Mine backfill porewater pressure dissipation: numerical predictions and field measurements

Mohammad Shahsavari & Murray Grabinsky
University of Toronto, Toronto, Ontario, Canada

GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

ABSTRACT
Cemented paste backfill (CPB) has gained popularity in underground mining operations over the past decade. Fresh CPB is being held in the stope by a barricade until it cures and is self-supportive. Therefore, barricade safety is crucial in the mining industry. The pressure acting on the barricade is dependent on the pore water pressure within the CPB. The problem of self-weight consolidation of an accreting material was first studied by Gibson (1958). Fahey et al. (2010) applied Gibson's solution to the consolidation of CPB and introduced lower and upper bound solutions. Shahsavari and Grabinsky (2014), based on in-situ measurements, introduced a new boundary condition and studied its effect on the pore pressure variations with time. However, the effect of the slurry layer weight on the pore pressure was not considered. In the current study, the stresses due to the presence of a slurry layer in addition to the hydraulic boundary condition are considered in the analysis. The process of consolidation is modeled in FLAC3D using Terzaghi's consolidation theory assumptions. The effects of slurry layer height and weight on pore pressure are studied. Finally, a comparison between numerical analysis results and field measurements is made.

RÉSUMÉ
Le remblai en pâte cimentée (CPB) a gagné en popularité dans les opérations minières souterraines au cours de la dernière décennie. Le CPB frais est retenu dans le chantier par une barrière jusqu'à ce qu'il durcisse et s'auto-soutienne. Par conséquent, la sécurité de la barrière est cruciale dans l'industrie minière. La pression agissant sur la barrière dépend de la pression d'eau interstitielle à l'intérieur du CPB. Le problème de la consolidation sous son propre poids d'une matière en accrétion a été étudié par Gibson (1958). Fahey et al. (2010) ont appliqué la solution de Gibson à la consolidation du CPB et introduit des solutions limites inférieure et supérieure. Shahsavari et Grabinsky (2014), à partir de mesures in-situ, ont introduit une nouvelle condition limite et étudié son effet sur les variations de pression interstitielle avec le temps. Cependant, l'effet du poids de la couche de boue sur la pression interstitielle n'a pas été considéré. Dans cette étude, les contraintes dues à la présence d'une couche de boue en plus de la condition limite hydraulique sont prises en compte dans l'analyse. Le processus de consolidation est modélisé dans FLAC3D en utilisant les hypothèses de la théorie de consolidation de Terzaghi. Les effets de la hauteur et du poids de la couche de boue sur la pression interstitielle sont étudiés. Finalement, une comparaison entre les résultats de l'analyse numérique et les mesures effectuées sur le terrain est présentée.

1 INTRODUCTION

Large voids (stopes) that are created after the extraction of an ore body are always backfilled for two main reasons: ground support for further excavations and reduction of surface disposal of mine wastes. One of the most popular backfilling materials is cemented paste backfill (CPB). CPB has a higher delivery rate compared to other backfilling materials such as rockfill or hydraulically deposited tailings and hence has gained popularity over the past decade. During backfilling fresh CPB is being held in the stope by means of a concrete slab called a barricade. The stability of the barricade is crucial as barricade failure would put mining personnel at high risk in addition to the extra financial costs it would impose on the mining operation (e.g. Sivakugan, 2008; Revel and Sainsbury, 2007).

Barricade stresses are induced from the development of effective vertical and horizontal stresses within CPB in addition to the pore water pressure. As CPB is being deposited in the stope, the pressure applied to the barricade is equal to the unit weight of the material times the height. However, pore water pressure dissipates with time and effective stresses develop within CPB. Pore pressure dissipation and effective stresses development would lead to a reduction in the stresses applied on the barricade due to arching. Pore pressure dissipation happens due to two mechanisms: 1. drainage of water and consolidation and 2. consumption of water in the hydration process. To simplify the problem and be able to apply soil mechanics theories, the effect of hydration can be ignored. In this case, CPB consolidation can be treated as the consolidation of an accreting soil with high water content. Gibson (1958) proposed an analytical solution to the problem of consolidation of a clay layer in which its thickness increases with time. Gibson (1958) introduced a set of isochrones to obtain pore pressure at different depth at different times. Gibson's (1958) PDE was developed based on Terzaghi (1943) theory of 1D consolidation assumptions. Fahey et al. (2010) applied the Gibson solution to the consolidation of CPB. To apply the Gibson solution to CPB, Fahey et al. (2010) considered a coefficient of consolidation (c_v) that was a function of effective stress. It was concluded that a varying coefficient of consolidation can have an effect on the pore pressure generation and thus must be considered in the cases where the initial analysis using the Gibson solution with a constant c_v suggests high degrees of consolidation at short times. However, due to strength and stiffness gains and at the same time a reduction in the permeability coefficient, the assumption of a constant c_v can be justified as was also mentioned by Terzaghi (1943). Thus for the sake of simplicity of the analysis a constant c_v is assumed for the whole duration of consolidation in the current analysis.

