Elastic Arching Effects in Tall Cemented Paste Backfilled Stopes

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Abstract
The term 'arching' has been used in the context of granular materials in (semi-)rigid containers, to describe the reduction of vertical stress compared with one-dimensional overburden calculations. The primary mechanism for the reduced vertical stress is shear resistance generated between the granular material and container sidewalls. This assumes that granular material shear resistance is fully mobilized along the contact surfaces, which is probably reasonable for uncemented material but may be unrealistic for cemented materials. A review of the best available mine backfill field data indicates Cemented Paste Backfill (CPB) can hydrate and gain significant strength and stiffness before pore water pressures dissipate and effective stresses develop within the backfill. Therefore, it is possible the response to developing effective stress is elastic, and so stresses will develop along the sidewalls during elastic loading, ie, pre-failure. The implications of elastic backfill behaviour are investigated using numerical simulations of stope filling and it is found that for tall stopes there is a maximum vertical centerline stress $\cong \gamma L$ (where γ is the backfill unit weight and L is the stope span) and this is virtually fully developed at H= 2.5 L (where H is the stope height). A normalized equation is proposed to describe the centerline vertical stress for elastic backfills, and this is compared to several published case histories where high-quality field monitoring data are available. The predictive equation reasonably captures the available field data within bounds of ±40%, whereas a conventional arching solution fit to match the "infinitely deep" vertical stress value γL captures only the lower-bound field measurements. The implications of these findings are particularly relevant to predicting the "main fill" stresses that may occur on CPB "plugs" that are subsequently undercut, and this design issue is considered in detail in terms of application to undercut backfill strength assessments.

Key words: arched stresses, net weight analysis, granular backfill, backfill plug pressures.

Introduction
Granular materials poured into containers with (semi-)rigid sidewalls will begin to settle under self-weight and impose shear stresses along the sidewalls. Integration of the shear stresses over the contact area results in a vertical resisting force that offsets the granular material's self-weight. Janssen (1895) reports a series of physical experiments and supporting theoretical calculations using corn in model scale silos, and the translation from the original German into English provided by Sperl (2006) uses the term 'arching'. Sperl goes on to note that the concept of an upper-bound stress realized at the base of tall silos, also called a 'saturation pressure', was known to Janssen and was demonstrated conceptually in physical experiments as early as 1829. The concept of soil arching appears in the early 20th century (Marston and Anderson, 1913; Marston, 1930) in the context of predicting the vertical stresses on pipes in backfilled trenches. These concepts were also successfully used in investigations of the response of uncemented hydraulic backfill at Näesliden mine in Sweden (Knutsson, 1980) where field stress measurements were explained using arching theories, with the theoretical model's parameters calibrated using laboratory data. As for cemented mine backfill, Mitchell et al. (1975) conducted field measurements of horizontal pressure acting

on rigid hydraulic backfill bulkheads at the Fox mine in Northern Manitoba. The stope was approximately 30 m × 30 m in plan and 180 m high and the backfill was placed at an average rate 0.625 m/day resulting in effective drainage and negligible pore water pressure development. The bulkhead near the stope's footwall experienced a load-time history that immediately fell away from the values predicted by one-dimensional earth pressure theories, and the maximum pressure recorded was ~ 100 kPa after 50 days at which point the pressure seemed to have stabilized and measurement readings were stopped. While this result is consistent with the conceptual notion of an upper-bound pressure from arching theories, the authors did not attempt to quantify their findings using arching theories incorporating backfill cohesion. Since the 1990's there have been several successful attempts to measure backfill stresses particularly in Cemented Paste Backfill (CPB) in tall stopes (as opposed to cut and fill stopes), but no one has yet to successfully correlate these results to available forms of arching theories. Developing an appropriate arching model has significant design implications, especially for undercut backfill plugs in tall stopes where the design must account for stresses imposed by overlying weaker backfills. Therefore, this work attempts a new interpretation of arching mechanisms in CPB filled stopes.

