The effect of transient drainage on the stress state in backfilled mine stopes.

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ABSTRACT

Backfill is increasingly used in mines to ensure the stability of underground openings where ore is extracted from the rock mass. Tools to evaluate the total and effective stresses within the backfill are required to assess the mechanical response of the stopes and to optimize fill placement. This paper presents some key results from a numerical study aimed at analyzing the response of backfill after placement in a narrow vertical stope, in the presence of arching effect. Three cases are presented here, namely: simulation of dry (or drained) backfill with different stope widths, a stope backfilled with saturated fill under hydrostatic pore water pressure, and a backfilled stope with progressive drainage and consolidation. The first two cases represent the stress state when the backfill reaches equilibrium, while the results obtained in the third case illustrates how the stress distribution varies with the groundwater conditions in the stope. The influence of other factors is also discussed in the paper.

RÉSUMÉ

L'utilisation du remblai est en croissance constante dans les mines souterraines afin d'assurer la stabilité mécanique des ouvertures où le minerai est extrait de la masse rocheuse. Il est nécessaire d'avoir des outils appropriés pour évaluer l'état des contraintes effectives et totales dans les chantiers remblayés afin d'évaluer leur réponse mécanique et pour optimiser la mise en place. Dans cet article, on présente quelques résultats d'une étude numérique qui vise à analyser la réponse du remblai après sa mise en place dans un chantier minier vertical étroit où se développe un effet d'arche. On présente ici trois cas, soit : la simulation d'un chantier remblayé en condition sèche (ou drainée), un chantier remblayé submergé soumis à une pression hydrostatique et un chantier remblayé avec évolution de la pression interstitielle suite au drainage et à la consolidation. Les deux premiers cas représentent l'état de contraintes lorsque le remblai atteint un état d'équilibre, alors que le troisième cas illustre l'évolution des contraintes et de la pression d'eau en fonction des conditions d'écoulement dans le chantier. D'autres facteurs d'influence sont aussi discutés dans cet article.

1 INTRODUCTION

The use of backfill in underground mines is gaining popularity in Canada and around the world because of the associated benefits, which include a reduction of the environmental footprint of mine wastes disposed underground instead of on the surface. For most mine operators, backfilling of large openings mainly serves to improve ground stability and increase ore recovery (Hassani and Archibald 1998). In this regard, it is necessary to evaluate the backfill response in mined stopes to ensure safe working conditions. This is a complex issue, in part because of the large contrast in stiffness and strength between the fill material and the surrounding rock mass. Upon placement, the "soft" backfill tends to settle under its own weight, producing shear stresses along the rough rock surfaces that tend to hold the fill in place. This stress transfer to the walls, known as "arching effect", is particularly significant in narrow stopes, where it leads to a decrease in the vertical stress at depth (Aubertin et al. 2003; Li et al. 2003, 2005; Pirapirakan and Sivakugan, 2007)

The characteristics of such arching effect in backfilled stopes have been investigated using analytical solutions and numerical simulations (e.g. Li et al. 2003, 2005; Li and Aubertin, 2009 a, b). The outcome of these investigations has been confirmed (in part) by experimental results obtained from laboratory (Mitchell 1992; Take and Valsangkar 2001; Pirapakaran, 2008) and in-situ measurements (e.g. Belem et al. 2004; Grabinsky 2010).

In many mines, the fill material is made from tailings, and transported as a pulp to the underground openings. Such hydraulic and paste backfills are initially saturated with water. The evolution of pore water pressure during filling and following drainage of the stope thus needs to be assessed to establish the stress state in the backfill and surrounding rock mass.

Few studies have been devoted to the drainage and evolution of pore water pressure within backfill (Ouellet and Servant, 1998; Godbout et al. 2004), resulting in a paucity of information on this critical aspect. A reliable assessment of the evolution of the total and effective stresses within the backfill is needed for mine safety and to enhance the overall production using optimized fill placement rates.

This paper presents results from a numerical modelling study of backfilled stopes conducted with the commercial finite element program SIGMA/W (Geoslope International, 2008). The simulations are used to evaluate factors that influence the stress state and pore water pressure within the backfill.