Previous studies on the consolidation of CPB considered a zero pore pressure boundary condition on top of each deposited layer (Doherty, 2015; El Mkdami et al, 2014; Fahey et al., 2010; Li and Aubertin, 2009; and Helinski, 2008). However, in-situ measurements over the past few years (Grabinsky et al., 2014 and 2013; and Thompson et al., 2012) suggest that the boundary condition on the top of each deposited layer is not zero. Shahsavari and Grabinsky (2014) studied the effect of a non-zero pore pressure boundary condition on CPB consolidation. However, in the previous analyses only a pore pressure boundary condition was imposed without applying the appropriate stress boundary condition due to the weight of the non-consolidating slurry layer on top of the consolidating layer. In the current study, the effect of both mechanical and hydraulic boundary conditions on pore pressure variations with time and height within CPB are considered. The results are then compared with in-situ measurements at Cayeli mine.

2 IN-SITU STRESSES

To provide additional support for the barricade and also to prevent the exceedance of stresses beyond the barricade load capacity, backfilling is usually done in two steps. First a layer of material is placed in the stope with a specific height which can be about one third of the stope height. This layer is called "plug". Then some time is given to the plug layer material to cure and gain strength before backfilling is resumed. The problem that is being addressed in this paper is relevant and applicable to plug backfilling prior to the initiation of hydration and formation of cement bonds.

Over the past several years an extensive in-situ monitoring of total stresses, pore pressure, and temperature during and after CPB backfilling was performed at the University of Toronto (Grabinsky et al., 2014 and 2013; and Thompson et al., 2012). Three different mine sites were monitored; Cayeli Mine in Turkey, Barrick's Williams Mine in Marathon, and Xstrata's Kidd Mine in Timmins, Ontario.

The pouring rate was 0.25 m/h on average in Cayeli and Kidd mine while it was 0.36 m/h in the Williams test stope (Grabinsky et al, 2014 and Thompson et al, 2012). The plug layer height is usually between 6 to 8 m (Grabinsky et al, 2014). Therefore, in this study the maximum plug height of 10 m is considered.

Total earth pressure cells (TEPC), tensiometers, piezometers, and thermistors were placed all together in several cages to measure the stresses, pore pressure, and temperature variations within the test stopes. The details of the instrumentation and measurement locations are provided in Thompson et al. (2012).

Variation of Total and effective stress, pore pressure and temperature with time at the William Mine test stope at one of the measurement points are shown in Figure 1. CPB reached the transducers at the 15th hour after the initiation of backfilling. Consolidation is defined as the drainage of excess pore water pressure and development of effective stresses (Terzaghi, 1943). As shown in Figure 1, the total stress and pore pressure have the same value for about 3 hours after the material hits the transducers. For this period of time, there is no effective stresses developed within CPB and hence no consolidation occurs. Since the material is in a slurry condition, Shahsavari and Grabinsky (2014) called this layer the "slurry layer". In continuous backfilling, new material is being added to the already consolidating layers. If it takes 3 hours for CPB to start the consolidation, there will always be a non-consolidation slurry layer on top of the consolidating material (Shahsavari and Grabinsky, 2014). Assuming that this 3 hour period of zero effective stress is constant and an average filling rate of 0.36 m/h in the Williams Mine, there will be always a ~ 1.1 m height of fresh CPB in the form of slurry on top of the consolidation layer. In the current study the same assumption in terms of the presence of the slurry layer is made in the numerical analysis.

Kidd Mine field measurements during the plug pour are shown in Figure 2. As shown in Figure 2, the zero effective stress zone only appears for about 2 hours (between the 21.5 and 23.5 hours). Therefore following the same logic as explained in the case of the Williams Mine, having a filling rate of 0.25 m/h, the slurry height above the consolidating material is expected to be about 0.5 m.

At Cayeli Mine, the slurry state lasted for about half a day (Figure 3). This time period is equivalent of 3 m of CPB when the filling rate is 0.25 m/h.

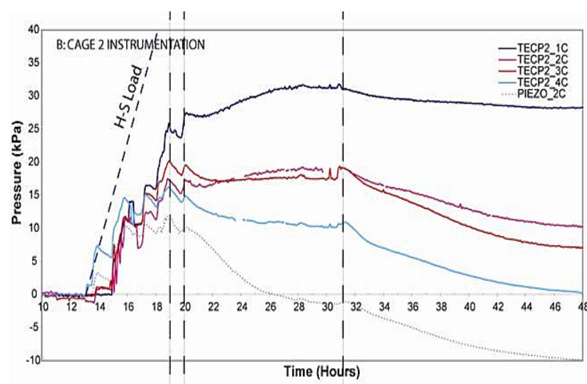

Figure 1. In-situ pressures and temperature variations at Williams Mine during the plug pour (Grabinsky et al., 2013)

