

2.3 Continuous pour trials

Subject to positive baseline testing data, a typical recommendation is to test the continuous pour concept under carefully controlled conditions. Barricade pressures should be monitored in real time and used to verify that pressures do not exceed a threshold, the definition of which will be discussed later.

In addition, ideally pressures should be measured at the stope brow and stope centre. As discussed, a more fundamental understanding of paste behaviour is provided from instruments located within the stope compared to those at the barricade (i.e. Figures 2 and 3). While combination of TEPCs and piezometers does provide an estimate of effective stress at the barricade, previous data has shown (i.e. Thompson et al. 2011) that such barricade data may show a faster development of effective stress than that measured within the fill mass, hence the preference for at least some data to be collected away from the barricade.

2.4 Routine monitoring to improve backfilling efficiency

If the concept of continuous or accelerated backfilling is proven under the carefully controlled conditions of the continuous pour trial, a mine should conduct a site-specific risk assessment and define a method (or conditions) by which continuous pouring or accelerated backfilling can be safely implemented as a routine operating procedure. A non-exhaustive list of best practice controls and conditions will be discussed.

3 Case study data 1: routine monitoring

As consistent with baseline testing recommendations in Section 2.1, initial testing was conducted at Mine X for three stopes as displayed in section view in Figure 4. Two TEPC and two piezometers were installed directly onto shotcrete arched barricades at approximately 1/3 and 2/3 barricade height. The strategy was to monitor barricades during routine backfilling to determine 'what is normal' in terms of barricade pressures. As such, a plug pour, a 24-hour cure period and a main pour was planned in each case.

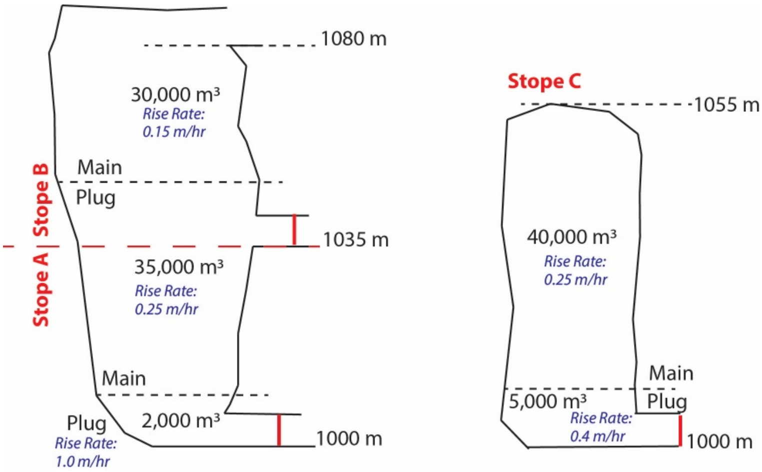

Figure 4 Section view of tested stope geometries,

Data from Stope A is presented in Figure 5. Total pressure peaked at 57 kPa, with a peak pore pressure of 40 kPa. Notably, pressures peaked during the plug pour when fill height was estimated to have just exceeded the brow. Pressures reduced during the plug cure period, consistent with previous measurements at other mines (i.e. Thompson et al. 2011, 2012). A rapid but relatively small (10 kPa) increase in total pressure was measured when the main pour started. The lower TEPC on the barricade stopped working approximately six hours into the main pour but pore pressure data from this location, and from the upper barricade TEPC and piezometer, indicate minimal change in pressure during this main pour. Temperatures increased from 30 to 37°C. This trial indicates a positive result in the context of feasibility of continuous pouring; pressures during the plug pour had peaked prior to the end of the plug and were relatively low, both during the plug pour and during the main pour.

