Matching stope scale numerical modelling results of early age cemented paste backfill to In-Situ instrumentation results

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2011 Pan-Am CGS Geotechnical Conference

ABSTRACT
This paper presents a 2D modelling study of a cemented paste backfill in an underground stope. A sensitivity study was undertaken to identify how the model behaved as different input parameters were changed over time. The paper chronicles the adjustments that were made to the input parameters in order to match situ pressure measurements from 1 set of instruments in the stope. The input parameters from the 2D model that best matched the measured results were then used in a 3D model. These model results were then compared to the other stope instrumentation results to check how useful the parameter modification was.

RÉSUMÉ
Ce document présente un 2D exercice de modélisation sur une pâte cimentée remblayent dans un gradin souterrain. Une étude de sensibilité a été entreprise pour identifier comment le modèle comporté en tant que différents paramètres d'entrée ont été changés avec le temps. Le papier fait la chronique des ajustements qui ont été faits au entrer des paramètres afin d'assortir des mesures de pression de situ de 1 ensemble d'instruments dans le gradin. Les paramètres d'entrée du 2D modèle que le meilleur a assorti les résultats mesurés ont été alors employés dans un modèle 3D. Ces résultats modèles ont été alors comparés aux autres résultats d'instrumentation de gradin pour vérifier combien utile la modification de paramètre était.

1 INTRODUCTION

Cemented paste backfill (CPB) is a popular backfilling method for underground mining operations due to its delivery speed and versatility, and engineered strength. It also decreases the area needed for and the degree of risk associated with surface disposal. However understanding of how CPB behaves in an underground opening, particularly during the early curing ages is limited. This lack of understanding poses several problems for mining engineers including how to optimize the design of backfill barricades and backfilling procedures. For instance, most mines use a two staged pour which is divided into a plug pour and a final pour. There is a delay in-between the two pours, usually 3 to 7 days, to allow the paste in the plug to harden and gain strength. This delay and subsequent paste strengthening is used to protect the backfill barricade when the rest of the stope is filled. There is a significant potential for cost savings if stope cycle times can be reduced or continuous pour procedures can be adopted. Increased understanding of CPB behaviour would also decrease the uncertainty associated with the barricade fences themselves, allowing for better and cheaper fence designs. However, these cost savings cannot be realized unless there is a reasonable and reliable method for determining what stresses the backfill barricade will experience. These stresses are dictated by a range of parameters including: binder content, binder type, tailings type, additional aggregates, filling rate, stope geometry, etc.

Numerical and analytical models have provided a starting point for investigating in-situ pressures within the stope and at the backfill barricade. However, there is a lack of in-situ pressure measurements to test the validity of these models. The University of Toronto has established a large field project which involves the instrumentation of several test stopes at three mine sites: Barrick Gold Corporation's Williams Mine, Inmet Mining Corporation's Cayeli Bakir Mine, and Xstrata Copper Canada's Kidd Mine. This paper presents a numerical modelling study of the 2010 test stope at the Williams Mine (Thompson et al, 2011).

The modelling was conducted using Itasca's Flac3D modelling software and attempts to incorporate the stope filling rate , the time-dependent strength behaviour of the paste, and the actual 3D stope geometry (Itasca, 2009). The model attempts to match the actual filling strategy used to fill the stope and compares these results with the readings from the in-situ instrumentation. This paper presents a sensitivity analysis on these parameters in an attempt to match the modelling results with the in-situ instrumentation results. The majority of the sensitivity analysis modelling was carried out on a 2D model. However, the parameters for the best matching 2D model were used in a 3D model.

2 MODELLING APPROACH

The current modelling approach is based on representing the paste as a series of layers which are sequentially added to the model. These layers mimic the continuous loading that the paste in the stope would experience. The modelled CPB is placed into and contained by a rock 'mould'. Each layer is assigned an initial age when it is created and is aged as each additional layer is added to the model. This aging process means that the bottom layer is oldest while the uppermost layer is the youngest. Each age has particular input parameters assigned to it. As the layer ages, the material parameters of that layer change so that the time-dependent behaviour of the paste can be mimicked. In order to determine the time-dependant input parameters for the modelling, a laboratory testing program of the CPB was undertaken and is described in the next section. The model was built using a Mohr-Coulomb failure criterion. For a more detailed explanation please refer to Veenstra. et al, 2011.