The starting hypothesis for this work is that the load-path during deposition for CPB is fundamentally different than that for uncemented fills, such as at Näesliden mine. There is now ample evidence from multiple mines where the backfills were heavily instrumented during backfilling, and where supporting laboratory test results for material properties exists, that the pore water pressure dissipation and effective stress development in the backfills occur after binder hydration has begun and the backfill has achieved appreciable strength and stiffness. Therefore, the response of the backfill would be elastic, and failure along the sidewalls would not necessarily occur. The supporting evidence for this will be reviewed, and then numerical models will be used to generate normalized solutions for the stresses developed in backfill that appears as elastic layers in a successively filled stope. The numerical results are then compared with available case history data to assess the reasonableness and the reliability of the proposed solution. Limitations of the current work and opportunities for further work are identified, and the design implications of the proposed solution are considered.

As-placed CPB properties

There are a few published studies where backfill field sampling results are correlated with the original bulk properties as prepared in the backfill plant, and where instrumentation results are correlated with the self-weight consolidation potential during backfilling. These studies are summarized below.

Been et al. (2002) report results from a test stope at Neves Corvo mine that was filled in three layers with different binder content: 2% in the bottom 0.5% in the middle, and 1% in the top layer. Void ratios from field samples were plotted against the expected void ratio based on one-dimensional consolidation results, and it was found that the 2% samples (which, being in the lowest layer, should have undergone the most consolidation) were consistently higher than the trend from the other binder contents. They concluded "… consolidation depends on cement content, a higher cement content resulting in less consolidation. The effect of the cement is to bond the material more strongly and, therefore, little volume change and consolidation can take place as the applied stress is increased." (p. 52).

A similar conclusion was drawn by le Roux et al. (2005) based on laboratory and field test results at Golden Giant mine. Water content, void ratio, and degree of saturation could not be correlated with deposition height in the stope, and the average water content was consistent with the as-prepared design water content from the backfill plant. However, occluded air was visible in the field samples. A clear trend was established between the bulk properties, showing that as occluded air raised sample void ratio, so to would it reduce the degree of saturation such that the average water content was unaffected. It was hypothesized that the additional air was occluded during backfill plant mixing and during end-of-pipe deposition into the 25 m high stopes, but that the binder hydration occurred faster than effective stresses developed, so self-weight consolidation effects were inconsequential. The testing and analysis approach used by le Roux et al. (2005) was later expanded and applied to fieldwork and laboratory test work for Williams, Kidd, and Cayeli mines (Grabinsky et al., 2014; 2013) with the same findings for these mines as well.

Alcott et al. (2019) show the results of a field monitoring and field sampling program at Casa Berardi mine. They note that the CPB is intentionally prepared with higher water content than conventionally considered for paste due in part to the gravity driven underground distribution system, and it is normal for about 20% of the as-delivered fill volume to be lost through water drainage during and after deposition. A plug with 8% binder content was poured 8 m high and the average void ratio of samples taken from the plug appears to be consistent with control samples taken during the pour (void ratio 1.15), although there is considerable variation (~ 0.95–1.50). Immediately above the plug in the 4% binder content main pour, the average void ratio is about 0.85 and scatter is less, however there is not a consistent trend through the main pour profile (perhaps reflecting the lower binder content with slower hydration, as well as the higher as-deposited water content).

Most recently, Shahsavari et al. (2023) carried out column tests in the laboratory intended to simulate the top 1.5 m of CPB deposition at full scale, using Williams mine CPB material. Compared to similar previous column tests, the CPB was prepared in small batches and deposited sequentially so that the overall deposition rate closely matched that occurring in the field. Additional test work carefully measured the evolving hydraulic conductivity and the stiffness at timescales relevant to the deposition, and the material parameters were used in a consolidation analysis for comparison with column test results. Electrical Conductivity (EC) measurements were also used in the column tests and in control samples, to evaluate the early hydration stages. The synthesized results conclusively demonstrated that CPB stiffness and strength gains associated with hydration were sufficient to resist self-weight consolidation as pore water pressures dissipated, resulting in as-deposited void ratios like those found in the Williams mine field test work.

It is possible that the potential for self-weight consolidation during CPB deposition and curing has been over-estimated for many mining operations. We are not aware of field studies that have shown a trend of increasing void ratio with height, as would perhaps be expected if self-weight consolidation was a primary strength gain mechanism for CPB. Certainly, for the cases considered where self-weight consolidation effects are minor or imperceptible, it can be considered that the backfill responds elastically to the evolving effective stresses as the pore water pressures dissipate. On this basis, numerical models attempting to simulate the elastic deposition processes are considered next.