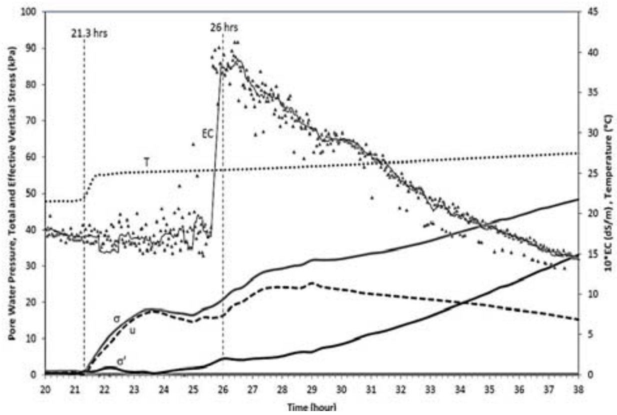

Figure 2. In-situ pressures and temperature variations at Kidd Mine during the plug pour (Grabinsky et al., 2014 and 2013)

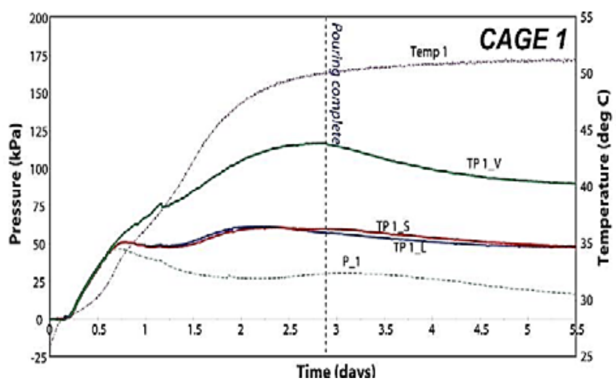

Figure 3. In-situ pressures and temperature variations at Cayeli Mine during the plug pour (Grabinsky et al., 2014)

3 NUMERICAL SIMULATION

Several studies in the past few years have tried to predict the variation of pore water pressure and total stresses within the backfilled stope (Doherty, 2015; Shahsavari and Grabinsky, 2014; El Mkdami et al., 2014; Veenstra, 2013; and Fahey et al., 2010). El Mkdami et al. (2014) used GeoStudio software package and Veenstra (2013) used Itasca's FLAC3D to model the backfilling process. Fahey et al. (2010) applied the Gibson (1958) solution to the problem of backfilling. They used variable constrained modulus and coefficient of consolidation and obtained upper and lower bounds for consolidating and non-consolidating CPB for the initial assessment of stresses applied on the barricade. The major discrepancy between these analyses and the in-situ measurements is that they all assumed a zero pore pressure on top of the consolidating material as mentioned by Shahsavari and Grabinsky (2014). Shahsavari and Grabinsky (2014) tried to address this new boundary condition using FLAC3D to study the problem of consolidation of CPB. However, they only considered the hydraulic boundary condition and did not consider the effect of the weight of the slurry layer in their analysis.

In this paper, this shortcoming is addressed and the results are compared with the in-situ measurements. Fist the analytical solution introduced by Gibson (1958) is reviewed briefly and then the details of the FLAC3D model are discussed. Finally, in this section, the effect of the new mechanical and hydraulic boundary conditions on pore pressure variations with depth is shown.

3.1 Analytical solution

Gibson (1958) studied the problem of consolidation of an accreting clayey soil. Gibson (1958) considered the same assumptions as Terzaghi (1943) considered to develop his theory of one dimensional consolidation. These assumptions include: 1- small strains, 2- constant permeability coefficient, 3- constant constrained modulus and consequently constant coefficient of consolidation (c_v), and 4- Elastic deformations. Gibson (1958) derived the PDE in Equation 1.

$$c_v \frac{\partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t} - \gamma \frac{dh}{dt} \qquad [1]$$

where u is the total pore pressure, γ is the material unit weight and h is the height of the layer. It must be noted that the height is a function of time $(h = H(t))$. For the specific case of backfilling the height is almost a linear function of time (i.e. $h = H(t) = mt$). The analytical solution for this case is given in Equation 2. It was assumed that the pore pressure is zero on top and bottom of the consolidating material.

$$u = -\gamma z(1 + \frac{mz}{2c_v}) + \frac{\gamma m}{2c_v}(\pi c_v t)^{-\frac{1}{2}}.\exp(-\frac{z^2}{4c_v t}). \int_0^\infty \xi^2 \coth(\frac{m\xi}{2c_v})\sinh(\frac{z\xi}{2c_v t}).\exp(-\frac{\xi^2}{4c_v t}).d\xi \qquad [2]$$

where z is the distance from the bottom of the layer and $0 < z < h = H(t)$. ξ is a dimensionless parameter and is used for the sake of integration.

To be able to interpret the results easily Gibson (1958) introduced a dimensionless time factor as

$$T = \frac{m^2 t}{c_v} \qquad [3]$$

Equation 4 can also be expressed in terms of the total height (H) as

$$T = \frac{mH}{c_v} \qquad [4]$$

The integral in Equation 2 is evaluated numerically and the isochrones in Figure 4 for different time factors are produced.

3.2 FLAC3D Analysis

Itasca's FLAC3D has been used to simulate the backfilling and consolidation of CPB in the past (Shahsavari and Grabinsky, 2014 and Veenstra, 2013).

