In Situ Backfill Monitoring—Lessons Learned and a New Case Study

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ABSTRACT

In the 10 years since Grabinsky and Bawden (2007) published initial data from an extensive campaign of in situ measurements of backfilling stopes, a better understanding of how in situ backfill behaves, and how operations can use this information to safely improve the efficiency of their backfilling operation has developed. In part, this is due to an ever increasing catalog of published field data. In order to continue this trend, we present a detailed review of the instrumentation, and installation techniques that have worked best as the initially research focused work has been applied on a consulting basis. A recent case study from Barrick Gold Corporation's Williams mine is presented, where relatively low (63 kPa) barricade pressures were measured during a trial to investigate the suitability of continuously backfilling. Importantly, the transition from hydrostatic loading occurred within several hours, which indicates the transition from a fluid backfill to soil-like material was relatively rapid, and likely is a key factor in the relatively low barricade pressures. This data indicates that subject to appropriate QA/QC, including real-time monitoring of barricade pressures, reduced stope cycle times through more efficient backfilling may be possible. Further, barricade displacement has been measured and demonstrated to correlate with barricade pressures. The peak displacement was 0.4 mm. This data will be useful in a site specific barricade strength calibration project.

INTRODUCTION

Cemented paste backfill (CPB) and hydraulic backfill are widely used backfilling materials in the mining industry, providing efficient and rapid backfilling, engineered strength properties, homogenous material properties, and environmental benefits in enabling the diversion of tailings from surface storage. Readers are referred to Potvin et al (2005) for a complete review. Typically, backfilling comprises a crucial component of a mine's ground control strategy, and as such, rates of mining can be significantly affected by delays in, or systemic inefficiencies within the backfilling process.

Mine staff, academics and consultants strive to better understand the engineering principles of backfilling, in order to increase the efficiency of the backfilling system. What happens to backfill within the stope is a subject that receives relatively little attention. This paper describes how instrumentation can be applied to provide a better understanding of the in situ behavior of cemented backfills, and specifically, how this information can be used to safely increase backfilling efficiency. Further, in situ data is essential for numerical modelling work and laboratory studies, both in terms of selection of suitable input parameters, and calibration purposes. Fieldwork is however, difficult to conduct due to logistical challenges, and a requirement for significant commitment from the mining operation.

REVIEW OF FIELDWORK CONTRIBUTION

One critical aspect for many mines is to determine the loading conditions imposed by backfill within a stope on the containment barricades (also termed bulkheads and fill fences within literature). For instance, if a mine knows a) the capacity of a barricade, and b) the pressure acting on a barricade, then it can backfill to maximize efficiency. Without this knowledge, then the mine must adopt a conservative strategy, and pour a limited height “plug” of backfill that is allowed to cure, so that it provides the barrier between backfilling of the “main” stope pour and the barricade. A mine must always verge on the side of caution, as barricade failures constitute high energy events that pose significant danger to mine personnel and equipment. Fortunately, such failures are extremely rare with some examples described by Revell and Sainsbury (2007), and Yumlu and Guresci (2007).

Between 2007 and 2011, fieldwork was conducted by University of Toronto (U of T) researchers to better understand the in-situ behavior of backfill (Grabinsky and Bawden, 2007, Thompson et al., 2011, 2012). Testing at three mines included ten instrumented stopes, and the authors have since conducted numerous other trials on a consulting basis (Thompson et al., 2014a). Other notable fieldwork has been conducted by Hassani et al., (1998), Helinski et al., (2011) and Hasan et al., (2014).

The U of T fieldwork supported the following points:

1. Initially, backfill induced pressure is proportional to the rate of rise of backfill.
2. The initially relatively constant loading rate (proportional to rise rate) is moderated as the fill transitions from the hydrostatic loading condition of a fluid backfill, to non-hydrostatic loading conditions associated with the development of shear strength within the backfill.
3. The positive correlation between binder content and speed of the transition to non-hydrostatic loading within the backfill indicates the rate of strength gain is affected by binder content.
4. In one case, variations between tailings streams apparently acted to retard cement hydration for a specific chemistry of tailings
5. Stope geometry affects pressure distribution of the backfill, with peak pressures measured at the center of the stope, reducing from this point, towards the sidewalls and under the brow.
6. The factors of rise rate, speed of transition to non-hydrostatic loading (or rate of shear strength gain), and stope geometry combine to determine the pressures measured upon a barricade.