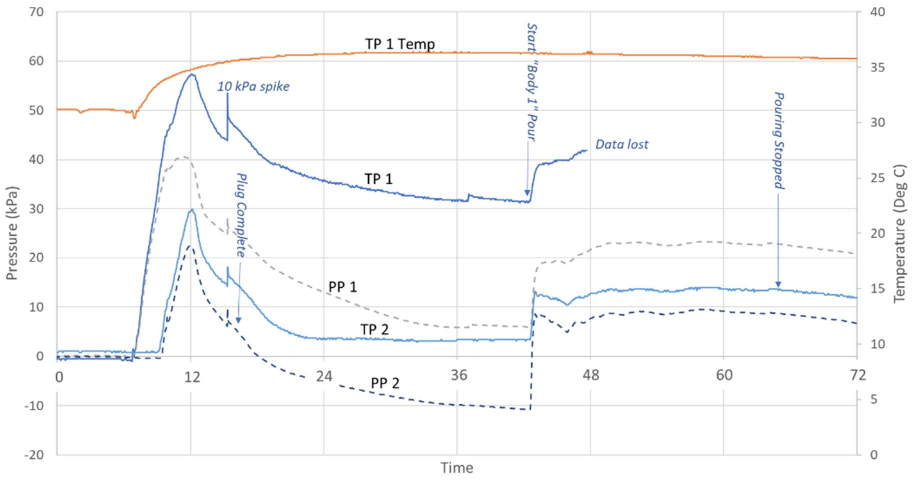

Figure 5 **Pressure and temperature data recorded during baseline testing for Stope A. TP 1 and PP 1 refer to total pressure and pore pressure measured at 1/3 of the barricade height. TP 2 and PP2 refer to instruments at 2/3 of the barricade height**

Data from Stope C is presented in Figure 6. In this case, piezometer data was not reliable and is not displayed. Pressures increased in a linear trend, with a reduction in the rate of loading correlating with paste exceeding the brow height. Pressures continued to increase in a near-linear trend until the end of the plug pour. A 24-hour plug cure elapsed, after which pressures continued to increase, albeit at a much-reduced rate. Barricade pressures were relatively high in comparison with Stope A, although they were consistent with allowable pressures. The results of this stope suggest a two-stage pouring strategy is sensible in this instance.

A third stope (Stope B) was tested showing inconclusive data, and the recommendation to site was that additional baseline testing was required to establish typical data patterns on site to enable more substantial conclusions.

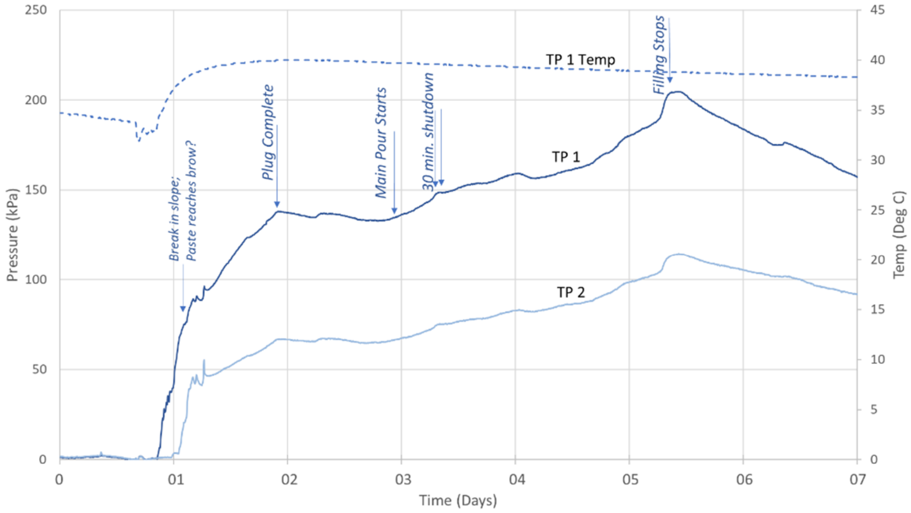

Figure 6 **Pressure data recorded during baseline testing for Stope C. TP 1 and PP 2 refer to total pressure and pore pressure measured at 1/3 of the barricade height. TP 2 and PP2 refer to instruments at 2/3 of the barricade height. Temperature is also displayed**

This case study is significant in showing the potential for a range of barricade pressures at a single mine. While the baseline testing shows it is feasible to continuously pour some stopes, it also highlights an important point that to our knowledge has not been raised within the literature. If baseline testing of barricade pressure data shows there is a reasonable likelihood that high barricade pressures may be experienced under specific operating conditions, the key question is not if the mine can continuously pour (as for this case study, they likely can in some circumstances) but if it can conduct such a process safely in the long term. Fundamentally the question is, should a mine continuously pour when there is potential for high pressures at some barricades? Perspectives regarding how to approach this topic will be discussed.

