

Influence of pore water pressures on the stress state in inclined backfilled stopes

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ABSTRACT

Backfilling is commonly used in underground mine stopes to improve openings stability and workers safety. Evaluating the stress state in backfilled stopes and surrounding rock mass is a crucial step for design. Various investigations have shown that settlement of the soft fill material after placement in relatively narrow stopes tends to produce shear stresses along the walls, leading to an arching effect associated with a load transfer from the backfill to the stiff rock mass. Most stress analyses reported in the literature have been obtained for dry (or fully drained) backfill in openings with vertical walls. In many cases however, there are significant pore water pressures in backfilled stopes, where the walls are inclined. This article presents an analytical solution and recent simulations results for the stress state in partially (or totally) submerged backfilled stopes with walls having different inclination angles. The influence of the backfill strength parameters is also assessed. The numerical results are used to validate (in part) the proposed solution for the total and effective stresses in inclined backfilled openings.

RÉSUMÉ

Le remblayage est couramment utilisé dans les opérations minières souterraines afin d'assurer la stabilité des ouvertures et la sécurité des ouvriers. Évaluer l'état des contraintes dans le remblai et le massif rocheux est une étape cruciale pour la conception. Des travaux récents ont montré que le remblai placé dans des chantiers relativement étroits engendre des contraintes de cisaillement aux interfaces avec le massif rocheux, ce qui produit un transfert aux éponges. La majorité des analyses de contraintes rapportées dans la littérature ont été réalisées pour des remblais secs (ou complètement drainés) dans des ouvertures verticales. Dans de nombreux cas toutefois, il existe des pressions interstitielles importantes dans les chantiers remblayés, dont les parois sont inclinées. Cet article présente une solution analytique et les résultats récents de simulations numériques sur l'état des contraintes dans les chantiers partiellement (ou totalement) submergés, avec différents angles d'inclinaison des éponges. L'influence des paramètres de résistance au remblai est également évaluée. Les résultats numériques sont utilisés afin de valider (en partie) la solution proposée pour les contraintes totales et effectives dans les chantiers remblayés inclinés.

1 INTRODUCTION

Backfilling is often used in underground mines. The main goal is to improve ground stability, ensure workers safety, and reduce the volume of solid waste disposed on the surface.

Different backfill technologies can be applied in mining operations (Hassani and Archibald 1998; Liston 2014). In the vast majority of cases, the filling material placed in stopes is much less stiff than the surrounding rock mass. Self-weight settlement of the backfill after deposition then tends to generate shear stresses along the rough walls of the opening. This leads to a load transfer to the adjacent rock mass and reduction of the stresses in the backfill (e.g. Askew et al. 1978; Knutsson 1981; Hustrulid et al. 1989; Aubertin et al. 2003; Li et al. 2003, 2005; Potvin et al. 2005).

Previous investigations have demonstrated that many factors can influence the stresses in backfilled stopes, including the size of the opening, the conditions along the fill-rock interfaces, and the backfill properties. The inclination of the walls was also shown to affect the stress state (Li et al. 2007; Ting et al. 2010; Jahanbakhshzadeh 2016). Key results in this regard indicate that the stress transfer between the fill and rock mass may be less

pronounced in inclined stopes, where the stresses can differ significantly between the hanging wall and footwall.

The effect of pore water pressures (*PWP*) has been largely neglected in earlier investigations dealing with inclined openings, but studies on vertical stopes have shown that *PWP* can have a major influence on the effective stress state in the backfill (e.g. Li and Aubertin 2009b, 2009c; El Mkadmi 2012; El Mkadmi et al. 2014).

In this article, a plane strain solution is proposed to assess the stress distribution in submerged or partially submerged backfill placed in inclined openings. The steady-state (equilibrium) solution is validated, in part, by comparing the calculated stresses with those obtained from recent numerical simulations. Some of the results implications are also discussed.

2 STRESS TRANSFER IN BACKFILLED OPENINGS

The arching theory of Janssen (1895) has been used to develop specific solutions for the loads or stresses within various types of confined geotechnical structures such as conduits in ditches (Marston 1930; Handy and Spangler 2007; Whidden 2009), storage in silos and bins (Blight 2006), slurry in cut-off trenches (Evans and Ruffing 2017),

dam cores (Kutzner 1997; Xu and Zhang 2009), and mine stopes with vertical (Askew et al. 1978; Aubertin et al. 2003; Li et al. 2003, 2005) or inclined (Jahanbakhshzadeh et al. 2017a, 2017b) walls.