Elastic arching models of CPB deposition
Examples of CPB field monitoring data are given for Williams, Kidd, and Cayeli mines in Thompson et al. (2011a). Cages with multiple instruments, including a piezometer (PWP) and three Total Earth Pressure Cells (TEPCs) each, are placed proximate to the barricade and extending out to approximately the midpoint of the stope base, and then vertically by hanging them on steel strand wires suspended from the stope roof (Figure 1).

In general, for each instrument cage the TEPCs and PWP register the same pressure for at least a few hours and the pressure is proportional to backfill unit weight and expected height of CPB above the cage elevation. This indicates fluid pressure loading but it does not mean the CPB has no shear strength. Instead, EC and temperature (T) measurements indicate the acceleration phase of hydration has begun and so the CPB is gaining strength and stiffness. As a result, the stress-time histories reach a breakpoint where the horizontal TEPCs and the PWP do not rise as fast as the vertical TEPC and may even start to register reducing stress. Therefore, from an effective stress perspective, it is as though there are discrete layers of elastic material being successively deposited within the stope. The self-weight of these elastic layers accumulates, involving shear resistance along the sidewalls (which are probably within the elastic range of interface behaviour) and shear and normal stresses on the interfaces between the layers. Modelling this behaviour is very different from the assumptions used in traditional arching analyses.

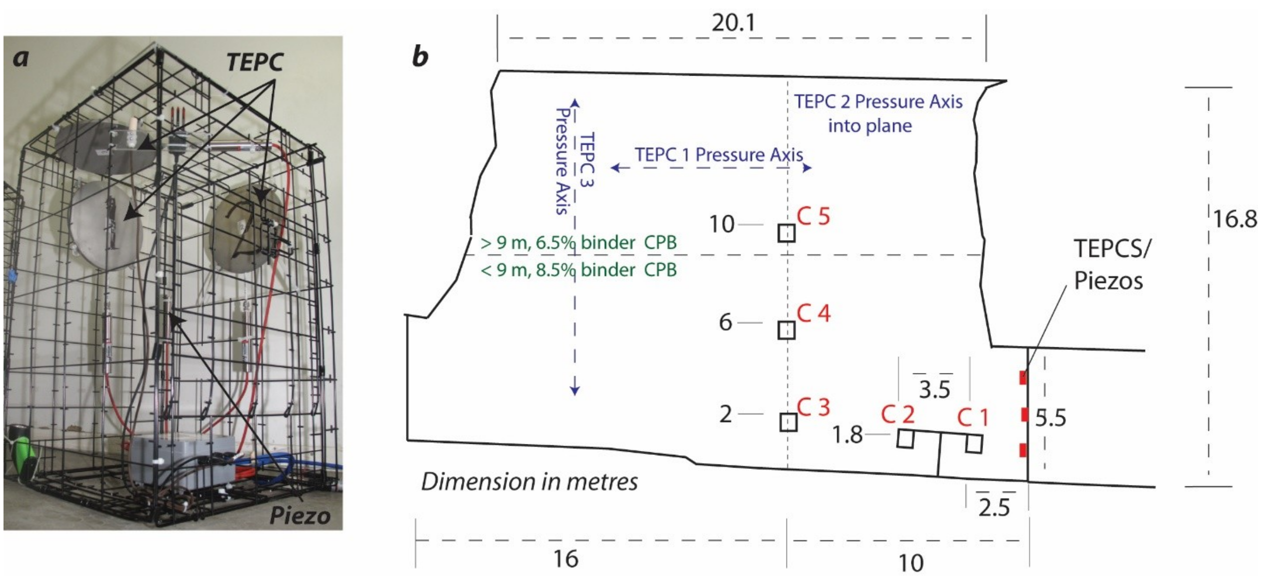

Figure 1: Example of field instruments (Total earth pressure cells, TEPC, and piezometer) and cross section view of Cayeli "685" stope showing instrument locations and dimensions; after Thompson et al, 2011.