The U of T fieldwork also demonstrated a new phenomenon whereby total pressure increases were measured during down-times in backfilling, exhibiting a positive correlation with temperature (which increases due to cement hydration). Analysis of the field results, and laboratory studies indicated a plausible explanation for these pressure increases to be the thermal expansion of the backfill within the confined volume of the stope (Thompson et al 2014b).

The U of T fieldwork programs featured significant quantities of instruments, requiring lengthy installation periods. This time and resource commitment was feasible on a one-off research project basis but is less practical on a consulting basis. The testing procedure was therefore adapted so key data could be collected without delaying a stope’s production cycle. Such work is now conducted by MDEng on a consulting basis, specifically to determine the potential for safely accelerating backfilling. Examples of such fieldwork within cemented hydraulic backfill are presented by Thompson et al (2014a).

In the next section, a new field study from Barrick Gold Corporation's Williams mine ("Williams") is used to demonstrate the logistics of, and typical data from a "production friendly" test to show how critical data can be efficiently and effectively collected and used to interpret in-situ backfill behavior. The objective of this test was to determine the feasibility of continuously pouring stopes and provide information for barricade calibration purposes.

WILLIAMS MINE CASE STUDY

Cemented Paste Backfill at Williams

The Williams mine is located in North West Ontario, Canada, and operates a mixture of long-hole and alimak stoping, with CPB used to backfill open stopes. The featured stope (9560-150-31) was backfilled with 3% binder content CPB. Binder comprises a 50:50 mix of normal Portland cement and fly ash. The geometry of the stope is shown in Figure 1 in both plan and cross section view, indicating a height of 68 m, footwall and hanging wall distance between 8 m and 10 m, and width of approximately 13.5 m. The estimated stope volume was 7003 m^3. The barricade location would typically be set back a distance of one and a half times the drift height from the brow (i.e. parallel to the brow) but the site engineers recognized the drift geometry was unfavorable and so the barricade position was set back, perpendicular to the brow, as shown in Figure 1.

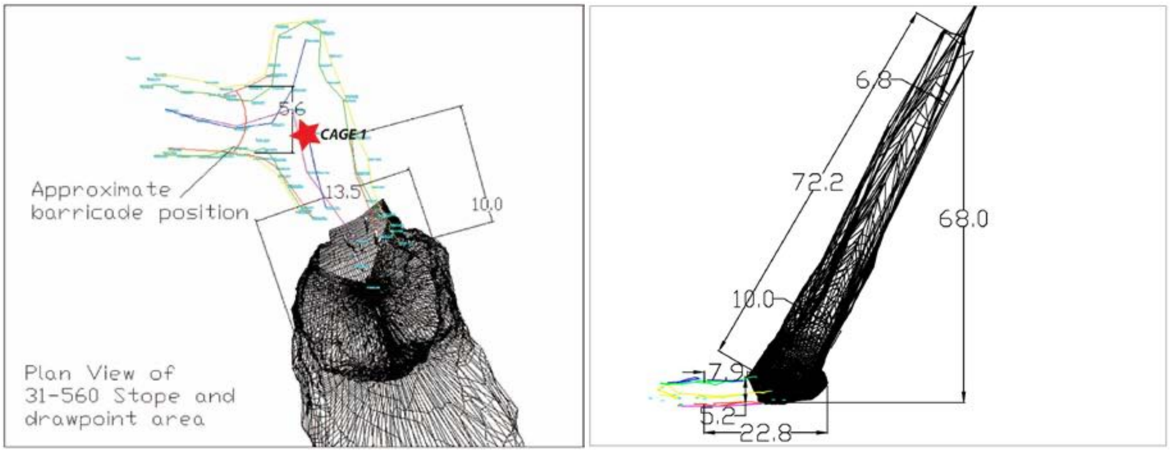


Figure 1. (Left) Plan view showing location of Cage 1 instruments within the stope. (Right) Cross Section view of the stope. The wireframe represents the stope geometry, with the colored lines showing the sidewall position. All units in meters.

