Drainage behaviour of three-dimensional hydraulic fill stopes: A sensitivity analysis

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Keywords: Hydraulic fills, drainage, mine tailings, numerical modelling

ABSTRACT

Recent barricade failures in underground hydraulic fill mines in Australia and overseas, have resulted in significant economic loss and on a number of occasions, loss of lives. As a result, there is an urgent need in the mining industry for proper understanding of underground filling practices and in particular the use of hydraulic filling. Using analytical solutions developed for flow through three-dimensional hydraulic fill stopes, an EXCEL model was developed to accurately and efficiently model the drainage behaviour in three-dimensional stopes. The model simulates the complete filling and draining of the stopes and was verified using the three-dimensional finite difference program and results showed excellent agreement. This paper investigates the variation and sensitivity in drainage behaviour and pore water pressure measurements with, the fill properties of a three-dimensional hydraulic fill stope. The model studied in this paper assumes a simple drain geometry, with a square based stope and single square drain outlet located at the centre of the stope face.

1. INTRODUCTION

The extraction and processing of most mineral ores, result in the generation of large volumes of finer residue or tailings. The safe disposal of such material is of prime environmental, safety and economical concern to the management of mining operations. Backfilling provides an effective means of tailing disposal whilst also improving local and regional stability and enabling safer and more efficient mining of the surrounding areas. The need for backfilling is a major issue in Australia.

One method of obtaining ore from underground metalliferous mines is by a process known as open stoping. In a simple open-stoping mining operation, ore body is divided into approximately rectangular prisms called stopes. The solid rock within each stope is blasted and the fragments removed via drives for processing, thus leaving an empty stope or void. The extracted ore is then processed, removing the minerals from the rock and leaving a waste material known as tailings. The tailings are then mixed into a slurry and hydraulically backfilled into the excavated void to provide local and regional support for future excavation of adjacent stopes. To contain the hydraulic fill, barricades are constructed at each of the entrances to the stopes. As hydraulic fill is poured into the stope, excess water is allowed to drain freely through the fill and exit the stope through the barricades, thus reducing the build-up of pore pressure behind the barricades. The remaining water either pools on the surface as decant water, or is tied up in the interstices of the fill. A portion of the water filling the interstices would drain gradually, still leaving some residual moisture in the longer term. After dewatering and resulting consolidation in stopes underground the fill becomes capable of accepting loads and the next stope is ready to be blasted. A schematic diagram of an idealized hydraulic fill stope arrangement is shown in Figure 1.

2. NUMERICAL MODEL

2.1 General

Using analytical solutions developed for flow through three-dimensional hydraulic fill stopes, the user can accurately and efficiently model the drainage behaviour in three-dimensional stopes. The model discussed in this paper simulates the complete filling and draining of the stopes and was verified using the finite difference software FLAC^{3D} (***F***ast ***L***agrangian ***A***nalysis of ***C***ontinua in Three Dimensions) and results showed excellent agreement. This paper focuses on the variation and sensitivity in drainage behaviour and pore water pressure measurements with, the variation in fill properties of a three-dimensional hydraulic fill stope.

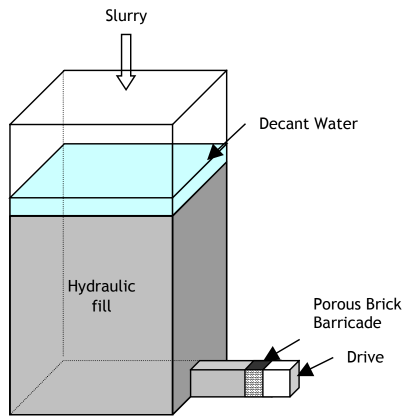


Figure 1. Diagrammatic representation hydraulic fill stope

2.2 History

Several numerical models have been developed to simulate the drainage and pore pressure developments within two and three-dimensional stopes. Isaacs and Carter (1983) developed the first drainage simulation, which provided a basic understanding of the concepts of the drainage of hydraulic fills in undergrounds stopes. Traves and Isaacs (1991) extended this model to three dimensions, but the model remains yet to be validated against field measurements. Rankine et al. (2003) developed two and three-dimensional drainage models in a finite difference program, with similar features and verified them against the predictions from Isaacs and Carter (1983) model. These simulations were often time consuming and in most cases, specialist knowledge of the corresponding software package is required. Therefore a quicker and less complicated solution is desirable.