Modelling used the finite element program RS2 from Rocscience. If the models assume the entire backfilled volume is placed under zero gravity conditions and then gravity is 'turned on', the results will not properly account for accumulating shear stresses on the horizontal interfaces between the modelled layers. Instead, discrete layers must be added with each layer acting under gravitational loading. A two-dimensional (2D) sensitivity study was conducted to determine the maximum discrete layer thickness, and results were reasonably convergent when the height of the discrete layer was *L*/10 where *L* is the stope span. The modelled displacements are proportional to the Young's modulus, *E*, but displacements are not relevant to the current analysis. In as much as both Shear modulus, *G*, and bulk modulus, *K*, can be expressed as functions of *E* and Poisson's ratio, v, keeping *E* constant and changing will have the effect of changing the relative contributions of shear and bulk stiffness to the overall backfill response and resulting stress distribution. Monitored horizontal and vertical effective stress in the field can be used to assess the *in situ* stress ratio and therefore Poisson's ratio. It is plausible that $v=¿$ 0.2–0.3 is appropriate for most cases. The stress results reported here are not significantly sensitive to assumed Poisson's ratio in this range, compared to field stress measurements that will be considered in the next section.

Several stope heights, *H*, were simulated with constant span to determine how quickly the modeled vertical centerline stress reached a stable upper-bound value (ie, 'saturation pressure'). It was found that a good approximation to this maximum possible vertical centerline stress is γL, where γ is the backfill's unit weight. This bears resemblance to previous arching solutions in that their respective upper bound values were also proportional to *L*. Figure 2 shows vertical stress results for models with *H/L* from 1.0 to 4.0 with contours plotted in terms of % γL, and the saturation pressure is reached at *H/L* = 2.5.

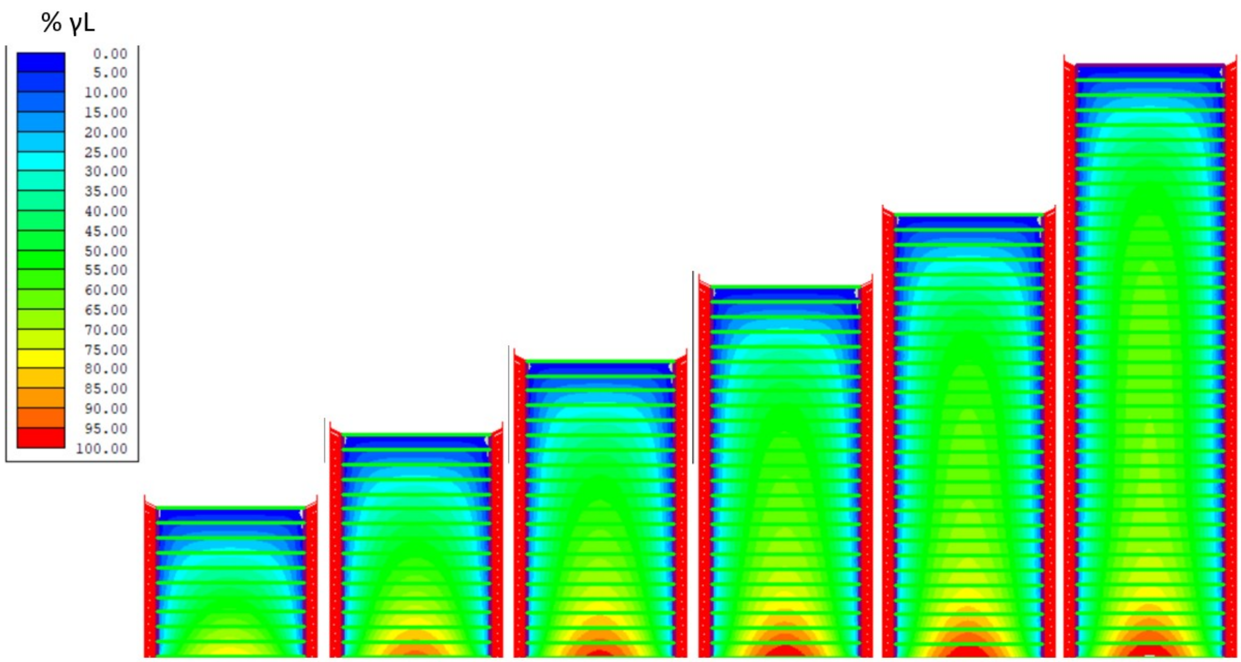

Figure 2. Vertical stress profiles for backfills with H/L = 1.0–4.0, showing contours as a normalized function of unit (γ) weight and stope span (L).