2 PREVIOUS INVESTIGATIONS

The arching theory was first adapted for geotechnical applications by Marston (1930), who evaluated vertical loads on conduits placed in trenches. Subsequently, the arching theory has been applied to many other geotechnical problems, including the evaluation of the stress state in backfilled stopes. Eqs. [1] and [2] represent a simple solution, proposed by Li and Aubertin (2009a), to assess the total and effective stresses in submerged backfilled stopes, considering an equilibrium (stationary) state (Figure 1) :

$$\sigma'_v = \frac{B\gamma_{sub}}{2K\tan\varphi'}\left[1-\exp\left(-\frac{2K(h-H_m)}{B}\tan\varphi'\right)\right] + \frac{\gamma_m B}{2K\tan\varphi}\left[1-\exp\left(-\frac{2KH_m}{B}\tan\varphi\right)\right] \times \exp\left(-\frac{2K(h-H_m)}{B}\tan\varphi'\right) \quad [1]$$

and

$$\sigma'_h = K \times \sigma'_v \quad [2]$$

In these equations,

$$K = K_a = \tan^2(45° - \varphi'/2) \quad [3]$$

This parameter represents Rankine's active earth pressure coefficient; φ' is the effective internal frictional angle of the backfill; γ_{sub} is the submerged unit weight of the backfill; γ_m is the unit weight of the wet (moist) backfill above the local water table; H_m is the distance from the top of the backfill to the water table elevation. Units for these parameters are provided below.

These equations can provide a useful estimate of the stress state within a backfilled stope. However, this solution relies on a number of simplifying assumptions, including the use of the limit equilibrium approach with vertical and horizontal stresses that are uniformly distributed across the width of the opening. Some of these simplifications can be alleviated somewhat (e.g. Li and Aubertin 2010a), but this type of solution is not directly applicable to conditions that differ significantly from the basic assumptions.

In particular, this solution does not consider explicitly the evolution of pore water pressure (PWP) and the effect of consolidation of the backfill. It can be expected however that the drainage process in hydraulic and paste backfills affects the PWP and the total and effective stresses in a stope. This type of problem is solved here using a numerical approach.

The following results first illustrate the effect of arching within vertical stopes, by comparing the analytical solution to numerical simulations conducted with SIGMA/W (2008). Numerical simulations involving backfill consolidation are then conducted to assess the evolution of PWP and effective stress state over time.

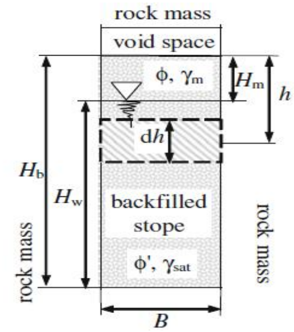

Figure 1: A vertical stope with partially submerged backfill (adapted from Li and Aubertin, 2009a)

3 CONCEPTUAL MODELLING APPROACH

Numerical modelling is often used to help solve complex problems. Numerical techniques are more flexible and versatile than analytical solutions, which typically apply to fairly simple (or idealized) situations. By introducing adequate parameters, boundary conditions, and constitutive models, numerical modeling can lead to a realistic assessment of the strain-stress behaviour of the backfill and of the interactions between the backfill and surrounding rock mass.

Comparisons between results obtained with analytical solutions and numerical simulations are often used as part of the validation process. Such comparisons also illustrate similarities and differences between the two approaches.

The base case simulated here represents a stope, 50 m in height and 6 m in width, using a plane strain (2D) model. The finite element mesh consists of 1508 nodes and 2790 triangular elements with an edge length (E.E.L) of 0.5 m. Figure 2 shows the geometry, boundary conditions, and rock mass properties (which is considered homogeneous, isotropic and linear elastic). The backfill is modeled as an elastoplastic Mohr-Coulomb material (using constitutive equations implemented in SIGMA/W). The backfill total unit weight is 18 kN/m^3 for the dry case and 20 kN/m^3 for moist and saturated cases.