Instrument Selection and Configuration

At this point, it is useful to discuss details of instrumentation. Pressure instrumentation has typically consisted of clusters of three, orthogonally mounted Total Earth Pressure Cells (TEPC), and one piezometer, which are attached in wire cages for quick installation into more robust steel cages for in-stope deployment. This is shown in Figure 2. The advantage of this instrument configuration is the three TEPCs allow determination of the hydrostatic (i.e. all axes measuring equivalent pressures) and non-hydrostatic loading stage, i.e. where the fill transitions from the fluid to soil-like material stage and vertical pressure will typically be greater than the horizontal axes. Strictly speaking, one horizontally and one vertically oriented TEPC would provide equivalent data, but frequently some variation in the horizontal axes is measured, and the additional axis provides greater confidence in the interpreted data.

The method of attachment of the TEPCs to the cage is important to consider, as some suppliers do not provide "lugs" for easy attachment by default. The piezometer which measures pore pressure within the backfill also enables interpretation of the hydrostatic versus non-hydrostatic loading state (i.e. this transition is indicated when total pressure is greater than pore pressure), and calculation of the effective stress within the backfill (i.e. total pressure – pore pressure = effective stress).

Vibrating wire technology is used for these instruments, all of which feature thermistors. Attention is required in selecting the correct instrument range. In this case, 700 KPa TEPCs and 350 KPa piezos are featured. Previous work investigating long term backfill response to mining required 5 MPa range TEPCs.

Figure 2. (left) Cages containing instruments are installed in steel cages (right) and bolted onto concrete bases for easy, remote controlled transport. Cage 1 was installed under the brow of the stope, with Cage 2 shown in the center of the stope.

Positioning of Instruments in the Stope

Test stopes during the U of T work typically featured ten instrumented cages, installed in a vertical string of eight, with two positioned about the brow (Thompson et al., 2011). Our current configuration typically consists of two instrumented cages in the stope, and a set of instruments installed directly on the barricade. The largest pressures during backfilling are measured in the center of the stope, and so positioning one instrument in this location is valuable. Arching potential is increased with distance from the center of the stope (as measured by Thompson et al. 2011) and so reduced pressures are expected under the brow. Both of these locations provide information on the transition from hydrostatic to non-hydrostatic loading regimes.

Two cages were installed at Williams, one in the center of the stope (Cage 2) and one under the brow (Cage 1), 3.5 m from the centerline of the barricade (Figure 2). The open stope cage is somewhat vulnerable to falling rocks, and protection of cables including their enclosure in protective hose, and burial in sand are shown in the figure. In this case, the cage was damaged and communications with Cage 2 was lost prior to testing. This emphasizes the importance of installing a cage in the relatively protected brow location. It may not provide the most representative "peak pressure" data but it provides critical information with a good chance of survival.

Typically, cages are bolted to concrete blocks that can be driven into the stope by remote-controlled scoop. The ingenuity of the Williams construction crew in casting four steel struts into the concrete block to latch onto the scoop bucket and enable easy transportation should be acknowledged (Figure 2).

Our favored method of attached instruments to a shotcrete barricade is to affix them to a wire cage which can then be attached to the barricade frame. Their locations are shown in Figure 3. This method ensures TEPCs are encapsulated within the backfill, minimizes concerns of ensuring uniform contact between the TEPC and the barricade, minimizes stiffness contrasts between the backfill and the barricade, and reduces potential complications with piezometers measuring the pore pressure at an interface. Even so, pore pressures will be compared at the barricade and at the Cage 1 location, 3.5 m from the barricade, and shown to be higher at Cage 1, indicating that pore pressures measured at, or close to a barricade may not provide representative data of the pore pressures within the stope.