The centerline vertical stress with depth in the backfill is shown for *H/L* = 0.5–3.0 (Figure 2). For *H/L* = 0.5 the distribution is almost linear with the maximum stress nearly equal to the expected vertical stress based on one-dimensional deposition assumptions. For *H/L* = 1.0 the distribution is super-linear with the vertical stress at the bottom ~ 80% of the one-dimensional assumption. For *H/L* = 1.5 the distribution starts to exhibit reverse curvature and the maximum stress is ~ 60% of the one-dimensional assumption. For increasing *H/L* the reverse curvature becomes more pronounced and the maximum vertical stress approaches the upper bound value for elastic arching, γL. Although distributions for higher *H/L* values are not shown, they can be approximated from the *H/L* = 3.0 curve by using the upper half to represent the stress distribution at the top of the backfill, and the lower half to represent the stress distribution at the bottom of the backfill, and a constant value connecting these two distributions. A general form of fitting equation for all *H/L* could not be conveniently determined, however an approximate fitting equation for *H/L* = 3.0 is:

$$12.1\left(\frac{H}{L}\right)^3 - 59.3\left(\frac{H}{L}\right)^2 + 102.8\frac{H}{L} \qquad \text{Equation 1}$$

The results presented so far are for a 2D case where the out-of-plane dimension is large compared to the stope span *L*. The other extreme case is a square stope, where the out-of-plane dimension is also *L*. Extending conventional 2D arching solutions to consider the out-of-plane dimension shows that the maximum vertical stress becomes proportional to the hydraulic radius in the horizontal plane, and a square with side lengths *L* has the same hydraulic radius as a circle with diameter *L*. Therefore, the square stope can be reasonably modelled as a cylinder using an axisymmetric analysis. This was carried out and it was found that the maximum vertical stress for *H/L* ≥ 1.5 is about 30% smaller than for the 2D case. Note that this difference (30%) is less than conventional arching solutions which would predict the maximum stress for a square based stope is 50% of an infinitely long stope. The out-of-plane effect will not be considered further here but its potential influence should be borne in mind when comparing with field case histories.

Case histories

The generalized result (Equation 1) will be compared with results from field monitoring programs. There are several criteria that should ideally be met for a field monitoring case history to be used in comparing measured stresses with the elastic arching model, which are as follows:

1. It is essential that both TEPC and PWP measurements be available to ensure effective stresses can be calculated.
2. Significant PWP dissipation should have taken place so that steady state conditions are being considered.
3. Temperature is known to influence TEPC measurements (Thompson et al., 2014), which may make data difficult to interpret if there is significant correlation between pressure and temperature changes.
4. The stable stresses at the point of interest should not have been disturbed by proximate mining.
5. The stope geometry should be reasonably vertical and rectangular in the horizontal plane.
6. The measurements should be made in center of the stope starting at the base and continuing higher up if instruments are suspended.