In conventional consolidation theory the coefficient of consolidation is defined as Equation 5.

$$c_v = \frac{k.M}{\gamma_w} \tag{5}$$

where k is the permeability coefficient, M is the constrained modulus and γ_w is water unit weight. However, Biot's (1941) consolidation theory is used in FLAC3D and hence the presence of occluded air and water bulk modulus can be considered in the analysis. c_v in FLAC3D is defined as in Equation 6 where K_f, ρ_f, K, and G are the fluid bulk modulus, fluid density, and solid material bulk and shear modulus, respectively. While n is the Eulerian porosity. This definition in Equation 6 reduces to Equation 5 and yields the same c_v if water bulk modulus and solid particles stiffness are considered extremely large compared to pore space constrained modulus.

$$c_v = \frac{k/\rho_f g}{\frac{n}{K_f} + \frac{1}{K + (4/3)G}} \tag{6}$$

FLAC3D is capable of performing both coupled and uncoupled analysis. Coupled in the context of consolidation means that the pore pressure is affected by the deformations and also deformations are also affected by the pore pressure. On the other hand in an uncoupled analysis only pore water pressure is being affected. Shahsavari and Grabinsky (2014) studied the problem of consolidation of an accreting material using a coupled FLAC3D code. It was shown that FLAC3D is capable of reproducing the same results as the analytical solution given making obtaining the same c_v as in Equation 5. The comparison between the numerical and analytical solutions is shown in Figure 4.

3.3 Effect of boundary condition

Shahsavari and Grabinsky (2014) introduced a non-zero boundary condition for the pore water pressure on the top of the consolidating material. This boundary condition was inferred from the in-situ measurements that were discussed in section 2. However, they only applied the boundary condition to the pore water pressure. This happened as in all the consolidation problems that follow Terzaghi's solution, the PDE is derived and solved for the pore ware pressure and hence no coupling is considered. In the current study, the effect of the mechanical boundary condition is also considered in addition to the hydraulic boundary condition. For the sake of comparison, the same assumptions regarding the material properties as Shahsavari and Grabinsky (2014) are made. The details of the FLAC3D model including the dimensions and filing rates can be found in Shahsavari and Grabinsky (2014). The material properties are shown in Table 1.

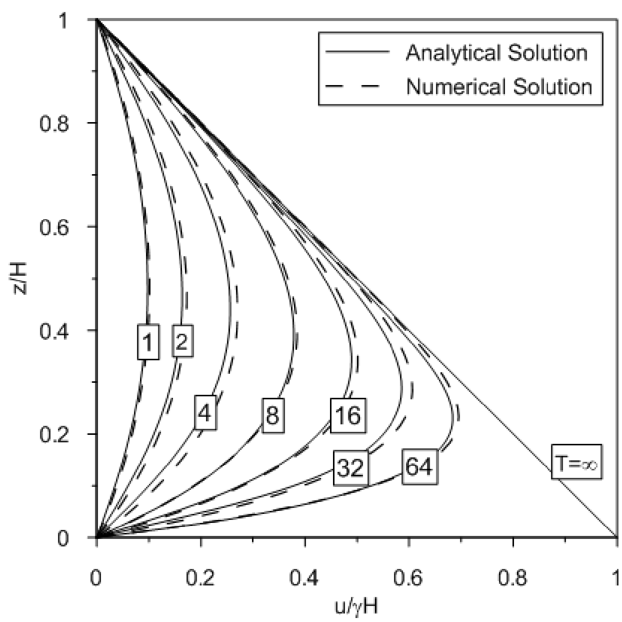

Figure 4. Isochrones of total pore pressure from analytical and numerical solutions (Shahsavari and Grabinsky, 2014)

Table 1. CPB properties used in FLAC3D model

Permeability Coefficient (m/s)	Shear Modulus (kPa)	Bulk Modulus (kPa)	Unit Weight (kN/m^3)
2.5e-7	2.7e2	6e2	22.46

The effect of consideration of the both mechanical and hydraulic boundary conditions on the pore pressure at the end of backfilling is shown in Figure 5. It is assumed that the height of the slurry layer is 1m and the plug heights were 4m and 8m. As shown in Figure 5, not considering the mechanical boundary condition due to the weight of the slurry layer would lead to the prediction of lower stresses on the barricade and hence an unsafe design. Therefore, in all the consolidation analysis if the pore pressure is not zero at the top boundary, the effect of the weight of the material or water itself on pore water pressure must also be considered. In the following analyses both mechanical and hydraulic boundary conditions are applied when the slurry layer is present on top of the consolidating material.