This stress transfer process in backfilled stopes has been investigated extensively over the last two decades or so. In the case of inclined openings, simulation results indicate that the vertical and horizontal stresses are not uniformly distributed along the width of the stope and that a decrease of the wall inclination angle typically usually leads to a decrease in the vertical stresses along the hanging wall (Li and Aubertin 2009a; Jahanbakhshzadeh et al. 2015; 2017b; Jahanbakhshzadeh 2016).

These numerical investigations have helped with the development of a new analytical solution recently proposed to assess the stress state inside inclined stopes in plane strain (Jahanbakhshzadeh et al. 2017a).

In parallel, Li and Aubertin (2009b, 2009c); Fahey et al. (2009), El Mkadmi et al. 2014 and Jahanbakhshzadeh (2016) also investigated the influence of the pore water pressure (PWP) on the stress distribution in vertical and inclined stopes. The effect of PWP is introduced here in the new analytical solution to obtain the total and effective stresses in inclined backfilled stopes.

2.1 Solution for the total stresses

A conceptual 2D (plane strain) model for an inclined backfilled stope is shown in Figure 1. In this figure, β ($^\circ$) is the inclination angle (from the horizontal); B (m) is the opening width; x (m) is the horizontal distance from the hanging wall ($0 \leq x \leq B$); H_w (m) is the height of water in the stope; H_m (m) is the thickness of (wet) backfill above the phreatic surface (where the pore water pressure is considered nil, i.e. $PWP = u_w = 0$).

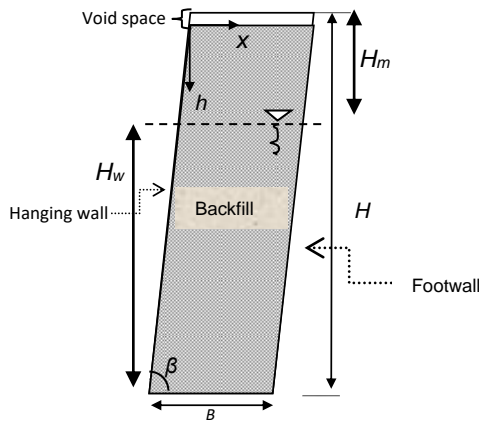


Figure 1. Conceptual model for an inclined stope with partially submerged backfill (not to scale).

The vertical (σ_v) stress (kPa) above the water table can be obtained from the plane strain solution developed by Jahanbakhshzadeh et al. (2017a), as an extension to the expressions proposed by Aubertin et al. (2003) and Li et al. (2003, 2005) for vertical openings (which were based on the well-known Marston 1930 solution).

The proposed equation for the vertical stress at depth h (m) in the inclined backfill stope can then be written as:

$$\sigma_{vh} = \frac{\gamma B(\sin \beta)}{2K_i \tan \phi'} \left(1 - \exp\left(-\frac{2K_i \tan \phi'}{B(\sin \beta)} \times h\right) \right) \quad [1]$$

In this equation the wall inclination angle $\beta \leq 90^\circ$ (see Fig. 1); δ ($^\circ$) is the friction angle between the fill and rock walls, which is taken as the internal friction angle ϕ' ($^\circ$) of the backfill (i.e. $\delta = \phi'$) for rough rock surfaces. Equation 1 also takes into account the effect of the horizontal position (distance) x (m) and elevation h (m) (Jahanbakhshzadeh 2016).

