INTRODUCTION

The recovery of underground hard rock ore bodies often involves the use of mine fills. The type of mine fill depends on the mining methods and sequences. Where later recovery is dependent on stability of exposures of earlier placed fill, cement and/or cementitious materials are added to the fill. Once such fill type is pastefill which is in fact becoming a standard practice in Canada (e.g. Landriault 1995, Landriault & Tenbergen 1995, Naylor et al. 1997). However, the use of pastefill to maintain ground stability involves some difficulties related to the complexities of its behaviour. These complexities are due to the continuous evolution of the properties of cemented fill during placement, consolidation, and hardening due to the hydration of binder agents.

Despite recent work conducted on cemented fills (e.g. Hassani & Archibald 1998, Benzaazoua et al. 2002, Bernier et al. 1999, Benzaazoua & Belem 2000, Belem et al. 2002) many questions remain concerning the stability analysis of a stope filled with pastefill. Indeed, after backfilling with cemented fill the structural integrity of a stope can be threatened by several macroscopic factors (exclusive of the hydration process) which influence the mechanical strength of the pastefill. These factors include: compression and consolidation of the pastefill, the volume and geometry of the stope, the stress distribution within the backfill and between the backfill and the stope, wall convergence, shrinkage, and the effect of arching within the pastefill. Consequently, an understanding of these various factors of influence is necessary to provide more efficient means of ground control. Indeed, knowledge of the magnitude of pressures on barricades will allow for better planning of mining sequences. Additionally, the knowledge of the stress fields within pastefill will facilitate analysis of its stability when one of its faces will be exposed or when an access gallery to a new stope is excavated through the pastefill mass.

The objective of this study was to follow the evolution of pressures developed in cemented fill during placement and consolidation. There is very little data or documentation regarding in situ measurement of the mechanical properties of pastefills. However, some work has carried out in this direction (Gay et al. 1988, Ouellet & Servant 2000, Been et al. 2002, Le Roux 2004). Work concerning the instrumentation of pastefill has been conducted by (Corson 1971, Hassani et al. 1998, Hassani 1999, Rankine et al. 2001, Revell 2003). A common point of these experimental studies is that the results are limited to the subject mines.

In this paper, we first briefly describe the Doyon Gold Mine where a selected trial stope was instrumented and backfilled. The influence of the curing time of the pastefill and the height of fill on the measured pressures will be discussed. Based on the results, analytical models will be proposed to predict the pressures developed in pastefill as well as the pressure on barricades during and after backfilling.
2 DOYON GOLD MINE

The Doyon Gold Mine, property of Cambior Inc., is located approximately 40 km east of the city of Rouyn-Noranda and has been in operation since the beginning of the 1980's. To-date, about 25,600,000 metric tons of gold ore have been extracted from the mine. Doyon Gold Mine uses the open stoping mining method in conjunction with post placed paste backfill since the late 1990's. The stoping extends to a maximum depth of 800 m over an area of 1200 m x 600 m. The long-hole method is the only mining method used at the site. Since the ore body consists of narrow veins of quartz-pyrite-tourmaline of different width (0.1 m to 1.2 m), the stope dimensions are not the same and vary from 3 m x 23 m in plan and 22 m high to 12 m x 21 m in plan and 30 m high.

Currently, up to approximately 140 stopes are backfilled per year at the mine (roughly 1700 tons of pastefill are placed per day). The pastefill is transported by gravity using 15-cm diameter pipes in a staircase network (Harvey 2004). The stope backfilling method consists of pouring first the "plug" (high cement content) up to 3 m behind the draw point followed by a 1-day curing time. After that the rest of the stope is filled ("residual fill").

3 DESCRIPTION OF THE INSTRUMENTATION

3.1 Location of measurement points

To follow the evolution of the pressures developed in the pastefill, two trial stopes were selected and instrumented each with eight pressure cells but only the Stope 8-1 FW of the Doyon Gold Mine is concerned in this paper. The pressure cells were placed at four locations within the stope: the floor of the stope, at the plug/residual fill interface, on the lower wall, and on the barricade. Figure 1 shows the geometry and the dimensions of the stope, which has an average width, \( B \), of 11 m (along the transverse axis, \( y \)), a length, \( L \), of 21 m (along the longitudinal axis, \( x \)) and a height, \( H \), of 29 m (along the vertical axis, \( z \)). The trial stope is oriented at an azimuth of 90° and a dip of 90° and is located at a depth of 450 m in a zone where there were no more production sequences planned temporarily. Consequently, the initial stress field was relatively stable and the access to the stope was safe. The pastefill pore pressures were not monitored in this study because any drainage of free water at the rock pile-shotcrete barricade was observed (no build-up of the total earth pressures).