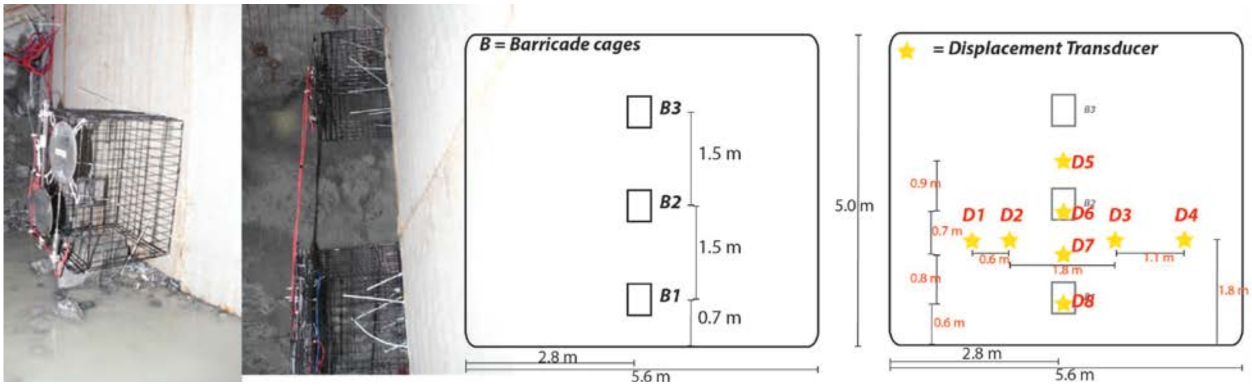


Figure 3. (left) Photos of the TEPC/piezo cages installed on the barricade, (center) map of barricade showing the TEPC and Piezo cage locations, and (right) map of barricade showing displacement transducer locations

Measurement of Barricade Displacement

This field test was partially conducted to calibrate the shotcrete barricade design. Therefore, pressure data was combined with displacement measurements. A suitable displacement instrument is the Novotechnik Position Transducer (series TR), which featured 25 mm displacement range in this case. An array of eight of these potentiometers were mounted to a steel frame, which was offset from the shotcrete barricade (Figure 4). The positions of the instruments on the barricade are shown in Figure 3. This displacement transducer frame required use of welding equipment, which can be difficult to obtain at some mines, in which case a pre-fabricated structure with a shotcrete base may provide a suitable solution.

Figure 4. View of the displacement array frame positioned in front of (but not in contact with) the shotcrete barricade. The insert shows a potentiometer attached to strut extending from the frame.

Methods of Transmitting Data

The method of transmitted data from the barricade location to surface has proven a significant challenge when seeking to use instrumentation in optimizing backfill efficiency. Ideally, the data should be viewed in the paste plant, and used to make real-time decisions in how a stope is backfilled. Fortunately, the use of wireless communication underground has increased significantly in the past ten years. Instrumentation featured in this paper can easily be connected wireless networks. Significantly, associated infrastructure costs can be shared by the use of communications systems that also allow for man-tracking, ventilation on demand, and geotechnical instrumentation applications. Other mines use 4-20 mA type systems that connect to fiber networks, to connect barricade instrumentation. For one-off backfill tests however, it is simple to connect the data acquisition system at the barricade to a remote monitoring station using a CAT5 network, although this method does require connection to powered network switches at approximately 200’ intervals. In this way, the monitoring station can be established at a safe location.

Results

The Williams test stope was poured continuously, aside from a one hour stoppage midway through the 78 hour duration pour. The pressure and temperature data from a seven day period including the pour is shown in Figure 5.

Barricade total earth pressures initially peaked at 27 kPa with a significant reduction in pressure then being measured. It is interpreted that this peak, and reduction is due to the backfill height exceeding the brow, after which the barricade location was temporarily isolated from the effects of continued backfilling. Reducing barricade pressures persisted for 10 hours, after which a gradual increase was measured.