3 LABORATORY TESTING

In order to determine the time-dependant behaviour of the CPB, a laboratory testing program was carried out. This program consisted of direct shear box testing of different ages of CPB. There were 6 main testing ages: 4, 12, 24, 48, 96, and 168 hours (1 week). The testing was conducted at 4 normal stresses: 50, 100, 250, and 400 kPa. This value was chosen as an upper value as it was at the higher range of observed stresses recorded by the instrumentation installed in test stopes (Thompson et al 2010). A total of 75 samples for this particular type of Williams CPB were tested.

Each test had a consolidation and shearing component. The sample was subjected to incremental normal loading. Before the next incremental load was applied, the sample was allowed to consolidate. After the sample had been loaded to the desired normal stress the sample was sheared.

All of the shear box results were analysed to determine both peak and residual values for cohesion and friction angle. Figure 1 is a graph showing how the cohesion changes with curing time while Figure 2 shows how the friction angle changes with time. These plots show how the parameters were changed to simplify the modelling but with keeping the original trends of the laboratory results intact.

The tested paste has no or very low cohesion when it is fresh. The cohesion then increases steadily for the first 96 hours of curing, after which the rate of cohesion gain plateaus at around 33 kPa. However, the friction angle of the tested paste shows remarkable little change with curing time, with the friction angle values varying from 35 to 41 over 168 hours. These curves were smoothed and then were used as input parameters in the model.

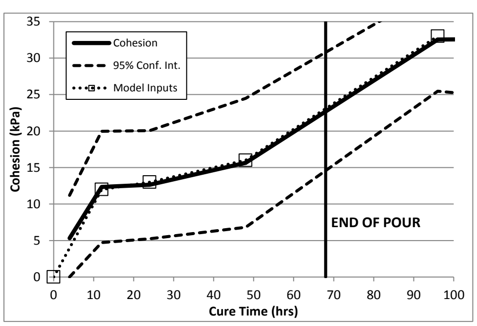


Figure 1. Cohesion versus Cure Time

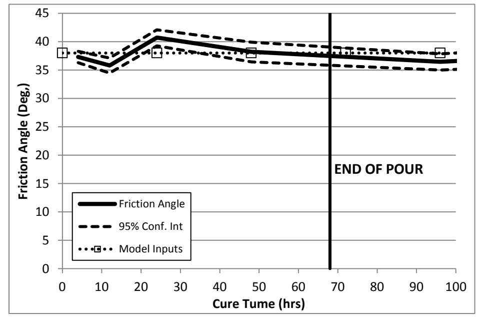


Figure 2. Friction Angle versus Cure Time

4 MODELLING SPECIFICS FOR WILLIAMS 2010 TEST STOPE

Figure 3a shows a 3D cavity monitoring survey (CMS) taken of the Williams 2010 test stope. Figure 3b shows the 2D model geometry, and Figure 3c shows the 3D model geometry of the Flac3D model. Note that some of the dimensions were changed to be divisible by 0.2 m, which was the model zone size. All of the following dimensions are for the model geometry and not the actual stope geometry. Please note that the dimensions shown in Figure 3b and 3c are for the paste contained within the rock mould and not for the rock mould that is shown in the figure. The 3D stope model was 6 m wide and was 18.8 m along strike length, while the body of the stope was approximately 50 m high and dipped at 65 degrees. The access drift was approximately 4.6 m high by 4.4 m wide, with the barricade being 9.2 m from the stope brow and located in the approximate centre of the stope strike length. It should be noted that this stope was a hanging wall access stope. The 2D model cuts a section through the body of the stope looking along the strike length. The total pour time was approximately 68 hours. The model was constructed with 0.2 m zones. This size was a compromise between the filling rate and the amount of zones within the model. This meant that the model was run at 2 hour increments.