The corresponding horizontal stress can be written as:

$$\sigma_{hh} = K_i \sigma_{vh} \quad [2]$$

In these equations, the value of K_i for inclined stopes is obtained from the following expression:

$$K_i = K_{aR} \times f_h \times f_e \quad [3]$$

where K_{aR} is Rankine's active earth pressure coefficient for the backfill with a horizontal top surface (e.g. McCarthy 2007):

$$K_{aR} = \tan^2 \left(45^\circ - \frac{\phi'}{2} \right) \quad [4]$$

In Equation [3], f_h and f_e represent the effect of stope geometry (width and height); these two functions are expressed as :

$$f_h = \left\{ 1 + \Lambda \left(1 - \frac{x}{B} \right)^4 \right\} \quad [5]$$

$$f_e = (1 + \cos \beta) - \left[\frac{h}{H} \times \tan \phi' \times \cos^2 \beta \right] \quad [6]$$

with

$$\Lambda = 3 \tan \phi' \cos(\beta - 10^\circ) \quad [7]$$

For a vertical stope ($\beta = 90^\circ$), function f_e reduces to unity; f_h then controls the values of K ($= K_i$). The results obtained with Eq. 1 are then similar to those given by the 2D solution proposed by Aubertin et al. (2003) and Li et al. (2003) for vertical stopes. In this case, the distribution is symmetric on both sides of the central axis of the vertical stope; the equations are adjusted accordingly, with the central axis becoming the origin used to define

the horizontal distance, i.e. $0 \leq x \leq B/2$ (Jahanbakhshzadeh et al. 2017b).

2.2 Effective stresses

The plane strain solution developed for the total stresses by Jahanbakhshzadeh (2016) is modified to obtain the effective vertical (σ'_{vh}) stresses (kPa) when the backfill is submerged partially or entirely. The value of σ'_{vh} at depth h (m) then becomes :

$$\sigma'_{vh} = \frac{B\gamma_{sub} \sin \beta}{2K_i \tan \phi'} \left[1 - \exp \left(-\frac{2K_i \tan \phi'}{B(\sin \beta)} \times (h - H_m) \right) \right] + \frac{\gamma B \sin \beta}{2K_i \tan \phi'} \left[1 - \exp \left(-\frac{2K_i \tan \phi'}{B(\sin \beta)} \times H_m \right) \right] \times \exp \left(-\frac{2K_i \tan \phi'}{B \sin \beta} \times (h - H_m) \right) \quad [8]$$

where γ_{sub} ($= \gamma_s - \gamma_w$) is the submerged unit weight (kN/m³) of the backfill; γ_s and γ_w (kN/m³) represent the total and water unit weight, respectively.

The corresponding effective horizontal stress (kPa) is :

$$\sigma'_{hh} = \frac{B\gamma_{sub} \sin \beta}{2 \tan \phi'} \left[1 - \exp \left(-\frac{2K_i \tan \phi'}{B(\sin \beta)} \times (h - H_m) \right) \right] + \frac{\gamma B \sin \beta}{2 \tan \phi'} \left[1 - \exp \left(-\frac{2K_i \tan \phi'}{B(\sin \beta)} \times H_m \right) \right] \times \exp \left(-\frac{2K_i \tan \phi'}{B(\sin \beta)} \times (h - H_m) \right) \quad [9]$$

For the zone above the water table ($h \leq H_m$) Equations. 1 and 2 are used to obtain the effective stresses, which are then equal to the total stresses; these equations are also used for a dry (or fully drained, with $PWP = 0$) backfilled slope.

3 APPLICATION AND COMPARISON WITH NUMERICAL RESULTS

The solutions presented above are used here to evaluate the total and effective stresses in inclined backfilled slopes with typical characteristics. Numerical calculations have also been conducted with FLAC (Itasca 2005) to help assess the validity of the equations presented in the previous section, with the influence of PWP , backfill properties and stope geometry. The numerical calculations considered a homogeneous, isotropic and linearly elastic rock mass with the following properties: $E_r = 30$ GPa (Young's modulus); $\nu_r = 0.3$ (Poisson's ratio) and $\gamma_r = 27$ kN/m³ (unit weight). The backfill obeys an elasto-plastic constitutive law with the Coulomb yield (ultimate) strength criterion. The fill properties are given by the values of E , ν and γ , and the internal (constant

volume) friction angle ϕ' . The cohesion $c' = 0$ (uncemented backfill) and dilation angle $\psi' = 0$ (see details in Jahanbakhshzadeh 2016; Jahanbakhshzadeh et al. 2016, 2017b).

Table 1 presents the geotechnical and geometric parameters used for the different simulations presented here.