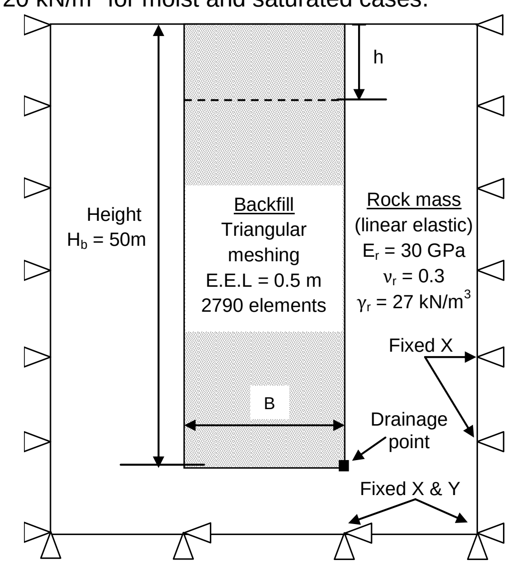

Figure 2: Stope geometry and finite element mesh

Parameters	Case 1 (drained)				Case 2 (saturated)	Case 3 (drainage)
	a	b	c	d		
Unit weight of backfill, γ_b	18 kN/m^3				20 kN/m^3	20 kN/m^3
Young Modulus of backfill, E_b	100 MPa				100 MPa	100 MPa
Friction angle of backfill, φ'	35°				35°	35°
Poisson ratio of backfill, ν	0.25				0.25	0.25
Dilatation angle of backfill, ψ	0°				0°	0°
Cohesion of backfill, c'	0 kPa				0 kPa	0 kPa
Saturated hydraulic conductivity of backfill, k_{sat}	-				10^{-7} m/s	10^{-7} m/s
Air entry value of backfill, (AEV)	-				15 kPa	15 kPa
Water entry value of backfill, (WEV)	-				50 kPa	50 kPa
Initial water table	-				Top (h= 0m)	Top (h= 0m)
Drainage	Not Applicable				Not allowed	Progressive
Stope width B	6 m	10 m	20 m	50 m	6 m	6 m
Stope height H_b	50 m				50 m	50 m

Table 1: Parameters used for the simulations

Table 1 gives the geotechnical parameters for the cases analysed (based on data taken from Aubertin et al. 1996; Belem et al. 2000, 2004; Belem and Benzaazoua, 2008). There are 3 cases analysed: dry (or fully drained), saturated (with equilibrium PWP), and with progressive drainage of the backfill. The dry case (1), without pore water pressure, is suitable for a rock fill which is placed in a dry state, or for the long term behaviour of low cohesion backfill made with tailings (when PWP = u = 0). The saturated case (2), which represents the stresses and pore water pressure under a (pseudo) steady-state, is suitable for the relatively short term behaviour of hydraulic and paste backfills after the excess PWP (Δu) has been dissipated (i.e. when u is due only to the unit weight of water). The progressive drainage case (3) simulates the evolution of the stress state in the backfill during consolidation (after a rapid placement). The effect of cohesion due to the addition of cement is not included in these calculations, but this aspect is discussed briefly near the end of the paper (with other influence factors).

4 SIMULATIONS RESULTS

4.1 Drained stope (Case 1, with u=0)

For this case, the effective and total stresses in the backfill are equal. Figure 3 shows the stress profiles along the vertical centre line (VCL) obtained from the simulation and the analytical solution; these are plotted with the overburden solution. It can be seen that the vertical and horizontal stresses calculated using the two approaches are quite similar. The calculated stresses are much lower than those predicted from the overburden solution (particularly in the lower part of the stope). The results also confirm that the analytical solution with K = K_a leads to a relatively good correlation with the numerical solution

