Quantitative Validation of Scaled Modelling of Hydraulic Mine Drainage Using Numerical Modelling

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Abstract: The recent spate of catastrophic fill barricade failures around Australia and numerous mines worldwide have identified a need for an increased understanding into the factors which lead to failure of the fill in underground mining operations. Several case studies have suggested that the majority of these failures result from poor drainage and subsequent build-up of pore water pressures behind the porous brick barricades constructed across the drives to contain the fill. This paper focuses on the fundamental aspects of permeability and drainage characteristics of hydraulic fill mines. A 1:100 laboratory scaled model, mimicking a typical underground stope was constructed at James Cook University. The filling process of the mine was mechanically simulated through the use of the scale model and the discharge measured for various drain arrangements and barricade positions. The findings were verified using a three-dimensional numerical model developed in the software FLAC^{3D}, a finite difference package, specifically designed to accurately model complex geotechnical problems. The scale model has been validated against an existing and currently used two-dimensional mine drainage simulation program. The numerical model was used to study the effects of various mine drainage parameters on the discharge quantity. These include drain location on the stope, distance of the drain within the drive, and the number of drains. It is shown through this research, that the numerical model developed is an effective tool for carrying out such parametric studies in the prototype mine stopes of any geometry. The scale model has been quantitatively validated through the numerical modelling exercise.

Keywords: *Hydraulic fill; drainage; scaled modeling; numerical modelling*

1. INTRODUCTION

A common method of obtaining ore from underground metalliferous mines is through open-stoping. A simple open-stoping mining operation involves the ore body being divided into separate rectangular prisms called stopes. Stopes are approximated as rectangular prisms, but the geometry may vary slightly depending on the geometry and governing characteristics of both the ore seam and the host rock. These stopes are sequentially excavated in the nine-stope grid arrangement shown in Fig. 1. The solid rock within each stope is blasted and the fragments removed via drives for processing, thus leaving an empty stope or void.

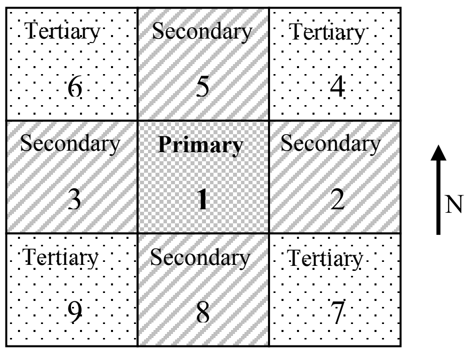

Figure 1. Plan view of an ore body showing a typical stope extraction sequence in a nine-stope grid arrangement

The extracted ore is then processed, removing the valuable minerals and leaving a waste material known as tailings. The tailings are 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 within the horiziontal access drives, at the entrances to the stopes. Permeable barricades are generally made of very porous concrete bricks, with a permeability constant comparable to that of gravels. As the 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 (refer to Fig. 2), or is tied up in the interstices of the fill.

This research uses laboratory scaled modelling and numerical modelling to provide a preliminary investigation into the fundamental drainage characteristics of hydraulic fill mines using this open-stoping mining method. Although pore pressure distribution throughout the filling and drainage of the stope is one of the governing factors in barricade design, this research considers only the drainage rates of the stope. Obviously the authors are aware the drainage characteristics directly effect the pore pressure developments, and research subsequent to this publication will encompass this.

1.1. Problem Definition

When hydraulic fill is backfilled into the voided stope, the excess water is allowed to drain freely through the highly permeable porous brick barricades (Fig. 2). To optimise mine safety and performance, it is essential to maximise the flow rate from the barricades, and hence minimise the pore pressure build-up within the stope. The main factors which influence the flow rate from the barricade include:

1- The permeability and the water/solids ratio of the hydraulic tailings at filling
2- The filling rates and rest durations adopted when backfilling the void
3- The geometry of the stope
4- The geometry and design of the drain. The drain refers to the length of drive from the entrance to stope up to and including the porous brick barricade.

The first objective of this research was to develop and verify a three-dimensional numerical modelling program capable of simulating the filling and drainage sequence of a single stope, and calculating the discharge from the barricades of various stope and drain geometries. An existing commercially used two-dimensional program was used to verify the three-dimensional program. The three-dimensional numerical model was then used to verify the results obtained from a 1:100 laboratory scaled model of a stope, which had been designed based on typical stope dimensions and constructed at James Cook University. A filling and drainage schedule which was feasible for plysical modelling, as well as representative of typical mine site schedule was adopted. These analysis tools were then used to analyse the effect of various drain location and geometries on the drainage of the stope.