3.2 Experimental devices for pressure measurement

3.2.1 Earth pressure cells used

The earth pressure cells were model TPC by RocTest, which were considered appropriate for this type of measurement as suggested by Weller & Kulhawy (1982). The model TPC consists of a sealed distribution pad composed of two 230-mm diameter circular plates welded together around their peripheries and filled with de-aired oil. These pads were connected via lengths of steel tubes to vibrating wire pressure transducers and 30-meter-long cables. This model has a built-in 3 KΩ thermistor which allows temperature readings from -55°C to +85°C (see Fig. 2). The cell capacity was 750 kPa with an accuracy of ± 0.5% of the full scale (i.e. ± 3.75 kPa). The cells were capable of operating at up to twice the rated capacity with reduced accuracy. The readings of the total pressure were taken using a model MB-6T portable read-out unit.

Figure 1. Stope 8-1 FW geometry and dimensions with the location of the earth pressure cells.

The development of pressures in the pastefill was measured in three dimensions corresponding to the \( x \), \( y \) and \( z \) axes at two locations (on the floor of the stope and at the plug/residual fill interface) as shown on Figure 1a. A single pressure cell was placed along each axis at these locations, 3 pressure cells on the floor of the stope (cells 1, 2 and 3) and 3 pressure cells at the plug/residual fill interface (cells 4, 5 and 6). A single pressure cell was placed on the lower wall (cell 7) at the same longitudinal axis as cell 4 and another pressure cell was placed at mid-height of the draw point of the stope at 1.5 m from the barricade (cell 8) on a longitudinal axis (Fig. 1a).

Figure 2. The RocTest pressure cell model TPC with a vibrating wire transducer and a built-in thermistor.
3.2.2 Device for the pastefill mass
Figure 3a shows the orientation of the three total pressures, $\sigma_x$, $\sigma_y$, $\sigma_z$, which were measured in Stope 8-1 FW. Two semi-stiff cubic metal boxes (60 cm) were manufactured. Three pressure cells were mounted on three faces of each box (Fig. 3b). This type of arrangement has been employed in the past for similar measurements (Hassani et al. 1998, Hassani 1999). To maintain alignment the boxes were assembled on a metal semi-stiff frame of 7.6 m high (Fig. 3c).

The frame is then placed in the stope by means of an in-house manufactured trolley mounted on two wheels and a mechanism of pulley and cords. The trolley supporting the frame is firstly thorough to 3 m inside the stope and then the frame is raised by pulling at the same time on two cords, one from the draw point and the other from the upper gallery. In the absence of angle indicators on the device, bands of fluorescent painting on the top of the frame allow its visual upright positioning in the stope. After its installation, it was observed that the device had a slight deviation from vertical estimated at 5 degrees. This deviation was neglected in our interpretations.

3.2.3 Device for the foot wall
The cell which was mounted on the lower wall of the stope was fixed to a 20-mm-thick wood board based on the recommendations of Weller & Kulhawy (1982). The corresponding aspect ratio (ratio of the cell diameter to the board thickness) was 11.5 (Fig. 4a). The device was easier to set up on the wall and prevented direct contact between the cell and the rock face. A similar device has been used by Yang et al. (1998) for the measurement of the pressures de-

3.2.4 Device for the barricade
The TPC cell near the barricade was installed vertically at the intersection of two 6-mm-diameter steel retaining cables (Fig. 4b). In such a configuration the cell could not undergo rotation, but could possibly undergo longitudinal displacement of 2 to 4 cm (Harvey 2004). Such a displacement could cause a slight underestimate of the pressure on the barricade.