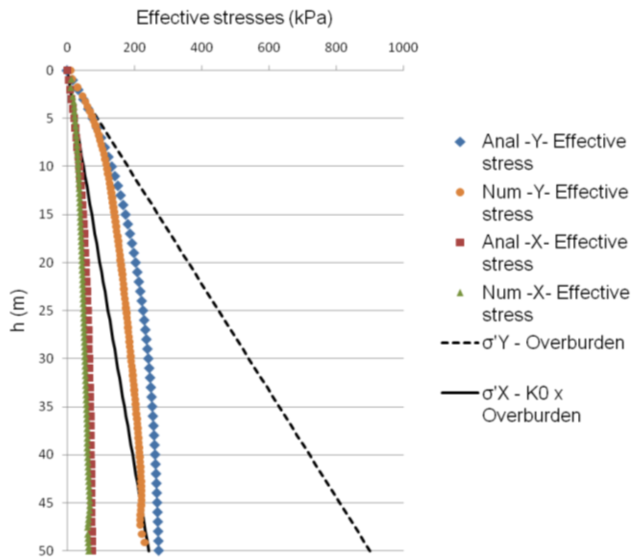

Figure 3: Vertical and horizontal effective stresses profiles along the VCL obtained from the numerical simulation and the analytical solution (Case 1).

along the vertical center-line; these results agree with those obtained from previous investigations (Li et al. 2003; Li and Aubertin, 2009a, b, c).

Figure 4 presents the iso-contours of the vertical stresses within the backfill stope. This illustrates the stress transfer from the backfill to the rock mass abutments associated with arching. From this figure, one sees also that the stresses are not uniformly distributed along the stope width: the vertical stress is lower near the wall than at the center. Similar observations have been made from calculations conducted with other analytical and numerical tools (e.g. Li et al. 2003, 2005; Li and Aubertin, 2010a).

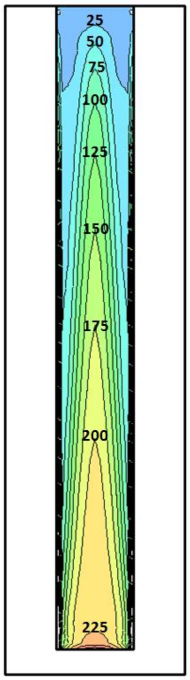

Figure 4 : Iso-contours of the vertical stresses within the backfill (Case 1; values given in kPa).

Figure 5 shows the effect of stope width (B) on the vertical stress distribution along the VCL. The results indicate that arching effects become less pronounced when the width is increased. For example, the vertical stress in a stope having a width of 50 m is almost equal to the stress due to the overburden weight of the backfill, whereas a 6 m width reduces the stress at depth by approximately 80%.

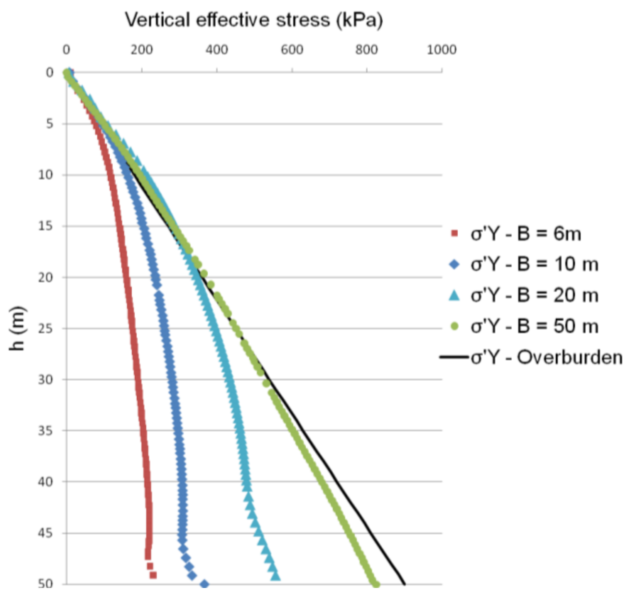

Figure 5: The effect of stope width B on the vertical stress along the VCL (Case 1).

4.2 Saturated stope (Case 2)

The placement of hydraulic and paste backfills, initially saturated with water, naturally induces the build up of pore water pressures in the stope. These should be included in the analyses of the stress distribution within the backfilled stope (Li and Aubertin 2009a).