4 Case study 2: Cayeli 2012

4.1 Background

Cayeli mine in Turkey conducted a significant quantity of fieldwork to measure in situ backfill pressures, as comprehensively reported by Thompson et al. (2012). This work built on earlier work conducted by Yumlu & Güreşçi (2007). Collectively, these datasets provide perhaps the best example of in situ backfill pressure behaviour available in the literature, in terms of showing how binder content, tailings stream, stope geometry and rise rate control in situ pressures. In the context of managing backfilling at Cayeli, the fieldwork showed two end member cases, as summarised in Figure 7. For some stopes, barricade pressures peaked during plug pours and the mine could pour stopes continuously and maintain pressures below 75 kPa (i.e. Figure 7a). Alternatively, other stopes experienced relatively high barricade pressures that mandated a two-stage pouring strategy to ensure barricade pressures remained within safe loading limits (i.e. Figure 7b). The Cayeli fieldwork provided proof of concept that continuously pouring could be managed under carefully controlled conditions by monitoring barricade pressure data.

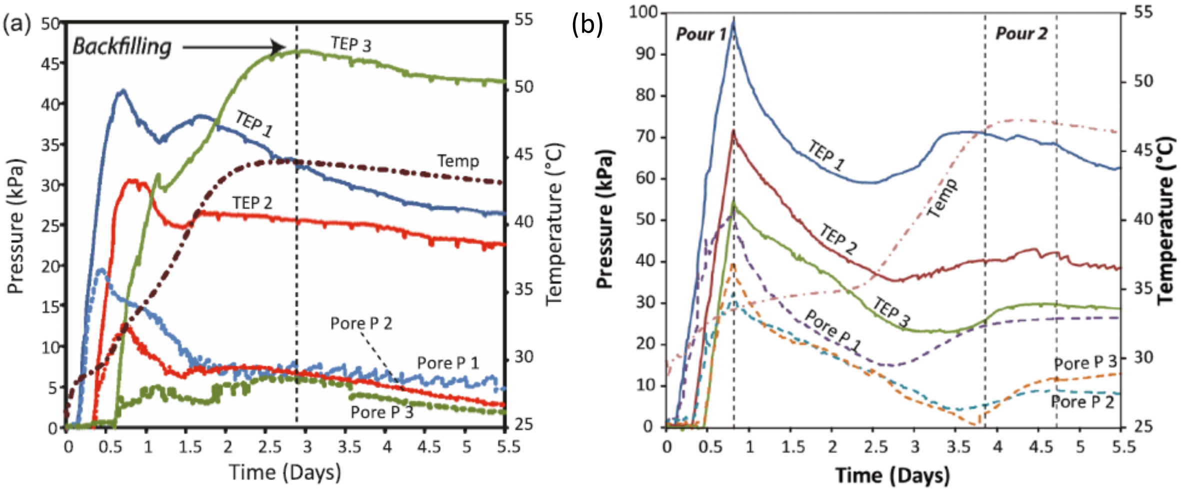

Figure 7 **Cayeli barricade total earth pressure (TEP) and pore pressure (Pore P), measured at the ¼, ½ and ¾ height of 5 m-high barricades. Stopes were poured (a) continuously and (b) with a plug, 3-day cure and main pour. From Thompson et al (2011)**

4.2 Barricade failure (2012)

Cayeli mine implemented the continuous pour strategy, controlled by barricade instrumentation, for approximately a year until a barricade failure led to the approach being re-evaluated. The mine concluded that the potential for relatively high barricade pressures that could exceed safe loading thresholds introduced an unacceptable level of risk. Continuous pouring was halted and a two-stage pouring strategy was re-adopted. It is important to note that the barricade that failed in 2012 was a planar barricade, and these are often considered weaker than the equivalent shotcrete arched barricade. Nevertheless, lessons learned from this event apply equally to continuous pouring at shotcrete arched barricades.

Cayeli has a demonstrated record of industry leadership in terms of safety and sharing lessons learned for the benefit of the wider industry. Yumlu & Güreşçi (2007) reported on barricade failures at Cayeli principally caused during 'blind' pours where tight filling is required in stopes for which there is no overcut access. They reported on measures defined to reduce the risk of such failures. Even today, anecdotal evidence within North America and Australia suggests that tight filling is by far the biggest cause of failure of shotcrete arched barricades, showing the importance of such reports in identifying industry-wide risks.