Table 1: Parameters used for the simulations with FLAC; total height $H = 45$ m; (the stope is filled to a final height of 44.5 m, with 0.5 m of void space left at the top of the stope); $\gamma_s = 18$ kN/m³ (total unit weight) and $E = 300$ MPa (Young's modulus).

Backfill properties and stope geometry	Case 0	Case I	Case II	Case III
Internal friction angle ϕ' (°)	30	30	30	40
Poisson's ratio ν ¹	0.33	0.33	0.33	0.26
Stope width B (m)	6	20	6	6
Depth of phreatic surface in backfill H_m (m)	5	5	-5	5
Inclination angle β (°)	60, 90	60, 90	60, 90	60, 90

¹ $\nu = \frac{1 - \sin \phi'}{2 - \sin \phi'}$ (see Falaknaz 2014; Jahanbakhshzadeh 2016).

3.1 Stress distribution

The vertical and horizontal stresses obtained from simulations with FLAC are compared with those given by the solution proposed above (Eqs 8 and 9) in Figure 2 for Case 0 (with $\beta = 90^\circ$ and $H_m = 5$ m); the numerical simulation results are shown along the central line CL (Fig. 2a) and near the walls (Fig. 2b). This comparison indicates that the two solutions correlate quite well for this vertical opening.

The results also show that the effective stresses become almost constant at a relatively large depth due to the lateral stress transfer to the rock walls. However, the total stresses (σ_{vh}, σ_{hh}) continue to increase with depth due to the pressures exerted by water.

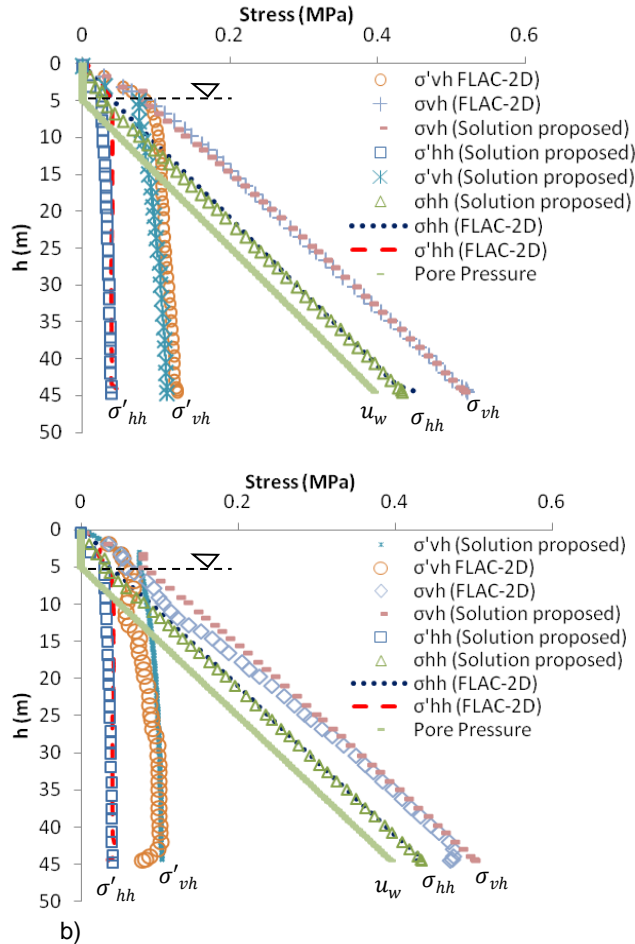


Figure 2. Vertical and horizontal stresses at different elevations h obtained with the proposed analytical solution (Eqs 8 and 9) and numerical simulations for Case 0 (see Table 1), with $\beta = 90^\circ$, $H_m = 5$ m; a) along CL (see text above) and b) near the walls (see text above).

Figure 3 shows the stresses within an inclined slope with $\beta = 60^\circ$ (Case 0, Table 1) given by Eqs 8 and 9 and obtained from the simulations along the footwall FW (Fig. 3a), center line CL (Fig. 3b) and hanging wall HW (Fig. 3c). The effective and total stresses (vertical and horizontal) obtained from both types of calculation are quite similar along the three lines (i.e. HW, FW and CL). These results also indicate that the effective vertical stress is lower near the hanging wall (Fig. 3c) than at the center and near the foot wall (Fig. 3a, b).

