



## A method to evaluate the size of backfilled stope barricades made of waste rock

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### ABSTRACT

Backfilling of underground stopes has become a common practice in mines across Canada. Many mining operations are using their solid wastes (i.e. tailings and waste rocks) as backfilling material. The advantages of doing so are obvious. This allows a significant reduction of the amount of wastes disposed in surface facilities, while improving ground conditions around large openings. However, such practice requires the installation of barricades to hold the fill material in the stope. The barricade must be stable during and after backfilling operations. Most barricades are made of bricks, concrete blocks, or shotcrete reinforced mesh. These types of barricade are usually expensive and time consuming to construct. An alternative method is to build the barricades with waste rock. There are yet very few solutions available to define the size of such barricades. This paper presents a new analytical solution for defining the dimension of barricades made of waste rock. This solution applies to the case of drained backfill (without pore pressure) and to some cases of undrained backfill (with water pressure).

### RÉSUMÉ

Le remblayage des chantiers souterrains est une pratique courante dans les mines au Canada. Plusieurs opérations minières utilisent alors leurs rejets miniers solides (i.e. roches stériles et rejets de concentrateur) comme matériau de remblai. Les avantages qui en découlent sont clairs. Cette pratique permet de réduire la quantité de rejets entreposés en surface, tout en améliorant les conditions de stabilité sous terre. Cependant, une telle pratique requiert la mise en place de barricades qui doivent être stables durant et après le remblayage du chantier. Les barricades sont usuellement construites avec des briques, des blocs de béton ou du treillis recouvert de béton projeté. Le temps de mise en place et le coût reliés à ces types de barricade sont toutefois élevés. Une méthode alternative consiste à construire les barricades à partir de roches stériles. Il n'y a toutefois que très peu de solutions disponibles pour définir la taille de telles barricades. Dans cet article, une nouvelle solution analytique est proposée afin de dimensionner les barricades formées de roches stériles. Cette solution s'applique au cas de remblais drainés (sans pression interstitielle) et à certains cas de remblais non-drainés (avec pressions d'eau).

## 1 INTRODUCTION

Backfilling in underground mines is a common practice in Canada, and in many other countries around the world. Backfill is mainly used for improving the stability of the rock mass around the stopes. Nowadays, backfilling also serves to reduce the amount of mine wastes disposed on the surface, thus reducing the potential environmental impact from the mining operation. Such practice requires the construction of barricades (also called bulkheads) to hold the backfill in place within the stope and drift. The stability of such barricades can become critical to the successful application of backfilling, as a barricade failure may lead to serious consequences such as flooding of the drift, damage to equipment, and in extreme cases personnel injury or fatality (e.g., Soderberg and Busch 1985; Grice 1998, 2001; Sivakugan et al. 2006a,b; Helinski and Grice 2007; Yumlu and Guresci 2007).

Usually, the barricades are placed at (or near) the entrance of drift, close to the base of the stope. These are typically made of bricks, concrete blocks, or shotcrete reinforce meshes that allow water drainage. Construction of such types of barricade is usually expensive and time

consuming. An alternative method used in Canada is to build the barricades with waste rock (e.g., Li and Ouellet 2008). However, the optimum sizing of the latter has not been investigated in details, so there are very few approaches available for their design.

In this paper, the authors first recall some analytical solutions that can be used to estimate the stresses in backfilled stopes and on barricades. Then, specific analytical solutions are proposed to determine the size of a barricade made of waste rock. The various specific solutions are generalized into a single general solution that can be applied to all cases considered here.

## 2 STRESS STATE SOLUTIONS FOR BACKFILLED STOPES AND BARRICADES

The pressure acting on barricades must be assessed to define their size. The evaluation of the pressures applied on a barricade requires in turn the knowledge of the stress state in the backfilled stope. Existing solutions developed in this regard are presented in the following.