Sivakugan and Rankine (2006) proposed a closed form solution, based on the method of fragments that can be used to determine the discharge and maximum pore water pressures within a two-dimensional stope with a single drain at the stope base. Since the deslimed hydraulic fills are granular, they consolidate quickly and the excess pore water pressure is assumed to dissipate immediately upon placement. Therefore the numerical models are solved as a flow-only problem, where the soil mass acts as an incompressible soil skeleton. Previous work with hydraulic fills also indicates that they undergo little consolidation (Clarke 1988, Potvin et al. 2005); therefore the coupling effect was ignored.

However, mine stopes are not two-dimensional, and a more adaptable three-dimensional solution was required. Using the method of fragment concepts and the finite difference software, Rankine and Sivakugan (2007) developed simple analytical solutions for estimating the maximum pore water pressure and discharge within three-dimensional hydraulic fill stopes of varying geometries.

The equations developed using the method of fragments only provide the user with quick and accurate estimates of maximum pore water pressure and discharge at specific geometries. This paper reiterates these computations during the filling and draining of hydraulic fill stopes.

2.3 Model Design and Assumptions

The following assumptions were made to simplify the model:

1- This paper only considers a square-based stope with a square drain placed at the bottom of the stope, in the centre as shown in Figure 1
2- The barricade bricks have permeability in excess of the fill by three orders of magnitude (Rankine et al. 2004), thus it was assumed the bricks did not contribute to pore pressure build-up within the fill material.
3- The fill and water levels were horizontal within the stope at each steady state time interval

4- The model was a fully saturated, flow only analysis applying Darcy's law through a homogeneous, isotropic fill material.

2.4 Model Verification
To verify the EXCEL spreadsheet, a hypothetical problem was designed based on a simple in situ stope filling and draining regime. Results from the spreadsheet were compared and validated against results obtained from the identical simulation done in the existing two and three dimensional programs. All material input parameters were identical for each of the models and is shown in Table 1.

Table 1. Input parameter for Verification Stope

Input	Value
Coefficient of permeability, k	0.0054 m/hr
Specific gravity, G_s	2.9
Dry density of fill, ρ_d	1.4 t/m^3
Residual water content, w	25 %
Percent solids of slurry placed	72 %
Steady state time step	1 hour
Solids filling rate	250 t/hr
Filling cycle	12 hrs filling, 12 hrs resting

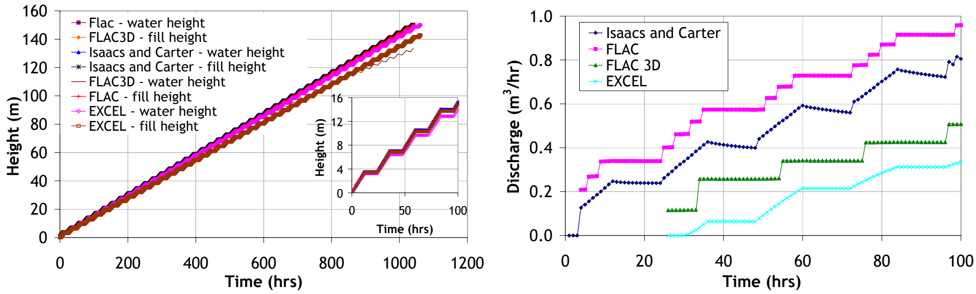
The geometry of the stope used in the verification exercise consists of a 25 m wide 25 m deep, 150 m high stope with one drain of cross-sectional dimensions 5 m x 5 m, located centrally along the base of one of the stope walls (refer to Figure 1). The two-dimensional programs (Isaacs and Carter, 1983 and Rankine et al. 2003) program is not capable of modelling drain depth and therefore, the drain was placed flush with the stope wall for this verification exercise to maintain consistency between the 2-dimensional and 3-dimensional results.

As in the 2-dimensional simulation, this verification is based on a 12-hour filling followed by 12 hours resting schedule, which is continued until the hydraulic fill reaches the height of the stope. No discharge calculations are done until the hydraulic fill height passes the height of the drain.

Figure 2 illustrates a very good comparison between the four different simulations (existing Isaacs and Carter 2D program, pseudo 2D program written in FLAC^{3D}, the 3D program with a 5m x 5m drain also written in FLAC^{3D} and the EXCEL spreadsheet). The water and fill heights during filling compare very well as shown in Figure 2a. Even when zoomed in over a 24-hour period (inset in Figure 2a) the variation in fill and water heights between the models are minimal. Figure 2b illustrates the discharge rates observed for the first 100 hours of filling. For the two-dimensional geometries, the drain is modelled as the full depth of the stope with sufficient height to give an equivalent cross-sectional area as the corresponding three-dimensional models. Thus, with the drain area located more closely to the base and stretching the full depth of the stope, it is expected (and shown in Figure 2b) that the two-dimensional simulations would produce slightly higher discharge rates tan the three-dimensional simulations. It should be noted that Figure 2b has been magnified for the initial 100 hrs of the filling cycle.