The effect of the slope width on the stress state was also assessed. Figure 4 shows the stresses obtained from the numerical and analytical solutions along the FW (Fig. 4a), CL (Fig. 4b) and HW (Fig. 4c) for $\beta = 60^\circ$, $B = 20$ m and $H_m = 5$ m (Case 1). These results can be compared with those obtained for $B = 6$ m (Fig. 3). The comparison indicates that the transfer of the backfill stresses to the rock mass is less pronounced in the wider opening (i.e. larger stresses at depth when B increases).

It can also be observed in Figure 4 that the vertical and horizontal stresses (effective and total) obtained from

the two types of solution are close to each other along the footwall and centre line. There is a somewhat more pronounced (although still limited) discrepancy for the stresses along the hanging wall (Fig. 4c), where the analytical solution tends to give a larger (often conservative) estimate of the vertical and horizontal stresses.

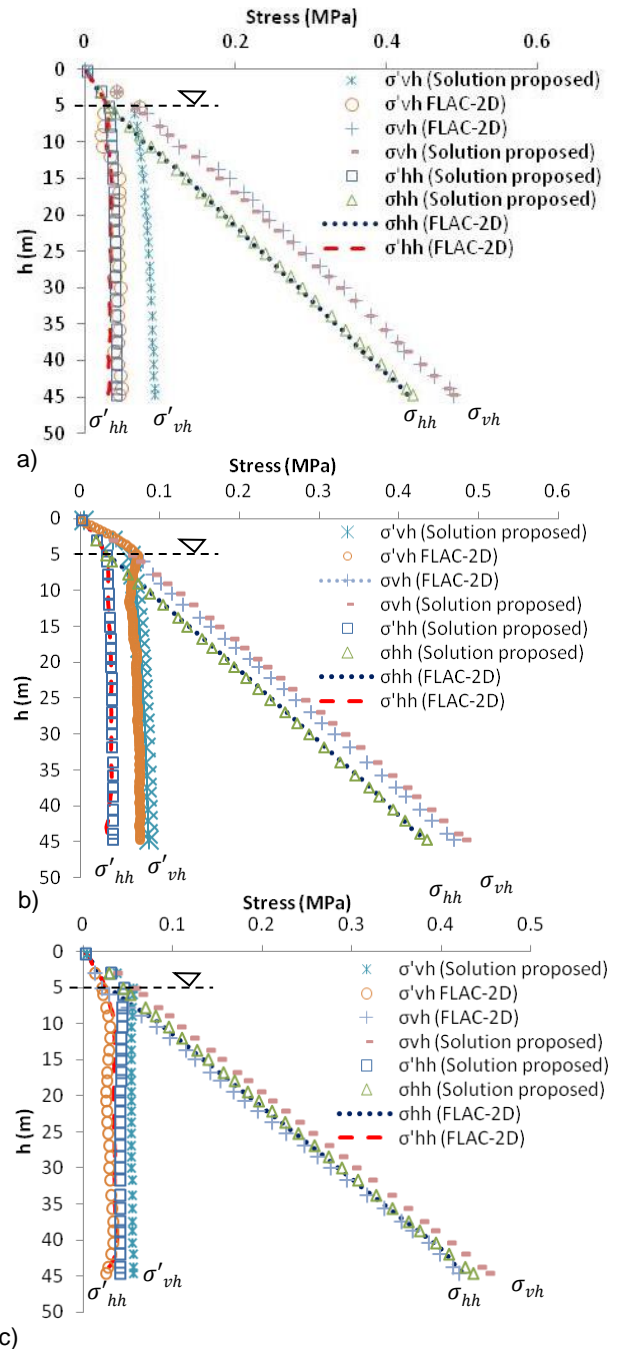


Figure 3. Vertical and horizontal stresses at different elevations h obtained with the proposed solution (Eqs. 8 and 9) and numerical simulations for Case 0 (Table 1), with $\beta = 60^\circ$, $H_m = 5$ m, along the: a) FW; b) CL; c) HW.