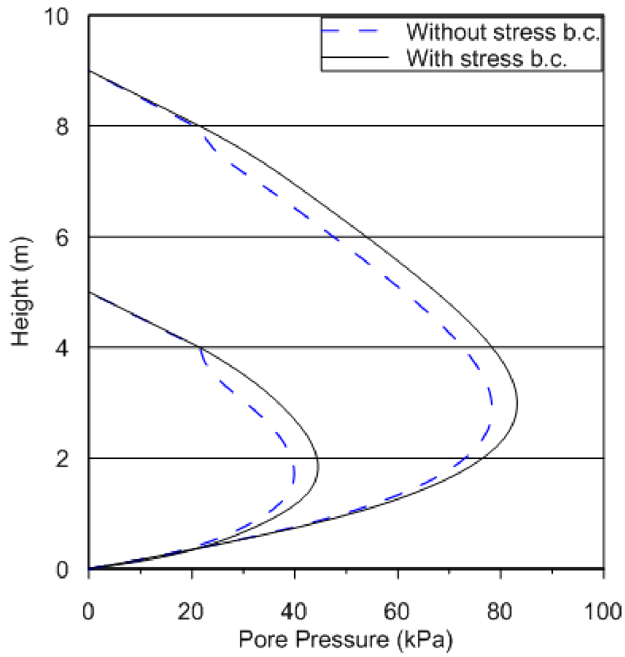

Figure 5. Numerical analysis with and without the mechanical boundary condition

To gain a better insight into the effect of the boundary condition on the pore pressure, three different levels of slurry height on the top boundary are considered. The slurry layer heights are 0.5 m, 1.5 m, and 3 m. These values were selected due to practical applications that were mentioned in section 4. Different plug heights: 2 m, 4 m, 6 m, and 8 m. Although 2 m and 4 m high plugs are not practical, these heights were chosen to understand the effect of the ratio of the slurry layer height to the plug height.

The filling rate for all the filling scenarios is considered to be 0.25 m/h which is a typical rate that is being used in the mining industry. Models are discretized into blocks of 0.0625 cm. Material is deposited into 25 cm thick layers and each layer is then consolidated for an hour. This process is repeated until the desired height is achieved. The slurry height is kept constant for all layers (Shahsavari and Grabinsky, 2014).

3.3.1 Analysis results

Figure 6 shows the total pore pressure distribution with depth at the end of backfilling when the height of the slurry, non-consolidating layer is 0.5 m. The dashed lines are the pore pressure values when the total pore pressure is zero on top of the consolidating material. Shahsavari and Grabinsky (2014) called this case “no slurry boundary”.

The top of the consolidating material is located at the elevations 2m, 4m, 6m, and 8m which means with 0.5m slurry layer, the total fill heights were 2.5m, 4.5m, 6.5m ,and 8.5m, respectively. The total pore pressure is zero on top of the slurry layer and there pore pressure increases linearly with depth with a gradient equal to the unit weight of the CPB. The total pore pressure then stays constant at the value of (slurry height x unit weight) on top of the consolidating material for the whole duration of the consolidation.

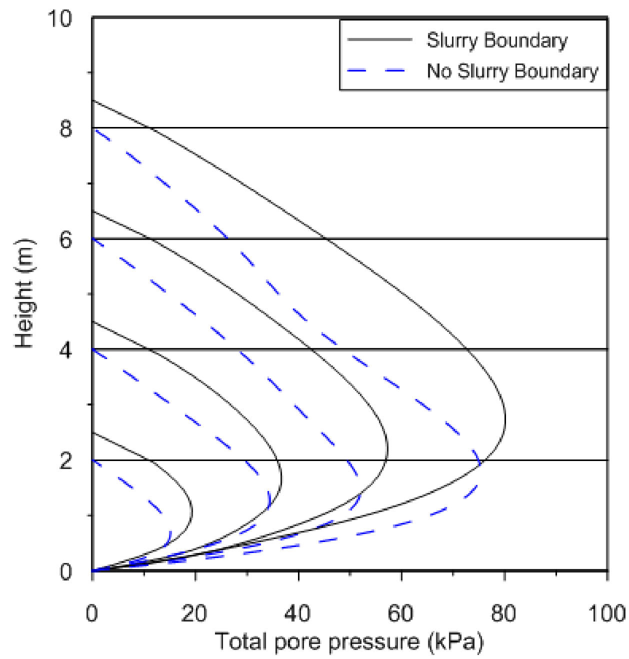

Figure 6. Total pore pressure distribution with depth at the end of backfilling with 0.5m slurry on top

The same analysis with slurry layer heights of 1.5m and 3m were also performed. The variation of total pore pressure with depth at the end of consolidation is for 1.5 m and 3m high slurry layers are shown in Figures 7 and 8, respectively.

The presence of a small layer of non-consolidating slurry layer can affect both the amount and location of the maximum pore pressure. It is shown in Figure 6 that as the ratio of the slurry layer height to the consolidating layer height increases its effect on the maximum pore pressure increases. For instance in the case of an 11m plug layer where the top 3m is slurry till the end of backfilling, the maximum pore pressure has increased by 67% and it is now being applied at 3.4m from the bottom of the stope instead of almost 2m compared to the case with no slurry boundary.