## 2.1 Normal stresses in backfilled stopes

In recent years, an extensive study has been conducted by the authors (and their collaborators) on the stress state in backfilled stopes (Aubertin et al. 2003, 2005, 2008; Li et al. 2003, 2005, 2007; Li and Aubertin 2008a,b, 2009c,d,e). This has led to the development of a general analytical solution for the normal stresses in a three dimensional stope with partly or fully submerged backfill, as shown in Figure 1. For a fully drained cohesionless backfill, this solution can be expressed as follows for the vertical ( $\sigma_{vh}$ ) and horizontal ( $\sigma_{hh}$ ) (effective = total) stresses at a depth  $h$  ( $h \leq H_m$ ) (Li et al. 2005, 2009e):

$$\sigma_{vh} = \frac{\gamma_m}{M_m} \{1 - \exp(-hM_m)\} \quad [1]$$

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

where  $\gamma_m$  is the unit weight of the moist (or wet) backfill;  $M_m$  is a parameter defined as:

$$M_m = 2K_m(B^{-1} + L^{-1})\tan\delta_m \quad [3]$$

Here,  $B$  and  $L$  are the width and length of the stope, respectively;  $K_m$  is the reaction coefficient (also called earth pressure coefficient) of the cohesionless backfill, while  $\delta_m$  is the friction angle along the interfaces between the fill and the rock walls. In most cases, the friction angle of the backfill  $\phi_m$  can be taken as the value of  $\delta_m$  (Li et al. 2003, 2005).

It should be noted here that Equation [1] is a simplified solution; a more general formulation was given by Li and Aubertin (2009e), who considered also the effect of cohesion and of a surface pressure applied on top of the backfill.

Equations [1] and [2] correspond to the case where the four walls around the stope react in the same manner and share the same properties; this is also a special case of the solution proposed by Li and Aubertin (2009e). This simplification equally applies to the solution given next for the case of submerged (undrained) backfill with pore pressure.

In a submerged backfill ( $h \geq H_m$ ), the vertical ( $\sigma'_{vh}$ ) and horizontal ( $\sigma'_{hh}$ ) effective stresses at a depth  $h$  are expressed as follows (Li et al. 2009e):

$$\sigma'_{vh} = \frac{\gamma_m}{M_m} \{1 - \exp(-H_m M_m)\} \exp[(H_m - h)M_{sat}] \quad [4]$$

$$+ \frac{\gamma_{sub}}{M_{sat}} \{1 - \exp[(H_m - h)M_{sat}]\}$$

$$\sigma'_{hh} = K_{sat} \sigma'_{vh} \quad [5]$$

where  $\gamma_{sub}$  ( $= \gamma_{sat} - \gamma_w$ ;  $\gamma_{sat}$  and  $\gamma_w$  are the unit weight of the saturated backfill and of water, respectively) is the submerged unit weight of the backfill; parameter  $M_m$  is defined by Equation [3];  $M_{sat}$  is another parameter of the saturated backfill, which is expressed as:

$$M_{sat} = 2K_{sat}(B^{-1} + L^{-1})\tan\delta_{sat} \quad [6]$$

Here,  $K_{sat}$  is the earth reaction coefficient of the saturated cohesionless backfill;  $\delta_{sat}$  is the friction angle along the interfaces between the saturated fill and rock walls. Again, the friction angle of the saturated backfill  $\phi_{sat}$  can be used for the value of  $\delta_{sat}$ .

The horizontal and vertical total normal stresses are then obtained as:

$$\sigma_{hh} = \sigma'_{hh} + \gamma_w(h - H_m) \quad [7]$$

$$\sigma_{vh} = \sigma'_{vh} + \gamma_w(h - H_m) \quad [8]$$

The pore pressure terms in these equations (second on the right hand side) are based on a hydrostatic equilibrium state.

The total and effective stresses at any position in a fully or partly submerged backfilled stope can be obtained with Equations [1] to [8]. These solutions have been validated, at least in part, using comparisons with numerical modeling and measurements on physical models. Figure 2 shows a comparison between the stresses calculated using the proposed equations and those based on the overburden weight. It can be seen that the stresses calculated with the proposed solutions are often much lower than those calculated from the overburden in the backfilled stope due to an arching effect in the stope (e.g. Aubertin et al. 2003; Li et al. 2003, 2005).