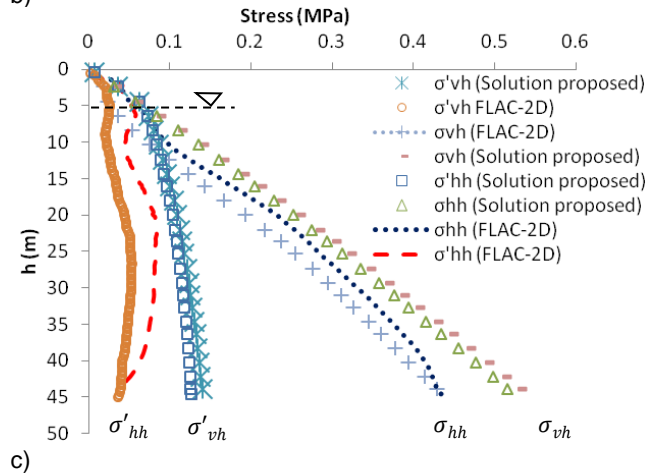
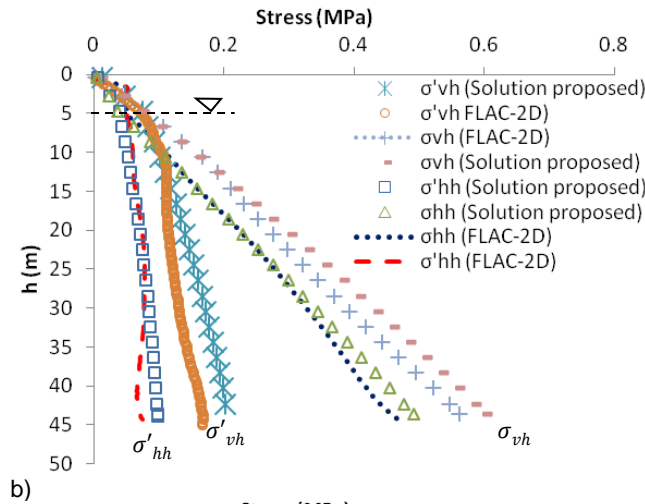
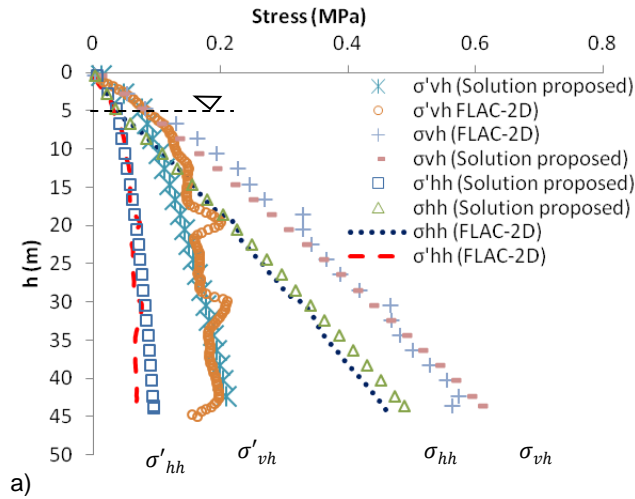


Figure 4. Vertical and horizontal stresses along the height h , obtained with the analytical solution (Eqs. 8 and 9) and numerical simulations for Case I (Table 1), with $B = 20$ m, $H_m = 5$ m and $\beta = 60^\circ$ along the: a) FW; b) CL; c) HW.

When the backfill is completely submerged under water (with the top 5 m below the phreatic surface, Case III, Table 1, $H_m = -5$ m, $\beta = 60^\circ$), the calculations results

indicate that the total stresses along the HW, FW and CL are significantly larger than those obtained for $H_m = 5$ m (particularly near the surface of the backfill). The comparisons between the analytical solution (Eqs. 8 and 9) and simulations results shown along the FW (Fig. 5a), CL (Fig. 5b) and HW (Fig. 5c) again illustrate the good agreement between the two types of results.