As the magnitude of the fixed total pressure on top boundary increases the magnitude of the maximum total pore pressure deviates more from the case where both boundary conditions are homogeneous. On the other hand, the effect of the top boundary condition is also dependent on the total consolidating material height. As the ratio of the slurry height to the consolidating material height increases the effect of top boundary becomes more prominent. For instance, as shown in Figure 8, for a 2m consolidating material with 3m non-consolidating material on top of it, the maximum total pore pressure occurs very close to the top of the consolidating material.

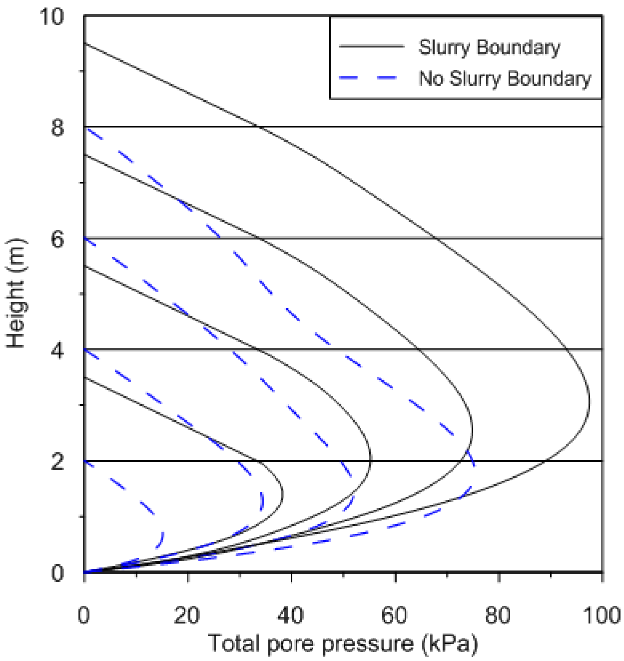

Figure 7. Total pore pressure distribution with depth at the end of backfilling with 1.5m slurry on top

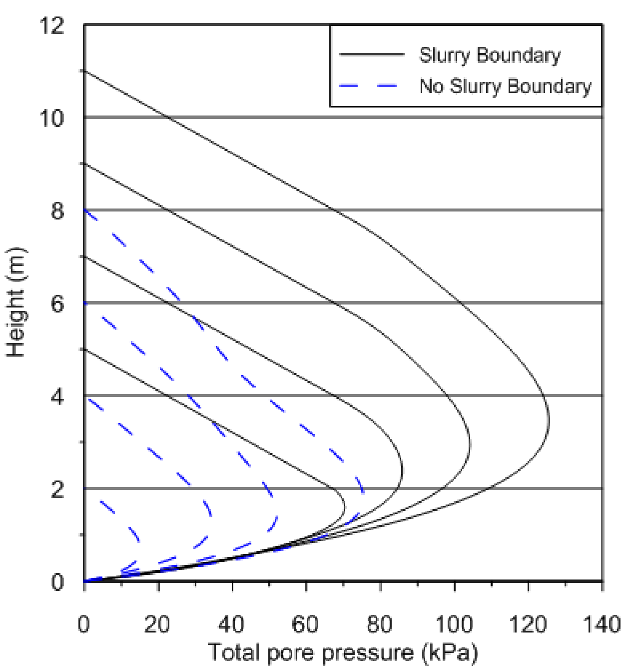

Figure 8. Total pore pressure distribution with depth at the end of backfilling with 1.5m slurry on top

Another difference between the new analysis with the slurry boundary and the Gibson (1958) solution is the pore water gradient direction. In the Gibson (1958) analysis, the pore pressure gradient is upward at the top, changes direction somewhere in the middle of the consolidating material and is downwards at the bottom. However, when there is a non-zero hydraulic and mechanical boundary condition on top of the consolidating material, the pore pressure gradient is always downwards. Although measurements of flow direction were not made in the fieldwork, relatively small amounts (about 1 liter/sec) of water flowing through the barricade were often observed.

In the next section the results of the numerical analysis are compared with the in-situ measurements at Cayeli Mine. The measured pore pressure variation with time at one location within the stope is compared with the pore pressure time history from the 1-D analysis results considering the slurry layer presence.

4 PREDICTIONS V.S. MEASUREMENTS

The new boundary condition and FLAC3D model is checked against the in-situ measurements. The in-situ measurements are taken from the Cayeli mine test stope 685N20 (Thompson et al., 2012). The stope dimensions are approximately 25 m x10 m in the undercut and 23 m x 11 m in the overcut. The backfilled stope height is 15.5 m. The stope was backfilled almost continuously. However, the binder content was 8.5% for the first 8 m and 6.5% for the rest of the stope. This change in the binder content was to achieve a stronger plug. The details of backfilling are mentioned in Thompson et al. (2012).

The instrumented cages were mounted at 5 location through the height. Figure 9 shows the location of the cages. As shown in Figure 9, cages 1 and 2 are in the undercut and very close to the barricade. Therefore, cages 1 and 2 are very close to the drainage boundary and hence their pore pressure readings are being affected by both the geometry and boundary condition. For this analysis, to be able to compare the results with the 1D model, cage 3 was selected. Cage 3 is located 2 m above the bottom of the stope.