The saturated case simulates a local water table in the stope at the top of the backfill. Drainage is not considered, but the excess PWP (Δu due to filling, see Case 3) has been dissipated. The pore water pressure in the backfill corresponds to hydrostatic conditions.

Figure 6 shows the vertical and the horizontal total stresses distributions within the stope along the VCL, obtained from the numerical simulation and analytical solution (Eqs. 1 and 2). It is seen that the total stresses obtained from the latter solution correlate well with the results obtained with SIGMA/W. Once again, the total vertical stress calculated with the overburden solution exceeds the simulated stress state within the backfill.

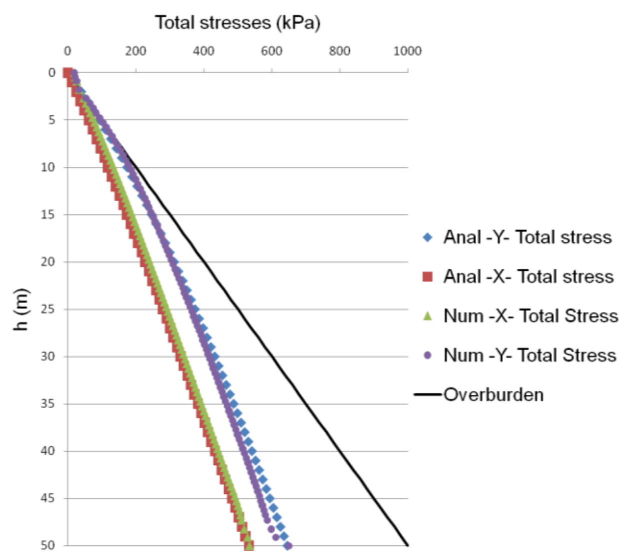

Figure 6: Vertical and horizontal total stresses within the backfilled stope, obtained from the numerical simulation and analytical solution (Case 2)

Figure 7 shows a comparison between the horizontal and vertical effective stresses obtained from the numerical calculation and the analytical solution. One sees that the stress magnitudes obtained from these solutions are smaller than those predicted with the overburden solution. Results presented in Figs. 6 and 7 further indicate that arching effects develop when the backfill is saturated (with equilibrium PWP). For instance, at the base of the stope, the effective vertical stress obtained with the numerical simulation equals about 100 kPa, i.e. approximately 20% of the effective vertical stress calculated with the overburden solution.

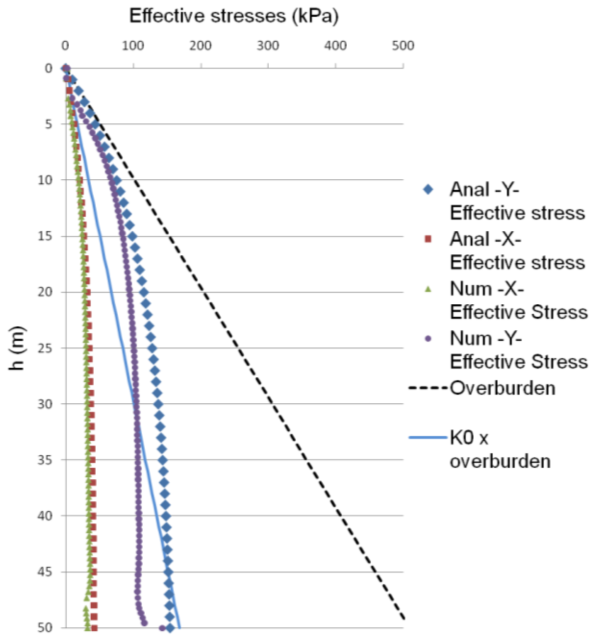

Figure 7: Effective stresses (horizontal and vertical) profiles obtained from the numerical calculation and analytical solution (Case 2)