There were then notable transient barricade pressure increases that were likely attributable to:

i) A flush (following a one hour plant shutdown) which induced a peak total pressure of 33 kPa (at 8:14, 15/06).

ii) Issues at the paste plant requiring additional flushes that induced a peak total pressure of 63 kPa (at 03:17, 16/6)

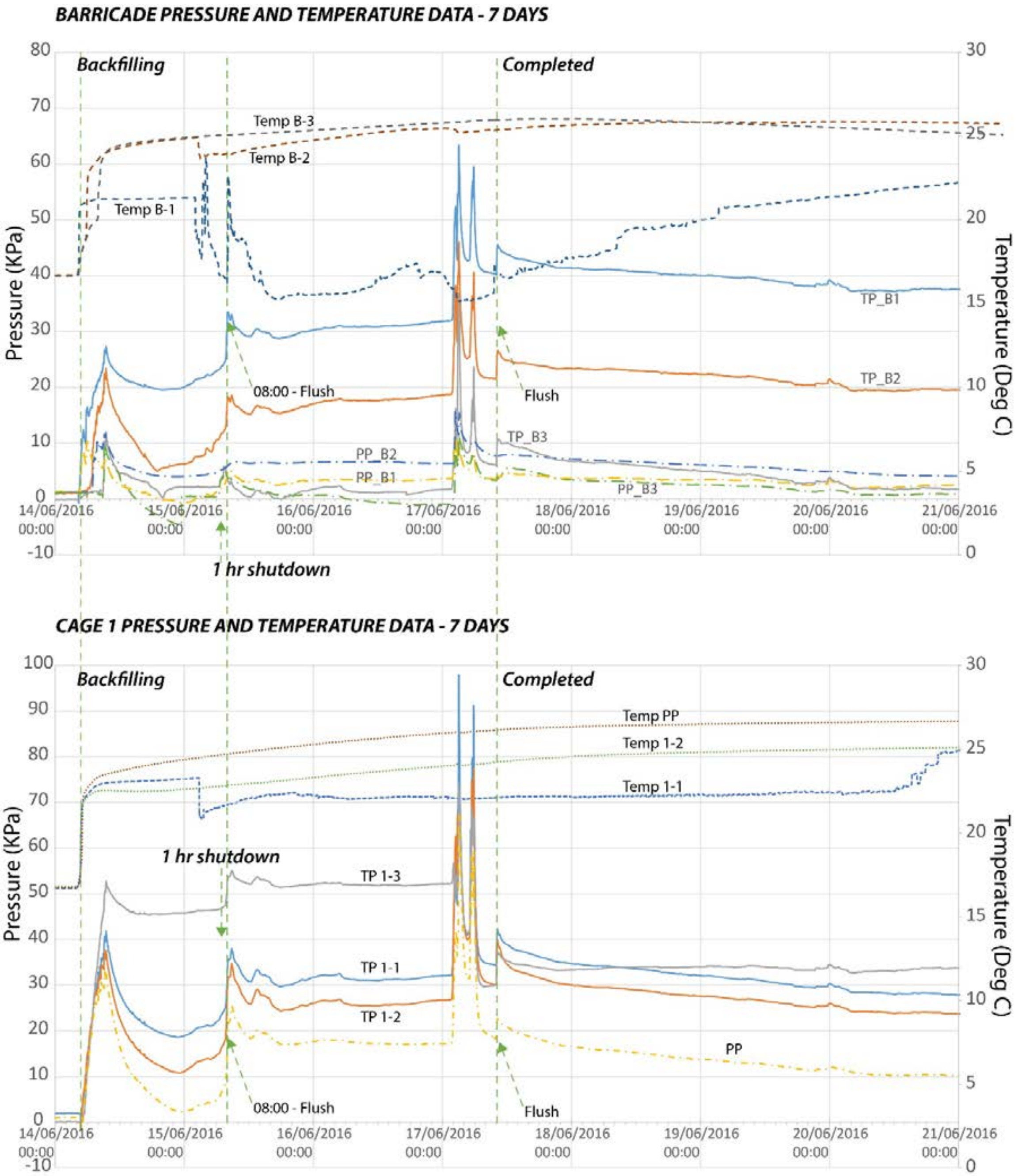
iii) The final flush (at 10:40, 16/6) inducing a total pressure of 45 kPa.