There were three sets of instruments installed in the stope. Two sets were centred around cages, while the third set was installed on the barricade fence. Figure 4a shows an instrumented cage: there are 3 orthogonally arranged total earth pressure cells (TEPCs) and a piezometer (PZ) in each cage. Figure 4b shows an example of the instrument panel that was installed on the fence and contains 1 TEPC and one PZ. Two such panels were installed along the centreline of the fence. Figure 4c shows the two instrumented cages installed into the stope. Note that one of the cages is in the approximate centre of the stope body while the other cage is located into the drift. Figure 5 is a schematic detailing the locations of the instruments within the stope. Note that for the 2D modelling only the results from Cage 2 were used for matching purposes, with the horizontal stress direction being perpendicular to the strike length (X-Direction in the models)

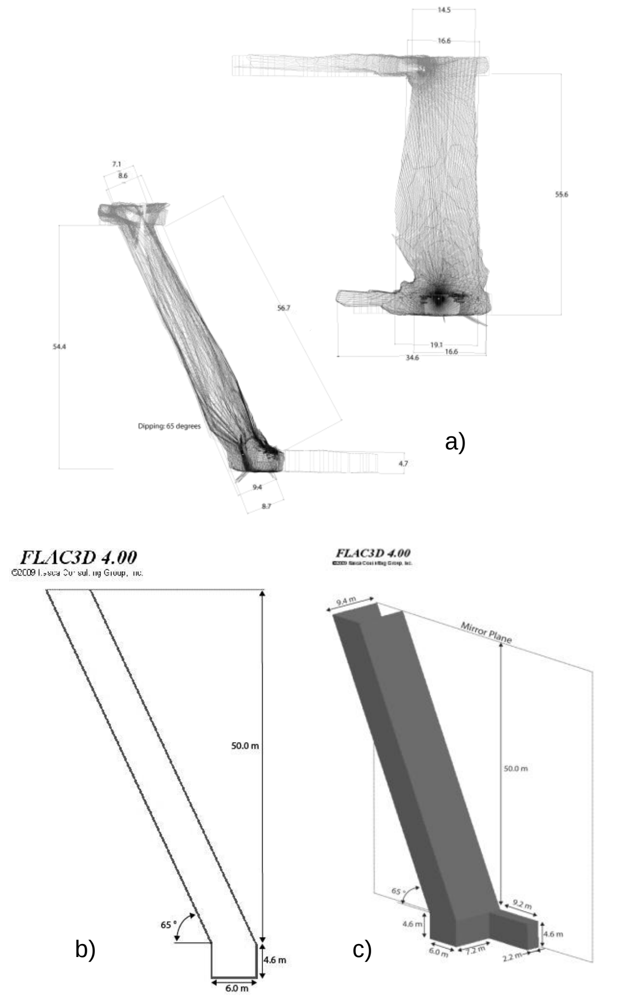
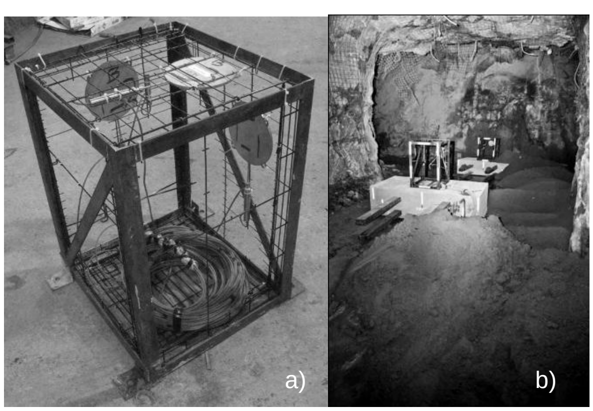


Figure 3.a) Stope CMS (from Thompson et al 2010) b) 2D Model Geometry c) 3D Model Geometry