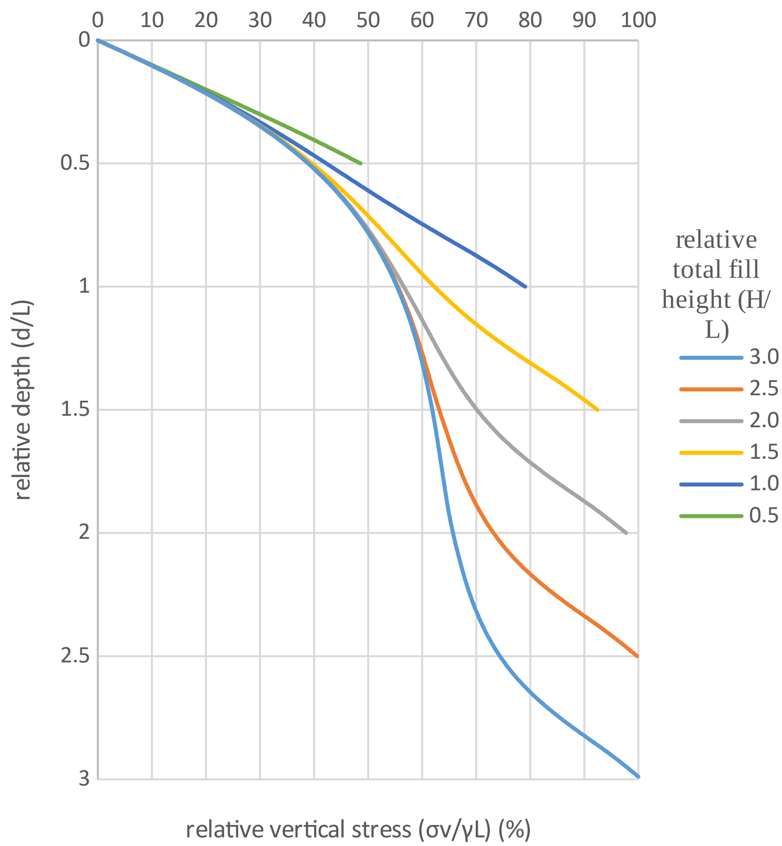

Figure 3. Vertical stress with depth along the centerline for backfills with H/L = 0.5–3.0

It can be difficult to strictly satisfy all these criteria and so some variations from the anticipated trend are expected, although quantifying the influence of any non-ideal parameter needs to be investigated subsequently. Considering the results presented in Figure 3, the geometric parameters needed for each case study are *H/L* for the total backfill height, and *d/L* for each instrumentation location where *d* is the depth below the final backfill surface.

Results from an instrumented backfilled stope at Bouchard-Hebert mine are reported by Zhu (2002). The stope is nominally 30 m × 20 m in plan (although detailed geometry is not provided) and the backfilled height is 55 m. Instrument clusters were located at the middle of the stope's base with one cluster near the base and the other positioned about mid-height. The relevant geometric parameters are therefore *H/L* = 2.75, and *d/L* = 2.7 for the bottom cage and *d/L* = 1.35 for the middle cage. The average rise rate is ~ 1 m/day above the bottom cluster but then the fill rate drops so that the average rise rate over the middle cluster is ~ 0.25 m/day. These rise rates are slow compared to the remaining case histories reviewed here. PWPs and thermistors are indicated by the author in the provided list of instruments but only TEPC results are given, and these indicate stable stress readings about 100 days after the sensors are covered. Backfill unit weight was 20.0 kN/m^3.

Helinski et al. (2011) monitored a backfilled stope at Kenowna Bell mine using one TEPC to measure vertical pressure and one PWP to calculate effective stress, located in the middle and at the base, respecitvely, of a stope nominally 15 m × 18 m in plan and about 40 m backfill height. For this case *H/L* = *d/L* = 2.7. A 10 m high plug was poured and allowed to cure for 24 h before resuming the main pour. Backfilling the entire stope took just over one week and by the end of pouring the monitored PWP was essentially zero and the TEPC was stable. Backfill unit weight was 20.9 kN/m^3.

An extensive field monitoring campaign was carried out at Williams, Kidd, and Cayeli mines as part of a long-term research project, with stress measurement results reported in Thompson et al. (2011a,b; 2012). The test stope at Williams mine was a 50 m high inclined stope approximately 4–6 m thick and backfilling was completed continuously in 67 h. An instrument cluster was located at the stope's base with three orthogonal TEPCs and a PWP. For this case *H/L* = *d/L* > 8. Backfill unit weight was 18.7 kN/m^3. Two stopes were monitored at Kidd mine but in one of them the temperature increase was so dramatic that the TEPC readings cannot be considered reliable for use. The other location, stope 67, provided reliable results. Its backfilled height was 32 m, and its plan dimensions were nominally 12 m × 28 m (although its shape was irregular) giving *H/L* = 2.7. Instrument clusters were placed close to the middle of the base and at three different heights, corresponding to *d/L* = 0.8, 1.4, and 2.4 (top to bottom cluster, respectively). Backfill unit weight was 20.1 kN/m^3. Two stopes were instrumented at Cayeli mine. Stope 685 was continuously poured, and its dimensions were 11 m × 25 m in plan and 16 m backfill height giving *H/L* = 1.4. Instrument clusters were placed mid-span at heights corresponding to *d/L* = 0.5, 0.85, and 1.2 (Figure 1). Stope 715 was a staged pour, and its dimensions were 8.7 m × 15 m in plan and 15 m backfill height giving *H/L* = 1.7. Instrumentation clusters were similarly placed corresponding to *d/L* = 0.7, 1.0, and 1.4. Backfill unit weights were 22.2 kN/m^3.