![Figure 4](image)

4 BACKFILLING OF THE STOPE
4.1 Paste backfill mix design
The tailings from the concentrator at the Doyon Gold Mine were used for the pastefill. At the outlet of the thickener the pulp is 60% solids by mass. It is then stripped of cyanide and routed to disc-type filters where it is dewatered to 80% solids. The tailings pulp is then mixed with the binder agents and water to create cemented paste. The mix used at Doyon Gold Mine is 7% by mass of Portland cement for the "plug" which is used to fill the lower portion of the stope (7 m in this case), and 3% by mass of binder (30% Portland cement and 70% slag) for the "residual fill" used to fill the remainder of the stope (22 m in this case).

Because of the clayey nature of the Doyon Gold Mine tailings (more than 40% clay fraction) its Specific Gravity is of 2.73 and the average solids concentration of the resulting pastefill is 70% by mass with an average slump of 210 mm (moisture content of 42.9%). This low solids concentration is due to pastefill low value of bulk density (1.8 m$^3$) and to the fact that Doyon Gold Mine tailings contain about 50% fines (grains diameter < 20 μm) while 15% of fines would have been optimal for the needs of the pastefill transport through pipes via gravity (Landriault et al. 1997). Also the clayey nature of this cemented fill exhibits its strong water retention capacity.
The bulk unit weight ($\gamma$) of the Doyon pastefill is of 18 kN/m$^3$ (degree of saturation $S_e = 100\%$) and its dry unit weight ($\gamma_d$) is of 12.6 kN/m$^3$. The initial void ratio ($e_0$) and corresponding initial porosity ($n_0$) of the pastefill is 1.18 and 0.54 respectively for the plug (7% Portland cement) and 1.17 and 0.54 for the residual fill (3% binder). Table 1 presents the variation of the moisture content and the solids concentration by mass, $C_w(\%)$ in the course of curing time.

<table>
<thead>
<tr>
<th></th>
<th>Plug</th>
<th>Residual fill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>$w(%)$</td>
<td>$C_w(%)$</td>
</tr>
<tr>
<td>0-day</td>
<td>42.9</td>
<td>70</td>
</tr>
<tr>
<td>7-day</td>
<td>41.6</td>
<td>70.6</td>
</tr>
<tr>
<td>14-day</td>
<td>41.0</td>
<td>70.9</td>
</tr>
<tr>
<td>28-day</td>
<td>40.0</td>
<td>71.5</td>
</tr>
</tbody>
</table>

The observed mechanical strengths are rather weak and the average 7-day compressive strength is about 170 kPa for the plug (7% Portland cement) and of 130 kPa for the residual fill (3% binder agent).

4.2 Stope backfilling with pastefill

Backfilling of Stope 8-1 FW with pastefill began four weeks following the last mining sequence (wall convergence was assumed to be complete by this time) and was carried out in three sequences (Fig. 5). The first sequence (3045 tons of pastefill) consisted of the pouring of the plug ($h = 7.3$ m) and lasted 44 hours ($\approx 2$ days) followed by a curing period of 94 hours ($\approx 4$ days).

The second sequence (10,339 tons of pastefill) consisted of the placement of 18 m of residual fill and lasted 190 hours ($\approx 8$ days) followed by a curing period of 37 hours. The third sequence (882 tons of CPB) consisted of the completion of the residual fill by an additional 2 m, the remaining 2 m of the stope were left empty. The total duration of filling including the curing periods was 356 hours ($\approx 15$ days) and a total of 14,266 tons of pastefill were placed (Harvey 2004).

5 RESULT OF PRESSURE MEASUREMENTS

The pressure readouts were taken from the start of backfilling until 320 days after the end of backfilling. Due to the geometry of the stope (see Fig. 5), the filled heights ($h$) were calculated from the pastefill quantities. The duration of filling and the stope volume were obtained from a CMS (Caving Monitoring System) scanning. Figure 6 shows the variation of filled height ($h$) with respect to the time elapsed since the start of filling.

5.1 Internal pressure in pastefill during placement

5.1.1 Pressure developed at the floor of the stope

Figure 7 shows the evolution of the vertical ($\sigma_{y_1}$), longitudinal ($\sigma_{x_1}$) and transverse ($\sigma_{z_1}$) pressures at the floor of the stope during the filling which lasted 15 days including the curing periods. After 4 days the filled height, $h$, was 7.3 m (actual plug height) and at the 15th day the filled height was 27 m. The point of measurement of the longitudinal and transverse pressures was located at elevation, $z$, of 0.3 m and for the vertical one at elevation of 0.6 m.