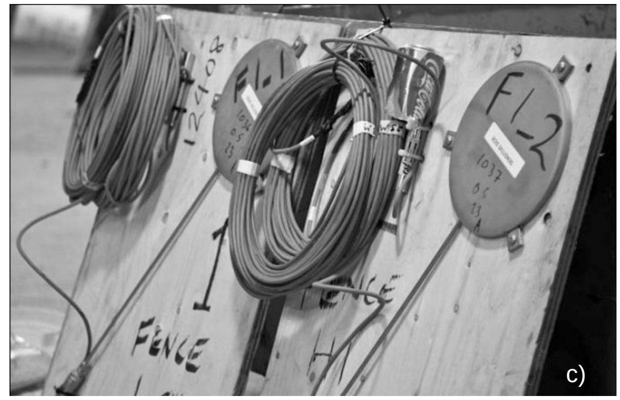


Figure 4.a) Instrumented cage (from Thompson et al, 2010), b) Installed Instrument Cages, c) Fence Instrumentation

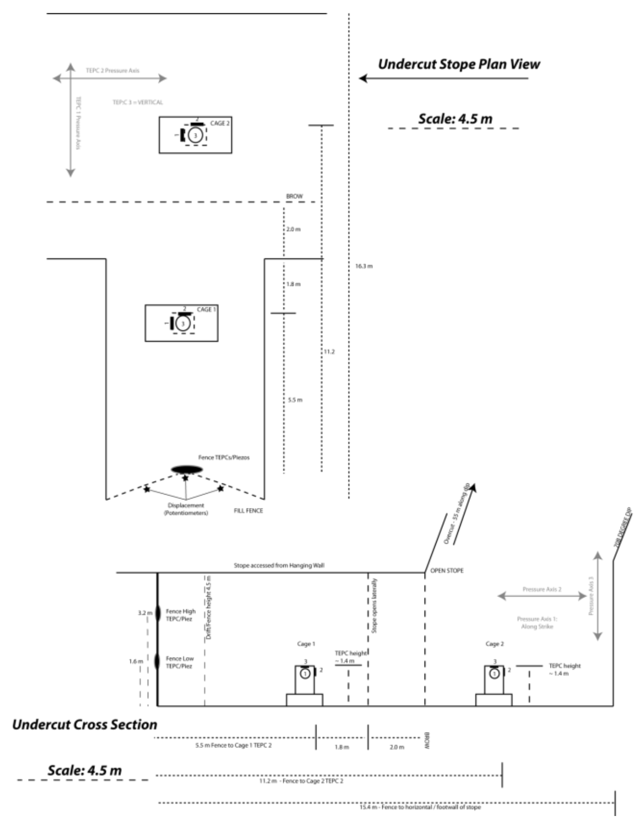


Figure 5. Schematic of Instrument Installation

5 MODELLING SPECIFICS FOR WILLIAMS 2010 TEST STOPE

This section presents the modelling results generated from the baseline input parameters. Figures 2a and b show how the baseline input parameters change over time. Figure 6 shows the results from the baseline model, with part a) showing the modelled and measured vertical and horizontal stresses versus time. Figure 6b presents the same data but concentrates on the first 30 hours of the pour. Figure 6c compares the ratio of horizontal to vertical stress for both the modelled and measured results. The three graph setup will be used for presenting the 2D modelling results in the remainder of this paper. Figures 6a and b both have a hydrostatic stress line representing the vertical stress. This was determined by multiplying the height of the paste by the unit weight of the material.

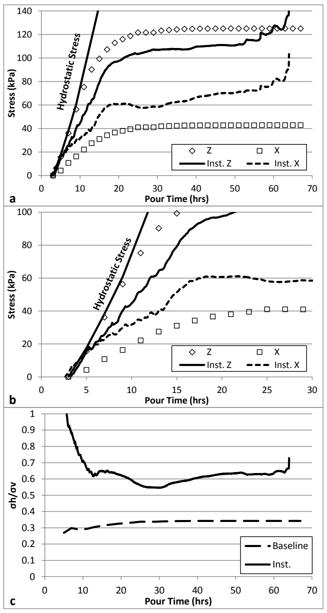


Figure 6. Baseline Model a) Modelled Stresses b) Closeup of 'a' c) Horizontal to Vertical Stress Ratio