It is important to recognize that these barricade pressures are relatively small, with the largest pressures measured in relatively cured backfill, i.e. 72 hours after placement. Pore pressures at the barricade will be considered in the following section.

Cage 1 Data allows a better interpretation of the in-situ behavior of the backfill that the barricade data, due to its location and additional instrumentation. The initial loading phase of the Cage 1 data on Figure 5 shows hydrostatic loading for between 2 and 2.5 hours. After this point, the vertical total pressure (TP-C1-3) axis continues to increase (to a peak of 53 kPa) at a greater rate than the horizontal TEPCs and pore pressure, as consistent with the material gaining shear strength. Pressures were hydrostatic until a magnitude of approximately 25 kPa.

Pore pressures at the barricade were initially equal to barricade total pressures for less than one hour, indicating that the paste transitioned more rapidly from a fluid state at the barricade than at the Cage 1 location. This demonstrates that caution is required when interpreting “whole stope” backfill behavior from barricade instrument data. While barricade data is satisfactory from a routine QA/QC perspective, the installation of instruments within the stope body is desirable when initially assessing backfill behavior to assess if safely increased backfilling efficiency is possible.

Following the 53 kPa peak in vertical total earth pressure, Cage 1 pressures reduced, and follow a similar pattern to the previously described barricade data, in terms of the brow height being exceeded, and subsequent flush induced pressure increases. The largest of the flush-induced pressure increases occurred at 03:17, 16/6, with a peak pressure of 97 kPa. Pore pressures also increased during these events. In our experience, flush induced pressure increases of this magnitude have not typically been measured at other mines.


BARRICADE PRESSURE AND TEMPERATURE DATA - 7 DAYS

CAGE 1 PRESSURE AND TEMPERATURE DATA - 7 DAYS

Figure 5. Total earth pressure (TP), pore pressure (PP) and temperature (Temp) measured at the barricade and Cage 1 at the featured Williams backfill test. The barricade features instruments at heights of 0.7 m (B1), 2.25 m (B2) and 3.75 m (B3). Cage 1 features TP measured towards (TP 1-1) and perpendicular to the barricade (TP 1-2) and vertical pressure (TP 1-3).

Displacement Data during the Williams field test is presented in Figure 6. Instrument positions were shown in Figure 3. Barricade pressures from the 0.7 m and 2.25 m height TEPCs are also included in Figure 6, indicating a clear positive correlation between pressure and displacement data. During the initial barricade loading phase (to the peak total pressure of 26 kPa), a maximum displacement of 0.13 mm was measured. During the remainder of backfilling, the correlation persists with the peak displacement of 0.39 mm coinciding with the peak barricade pressure of 63 kPa. Curiously, the reduction in pressure following the initial (filling above the brow related) peak in pressure apparently induced a reduction of displacement past the initial starting point (i.e. the barricade moved further back into the stope) and so more movement was induced than a simple unloading elastic response would predict.

Ultimately, barricade displacement was relatively small, which is expected given the pressure induced on the barricade was likely small as a function of the barricade's strength. Further analysis of barricade response is likely not justified by the small magnitude of the data, and it should be recognized that displacement response will be affected by local variation in barricade construction, non-uniform strength distribution, and other factors. This test does however demonstrate a method by which mines may calibrate their barricade strength models, which may allow a more rational approach to designation of strength factors by barricade design engineers.