The barricade failure in 2012 occurred when a stope was poured faster than would have been permissible without pressure monitoring controls. A volume of 800 m^3 of fluid paste was discharged through the barricade, as consistent with the high energy events previously described by Yumlu and Güreşçi. Such incidents highlight the general risks associated with backfilling which are increased by continuous pouring, and the potentially serious consequences of barricade failure, including the risk of fatalities.

The timeline and summary of the 2012 failure was as follows:

- 600 m^3 of paste was poured to an estimated fill height of 6 m, in 19 hours. The data acquisition system (DAS) malfunctioned and so pressures during this period were not recorded.
- Backfilling stopped for 9 hours and a replacement DAS was connected to the barricade instruments.
- Backfilling continued for 10 hours (an additional 350 m^3) to an estimated 10 m fill height.
  - An 8 kPa pressure increase was measured, which was presumed due to a dynamic loading event as ground falls had been observed in the stope during barricade construction.
  - 20 minutes after the 8 kPa pressure increase, the barricade failure occurred.

Pressure data and video images were recorded and transmitted in real time to the paste plant. Several factors are considered to have contributed to the failure, as detailed below.

The most significant problem was incorrect configuration of the DAS used to verify safe barricade pressure conditions. To obtain data in engineering units of pressure (i.e. kPa) from a vibrating wire TEPC it is necessary to apply an instrument-specific calibration equation to unprocessed (raw) data. As a final step, an atmospheric zero correction was applied, such that the calibration equation was adjusted so that the initially installed, unloaded TEPC registers an air pressure of zero. Critically, this pressure correction was applied when the replacement DAS was installed and so a pressure of 0 kPa was registered at the paste plant when 600 m^3 of paste had already been poured. Analysis suggests the actual pressure acting upon the barricade was 70 kPa when the DAS was attached.

Pressure data from the time the DAS was connected is shown in Figure 8. Initially pressure declined consistently, with the initially placed backfill experiencing a reduction in pore pressure due to either cement hydration or consolidation. When backfilling re-started, pressure was measured at -10 kPa. When the failure occurred, 38 kPa was registered. Reprocessed data (Figure 8) indicates that the barricade likely failed at a pressure of 105 kPa. If the barricade pressures had been correctly displayed at the paste plant, backfilling would have been halted after 3.5 hours of backfilling during the second pour.

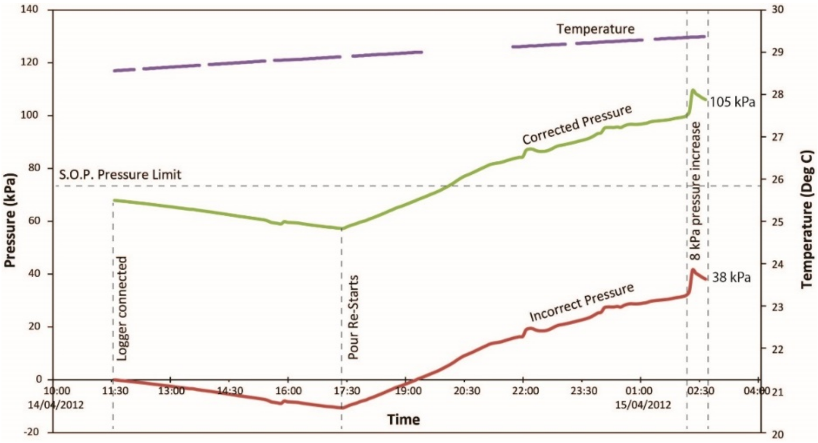

Figure 8 Pressure measured at the approximate 1/3 barricade height for the 2012 barricade. The green 'corrected pressure' value is an estimate of actual barricade pressure based on previous zero offset values. The red 'incorrect pressure' resulted from instrument calibration error. The mine's standard operating procedure pressure limit is indicated

Data indicates that 20 minutes before the failure an 8 kPa pressure increase was measured. Mine personnel had reported ground falls into the stope during barricade construction and so it was hypothesised that a dynamic loading event contributed to the barricade failure by further loading the fluid paste. This 20-minute delay was consistent with accounts of earlier failures from Yumlu and Güreşçi. Review also indicated the barricade had not been constructed to standard. Ultimate capacity was not defined for this planar barricade design although a safe working limit of 75 kPa was defined based on site experience and previous pressure measurements. Personnel access limits had been established as a contingency measure and so no risk of injuries occurred.