3. RESULTS

The EXCEL three-dimensional filling program has been used to investigate the effects of fill permeability, specific gravity and solids content on the drainage and maximum pore pressure of stopes. Previous laboratory testing carried out at James Cook University (Rankine et al. 2004) provided a range of values for the various parameters investigated. For each of the parameters investigated, a sample stope of 25 m x 25 m x 100 m stope dimensions, with a 5 m x 5 m drain cross-section of 5 m length was used. A filling schedule of 12 hours pour followed by 12 hours rest at 250 t/hr was assumed. Table 2 outlines an overview of the sensitivity analysis carried out in this paper.



(a) (b)

Figure 2. Verification Results between Isaacs and Carter; FLAC; FLAC^{3D} and EXCEL models (a) Fill and water height comparison (b) Discharge rate comparison

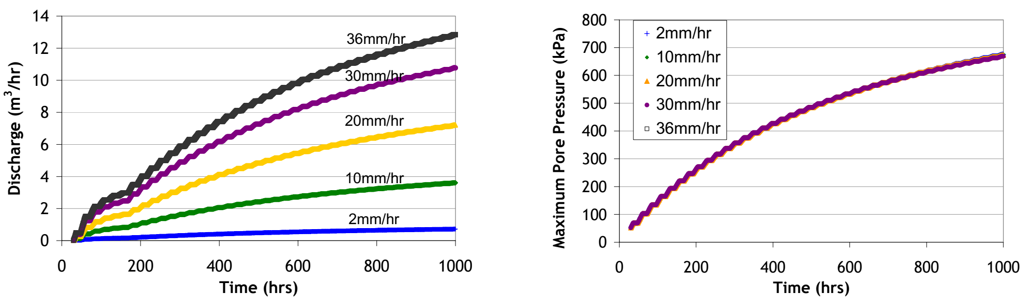
Table 2. Overview of Sensitivity analysis

Case	Parameter		
	Coefficient of permeability, k (mm/hr)	Specific gravity Gs	Percent solids of slurry placed (%)
1	2mm/hr – 36mm/hr	2.9	72
2	6	2.9 – 4.2	72
3	6	2.9	70% - 74%

Note: A dry density of 1.4t/m^3 and residual moisture content of 25% was assumed for all models

3.1 Fill Permeability

The effect of permeability values of 2 mm/hr, 10mm/hr, 20mm/hr, 30mm/hr and 36 mm/hr were investigated and results are summarised in Figure 3.



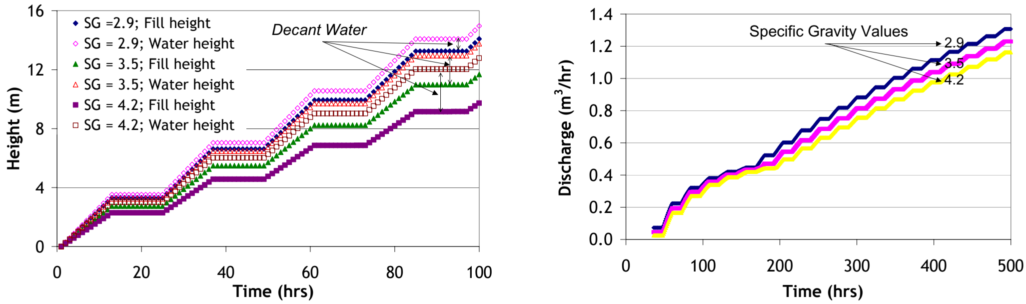
(a) (b)

Figure 3. Permeability Sensitivity Results (a) Discharge rate comparison (b) Maximum Pore Pressure comparison

The discharge over time plot (Figure 3a) illustrates a marked difference in the water discharge rate from the stope for the typical range of fill permeability values. However, the maximum pore pressure over time plot (Figure 3b) shows little variation in permeability sensitivity. Since discharge water represents only a small proportion of the water placed into the stope, the relative influence the drainage rate has on the water height may be very small, as shown in Figure 3b by the minimal variation in pore pressure measurements between the range of permeability values. Velocity is proportional to the permeability (Darcy's law), thus, it can be expected that the rate of discharge also would be proportional to the permeability. This is clearly evident in Figure 3a.