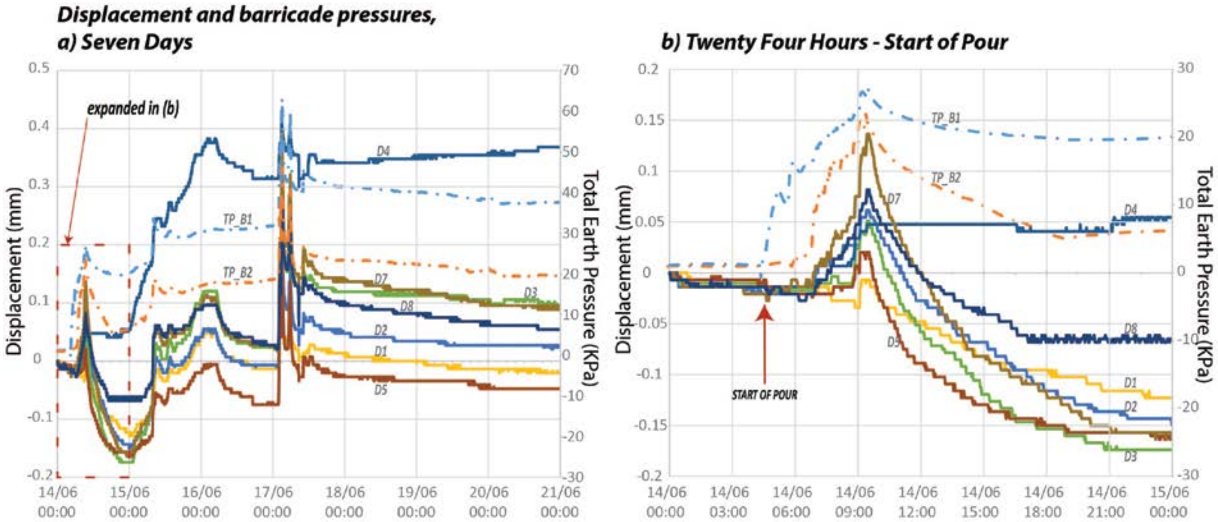


Figure 6. Displacement data for two time periods. Barricade total pressures are shown on the secondary axis for comparison purposes (B1 = 0.75 m height, B2 = 2.25 m height instruments). The position of displacement instruments (D1 to D8) are indicated on Figure 3. Positive displacement implies movement of the barricade "out" of the stope

Comparison with Previous Pressure Data. A previous test conducted at Williams is reported by Thompson et al, (2011) with the data summarized in Figure 7. There are close similarities between the 2011 and 2016 datasets. For instance there was a relatively quick transition from fluid loading to a soil-like material response in both (2-3 hours in 2016, 4-6 hours in 2011). Again, there was a transition interpreted to be due to the brow being backfilled, with total pressures at the barricade of 30 kPa and negligible pore pressure at this point in 2011, compared to 27 kPa and 7 kPa for total pressure and pore pressure in 2016. The 2011 test also indicated a pore pressure spike during the main pour portion of the test had caused an increase of total pressure at the barricade. The flush at the end of backfilling caused an increase in barricade total pressure to 80 kPa in 2011, with a similar flush inducing barricade pressures of 45 kPa in 2016.

Comparison of the two tests indicates broad similarities in the behavior of the backfill in terms of rapid “set up” of CPB, relatively low barricade pressures during the test, and ability of pressure increases within the fill to be induced by flushes.