## 2.2 Pressure on barricades

It can be understood, from Figure 1, that the fill in the drift is being pushed away from the stope opening by the horizontal pressure caused by the backfill weight. On the other hand, the drift walls tend to hold the fill in place. This leads to shear stresses between the backfill and drift walls. A horizontal stress transfer, somewhat similar to an arching effect (Sperl 2006), can thus occur in the drift, and decrease the pressure on the barricade.

Using an analogous approach to that used for the stope, Li and Aubertin (2009a) developed an analytical solution for calculating the pressure  $P$  applied on a barricade for fully drained (or dry) backfill conditions (without pore pressure); this solution is expressed as:

$$P = \frac{L_d H_d}{2} (\sigma_{hB0} + \sigma_{hT0}) \exp\left\{-\frac{2\tan\delta_m}{K_{dt}} \left(\frac{1}{H_d} + \frac{K_{dt}}{L_d}\right) l\right\} \quad [9]$$

In this equation,  $H_d$  is the height of the drift;  $L_d$  is the width of the drift;  $l$  is the distance between the drift entrance and the barricade;  $\sigma_{hB0}$  and  $\sigma_{hT0}$  are the horizontal (effective = total) stresses at the entrance of the drift at the base and top levels, respectively (these two values can be calculated with Equations [1] to [3]);  $K_{dt}$  and  $K_{dl}$  are the reaction coefficients of the fully drained backfill along the transversal and longitudinal orientations of the drift, respectively. The investigation of Li and Aubertin (2009a,b) indicates that  $K_{dt}$  is close to the active reaction coefficient  $K_a$ , while a value closer to the passive reaction coefficient  $K_p$  applies for  $K_{dl}$ . Hence, one can write:

$$K_{dt} \approx K_a = \frac{1 - \sin\phi_m}{1 + \sin\phi_m} \quad (\sim 0.3, \text{ for } \phi_m \sim 30^\circ) \quad [10]$$

$$K_{dl} \approx K_p = \frac{1 + \sin\phi_m}{1 - \sin\phi_m} \quad (\sim 2 \text{ to } 3) \quad [11]$$

For the case of a submerged backfill with positive pore pressure, Li and Aubertin (2009b) developed a complementary solution to estimate the total and effective stresses along the drift. This solution can be used to

evaluate the total pressure  $P$  applied on the barricade as follows:

$$P = \frac{L_d H_d}{2} \left\{ (\sigma'_{hB0} + \sigma'_{hT0}) \exp \left[ -\frac{2 \tan \delta_{sat}}{K'_{dl}} \left( \frac{1}{H_d} + \frac{K'_{dt}}{L_d} \right) l \right] + \gamma_w (2H_{sat} - H_d) \right\} \quad [12]$$

In this equation,  $H_{sat}$  is the height of the saturated backfill in the slope (Fig. 1);  $\sigma'_{hB0}$  and  $\sigma'_{hT0}$  are the horizontal effective stresses at the entrance of the drift at the base and top levels, respectively (these can be calculated with Equations [4] to [6]);  $K'_{dt}$  and  $K'_{dl}$  are the reaction coefficients of the saturated backfill in the transversal and longitudinal orientations of the drift, respectively. Again, the investigation of Li and Aubertin (2009a,b) shows that  $K'_{dt} \cong K_a$  and  $K'_{dl} \cong K_p$ .

Figure 3 shows the stress distribution along the drift axis for fully drained (Fig. 3a) and undrained (Fig. 3b) conditions. It can be seen that the total and effective stresses quickly decrease when the calculation point is moved away from the entrance of the drift. This indicates that it can be advantageous to place a barricade farther from the drift entrance (to reduce the applied pressure).