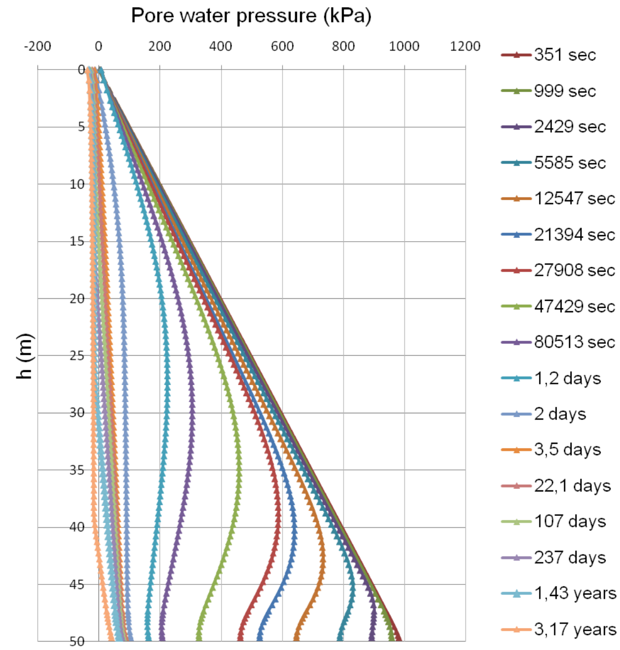

Figure 8: Evolution of the pore water pressure along the VCL of the initially saturated backfilled stope (Case 3)

4.3 Progressive drainage and consolidation (Case 3)

Drainage of initially saturated backfill occurs mainly through the retaining barricade (or bulkhead) located at the base of the stope. The barricade is not explicitly modeled in this analysis. Instead, its effect is represented by the boundary condition, which allows drainage at the base of the stope on the right hand side (Figure 8), where the hydraulic head is zero (h = 0 m).

Figure 8 shows the evolution of the pore water pressure (PWP) along the VCL. Shortly after the "instantaneous" filling of the stope, it is seen that the PWP is distributed almost linearly with depth to reach a maximum value of about 1000 kPa at the base of the stope. Therefore, an excess PWP (Δu) of approximately 500 kPa exists early; this means that the initial effective stresses are nil ($\sigma'_h = \sigma'_v = 0$) and that the backfill behaves like a fluid with a total unit weight equals to that of the saturated fill (i.e. 20 kN/m^3). Fairly rapidly thereafter, the PWP starts decreasing with time. As the backfill (made of fine-grained tailings) has a relatively low saturated hydraulic conductivity, it takes a few days to consolidate and drain the material and dissipate the PWP. It can be noted that the evolution of the PWP distribution profiles is similar to that of a consolidating medium in a column with the main drainage at the base. When sufficient draining time is allocated, negative PWP (suction) develops in the upper part of the backfill, indicating the presence of an unsaturated zone.

Figure 9 shows the progression of the effective vertical stress distribution within the backfilled stope along the VCL. As indicated above, the figure confirms that there is virtually no effective vertical stress initially, so the backfill behaves like a viscous fluid. The effective vertical stress increases when drainage and consolidation take place, leading to an increase in frictional resistance and the progressive development of an arching effect within the backfilled stope.

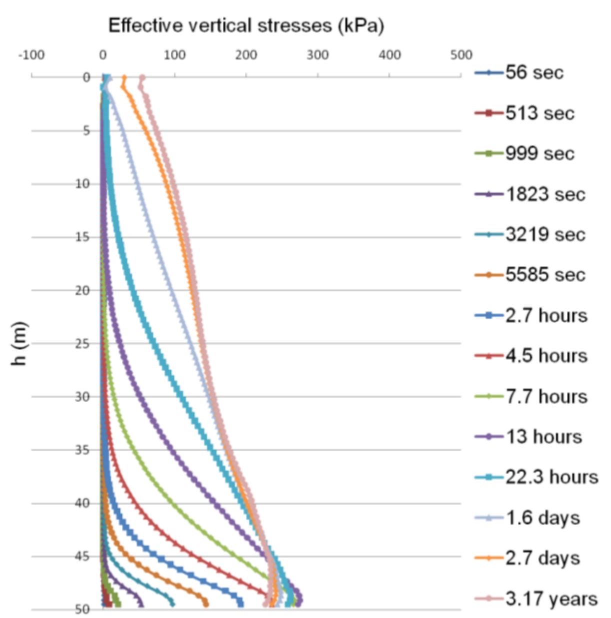

Figure 9: Evolution of the effective vertical stress σ'_v along the VCL within the backfilled stope (Case 3)