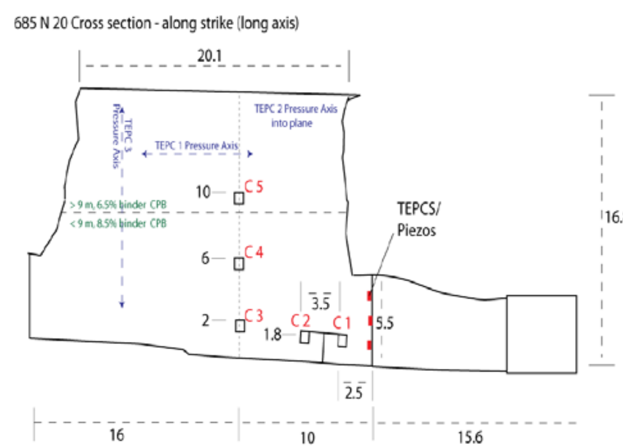

Figure 9. The 685N22 stope geometry and instrumentation cages location (Thompson et al., 2012)

The stope was backfilled with an average rate of 22 cm/hr. The same filling rate was considered in the numerical analysis. However, it must be noted due to the irregular geometry of the stope, a constant filling rate is not possible in the field. The fresh CPB bulk modulus was about 22 kN/m^3. The permeability coefficient was assumed to be 1e-7 m/s based on Veenstra (2013) measurements. Other material properties including the shear and bulk moduli were assumed to be the same as the ones mentioned in Table 1. As previously mentioned, the effect of hydration was ignored and pore pressure variations were solely related to drainage. The FLAC3D model consisted of 26 layers each consolidated for an hour. The slurry layer height was 2.8 m which means for an 8 m plug, only 5.2 m had enough drainage to cause a change in pore water pressure. The 2.8 m slurry height was obtained from the data reported by Thompson et al. (2012) in the same way as mentioned in section 2. The 2.8 m slurry layer height was consistent between cages 2 to 4. The total height was discretized into 104 zones.

The assumption of one dimensionality may not be suitable to this stope due to its geometry. However, 1D analysis is faster than a 3D analysis and it might have sufficient accuracy for this comparison. It took 1.8 days to backfill the plug and since the analysis presented here is relevant to the plug, only the first 1.8 days of the backfilling are analyzed and the results are compared with the in-situ measurements.

Figure 10 shows the pore pressure variation with time at the location of the C3 cage from both the in-situ measurements and FLAC3D analysis. As shown in Figure 10, the pore pressure follows the hydrostatic pressure for up to 14 hrs. After 14 hrs, the pore pressure keeps increasing until it reaches to a value of about 82 kPa. After this point, the in-situ pore pressure starts to decrease, while the in the numerical model, the pore pressure still tends to increase with time but at a lower rate.

In the numerical simulation it was assumed the 2.8 m plug was already on top of the cage location when the consolidation and hence water drainage began. Therefore, there is a difference between the real backfilling time and the one used in FLAC3D model. This time lag can also be attributed to the fact that the pouring rate is not constant in the field and due to the irregular geometry of the stope the filling rate changes. Therefore, CPB might hit the transducers sooner or later compared to the numerical analysis.

It is evident from Figure 10 that the numerical simulation is capable of predicting the maximum pore pressure at a certain location. However, since the effect of hydration is ignored in the simulation, the decrease in the pore pressure cannot be since until after the cessation of the backfilling. However, in the field, the pore pressure reduces due to self-desiccation even though the backfilling is still going on. On the other hand, the in-situ pore pressure reduction can also be attributed to the drainage through the surrounding rock. Therefore, a 1D analysis might not be sufficient.