It can be observed from Figure 7, that during filling the longitudinal pressure ($\sigma_{x_1}$) was the highest on the floor of the stope (Fig. 7). This pressure reached its maximum value ($\sigma_{x_{1,\text{max}}}$) of about 150 kPa during the second sequence of filling (after the 10th day). This maximum value is almost twice that of the vertical ($\sigma_{y_1}$) and transverse ($\sigma_{z_1}$) pressures which were similar in magnitude ($\sigma_{x_{1,\text{max}}} > \sigma_{y_1} \approx \sigma_{z_1}$). It should be noted that the 882 tons of pastefill added during the 3rd sequence of filling, from the 13th day, had no influence on the internal pressures at the floor, which actually began decreasing. This reduction continued until day 91.
5.1.2 Pressure developed at the plug/fill interface
The TPC cells which were located at elevation 7.6 m for $\sigma_{z2}$ and at elevation 7.3 m for $\sigma_{x2}$ and $\sigma_{y2}$ began recording pressures only after the pastefill rose to that level, some 30 hours after the start of the placement of the residual fill (124 hours from the start of filling). Figure 8 shows the evolution of the vertical ($\sigma_{z2}$), longitudinal ($\sigma_{x2}$) and transverse ($\sigma_{y2}$) pressures at the plug/residual fill interface from the 5th day of filling. Again, it can be observed that the longitudinal pressure is the highest of the three measured pressures ($\sigma_{x2} > \sigma_{y2} > \sigma_{z2}$). The maximum value of the longitudinal pressure ($\sigma_{x2}$) is about 53 kPa ($\sigma_{y2} = 38$ kPa and $\sigma_{z2} = 25$ kPa).

5.3 Lateral pressure on the barricade
Figure 10 shows the evolution of the longitudinal pressure ($\sigma_{x_b}$) exerted on the barricade at mid-height ($z' = 2.1$ m). It can be observed that the maximum pressure exerted on the barricade was about 54 kPa and was reached on the 10th day of filling. However, this pressure begins to decrease just after having reached this maximum.

6 DISCUSSION
6.1 Long-term behaviour of pastefill
The time history of pressure measurements permits observation of both the variation of the developed internal pressures and the effect of hydration of the pastefill on the lower wall of Stope 8-1 FW. The readings began the 5th day and the maximum value reached was about 45 kPa.
binder reagents. The pressures on the floor of the stope will become critical when they approach the compressive strength of the pastefill. For example, an increase in the transverse pressure ($\sigma_y$) would probably indicate wall convergence. From the point of view of the mine production and safety, it is also important to know when the pressure being exerted on the barricade will be dissipated. Finally, the long-term evolution of the pressures in the pastefill allows estimation of its consolidation characteristics, and the stress redistribution due to the mining at the vicinity of filled stope.

Figure 11 shows the evolution of the internal stresses of the pastefill at elevation 0.6 m as a function of the elapsed time since the beginning of the filling. It can be observed that after reaching their peak values, all the pressures decrease after the end of the filling (15th day) until approximately the 110th day. Beyond 122 days a continual increase in the longitudinal ($\sigma_x$) and vertical ($\sigma_z$) pressures until 361 days is observed. On the other hand the transverse pressure ($\sigma_y$) increases and then began decreasing. The same tendencies were observed for the pressures ($\sigma_{2x}$, $\sigma_{2y}$, $\sigma_{2z}$) measured at elevation 7.6 m.

Pore pressure of pastefill is necessary for the calculation of the effective earth pressure, but was not measured in this study. Even if the rock pile barricade of the trial stope allows the drainage of free water, any drainage was quantified. Due to its strong water retention capacity the Doyon Gold Mine pastefill remains saturated (moisture contents of about 38%) a long time until 360 days and the drainage period, if any, does not exceed 5 days. Indeed, in situ measurements of pore pressure of pastefill on barricade showed that pore pressure is negligible as shown on Figure 12 (Bridges, 2003).

6.2 Effect of filled height on the developed pressure

6.2.1 Vertical pressure

Figure 13 presents the evolution of the vertical pressure ($\sigma_z$) at elevation 0.6 m (bottom of the plug) and at elevation 7.6 m (plug/residual fill interface) compared to the theoretical overburden stress of the pastefill ($\gamma h$). This comparison allows verification of the existence of an arching effect. An arching effect would reduce the magnitude of the vertical pressure at the floor of the stope ($\sigma_z < \gamma h$) which will be compensated by an increase in the longitudinal pressure ($\sigma_x$) on the walls of the stope (Aubertin et al. 2003; Li et al. 2003, 2004). The curves thus show that there was an arching effect in the filled stope.