When sufficient draining time is allocated, an unsaturated zone appears in the upper part of the stope, increasing the effective vertical stress σ'_v. Figure 9 shows for instance that $\sigma'_v \sim 50$ kPa at the top of the backfill due to suction. This would produce a gain of mechanical strength due to capillary forces. At the base of the stope, the long term PWP becomes very low (but still positive – Figure 8) and the effective stress is close to that observed for the dry (drained) case. The effective stresses are however somewhat different for Cases 1 and 3 (in the long term) because of the above mentioned development of negative PWP in the stope.

5 DISCUSSION

The magnitude of the stress transfer and arching effects in backfilled stopes depend on many parameters, including the stope width and height, internal friction angle and the evolution of pore water pressure within the backfill.

Although not presented here, the influence of other properties of the backfill on the stress distribution was also investigated in this study, including the effect of cohesion, internal friction angle, dilation angle, stiffness (Young's modulus), and saturated hydraulic conductivity. These results indicate that increasing the value of the backfill cohesion, friction angle, and dilation angle tends to reduce the vertical stress magnitude. On the other hand, the value of Young's modulus of the backfill has little influence on the stress state (for representative values). Similar observations were obtained by Li and Aubertin (2009b), who performed calculations with a different code.

The saturated hydraulic conductivity also plays a major role on the response of the backfill. A lower hydraulic conductivity means that the large PWP generated at the early stage takes more time to dissipate. This however does not influence the long term response of the backfill.

The results presented for Case 3 considered an "instantaneous" filling of the underground opening by the backfill. Admittedly, this is an unrealistic (but often conservative) assumption, as placement is performed over a period varying from hours to days (depending on the stope size and production rate). Because of this, calculations were also conducted to assess sequential filling, to better represent and understand the evolution of the stress state and pore water pressure distribution during and after progressive placement. The results indicate that there is a major influence of the filling rate on the stress state in the stope and on the pressures acting on barricades (El Mkadmi et al., 2011; El Mkadmi, 2011). The response of the barricade itself is also seen to depend on the filling rate and backfill properties, and on its own dimensions and properties (Li et al. 2009; Li and Aubertin 2010b).

Another aspect being investigated is the effect of the evolution of backfill properties when a binder is added (as in cemented paste backfill). Laboratory and field tests results show that curing of the binder modifies various properties of the material, including its strength (i.e. increased cohesion and stiffness) and its hydrogeological characteristics (i.e. lower saturated hydraulic conductivity and higher air entry value). When these progressive changes are introduced in the calculations, the results show that the evolution of the total and effective stresses may become quite different (during a transient phase) from those observed without taking these effects into account. For instance, the water content in the backfill may remain much higher as drainage is reduced following cement hydration (see also Godbout et al. 2004). Other factors such as stope inclination and characteristics of the barricades are also being investigated; the results of these simulations are included in El Mkadmi (2011).

These complementary results also indicate that a proper control of the filling rate can help reduce the negative impact of a high PWP that may occur when the sequence is too rapid.

6 CONCLUSION

The numerical results presented here indicate that arching effects in backfilled stopes can be quite significant in narrow openings. However, the influence of the vertical stress transfer to the rock walls tends to disappear as the width increases.

Also, the analysis of initially saturated backfill shows that rapid placement produces high excess pore water pressure, leading the backfill to behave as a heavy fluid. Under these early conditions, there is little to no effective stress, no frictional strength and no arching; this is a critical time for the retaining barricade. The dissipation of pore water pressure associated with consolidation and drainage of the backfill leads to progressively larger effective stresses. Shear stresses can then be created along the interfaces with the adjacent rock mass, so a portion of the backfill weight can be transferred to the surrounding walls. The evolution of the effective and total stresses profiles is also affected by the appearance of an unsaturated zone with negative PWP in the stope, and by other factors discussed in the latter part of the paper.

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