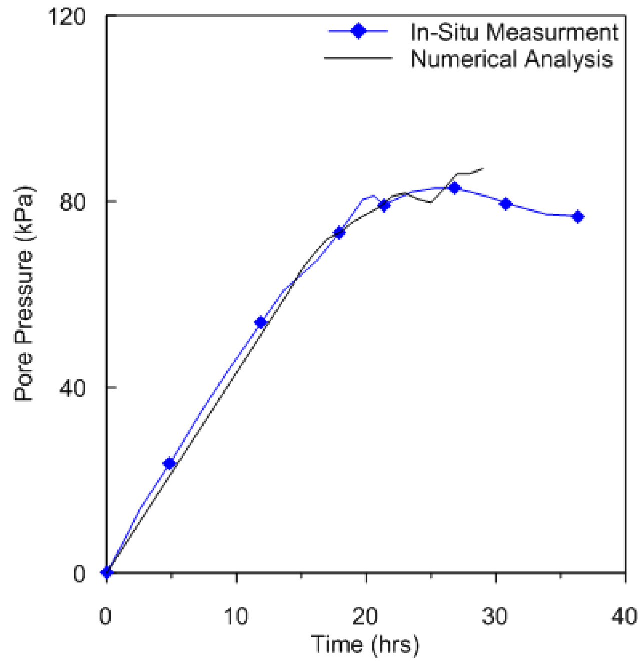

Figure 10. Predicted and measured pore pressure variations with time at cage 3

5 CONCLUDING REMARKS

The problem of consolidation of cemented paste backfill under its own weight was studied. FLAC3D was used to perform numerical analysis. It was shown that based on the in-situ measurements there is a layer of CPB that stays in the slurry state for some time and does not consolidate. This slurry layer imposes a non-zero pore pressure on the top boundary of the consolidating layer. It was shown that this non-zero pore pressure can have a huge impact on both the location and the magnitude of the maximum pore pressure within the stope during and after backfilling. The slurry layer not only imposes a hydraulic boundary condition but it also applies a stress boundary condition due its weight. It was shown that neglecting the mechanical boundary condition might happen if one follows Terzaghi’s non-coupled consolidation analysis. The effect of the mechanical boundary condition was also studied and it was shown that the consideration of the mechanical boundary condition can have a huge impact on the maximum pore pressure depending on the magnitude of the stresses due to the slurry layer.

The predicted and in-situ pore pressures at one location in a test stope were compared. The prediction was matched well with the in-situ measurements up to a certain point and the same maximum pore pressure was predicted. However, there is a time difference between the numerical model and the in-situ measurements for the end of plug fill. This time difference can be related to the fact that in the numerical model it was assumed that the slurry layer is already present and its pour time was not considered. Also, due to the stope geometry and factors related to pumping the filling rate is not constant in the field and the CPB would hit the transducers sooner or later in the field compared to the numerical model.

All the presented analysis ignored the effect of hydration and self-desiccation on the pore pressure variations in CPB. To be able to fully predict the in-situ pore pressures a numerical analysis which considers the effect of hydration must be performed. In addition, 3D analysis with the surrounding rock permeability consideration will also be necessary.

ACKNOWLEDGEMENT

The first author is a recipient of an Itasca Education Partnership which provides training for, and use of Itasca codes including FLAC3D. The support of Jim Hazzard in Itasca's Toronto Office is gratefully acknowledged. Authors very much appreciate the help of Marie-Helene Fillion in translating the abstract. Funding for this work has been provided by Barrick Gold Corporation as part of a larger investigation into the behaviour of high performance paste backfill.

6 REFERENCES

Biot, M.A. 1941, General Theory of Three-Dimensional Consolidation, *Journal of Applied Physics,* 12(2): 155-164

Doherty, J.P., 2015, A numerical study into factors affecting stress and pore pressure in free drainage mine stopes, *Computer and Geotechnics*, 63: 331-341

El Mkadmi, N., Aubertin, M., and Li, L. 2014, Effect of drainage and sequential filling on the behaviour of backfill in mine stope, *Canadian Geotechnical Journal*, 51(1):1-15

Fahey, M., Helinski, M. and Fourie, A. 2010.Consolidation in accreting sediments: Gibson's solution applied to backfilling of mine stopes. Géotechnique 60(11): 877-882

Gibson, R.E. 1958. The progress of consolidation in a clay layer increasing in thickness with time. Géotechnique 8(4): 171-183

Grabinsky, M.W., Bawden, W.F., Simon, D., Thompson, B.D. and Veenstra, R.L. 2013. In situ Properties of Cemented Paste Backfill from Three Mines, *Proceedings of the 66th Canadian Geotechnical Conference*, Montreal, Quebec, Canada

Grabinsky, M.W., Simon, D., Thompson B.D., Bawden, W.F. and Veenstra, R.L. 2014, Interpretation of as-placed cemented paste backfill properties from three mines, *Proceedings of the 11th International Symposium on Mining with Backfill,* Australian Centre for Geomechanics, Perth, Australia

Helinski, M. 2008. *The Mechanics of Mine Backfill*, Ph.D. Thesis University of Western Australia

Li, L. and Aubertin, M. 2009, The Influence of Water Pressure on the Stress State in Stopes with Cohessionless Backfill, *Geotechnical and Geological Engineering*, 27(1): 1-11

Revell, M.B and D.P. Sainsbury. 2007, Paste Bulkehead Failures, *Proceedings of the 9th International Symposium on Mining with Backfill*, Montreal, Quebec, Canada.

Shahsavari, M. and Grabinsky, M.W. 2014, Cemented paste backfill consolidation with deposition-dependent boundary conditions, *Proceedings of 67th Canadian Geotechnical Conference,* Regina, Saskatchewan, Canada

Sivakugan, N. 2008, Drainage issues and stress developments within hydraulic fill mine stopes*. Australian J. of Civil Eng*. 5(1): 61-70

Terzaghi, K. 1943. *Theoretical Soil Mechanics*, John Wiley and Sons, New York, NY, USA

Thompson, B.D., Bawden, W.F. and Grabinsky, M.W., 2012. In-situ Measurements of Cemented Paste Backfill at the Cayeli Mine, *Canadian Geotechnical Journal*, 49(7):755-772 (available for free download at www.nrcresearchpress.com/doi/abs/10.1139/t2012-040)

Veenstra, RL 2013, *A design procedure for determining the in situ stresses of early age cemented paste backfill*, PhD thesis, University of Toronto