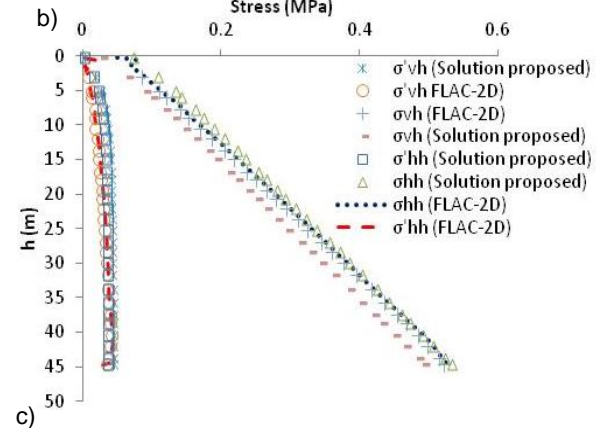
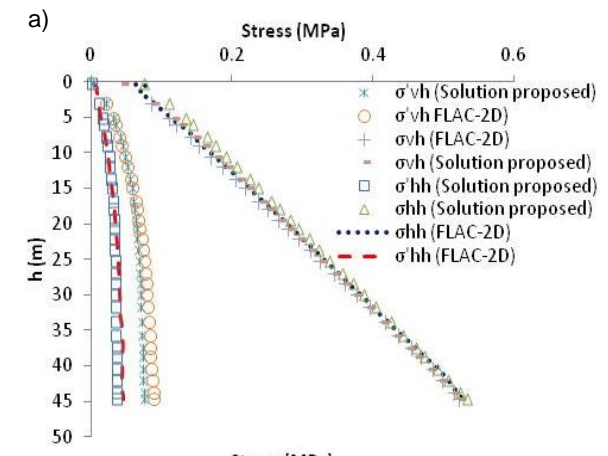
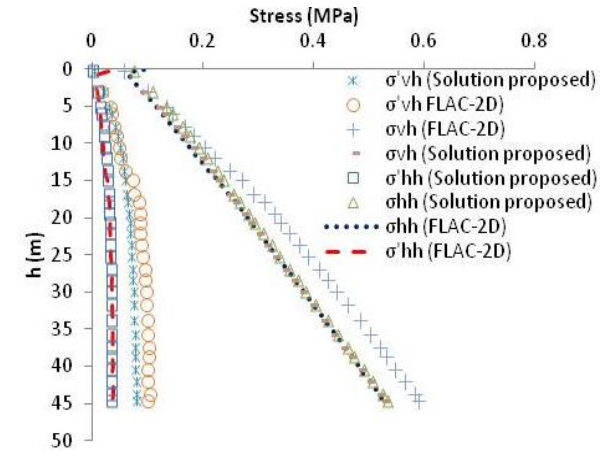


Figure 5. Vertical and horizontal stresses along the height h , obtained with the proposed solution (Eqs 8 and 9) and numerical simulations for Case II (Table 1), for $H_m = -5$ and $\beta = 60^\circ$ along the: a) FW; b) CL; c) HW.

Earlier investigations demonstrated that the stresses in slopes can be affected by the internal friction angle of the backfill (e.g. Li and Aubertin 2009a; Falaknaz et al. 2015a; Jahanbakhshzadeh et al. 2017b). The effect of this parameter is also considered here by increasing the value of the internal friction angle ϕ' from 30° to 40° . The stresses obtained from the proposed solution (Eqs. 8 and 9) and numerical simulations (which also considered a change in Poisson's ratio ν , see Table 1) are illustrated in Figure 6 (Case III, Table 1, $\beta = 60^\circ$; to be compared with those in Fig. 3). The results indicate that the vertical stresses (effective and total) along the CL, HW and FW are not affected much by this variation of the internal friction angle ϕ' . However, there is a decrease of the effective horizontal stresses (σ'_{hh}) as the friction angle ϕ' increases. These results further confirm that both the effective and total stresses are well correlated for the two solutions at the three locations (FW, HW, and CL).