In the context of continuously pouring, the Cayeli 2012 case study is critically important in understanding risks and so proactively planning for safe backfilling. Continuous pouring can result in significant heights of fluid paste, which comprises a large quantity of potential energy that requires careful management. Reliance on instrumentation to manage hazards requires an appreciation of inherent limitations and potential errors. Equally, the potential for dynamic loading events requires consideration in terms of the potential for overloading barricades. As an aside, the true magnitude of the hypothesised ground fall event recorded as an 8 kPa pressure increase could have been larger than was actually recorded. For instance, if the ground fall occurred at minute one of the five-minute long data sampling interval, then significant dissipation of pressure could have occurred prior to the 8 kPa measurement.

4.3 Lessons learned

Several 'lessons learned' should be noted to improve backfilling safety at any mines seeking to optimise backfilling placement efficiency.

4.3.1 Instrumentation

- In any system, both the potential for, and consequences of, errors should be assessed.
- This case shows that instrumentation cannot be the only control on safe backfilling given the potential consequences of barricade failure.
- Instrument calibration should be checked when instruments are used for critical decisions.
- Adequate training for technicians and designation of responsible persons to oversee are essential.
- Redundancy of instrumentation is necessary. For instance, the use of two TEPCs, or a combination of TEPC and piezometer, at a barricade could be considered as a consistency check to verify that an

instrument being relied on for critical decisions has not been damaged and is therefore not providing misleading results.

- Specifically, the atmospheric calibration correction at Cayeli was typically small (i.e. < 10 kPa), and it may be preferable to ignore this calibration correction and simply reduce safe loading thresholds to account for the worst-case site-specific atmospheric correction.
- Similarly, the individual calibration equation for each TEPC and piezometer may introduce potential for operator error. The use of multiple instruments mitigates this potential to an extent.
- If a mine is ordering large numbers of instruments it may be useful to consider the use of a generic calibration equation for that batch of instruments, as resultant errors could be taken into account by reducing safe loading thresholds. This may be a valid trade-off if it reduces the potential for user error.

4.3.2 Barricades

- As a best practice, continuous pouring or use of pressure instruments to optimise backfilling should only be attempted with an engineered barricade. As such, safe loading thresholds can be defined as a function of barricade capacity, with significant factors of safety included. Engineer-designed shotcrete arched barricades are preferred to planar barricades.
- QA/QC is required to confirm that barricades are built consistent with design assumptions. This includes rock stiffness and siting instructions, as discussed in Oke et al. (2018), which may have contributed to one tight-fill induced barricade failure in North America.
- Backfilling shutdowns during the plug pour may influence the reliability of barricade pressure data, and so placement of the full plug height and the requirement for a plug cure period may then be mandated irrespective of pressure data.

It is useful to provide additional context for the last point. The full design plug height (i.e. ~7 m) was likely not reached during the initial Cayeli 2012 pour, although data indicates the fill height likely reached or exceeded the barricade height (although this is not proven). This raises a potential problem as illustrated in Figure 9. If the fill does not exceed the barricade height and a significant cure period elapses before filling resumes, then relatively high fluid pressures may be exerted on the top of the barricade. A barricade failure event corresponding to this incomplete plug height mechanism was reported by Revell & Sainsbury (2007). In the present context, instruments contained within an ‘older’ volume of plug (i.e. Figure 9) may not provide representative data for pressures induced by a ‘newer’ paste volume if a significant cure period had elapsed. As such, there is potential that critical filling decisions may be made based on inaccurate data. This is an additional reason that a second TEPC is recommended for routine monitoring. Reliability of instrument data should be questioned if there are extended shutdowns during the plug pour.