Figure 6b highlights two differences between the instrumentation and modelled results. The first difference is that the modelled vertical stress rises more rapidly than the measured vertical stress. Explanations for this include a difference in filling rate or density; however this discrepancy will not be examined further in this paper. The second difference is that the measured data tracks together for the first 2 to 4 hours and then starts to separate. Please note that the time axis is pour time and not cure time. However, the modelled data separates right from the beginning and never tracks. The observed tracking indicates that the vertical and the horizontal stress are equal or hydrostatic. This also indicates that, during this early age of curing, the CPB has very little shear strength. The Mohr-Coulomb shear stress equation is given below:

$$\tau = c + (\sigma_n - \mu)\tan\varphi \qquad [1]$$

where τ is shear stress, c is cohesion, σ_n is the applied normal stress, μ is the pore water pressure (PWP), and φ is the friction angle. If the PWP is equal to the normal stress, the frictional component of the equation is zero whereas, if the PWP is zero, the frictional component is at a maximum value.

In the case of the laboratory testing presented in Section 3, the tests were run allowing free drainage and were allowed to consolidate before the sample was sheared. This means that the testing was carried out with greatly reduced PWP meaning that frictional component of the above equation would be some value above zero. However, it is unlikely that the in-stope CPB would drain as quickly as the test sample. This means that the in-stope CPB, at least during early curing ages, is either undrained or partially drained, thus the frictional term will vary from zero in early age paste to some value in older paste.

In this paper the approach for modelling this behaviour was to change the friction angle instead of incorporating PWP pressure into the model. This would still cause the frictional component to increase from 0 in the early age paste to the laboratory friction values of older paste. A sensitivity analysis for friction angle is presented in the next section (6). Cohesion, according to the equation, should not be affected by PWP. However, it is important to know what effect cohesion has on the model. Therefore, a sensitivity analysis for cohesion is presented in Section 7.

6 SENSITIVITY ANALYSIS OF FRICTION ANGLE

Six different scenarios for frictional change were examined and are summarized in Figures 7a-e. The first (a) assumes constant friction at 0°, 20°, 40°, and 60° of friction. The second (b) assumes a constant increase of friction from 0° to 20° over the first 96 hours of curing time, with the same scenario repeated for 40° and 60°. The third (c) assumes that there is no frictional increase over the first 4 hours of curing and then repeats the pattern over the remaining 96 hours. A delay of 4 hours was used as this was the maximum length of time, observed in Figure 6b, where the measured vertical and horizontal stresses were hydrostatic. The fourth (d) scenario assumes no frictional increase over the first 4 hours, with increases then taking place over the next 6 hours, followed by constant friction values. The final scenario (e) assumes no frictional increase for 4 hours, followed by an instantaneous frictional increase, followed by constant friction values for the remainder of the 96 hours.

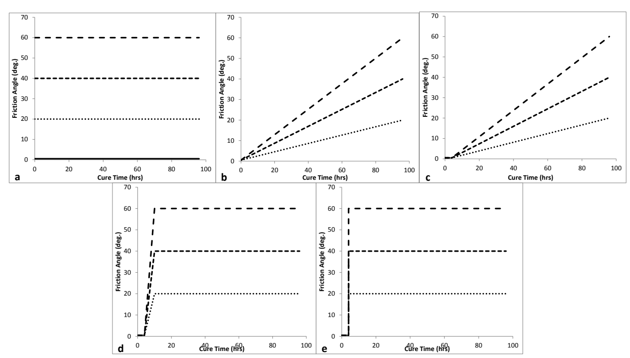


Figure 7.a) Constant Friction b) Ramped Friction c) Delayed Ramped Friction d) Delayed Steeply Ramped Friction e) Delayed Instantaneous Friction

Figures 8a-b show the results of the scenarios presented in figure 7a. This figure shows that the friction has a large impact on the shape of the curves, which is observed in the difference between the 0° friction and 20° friction curves. However there is less impact at higher friction angles as observed by the limited differences between the 40° and 60° friction curves. Please note that the modelled horizontal and vertical stresses in the 0° friction curves track. This is seen in the Figure 7c).