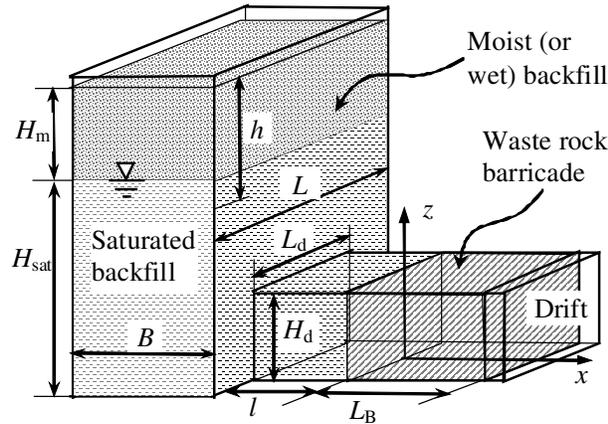


Figure 1. A backfilled stope with an access drift and a waste rock barricade.

### 3 SIZING OF WASTE ROCK BARRICADES

Once the pressure acting on the barricade is known, the minimum length required for the waste rock structure can be evaluated. New solutions for this purpose are presented in this section.

#### 3.1 Fully drained condition

Figure 4 shows a fully drained barricade and the various forces acting on its boundaries.  $C_T$  and  $C_B$  are the normal compressive forces on the top and base surfaces of the barricade, respectively;  $C_L$  is the lateral normal compressive force on the side of the barricade;  $S_T$  and  $S_B$  are the shear forces at the top and base surface of the barricade, respectively;  $S_L$  is the shear force along the lateral walls. The corresponding normal stresses are also shown in Figure 4;  $w$  is the weight of the layer element.

The force  $C_T$  (or the stress  $\sigma_{vT}$ ) acting on the top surface of the barricade can be generated by pushing and

compacting the waste rock barricade along the drift axis during its construction. It is, however, conservative to neglect this component for the barricade size estimation (considering the large uncertainty when assessing the magnitude of this force). The vertical normal stress at the base of the barricade can then be expressed as:

$$\sigma_{vB} = \gamma_r H_d \quad [13]$$

This equation is based on the overburden weight. Neglecting a possible vertical stress transfer (arching effect) along the two side walls is justified because most drifts (and barricades) have a limited height (usually  $\leq 5$  m) when compared with their width and length. The authors' previous work indicates that the ensuing vertical pressure would be close to the overburden stress in this case (Li et al. 2003, 2005, 2007, 2009c).

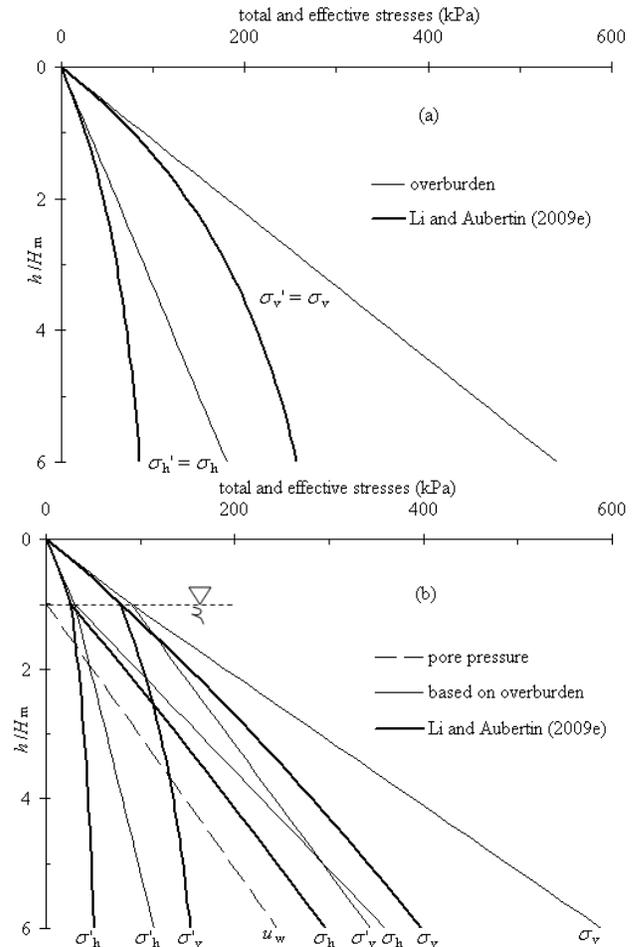


Figure 2. Comparison between the stresses calculated with Equations [1] to [8] and those based on the overburden weight: (a) for fully drained condition; (b) for partly submerged condition (with an equilibrium pore pressure  $u_w = \gamma_w(h - H_m)$ ).