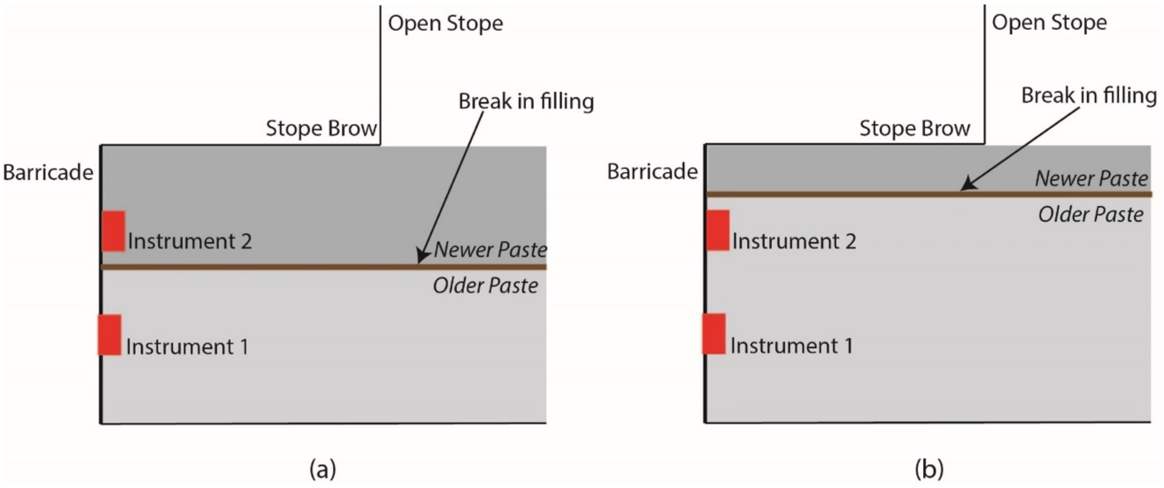

Figure 9 Hypothetical cases demonstrating how instruments may (a) or may not (b) provide representative pressures for 'newer' paste if a break in filling results in two volumes of paste with significantly different strengths

5 Other case study examples

Numerous operations successfully pour stopes continuously. A recent example is Jabal Sayid mine (Saudi Arabia), as reported by Brown et al. (2019). This mine commissioned its paste plant and immediately implemented routine barricade instrumentation with a conventional shotcrete arched barricade. The mine gradually built a barricade pressure database during two-stage pouring. This baseline data was reviewed and, after approximately six months of routine operation, continuous pour trials were performed. The mine pours almost all stopes continuously (the exception being where non-routine geometries are experienced) and peak barricade pressures are in the order of 50 kPa. Barricades are subject to rigorous QA/QC processes and, as an additional safety precaution, personnel exclusion zones are used. Kidd mine (Ontario, Canada) is another well-known example where continuously pouring is enabled through barricade pressure instrumentation (Thompson et al. 2009).

As reported by Li et al. (2014), Cannington mine (Queensland, Australia) provides an example of a mine using instrumentation to measure barricade pressures and enable continuous pouring. It is understood that Cannington has stopped continuously pouring, partly in response to a change in binder resulting in observations of reduced early age paste strength.

Oke et al. (2021) presented case study data from an operation seeking to accelerate backfilling. The four reported tests featured downtime of between 20 and 45% of total backfilling time, and, as such, no continuous pours were conducted. They conclude that continuously pouring would be possible with appropriate safeguards and protocols in place, including exclusion zones and minimum strength targets for the paste plug. The accelerated pouring recommendation was based on relatively low pressures of around 30 kPa during plug pours. This study contains novel aspects, including that the operation uses a variety of containment structures including a non-engineered 'muck fence' which has a 1.2 m top section comprising rebar, wire mesh and shotcrete. It is perhaps a function of the fence design that the use of instrumentation as a routine monitoring tool is not specified as a requirement for accelerated backfilling (instead, the emphasis is on exclusion zones and plug strength). This may be because there is limited potential for routine application of instrumentation at waste rock berms, certainly in comparison with the ease of placing instruments on a shotcrete arched barricade.

In addition to being harder to instrument, pressure data measured at waste rock berms require careful interpretation. For example, as per Figure 7b, pressures measured at three locations on a barricade correspond to applied loads such that the pressure differences are consistent with the variation in height of the instruments within the fill column. Instruments positioned close to the top of a waste rock berm, therefore, do not provide representative, average pressures that would typically be measured at the mid-height of a shotcrete barricade.