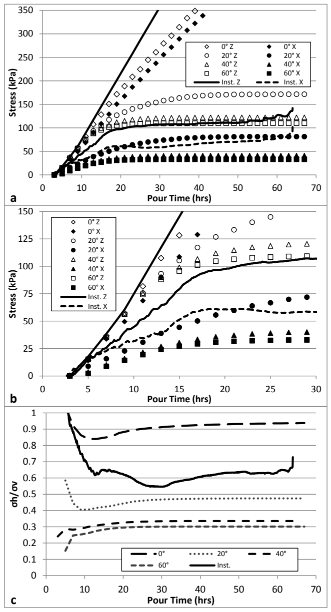


Figure 8. Modelling Results from Figure 7a) Parameters

Figures 9a-b show the results of the scenarios presented in figure 7b. This figure shows the impact that frictional variation has on the model. The first effect is the stresses are much higher than in Figure 8. However, the vertical and horizontal stresses are tracking as is shown in c).

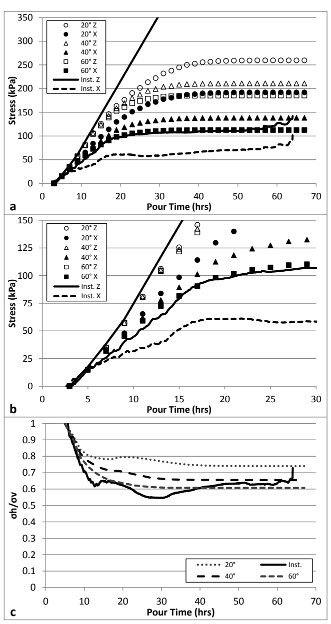


Figure 9. Modelling Results from Figure 7b) Parameters

Figures 10a-b show the results of the scenarios presented in figure 7c. This scenario was designed to see how delaying the onset of friction would change the stresses. The modelled stresses are higher than what was seen in Figure 9. However, the ratios observed in 10c) are similar to in 9c).

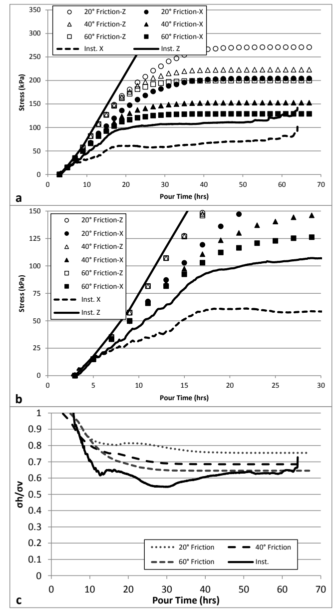


Figure 10. Modelling Results from Figure 7c) Parameters

The previous figures (8, 9, and 10) all show stresses that are much higher than the measured stresses. The next scenario was designed to examine how an instantaneous increase in frictional strength would decrease the stresses in the CPB. Figures 11a-b show the results of the scenarios presented in Figure 7d. This scenario has significantly dropped the CPB stresses though they are still too high when compared to the measured values. However the horizontal to vertical stress ratio in 11c) is a good match to the measured stress ratio

However, the stresses observed in Figure 11 are still high so the next scenario incorporated an instantaneous gain of friction. Figures 12a-b show the results of the scenario presented in Figure 7e. The use of instantaneous friction successfully lowers the modelled stresses by 20 kPa and is much closer to the measured values. This is particularly true of the 40° friction curve, which is the close to the laboratory friction value of 38°. However, the difference in the behaviour between the 20° and the other friction angle curves was unexpected.

There are some relationships observed in the modelled data. The first is that friction has a large impact on the behaviour of the modelled paste, particularly at lower friction angles. The second is how fast the model requires the friction angle to rise from zero to the laboratory values. This indicates, using the process described in Section 5, the PWP in the in-stope CPB dissipates relatively quickly.