6.2.2 Longitudinal pressure

Figure 14 presents the evolution of the longitudinal pressure at elevations 0.6 m (plug) and 7.6 m (plug/residual fill interface and lower wall). The longitudinal pressure at the bottom of the stope ($\sigma_{x1}$)
is more than twice that measured at the plug/residual fill interface ($\sigma_{x2}$) as well as at the lower wall ($\sigma_{x_{wall}}$). It is also noted that the pressure exerted on the lower wall ($\sigma_{x_{wall}}$) is slightly lower than that measured on the same axis but at a distance of 3 m ($\sigma_{x2}$). The maximum longitudinal pressures $\sigma_{x1}$ and $\sigma_{x2}$ were obtained at a filled height of 22 m while the maximum longitudinal pressure on the lower wall ($\sigma_{x_{wall}}$) was obtained at a filled height of 18 m.

**6.2.3 Transverse pressure**

Figure 15 presents the evolution of the transverse pressure at elevations 0.6 m (plug) and 7.6 m (plug/residual fill). This figure shows that the transverse pressure at the bottom of the stope ($\sigma_{y1}$) was twice that measured at the elevation 7.6 m ($\sigma_{y2}$). The maximum lateral pressure $\sigma_{y1}$ was obtained at a filled height of 19 m while $\sigma_{y2}$ reached a maximum value at a filled height of 14 m.

**6.3 Modeling pressures development in the CPB during stope filling**

The results of the pressure measurements presented in this paper clearly show that the pressures decreased slightly, by about 8 kPa, (except for the pressure on the barricade, see Fig. 10) during the curing period (between the 2nd and the 5th day). This indicates that the development of the internal pressures may be independent of the hydration of the binder reagent (see Fig. 7). Consequently, the dominant factor appears to be the filled height. Moreover, during pastefill placement it is helpful to know the evolution of the pressures developed within the pastefill based on the filled height. Accordingly, we propose simple 3D models to allow the prediction of both the three-dimensional pressures ($\sigma_x$, $\sigma_y$, $\sigma_z$) developed in the pastefill and the pressure exerted on the barricade ($\sigma_{x_{b}}$) during filling.

**6.3.1 Filled height-dependent 3D model to predict the internal stresses of pastefill**

According to the results presented, the internal stresses of the CPB increased gradually as a function of the filled height to some maximum values. These stresses then remained relatively constant at the end of the filling. With regard to the bottom of the stope, the longitudinal pressure ($\sigma_{x1}$) was almost twice that developed vertically ($\sigma_{z1}$) or transversely ($\sigma_{y1}$). This type of variation suggests that the pressure at the
Floor of the stope depends on the unit weight of the pastefill, and more importantly on the dimensions of the stope. Thus, the variation of the longitudinal pressure ($\sigma_x$) depends on its maximum value ($\sigma_{x,\text{max}}$) and on the filled height ($h$). This variation of $\sigma_x$ can be described by an exponential relationship (as proposed by the Marston theory; see McCarthy 1988 and Aubertin et al. 2003), which can be formulated as follows:

$$\sigma_x(h) = (\sigma_{x,\text{max}}) \left[ 1 - \exp\left( -\frac{(h-z)}{a} \right) \right]$$

(1)

where $a$ is a constant of proportionality; $h$ is the filled height (m); $z$ is the elevation (m); and $h \geq z$.

The maximum longitudinal pressure, ($\sigma_{x,\text{max}}$), depends on the overburden stress of the CPB ($\gamma H$) and can be estimated by the following relationship:

$$\sigma_{x,\text{max}} = \gamma(H_m - z) \left[ \frac{H_m}{3(B+L)} \right]$$

(2)

where $\gamma$ is the bulk unit weight of the CPB (kN/m$^3$); $H_m$ is the total height of the filled stope (m); $z$ is the elevation (m); $z = 0$ at the floor of the stope, $z = H_m$ at the top of the filled stope; $B$ is the stope width; and $L$ is the stope length.