6 Discussion of best practice approaches

Some mines experience relatively low barricade pressures under almost all operating conditions, with low pressures here defined in the context of peaking during the plug pour and being low compared with a site-specific engineered barricade design. Assuming other controls, these mines can demonstrate that backfilling efficiency can be safely optimised through continuously pouring. Even for such mines there are relatively higher risk cases, such as tight filling, where continuous pouring would logically not be recommended.

Alternatively, some mines as cited may experience barricade pressures ranging from low to high in terms of typical pressure thresholds. While initial research-based work (i.e. Thompson et al. 2012) was correct in stating instrumentation could be used to identify when barricade pressures approached allowable limits, a decade of experience considering practical application provides more nuanced situational perspective.

Clearly the risk of barricade failure for a mine that uses instrumentation as an active tool to identify high pressure barricades is higher than for a mine where barricade pressures are consistently low. In the latter case, pressure monitoring is effectively more passive in verifying that pressure trends remain low over time and identifying very rare 'black swan' events to reduce risks of barricade failure. It is therefore necessary for baseline testing to provide an estimate of the proportion of stopes that may experience high barricade pressures as this fundamentally informs the required risk assessment.

Risks may evolve if maturing ore bodies or changes in mining methods result in changing stope geometries. Unusual geometries may be encountered when remnants are mined. While miscellaneous filling cases (i.e. ore passes, vent raises) with very high rise rates exceed the scope of discussion, it is emphasised that rise rates and early age paste strength should be checked in fill-design stages for all stopes to identify higher risk cases. It is a useful observation that mines most benefiting from continuous pouring in terms of a higher frequency of smaller stopes may tend to experience higher rise rates and, so, increased risk potential.

Variation in paste quality can result in higher-than-normal barricade pressures, and changes in mix design, including binder type, can affect early age strength and so barricade pressures. As such, temporal changes in a mine's paste represent an additional factor in assessing an appropriate backfilling strategy while highlighting the essential role of communication between plant and underground teams in managing operational risks.

In cases where there is demonstrated potential for high barricade pressures, consideration is required of if and how systems can be designed to minimise uncertainty and ensure safe backfilling. There is now a body of evidence where mines have reverted to a less aggressive backfilling strategy upon a deeper understanding of risks and consequences. Ideally such risks should be identified during initial testing and, in our experience, three baseline tests do not provide an adequate number for such assessment. For instance, in the cited Mine X example, three baseline trials did not provide enough data for a substantial recommendation on the feasibility of accelerated backfilling. The data indicated that continuously pouring was likely feasible for some stopes but not others. There was, therefore, uncertainty regarding the larger question of *should* the mine consider accelerating backfilling.

The Cayeli 2012 study shows the limitations associated with relying on barricade pressure instruments as a catch-all solution to ensuring safe backfilling. While all mines using instruments need to look carefully at potential sources of error that could result in high pressure conditions not being properly identified, the consequences of instrument system failure imply much greater risk for mines where there is frequent potential for high pressure barricade conditions.

Best practice approaches would suggest that the safest way of accelerating backfilling is to combine pressure measurements with shotcrete arched engineered barricades and ensure that backfill is 'well-behaved' in the context of barricade pressures consistently peaking before the end of the designated plug volume. As an aside, it is assumed such well-behaved fill will be enabled by defining and providing adequate plug strength.

It is accepted that mines may look to optimise their available systems. In cases of (a) non-engineered confinement structures, (b) engineered barricades that feature relatively low strength ratings or (c) unreliable QA/QC protocols, even the possibility that backfilling can generate relatively high barricade pressure conditions should tend to the recommendation for conservative backfilling strategies be adopted.

High (measured) barricade pressures described in this paper refer to pressures of around 100 kPa, i.e. consistent with a near-fluid plug that has not cured sufficiently quickly to enable continuous pouring under the considered criteria. Barricade pressure data requires a threshold against which it can be measured to quantify allowable pressure limits during backfilling. It may be appropriate to set allowable barricade pressure thresholds equivalent to the fluid plug height, as consistent with typical barricade design loading assumptions, or to assume 'well-behaved' paste is a requirement for continuous pours and so limit pressures to 100 kPa. The typical shotcrete arched barricade designed and constructed under optimal conditions may feature a considerable safety factor in respect to such allowable pressure thresholds. An alternative approach would be to rely more completely on barricade strength and define allowable pressure thresholds as a function of ultimate barricade capacity. However, this approach is not empirically proven, and is not recommended within our preferred framework of ensuring adequate paste strength and quality, given inherent uncertainties within the mining environment.