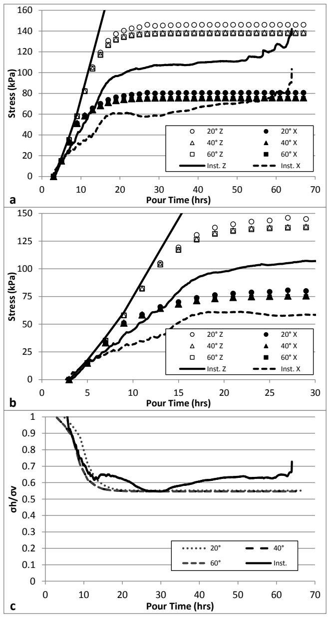


Figure 11. Modelling Results from Figure 7d) Parameters

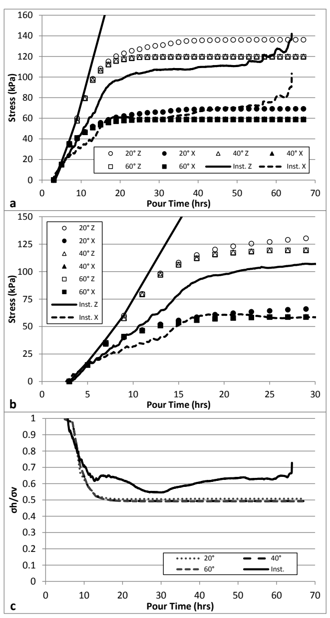


Figure 12. Modelling Results from Figure 7e) Parameters

7 SENSITIVITY ANALYSIS OF COHESION

The two scenarios were used to examine cohesion are summarized in Figures 13a and b. Both scenarios assume the frictional properties of the 40° line in Figure 7e. The first scenario assumes constant cohesion over the first 96 hours of curing at 0 kPa, 17 kPa, 35 kPa, and 70 kPa. The second scenario assumes an increase in cohesion from 0 kPa to the values mentioned above, over the first 96 hours of curing.

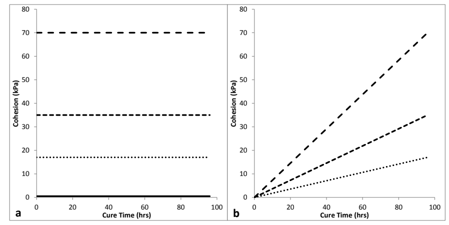


Figure 13. a) Continuous and b) Ramped Cohesion

Figures 14a-c show the modelling results based on the scenario shown in Figure 13a). The main trend in this figure is that changing the cohesion, except for the change from 0 kPa to 17 kPa, has little impact on the overall strength of the paste. However, when this figure is compared to the 40° line of Figure 12a, the main difference is the observed stress increases due to the instantaneous cohesion at the start of curing. However, this instantaneous cohesion has a negative impact on the horizontal to vertical stress ratio. The next scenario (13b) examines the influence of this early cohesion and the modelling results are shown in Figures 15a-c.

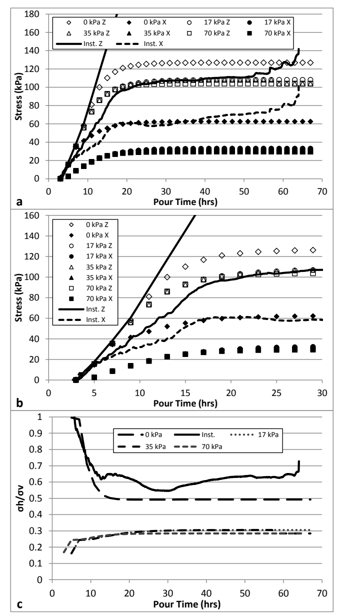


Figure 14. Modelling Results from Figure 13a) Parameters

There is very little difference between Figure 15 and Figure 12. This implies that the ramping up of cohesion, as exhibited in the laboratory testing in Figure 2, has very little impact on the strength of this CPB. These results indicate that cohesion has minimal effect on the strength of the paste, and only if it is applied early during curing. It seems that the behaviour of the paste is driven mainly by friction angle.