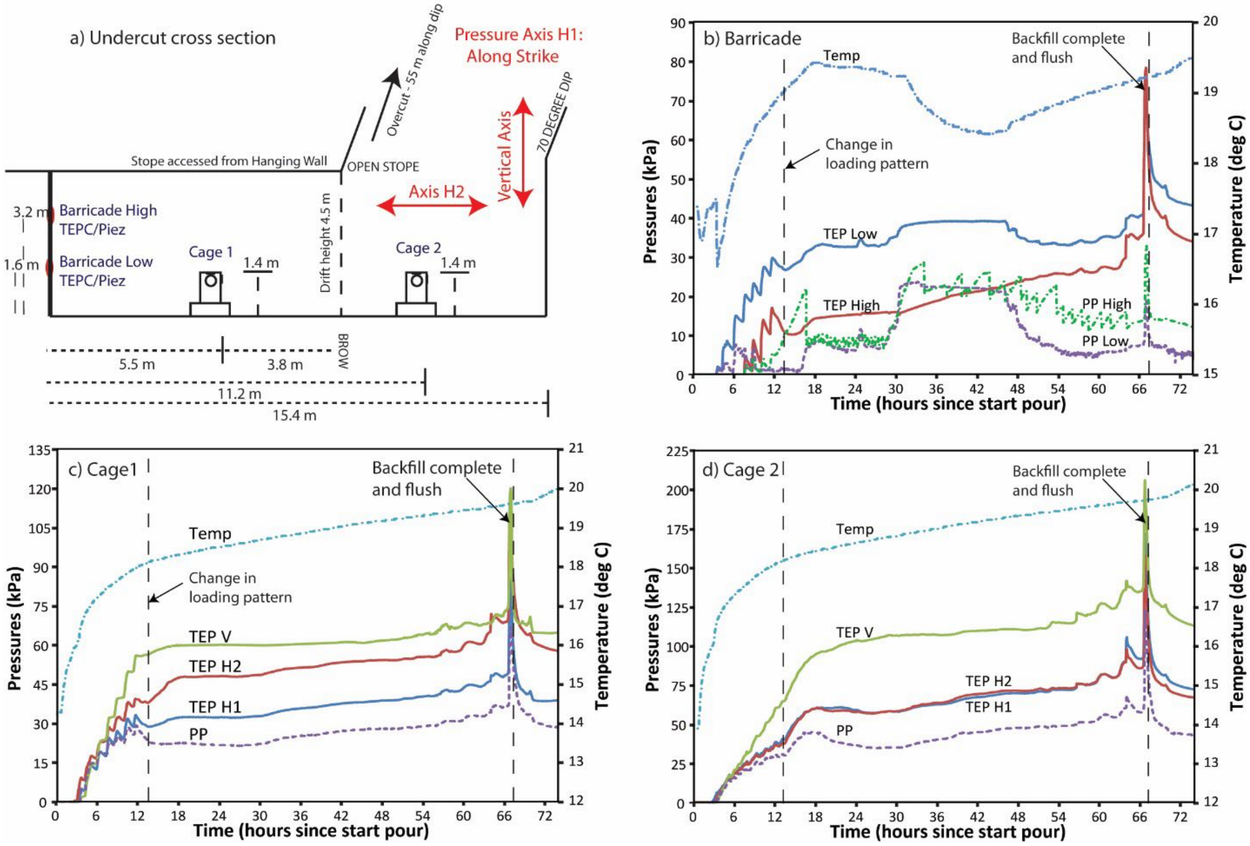


Figure 7. Results of the 2010 Williams Mine Fieldwork taken from Thompson et al (2011) showing a similar instrument configuration to the recent fieldwork, with instrumentation annotated on the section view.

CONCLUSION

This paper has presented a review of how in-situ instrumentation can be deployed to measure in-situ backfill behavior, including practical pointers based on ten years of experience that may be useful to other practitioners. A new case study at the Williams mine is presented, in which pressures and temperatures were measured for a continuously backfilled CPB stope. During this test, relatively low barricade pressures were measured, and in-stope data indicated a rapid transition from fluid loading occurs as the CPB quickly gains shear strength. This data is similar to previous measurements on site, which suggests the in-situ backfill behavior has not changed over time (as could be expected with variations in tailings source, etc.). Subject to suitable QA/QC controls, likely including real-time monitoring of barricade pressure data, continuously pouring stopes is a realistic proposition at this mine, which will reduce stope cycle times by one day, and maximize plant efficiency by reducing associated line changes and shutdowns. During the field test, displacement data was measured to correlate to pressure measurements on the barricade, with a peak displacement of 0.4 mm. This type of measurement provides a useful method of calibrating barricade strength models.

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