The horizontal stress acting on the side of the vertical layer element (Fig. 4) can then be calculated as follow:

$$\sigma_h = K_r \gamma_r H_d \left( 1 - \frac{z}{H_d} \right) \quad [14]$$

where  $z$  is the height of the calculation point (Fig. 1);  $K_r$  is the reaction coefficient of the fully drained waste rock, which can be obtained from Equation [10], in which  $\phi_{rm}$  is the friction angle of the waste rock.

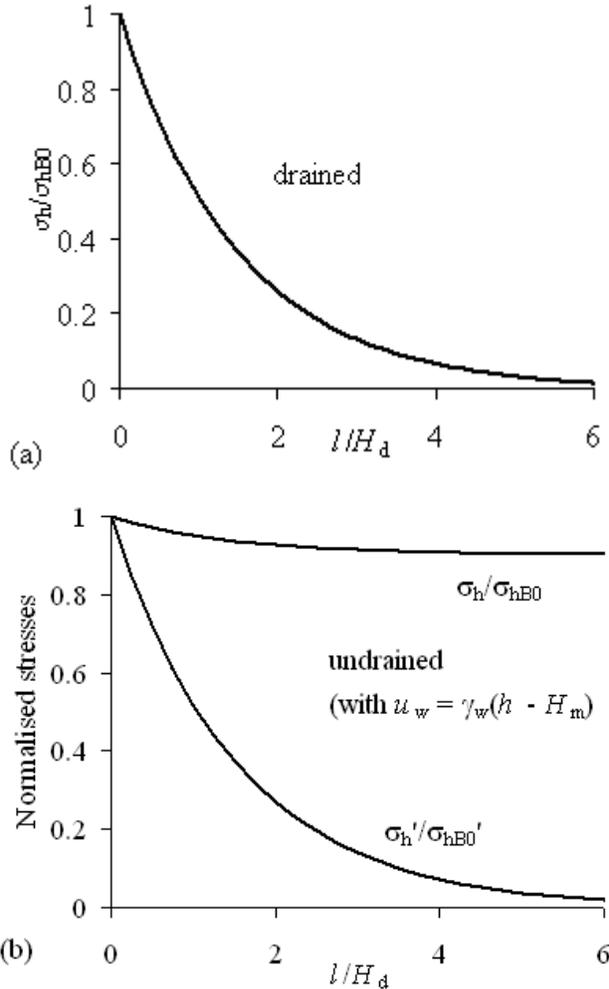


Figure 3. Stress distribution along the drift axis based on the analytical solution of Li and Aubertin (2009a,b) for the fully drained condition (a) and undrained condition (b).

The shear forces can be estimated by using the Coulomb shear strength criterion:

$$S_B = C_B \tan \delta_r = \sigma_{vB} L_d L_B \tan \delta_r = \gamma_r H_d L_d L_B \tan \delta_r \quad [15]$$

$$S_L = C_L \tan \delta_r = \frac{K_r \gamma_r H_d^2}{2} L_B \tan \delta_r \quad [16]$$

where  $\delta_r$  is the friction angle along the interface between the fully drained waste rock and the drift walls. In many cases, the  $\delta_r$  value can be influenced by the geometrical irregularity on the drift walls. In practice, any shearing probably takes place in the waste rock rather than directly along the rock-wall interface. Thus, the value of  $\phi_{rm}$  should be taken for  $\delta_r$  in Equations [15] and [16].