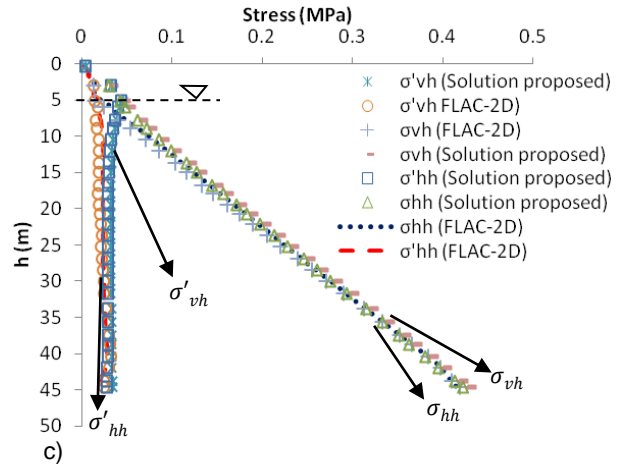
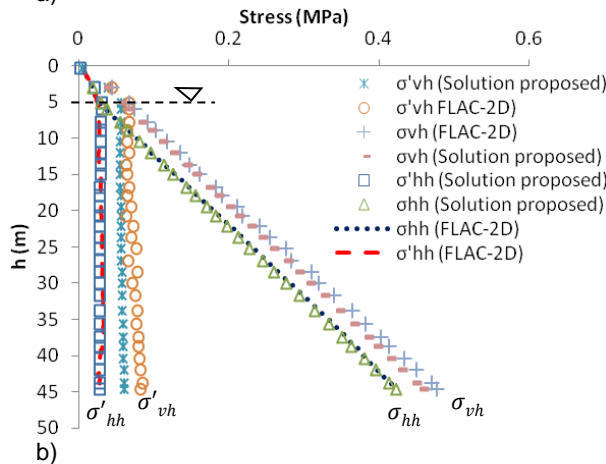
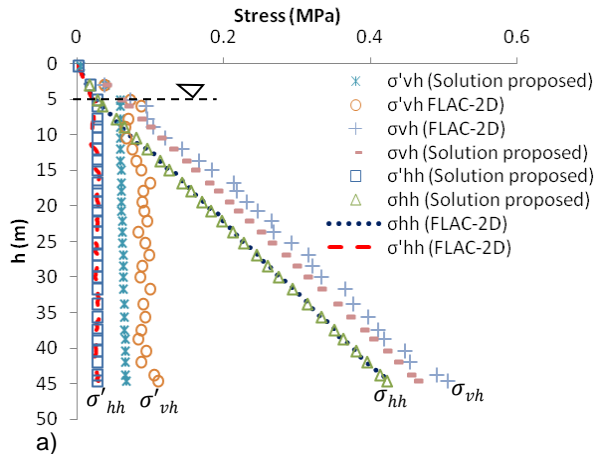


Figure 6. Vertical and horizontal stresses along the height h , obtained with the proposed solution (Eqs. 8 and 9) and numerical simulations for Case III (Table 1), for $\phi' = 40^\circ$ $H_m = 5$ m and $\beta = 60^\circ$ along the: a) FW; b) CL; c) HW.



The results shown above, and others not presented here, tend to demonstrate that the effective and total stresses obtained from the proposed analytical solution are generally in good agreement with those given by the numerical simulations (which have been successfully compared to available experimental results in earlier publications).

4 DISCUSSION AND FINAL REMARKS

In this article, the analytical solution developed by Jahanbakhshzadeh et al. (2017a) is modified to include the influence of PWP , and distinguish between the effective and total stresses in t inclined backfilled openings. The results obtained along the hanging wall, footwall and central line are validated using numerical simulations performed with FLAC2D for submerged backfill and various wall inclination angles β (from 90° to 60°).

These results presented here illustrate how the (effective and total) stresses distributions change with the inclination angle, with a decreasing value of β (from 90° to 60°) usually producing a reduction in the vertical stresses along the FW, CL and HW. These results also indicate that the presence of water in backfilled slopes can significantly reduce the effective stresses (and backfill strength), while the total stresses tend to increase with the water pressure (and additional weight).

Despite the encouraging results presented above, it should be recalled that the approach described here is only applicable to openings for which the effect of the third dimension can be neglected (i.e. plane strain condition). Additional work is underway to assess the effect of stope length on the effective and total stress state in inclined openings (following the approach of Jahanbakhshzadeh 2016).

Other factors, not taken into account here, may also influence the stress state in backfilled stopes, including the evolution of pore-water pressures (PWP) and related

fill consolidation (El Mkadmi 2012; El Mkadmi et al. 2014), and also the excavation and filling of neighboring stopes (Falaknaz et al. 2015a, 2015b). These aspects and others have been addressed elsewhere.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support from NSERC, FQRNT, and partners of the Research Institute on Mines and the Environment, RIME UQAT Polytechnique (<http://rime-irme.ca/en>).

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