3.2 Specific Gravity

Hydraulic fill slurry is generally pumped at specific solid contents. Therefore the quantity of water entering the stope is significantly influenced by specific gravity of the fill material. As the specific gravity increases, so does the quantity of water entering the stope for a specific slurry density. Figure 4a illustrates the fill and water heights versus time for various specific gravities for the specified stope at a specific solids content. From Figure 4a we can deduce that the water heights and the drainage times during any particular filling schedule will vary significantly with various specific gravities. Also, as the specific gravity increases, so does the height of decant water within the specified stope. The maximum pore pressure is dependent on the water height in the stope, therefore during the filling; the maximum pore pressure will also be affected. Figure 4b illustrates discharge versus time for the various specific gravities. As shown in figure 4b, the discharge rates don't vary significantly between the three specific gravities.

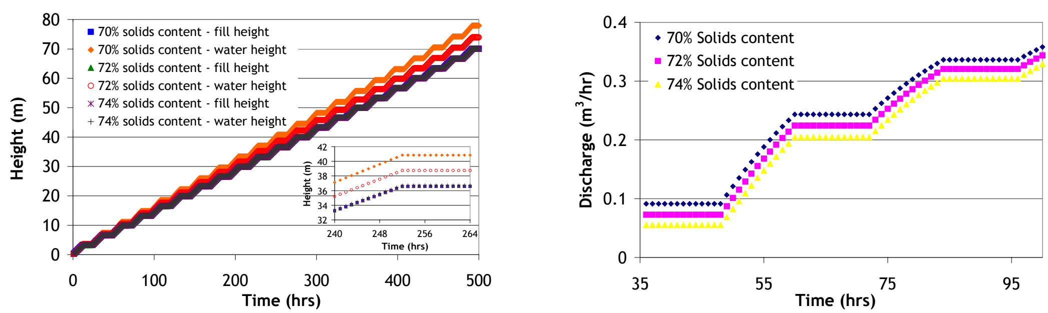


(a) (b)

Figure 4. Specific Gravity Sensitivity Results (a) Fill and Water heights (b) Discharge rate comparison

3.3 Percent Solids

For optimal economic advantage, stopes should be filled with a solids content that maximises solid waste disposal, minimises the quantity of water requiring removal, while still being sufficiently moist to meet rheological requirements. The tailings slurry is dewatered to minimise the quantity of water that will be placed underground and must drain out of the fill during and after placement. However if the slurry is pumped at too high a solids content, the mine runs the risk of additional costs and schedule delays associated with blocked pipes. Each fill material has a specific optimum solids content for which the slurry best meets the balance between maximised solids disposal and minimised water added. Thomas et al. (2005) suggests a range of slurry densities that correspond to the common range of specific gravities encountered in hydraulic fill. Using these values, this paper investigates the effect of the suggested percent solids for the specified specific gravity in this sensitivity analysis (Refer to Table 2).



(a) (b)

Figure 5. Percent Solids Content Sensitivity Results (a) Fill and Water heights (b) Discharge rate comparison

Figure 5a details the fill and water heights for the first 500 hours of filling. As the percent solids content is increased, the volume of tailings is also increased. For each of the percent solids contents investigated, the amount of tailings entering the stope remained the same (250 t/hr) however; the amount of water was decreased with increased percent solids. This results in decreased water height in the stope with increased percent solids. This is magnified in the inset in Figure 5a. Figure 5b illustrates the results for discharge versus time for the various percent solids investigated. The discharge rates between the various percent solids does not vary significantly, however when magnified it can be shown that with decreased percent solids there is a slight increase in discharge. Note that Figure 5b only illustrates results for the initial 35 – 100 hours of filling to magnify the effect of percent solids content on discharge results.

4. CONCLUSIONS

The EXCEL spreadsheet developed in this paper provides an effective means by which drainage behaviours may be analysed and the variation and sensitivity in drainage behaviour with fill properties may be easily and effectively studied. Using analytical solutions developed for flow through three-dimensional hydraulic fill stopes, the model simulates the complete filling and draining of the stopes and was verified using a three-dimensional finite difference program. The model developed in EXCEL showed that permeability has a significant influence on discharge however shows little variation in pore pressure measurements. Since the discharge water represents only a small proportion of the water placed into the stope, the relative influence the drainage has on the water height may be small, thus resulting in minimal variation in the pore pressure measurements. Also, the solids content and specific gravity of the slurry will have a significant influence on the relative fill and water heights with time, within the specified stope and minimal variation in discharge measurements. With all other parameters equal, the higher the specific gravity of the slurry, the greater the quantity of water entering the stope for a specific slurry density. Also, increasing the solids content decreases the excess water requiring removal within the stope. However, it is important that stopes be filled with a solids content that maximises the solids waste disposal, minimises the quantity of requiring removal, while still being sufficiently moist to meet rheological requirements.

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