As mentioned previously, Alcott et al. (2019) monitored stresses at Casa Berardi mine. The backfilled height is 17 m. Only a cross section is provided from which it is estimated the average span is 15 m, giving *H/L* = 1.3. One instrumentation cluster is located near the base and another near the plug/main pour interface corresponding to *d/L* = 0.65 and 0.86. Backfill unit weight is 18.6 kN/m^3.

Finally, Oke et al. (2021) give details on three monitored stopes at Red Lake mine. All instrument clusters were at the bottom of the stope in a narrow vein deposit, such that all have *H/L* > 2.5. Some of the clusters a located off center along the strike length but the results are considered here anyway because of the high values of *H/L*. These and the Williams stopes are listed as 'tall stopes' in Figure 3.

Comparison of elastic arching model with case histories

The case histories ordered by *H/L* values are: Casa Berardi (1.3); Cayeli 685 (1.4); Cayeli 715 (1.7); Kenowna Bell and Kidd 67 (2.7); Bouchard-Hebert (2.75); and then the tall and narrow stopes at Williams and Red Lake (2.5). For purposes of comparison, the results from these case histories will be considered in the same normalized space as in Figure 3 but considering the profile for *H/L* = 2.5 as the representative case, while recognizing that this trend will under-estimate values for lower *H/L*. For the case studies with higher *H/L*, only stresses at the bottom of the stope were measured and so they can all be compared with the saturation pressure, . The fitting equation for the *H/L* = 2.5 curve can be written as:

$$17\left(\frac{H}{L}\right)^3 - 70\left(\frac{H}{L}\right)^2 + 109\frac{H}{L} \qquad \text{Equation 2}$$

The comparisons then plot against the fitting curve (Figure 4). The extent of arching for any of the datapoints can be visually assessed by comparison with the normalized prediction using the one-dimensional assumption, ie, the vertical stress = γd. To assess the variation in the data, a lower-bound is shown based on 60% of Equation 2, and an upper bound is shown based on 140% of Equation (but not exceeding the one-dimensional assumption).