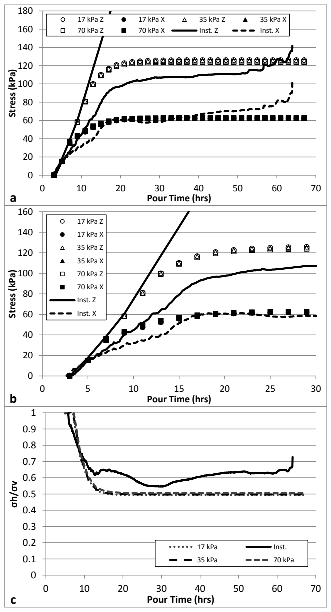
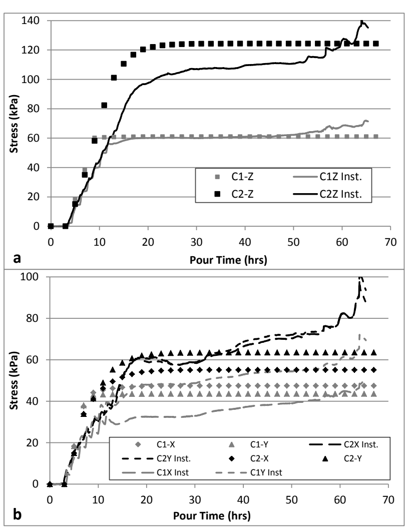


Figure 15. Modelling Results from Figure 13b) Parameters

8 3D RESULTS BASED ON INPUTS FROM 2D MODELLING

The 3D model was run using the same parameters that were used in the cohesion sensitivity analysis. This is a partial check on the 2D results. The 2D model could only be compared to one of the instrumented cages so running the 3D model will check the modelling results against the other instrumentation. The results are shown in Figures 16a-d. These results show that 3D modelling results agree well with the measured data, and are much closer than the original iteration of the model presented in Veenstra et al, 2011. The modelled and measured horizontal stresses match more closely; in particular, the difference between the measured and modelled fence pressures has been reduced.



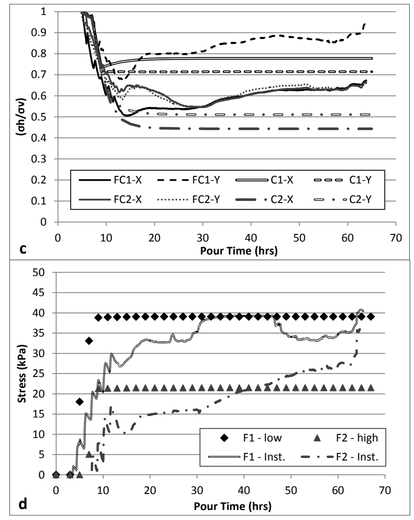


Figure 16. 3D Model using the Parameters from the Best Matched 2D Model a) Vertical Stresses b) Horizontal Stresses c) Horizontal to Vertical Stress Ratio d) Fence Pressures

9 SUMMARY

This paper presents the modelling results of a sensitivity analysis performed on CPB laboratory testing results. The goal was to match the modelling data to the measured field data from in-situ instrumentation in the stope. In order to do this the frictional component of the Mohr-Coulomb equation [1] was examined. In order to match the hydrostatic stress tracking measured by the instrumentation it was necessary to decrease this frictional component. The rationale behind this was the idea that the CPB is either undrained or partially undrained during early curing ages. This means that the PWP was equal or only slightly less than applied normal stresses resulting in a decreased frictional component of the equation [1].

The frictional sensitivity study found that the modelled CPB is very dependent on the friction angle. It also found that the model required a very rapid increase in friction angle in order to match the measured data. This implies that the PWP pressure in the CPB dissipates relatively quickly. The scenario where there was no frictional increase for 4 hours, followed by an instantaneous frictional increase to 40°, after which the friction angle was constant provided the closest match between the modelling and measured results. A more detailed examination of this early curing age frictional behaviour may provide a better match. Additionally, the actual rise-rate in the stope needs to be better qualified as the currently modelled rate seems faster than the actual rate.

An examination of the effects of cohesion showed that cohesion, unless applied early during the curing period, has limited effect on the strength of the CPB. It also found that increasing the amount of cohesion, as long as there was cohesion, produced minimal differences in the strength of the modelled CPB.

10 ACKNOWLEDGMENTS

Matt Pierce and David Sainsbury of Itasca Consulting, Summer Students Robin Malik and Michelle Moore, Research Associate Dragana Simon, and Brian Zurawski. of WOC.

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