Substituting Equation 2 into Equation 1 and assuming that the constant $a$ is half of the stope width $B$ ($a = B/2$) leads to the following 3D model:

$$\sigma_x(h) = \frac{\gamma H_m (H_m - z)}{3(B+L)} \left[ 1 - \exp\left( -\frac{2(h-z)}{B} \right) \right]$$

(3)

where $z \leq h \leq H_m$.

Figure 17 shows the measured longitudinal pressures at the elevations 0.6 m ($\sigma_{x1}$) – floor of the stope – and 7.6 m ($\sigma_{x2}$) – plug/fill interface – compared to the predicted values using Equation 3. Note that this 3D model describes the longitudinal pressure at the floor of the stope ($\sigma_{x1}$) reasonably well, but at the plug/residual fill interface ($\sigma_{x2}$) is not as accurate.

From the results of pressure measurements presented in this paper (e.g. Fig. 7) one can reasonably assume that the vertical pressure ($\sigma_y$) developed in a stope backfilled with pastefill is approximately equal to the developed transverse pressure ($\sigma_x$). From this figure one can also consider that the longitudinal pressure ($\sigma_{x1}$) at the floor of the stope is about 1.8 times the transverse pressure [$\sigma_x \approx 1.8 \times (\sigma_y \approx \sigma_z)$]. This observation is not true for the pressures measured at the plug/fill interface (see Fig. 8). Consequently, the transverse and vertical pressures can be evaluated using the following relationship:

$$\sigma_{y,z}(h) = \frac{0.185 \cdot \gamma H_m (H_m - z)}{B+L} \left[ 1 - \exp\left( -\frac{2(h-z)}{B} \right) \right]$$

(4)

Figure 18 shows the measured transverse pressures at the elevations 0.6 m ($\sigma_{y1}$) and 7.6 m ($\sigma_{y2}$) compared to the predicted values using Equation 4. It is noted that the model reasonably well predicts the transverse pressure at the floor of the stope ($\sigma_{y1}$), but less accurately at the plug/residual fill interface ($\sigma_{y2}$).

Figure 19 shows the measured vertical pressures at the elevations 0.6 m ($\sigma_{z1}$) and 7.6 m ($\sigma_{z2}$) compared to the predicted values using Equation 4. Note again that the model predicts the vertical pressure at the floor of the stope ($\sigma_{z1}$) rather well, but predicts that at the plug/residual fill interface ($\sigma_{z2}$) less well. Other approaches developed to model the stresses in backfilled stopes have been presented in recent companion papers (Aubertin et al. 2003; Li et al. 2003, 2004).
points (z1 = 0.6 m and z2 = 7.6 m) using Equation 4: \( \gamma = 18 \) kN/m³, \( H_m = 29 \) m, \( B = 12 \) m, \( L = 21 \) m.

6.3.2 Filled height and time-dependant 3D model to predict the internal pressures of the paste fill

The formulation of Equations 3 and 4 does not take into account the elapsed time during the stope filling with paste fill. In these relationships the only parameter which can vary with time is the bulk unit weight (\( \gamma \)) of the paste fill. However, this parameter is constant in the initial formulation of Equations 3 and 4. To take the time factor into account in these equations we propose a relationship describing the evolution of the bulk unit weight of the paste fill with time (\( \gamma^* \)) as follows:

\[
\gamma^* = \frac{\gamma}{1 + \left( \frac{\gamma - \gamma_d}{\gamma_d} \right) \frac{t}{t_{\text{max}}}}
\]  

(5)

where \( \gamma \) is initial bulk unit weight of the paste fill (kN/m³); \( \gamma_d \) is the dry unit weight of the paste fill (kN/m³); \( t \) is the time elapsed since the beginning of paste fill placement in the stope (day); \( t_{\text{max}} \) is the maximum elapsed time (day) at which \( \gamma = \gamma_d \) (\( t_{\text{max}} \) is estimated to be approximately 2 years or 758 days).