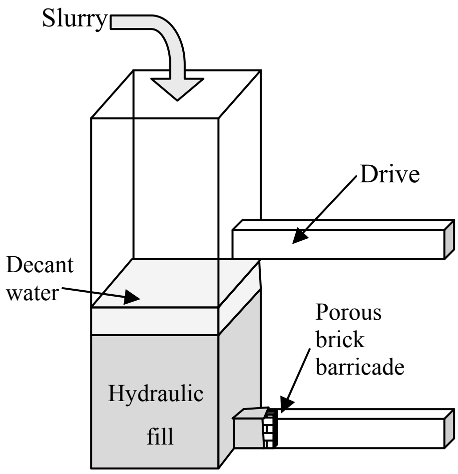

Figure 2. Diagramatic representation of the problem

2. NUMERICAL MODEL

A generic finite difference software, FLAC^{3D} was used to model the filling and drainage of a three dimensional stope of specific geometry. The program was written in FISH, a programming language specific to FLAC and FLAC^{3D}. Initially the simulation was designed to accommodate a two dimensional stope so results could be easily verified against an existing two dimensional finite element program developed in Australia in 1982 (Isaacs and Carter, 1983).

2.1. Drainage Model

The FLAC^{3D} program simulated the problem through a series of steady state seepage only calculations. This mimicked the existing two-dimensional simplification for the problem. The time component of the problem was accounted for by the adjustments to the zone properties that were made at every steady state interval. The general solution approach adopted to solve the problem is as follows:

1- The initial and boundary conditions, pour and rest durations and fill rates, tailings flow parameters and the stope and drain geometry were defined.
2- The simulation for the steady state flow-only condition at time t was solved, and the values for the discharge vectors for all grid

points located across the face of the drain were computed.
3- The gridpoint discharge vectors (q) across the face of the drain summed, and the total discharge (Q) calculated, for time interval Δt. ($Q = \sum q \Delta t$).
4- The change in tailings and water levels in the stope are calculated for the next time interval.
5- The boundary conditions and region of analysis are changed.
6- Steady state at $t = t + \Delta t$ is solved.
7- Steps (2) to (6) are repeated until the stope has been completely filled with tailings material.
8- Once filled, the simulation only requires water level calculations at step (4) to simulate the stope continuing draining over time until there is no decant.

This research does not consider the unsaturated and partially saturated flow regimes that are required for analysis when the water level falls below the height of the tailings.

2.2. Assumptions

All assumptions made for the water movement through the saturated fill, are the same as those made for the program written by Isaacs and Carter. The following assumptions were made for the simplification of the model:

1- The simulation was a flow-only analysis for a completely saturated material. The calculations applied Darcy's law which is only applicable to a homogeneous, isotropic fill material with laminar flow. The limited velocity by the flow of water through a fine grained soil such as hydraulic tailings justifies this analysis.
2- It was assumed that the porous barricade bricks are free draining and did not contribute to the pore pressure build-up within the material. Extensive laboratory testing at James Cook University showed the barricade bricks to have a permeability in excess of the fill by three orders of magnitued, thus verifying the validity of this assumption.
3- The fill and water levels were horizontal within the stope for each steady-state time interval.

The two dimensional Isaacs and Carter program, has been used commercially within the mining industry, and was verified by a comprehensive in-situ study conducted at Mount Isa Mines Limited, Cowling (1988).

2.3. Verification

Using a typical filling and drainage regime, a hypothetical problem was designed for the verification of the FLAC^{3D} program. Results from the three dimensional model were compared and validated against results obtained from the identical simulation done in the existing Isaacs and Carter two dimensional program.

Table 1, describes the geometry of the actual problem, and how the various simulations model it. All programs used identical input material properties, and filling and draining parameters. A 12 hour pour, 12 hour rest filling cycle was adopted for 190 hours of filling with a fill rate of 200 tonnes per hour placed at 70% solids to water ratio.

Initially, a pseudo two-dimensional solution was formulated in FLAC^{3D}. This simulation mimicked the simplification in geometry required to apply the problem to the two dimensional analysis.