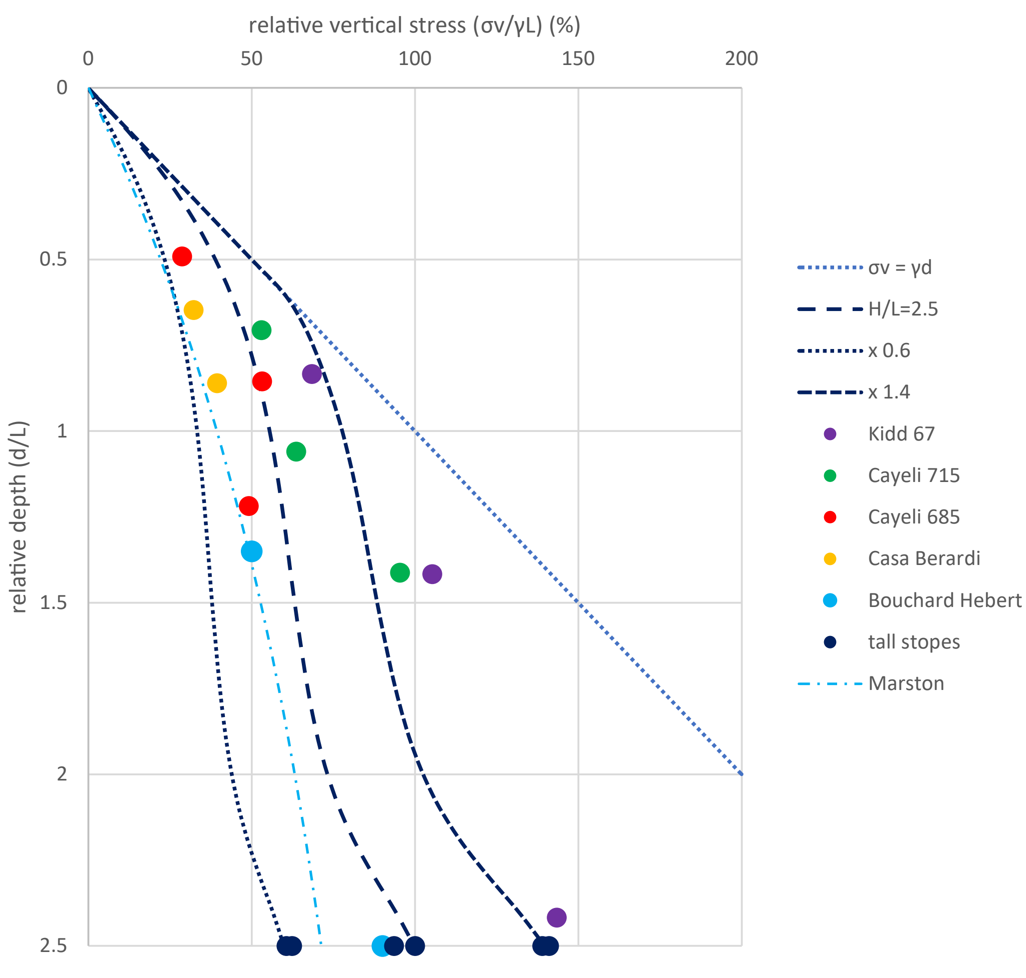

Figure 4. Comparison of case history data with elastic arching solution.

Also shown in Figure 4 is a prediction based on the Marston solution for cohesionless materials, where the maximum value is set to be equal to γL. Doing so then also determines the value of the exponent used in the decay portion of the Marston solution. Such a fit reasonably captures only the lower bound of the data from the case histories.

Analysis limitations and design implications

The analysis presented here assumes vertical sidewalls, homogeneous material properties (in particular, no differentiation in binder contents as would be the case if a backfill plug were used in the stope's bottom layer), two-dimensional geometry (as though the stope was an infinitely long trench), and that the field instruments were located at the stope's centerline. All these simplifying assumptions warrant subsequent retesting in more refined analyses. Regardless, field data are reasonably represented by the simplified elastic analysis presented here, and the proposed generalized fitting function (Equation 2) captures the average field trends, and ±40% of the predicted trend reasonably captures upper and lower bound field measurements.

The proposed maximum vertical stress at the stope centerline equal to γL is a significant simplification compared to conventional arching equation predictive values that also require specifying cohesion, lateral stress coefficient, and friction angle. For backfill in tall stopes where a plug is used, the stress imposed by the main fill can simply be estimated by backfill unit weight and tope span, and if the height of the overlying main fill is appreciably less than 2.5 × span then the maximum value can be further reduced using Equation 2.

In design of strength requirements for undercut backfill, there is often a requirement to include load upon the backfill "beam" that will be undercut. The analysis here presented provides a rational approach in assessing such a vertical surcharge. This is a key design element of undercut strength design, as featured in the proposed approach described in the companion paper (Grabinsky and Thompson, this volume). A conservative approach is recommended in undercut strength design applications. It would therefore be beneficial to increase the field-testing data base as presented, and as such improve calibration of the interpreted loading behaviour response within backfilled stopes.

Conclusion

It is inarguable that many factors will influence the as-placed stress state in mine backfill. But as Starfield and Cundall (1988) point out for rock mechanics problems, and for poorly constrained problems in general, one should *not* start with the most complicated model; instead, one should isolate the most likely parameters controlling system behaviour and then start with the simplest possible model and only add details in material properties, geometry, and boundary conditions in isolated increments to determine how each model enhancement improves (or does not improve) the predicted response as compared to the response determined from field measurements.

The uncemented granular material behaviour in Janssen's (1895) model studies and in the backfill response at Näesliden mine (Knutsson, 1980) suggested that conventional arching models work well for uncemented granular materials. However, for cemented materials possessing cohesion contemporaneously with effective stress development the conventional arching models do not work well. The results generated in our analysis assume the effective stresses are applied to the backfill when the binder hydration has already generated sufficient backfill strength and stiffness such that the response to effective stress is elastic. The maximum possible vertical stress at the stope centerline is then γL, and the variation of centerline stress with relative depth in the backfill can be predicted using Equation 2. If one wishes to conduct a sensitivity study, then these predicted values can be varied by ± 40%. This simplified result offers significant design advantages over conventional arching solutions, and its underlying assumptions are more consistent with field data obtained from the most thoroughly investigate case histories. While providing academic interest in proposing better understanding of the fundamental behaviour of *in situ* backfills, the described analysis provides a rational approach for consideration in determining what is a key variable in undercut backfill strength design.

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