What is clear based on the case study data is that instrumentation cannot be considered a 'magic bullet' to enable faster backfilling. While instrumentation remains a key component (as per Section 2), a systems approach is required. The following steps are recommended in optimising backfilling placement efficiency:

- Adequate backfill plug strength should be defined based on engineering methods.
- QA/QC should be applied to verify that early age paste is consistent with plug strength requirements.
- Barricades should feature a well understood design with proper controls and QA/QC checks to verify 'as-built' compliance.
- Monitoring of real-time pressures should be conducted as part of a properly designed instrumentation strategy.
- Other best practice considerations consistent with routine pouring such as cameras, personnel exclusion zones, geotechnical risks (in-stope fall of ground) etc. should be assessed.

Collectively these steps provide a comprehensive safety net which reduces the potential that failure of any element of the QA/QC process will result in critical failure in terms of a high energy backfill release into mine workings. Safeguards are required to identify and correct isolated QA/QC issues such that systemic issues with the above can be avoided.

Hydraulic backfilling is likely not appropriate for continuous pouring. While it should be possible to optimise hydraulic backfilling placement efficiency, lessons of the past should be considered. Failures (as documented by Grice 1998, and references therein) indicated the plausible failure mechanism for poorly controlled and managed hydraulic fill is piping failure, which implies a point loading event that would not necessarily be detected by TEPC or piezometers. Indeed, Thompson et al. (2014) demonstrated that significant heterogeneity in pressures can be expected in cemented hydraulic backfill due to localised variations in cement and grain size. Interpretation of pressure data is therefore more challenging for hydraulic compared to paste backfill. Best practice recommendations for hydraulic backfill require drainage to minimise the 'ponding' height of water on the fill surface (Grice 1998). In our experience this does not occur quickly enough to enable continuous pouring.

The Cayeli and Mine X case studies did not feature plug volumes with paste strength specifically designed to enable accelerated backfilling. While the method proposed by Grabinsky et al. for designing plug strength adequate to enable continuous pouring was verified based on review of field data, we have not collected barricade data from operations which have adopted this method. Therefore we can not comment on how barricade pressures are affected by such targeted control of plug strength. Logically the expectation is that these relatively strong, early age plug strengths will result in well-behaved paste and low barricade pressures. As such, it is hypothesised that the potential for an operation to experience a range of high and low barricade pressure conditions will be significantly reduced if a continuous pour-specific plug strength has been defined.

This paper was partially motivated by concerns that the term ‘continuous pouring’ is occasionally applied in discussion or documentation without adequate context or consideration. Indeed, we question if the focus on continuous pouring is entirely beneficial, and instead consider that ‘safely optimising backfilling efficiency’ provides a more realistic aim. The focus should be on rationalising, and so minimising, plug cure requirements which under optimal conditions will result in continuously backfilling stopes while ensuring realistic expectations.

7 Conclusion

Barricade instrumentation was initially identified as a key tool in enabling safe barricade loading conditions to be maintained under continuous or accelerated backfilling conditions. While such strategies have been successfully implemented, greater realisation has emerged that a broader systems approach should be emphasised to ensure safe backfilling. Potential for errors, both human and otherwise, demonstrate that barricade instrumentation cannot be the only control for safe backfilling. Indeed, some operations that initially adopted continuous backfilling have reverted to more conservative filling strategies as experience provides greater awareness of risks or changes in conditions. Adequate testing is required to determine the range of risk factors and frequency with which non-ideal conditions for accelerated backfilling may occur. Such evaluation should be viewed as a continual process, emphasising focus on ‘the journey, not the destination’ in the context of safely accelerating backfilling and continuous pouring.

A heightened risk profile exists where the potential is shown for an operation to experience both low and high barricade pressures (as defined elsewhere in this paper) as there is more critical pressure on QA/QC systems to identify high pressure barricades. Continuous pouring should not be conducted if there is a demonstrated possibility of high pressure conditions unless adequate mitigation steps are rigorously applied. Factors including barricade type, a specifically designed plug strength, site experience and QA/QC processes should be considered.

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

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