The equilibrium of the barricade along the drift axis ( $x$ ) direction gives:

$$P = S_B + 2S_L \quad [17]$$

Introducing Equations [15] and [16] into Equation [17] leads to the minimum required length of the waste rock barricade (for a factor of safety FS = 1):

$$L_B = \frac{P}{\gamma_r H_d (L_d + K_r H_d) \tan \delta_r} \quad [18]$$

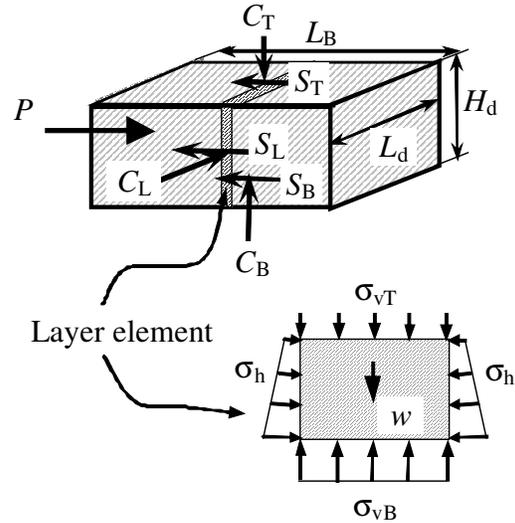


Figure 4. A fully drained barricade made of waste rock, with the acting forces on its boundaries.

### 3.2 Submerged condition

In most cases, the backfill contains water. Before the pore pressure can be dissipated, one should consider that the barricade is under a submerged condition, with positive pore pressure acting in the backfill located in the stope and drift. However, this hydrostatic pressure can be rapidly dissipated along the length of the barricade because waste rock is typically much more pervious than the backfill (especially if the latter is a cemented paste made with tailings). Thus, efficient drainage should occur through a well design waste rock barricade, so the pore pressure can be expected to decrease across its length.

Figure 5 shows a barricade along which the pore pressure,  $p_w$ , is assumed to be linearly distributed. The linear distribution of  $p_w$  shown in Figure 5 (and 6) is considered conservative given the large contrast in hydraulic conductivity (often by more than 2 orders of magnitude) between the waste rock and backfill material. A more precise distribution can be obtained by a detailed analysis, but this is not deemed necessary for the cases treated here (see other assumptions below).

It is postulated that the pore pressure distribution inside the barricade can be approximated by using the following expression (see Figure 6):

$$p_w(x, z) = \left(1 - \frac{x}{L_B}\right) u_w - \gamma_w z \quad [19]$$

where  $x$  is the distance between the fill-barricade interface and the cross section considered;  $u_w (= \gamma_w H_{sat})$  is

the hydrostatic pressure at the base of the drift at the interface between the barricade and the backfill ( $x = 0$ ).

Only cases where the pore pressure in the drift (or slope) is relatively low are treated here (i.e.  $u_w \leq \gamma_w H_d$ ). For a larger pore pressure at  $x = 0$ , the solution proposed here does not apply, so another formulation is required; this case is considered elsewhere.

For the situation addressed here, the whole lateral and base surfaces of the barricade contribute to the resistance against the pushing pressure  $P$  induced by the backfill, as shown in Figure 6. In this case, the upper part of the barricade is under a fully drained condition ( $\rho_w = 0$ ), while the lower part remains submerged with a positive pore pressure (Fig. 6).

The assumed linear distribution of the pore pressure leads to the following expression for the hydraulic head (using the drift floor as the datum):

$$z_w = (1 - x/L_B)H_{sat} \quad [20]$$

where  $z_w$  defines the profile of the water pressure head inside the barricade. This expression (Eq. 20) applies for  $L_B \geq x \geq 0$  (Fig. 6).

In the fully drained ( $\rho_w = 0$ ) zone ( $z \geq z_w$ ), the normal vertical stress (total = effective) can be expressed as:

$$\sigma'_v(x, z) = \gamma_r(H_d - z) \quad [21]$$

In the saturated part ( $z \leq z_w$ ), the vertical effective stress is given by:

$$\sigma'_v(x, z) = \gamma_r H_d + (\gamma_{sub} - \gamma_r)z_w - \gamma_{sub}z \quad [22]$$

where  $\gamma_{sub}$  ( $= \gamma_t - \gamma_w$ ;  $\gamma_t$  is the unit weight of the saturated waste rock) is the submerged (effective) unit weight of the saturated waste rock.