Substituting Equation 5 into Equations 3 and 4 leads to the models to predict the evolution of the internal pressures of the paste fill as a function of elapsed time since the beginning of the filling as follows:

\[
\sigma_z(t) = \frac{\gamma H_m (H_m - z)}{3(B + \frac{L}{1 + \left( \frac{\gamma - \gamma_d}{\gamma_d} \right) \frac{t}{t_{\text{max}}}})} \left[ 1 - \exp \left( -\frac{2(h - z)}{B} \right) \right]
\]  

(6)

Figure 19. Comparison between experimental data and predicted curves of the vertical pressure \( \sigma_z \) at two elevation points (z1 = 0.6 m and z2 = 7.6 m) using Equation 4: \( \gamma = 18 \) kN/m³, \( H_m = 29 \) m, \( B = 12 \) m, \( L = 21 \) m.

\[
\sigma_{\text{h}}(t) = \frac{0.185 \cdot \gamma H_m (H_m - z)}{(B + \frac{L}{1 + \left( \frac{\gamma - \gamma_d}{\gamma_d} \right) \frac{t}{t_{\text{max}}}})} \left[ 1 - \exp \left( -\frac{2(h - z)}{B} \right) \right]
\]  

(7)

Figure 20 shows the longitudinal pressure measured at the elevation 0.6 m (\( \sigma_{x1} \)) compared to the predicted values using Equation 6. It can be observed that the model predicts the longitudinal pressure at the floor of the filled stope (\( \sigma_{x1} \)) as a function of the filled height and elapsed time rather well, thus indicating that Equation 5 is well formulated.

6.3.3 3D model to predict pressure on barricades

Because of the complexity of the paste backfill the adaptation of the Rankine theory of earth pressures is not conducive to the prediction of the lateral (or longitudinal) pressure exerted on the barricade. Even though the Rankine passive and active earth pressures equations are simple to use, they nevertheless need the intrinsic parameters of the paste fill (\( c \) and \( \phi \)) which can be obtained from laboratory tests. From the analysis of the experimental results presented in this paper we propose a simple 3D exponential model to predict the lateral pressure exerted by the paste fill on the barricade (\( \sigma_{\text{h}} \)) as a function of filled height which is given by the following relationship:

\[
\sigma_{\text{h}}(h) = \frac{\gamma(h - z')}{2} \exp \left( -\frac{4}{9} \frac{(B + L)(h - z')}{L \cdot B} \right)
\]  

(8)

where \( \gamma \) is the bulk unit weight of the paste fill (kN/m³); \( h \) is the filled height (m); \( z' \) is the elevation of the point of measurement (m) in the draw point; \( B \) is the stope width (m); and \( L \) is the stope length (m).

Substituting Equation 5 into Equation 8 leads to a model to predict the lateral pressure on the barricade
as a function of elapsed time since the beginning of the filling:

\[ \sigma_x(t) = \frac{\gamma (h - z')}{2} \exp \left( -\frac{4}{9} \frac{(B + L)(h - z')}{L \cdot B} \right) \]

Figure 21 shows the measured lateral pressure on barricades of two stopes of different size (large and small) compared to the predicted values using Equation 8. Barricade 1 (large stope) is that of the stope studied in this paper while the barricade 2 is that of another instrumented filled stope (small stope) which is not presented herein. It can be noted that Equation 8 predicts the lateral pressure on the barricade of the large stope (barricade 1) rather well, but predicts the lateral pressure on the barricade of the small stope (barricade 2) less accurately.

7 CONCLUSION

The objective of this study was to follow the evolution of internal stresses in cemented fill during and after stope filling. To reach this objective, a stope at the Doyon Gold Mine (Cambior Inc., Canada) was instrumented at various points using earth pressure cells (model TPC). The stresses induced in the pastefill (\(\sigma_{\text{longitudinal}} = \sigma_x\), \(\sigma_{\text{transversal}} = \sigma_y\) and \(\sigma_{\text{vertical}} = \sigma_z\)) as well as on the lower wall and on the barricade (lateral or longitudinal pressure) were recorded during and after placement of pastefill. The resulting data indicate that the internal longitudinal pressure of the pastefill is higher than the transversal and vertical pressures. This tends to confirm the existence of an arching effect which develops in the stope during filling. In order to have tools for stability analysis of the filled stopes with pastefill, four 3D models were proposed to predict the internal pressures and the pressure on barricades and both as a function of the filled height (Eqs. 3 & 8) and as a function of elapsed time since the beginning of backfilling (Eqs. 5 & 9). The proposed models responses are in good agreement with the experimental data. This result is very encouraging to the on-going study of ground control using pastefill in underground mines.

The results presented herein are based on the measurements made in a specific stope filled with a specific type of pastefill and may not be applicable elsewhere.

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