Considering the limit equilibrium of the barricade, one can write:

$$P = \int_0^{L_B} \kappa(x, z) dx \quad [23]$$

where

$$\kappa(x, z) = \int_0^{z_w} 2K_{rs} \sigma'_v(x, z) \tan \delta_{rs} dz + \int_{z_w}^{H_d} 2K_r \sigma'_v(x, z) \tan \delta_r dz + \sigma'_v(x, 0)L_d \tan \delta_{rs} \quad [24]$$

Solving Equation [23] leads to the following minimum required length for the barricade:

$$L_B = \frac{P}{\lambda} \quad [25]$$

where

$$\begin{aligned} \lambda = & \tan \delta_{rs} K_{rs} \left( \gamma_r H_d + \frac{\gamma_{sub} - 2\gamma_r}{3} H_{sat} \right) H_{sat} \\ & + \tan \delta_{rs} \left( \gamma_r H_d + \frac{\gamma_{sub} - \gamma_r}{2} H_{sat} \right) L_d \\ & + \tan \delta_r K_r \gamma_r \left( H_d^2 - H_{sat} H_d + \frac{H_{sat}^2}{3} \right) \end{aligned} \quad [26]$$

As a special case, it can be shown that Equations [25] and [26] reduce to Equation [18] for the fully drained condition when  $H_{sat} = 0$  (and assuming  $\delta_{rs} = \delta_r$ ). Hence, Equations [25] and [26] can be considered a general solution that applies to all cases addressed here.

#### 4 SAMPLE APPLICATIONS

The use of the proposed solution is illustrated with a sample application. The following parameters are used:

Stope and drift geometry:

$$H_m + H_{sat} = 40 \text{ m}$$

$$B = L = 10 \text{ m}$$

$$L_d = H_d = 4 \text{ m}$$

Backfill:

$$\gamma_m = 18 \text{ kN/m}^3, \gamma_{sat} = 20 \text{ kN/m}^3$$

$$\phi_m = \phi_{sat} = \delta_m = \delta_{sat} = 30^\circ$$

Waste rock:

$$\gamma_r = 22 \text{ kN/m}^3, \gamma_t = 24 \text{ kN/m}^3$$

$$\phi_r = \phi_{rs} = \delta_r = \delta_{rs} = 38^\circ$$

Figure 7 shows the variation of the minimum required length of the barricade as a function of the distance  $l$  from the drift entrance. It can be seen that the minimum required barricade length  $L_B$  decreases with an increase of distance  $l$ . It can be also observed that the minimum required barricade length  $L_B$  for a fully drained barricade and backfill can be much shorter than that required under submerged conditions.

The variation of the minimum required barricade length  $L_B$  with a variation of the pore pressure at the base of the drift  $u_w$  is shown in Figure 8 (for  $u_w \leq \gamma_w H_d$ ). It can be seen that the minimum required barricade length increases rapidly with a rise of the pore pressure in the drift. When this pressure is large, the minimum required length for the waste rock barricade may become very long, so other options may need to be considered. This aspect will be discussed elsewhere.

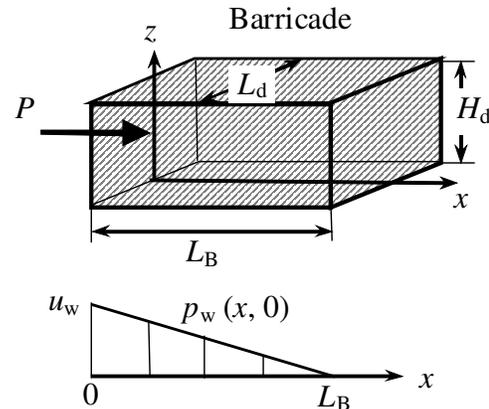


Figure 5. A saturated drift and the assumed pore pressure distribution in the barricade along the drift axis.

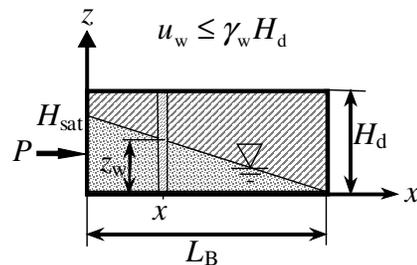


Figure 6. Pressure head profile in the barricade.

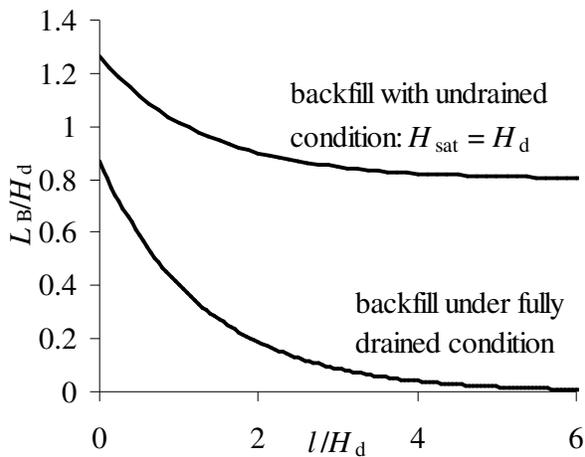


Figure 7. Variation of the minimum required barricade length with its position along the drift; for fully drained ( $\rho_w = 0$ ) and submerged conditions.

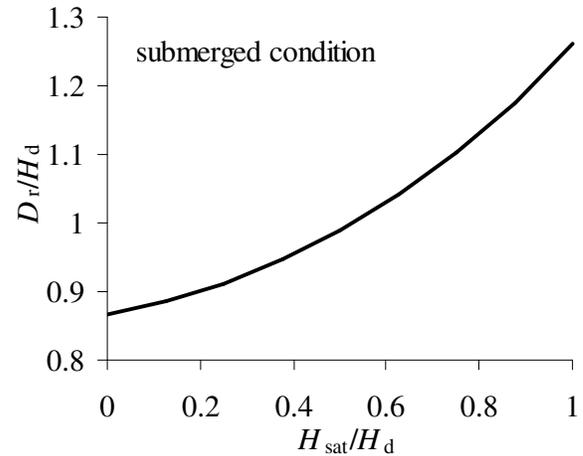


Figure 8. Variation of the normalised minimum required barricade length with the water height in the stope (for  $l = 0$ ).

## 5 DISCUSSION AND CONCLUSION

A new analytical solution is proposed to evaluate the minimum required length of barricades made of waste rock. The solution applies to cases where the water pressure head is equal or lower than the drift height. The results obtained with the proposed solution indicate that the waste rock volume required in most situations is compatible with its use to construct barricades.

The results obtained from the proposed solution also shows that the pore pressure in the drift (or stope) and the position of the barricade in the drift significantly affects the required length of the barricade. By placing the barricade farther from the entrance of the drift, the pressure applied on the barricade can be significantly reduced (particularly under drained conditions). This, in turn, leads to a reduction of the required barricade length as shown in Figure 7.

This result further indicates that the required barricade length can be reduced by implementing an effective drainage system for the backfill. When the drainage system does not reduce sufficiently rapidly the pore pressure in the stope and drift, progressive backfilling in multiple layers can be considered to avoid excessive water pressure on (and inside) the barricade.

It should be recalled here that the proposed solution has been developed by considering a limit equilibrium state for the barricade. No factor of safety (FS) was included in the calculations for the barricade length (implicitly  $FS = 1$ ). In practice, depending on the degree of uncertainty and possible consequences of a barricade failure, a factor of safety well above unity should be applied to define the actual barricade length.

It is recalled also that the possible shear resistance that may develop between the drift back (roof) and the barricade has been neglected in the solutions proposed here. This is conservative for the design. It can be expected that a significant resistance may be obtained by when a tight contact exists between the drift back and the barricade. Other practical considerations regarding barricade design and construction will be discussed elsewhere.

## ACKNOWLEDGEMENTS

The authors thank Genivar L.P. (<http://www.genivar.com/>) and partners of the Industrial NSERC Polytechnique-UQAT Chair in Environment and Mine Wastes Management (<http://www.polymtl.ca/enviro-geremi/>) for their support.

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