Table 1. Geometric specifications for the drainage problem and simulations

Case	Stope Dimensions (m)	Drain Dimensions (m)
Actual Problem	*15 x 15 x 60 (H)*	*15 m^2 center of base of one stope wall*
Isaacs & Carter	15 x 60 (H)	One unit high 15 x 1 (H)
Pseudo2D (FLAC^{3D})	15 x 1 x 60 (H)	One unit high, one unit deep, 1 x 1 (H)
3D (FLAC^{3D})	15 x 15 x 60 (H)	15 m^2 center of base of one stope wall 5 x 3 (H)

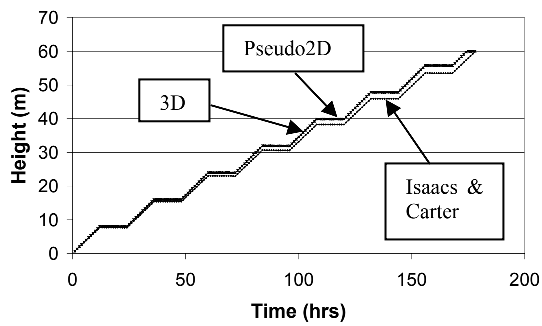

Figure 3. Water level comparison between drainage simulations

Figures 3 and 4, plot the water level and discharge comparisons respectively, between the three different simulations, for the above stope drainage problem. As shown through both the plots, the results compare very well, validating the FLAC^{3D} model.

Although there is very slight difference between the results obtained from the Pseudo2D program and the 3D program, the difference is so insignificant, that the water levels are plotted on the same curve in Fig 3. Figure 4 exaggerates the slight discrepancy in Figure 3, when plotting the quantity of water that the stope discharges per hour, based on the steady-state initial conditions. Through this exaggeration, it appears that the inconsistencies between the Isaacs and Carter program and two the FLAC^{3D} models is due to the numerical accuracy to which the tailings and water level heights are calculated at each time interval. This is seen from both the FLAC^{3D} models showing higher water levels (Fig. 3) despite having larger quantities of water discharging the stope over each hour (Fig. 4). A one meter grid spacing was found suitable from a mesh fineness sensitivity analysis.

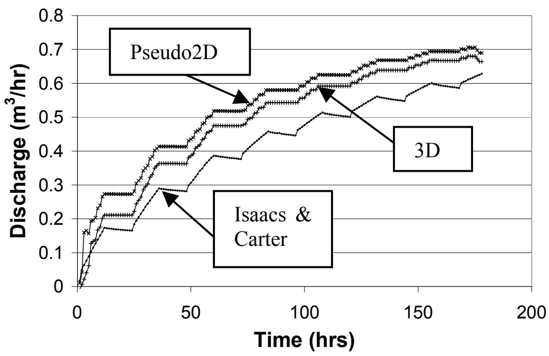

Figure 4. Discharge comparison between drainage simulations

3. MODEL STOPE

An investigation into the fundamental aspects of permeability and drainage processes in hydraulically backfilled stopes was undertaken using a laboratory scaled model. The stope was designed and constructed to represent a similar stope located at Mount Isa Mines Ltd in Central Queensland.

3.1. Scaled Model Apparatus

The scale adopted for this research was at 1:100; that is 1 cm to 1 m. The 15 cm x 15 cm x 60 cm model stope was designed and constructed to represent a scale stope 15 m wide, 15 m long and 60 m high. It was constructed of 6 mm thick perspex with the side walls and base glued together. The hollow drain outlets were also constructed of perspex and had inside dimensions of 4 cm x 4 cm x 15 cm to simulate drives of 16 m^2 cross-sectional area. Drains 1 and 2 were placed along the vertical centre line of one walls of the stope (Fig. 5). Drain 1 was positioned at the bottom centre of the stope face, whilst drain 2 was positioned 45 cm up from the base. This simulated the typical drive depth difference of 45 m. The arrangement was repeated on the opposite side of the stope using drains 3, 4, 5 and 6. Each set of drains (i.e. drains 3 & 4 or drains 5 & 6) were positioned on corners of the opposite stope face. A drop-gate was designed at each of the six drain outlets enabling complete closure, thus allowing the stope to simulate a number of standard drainage outlet arrangements having any drain either open or closed.

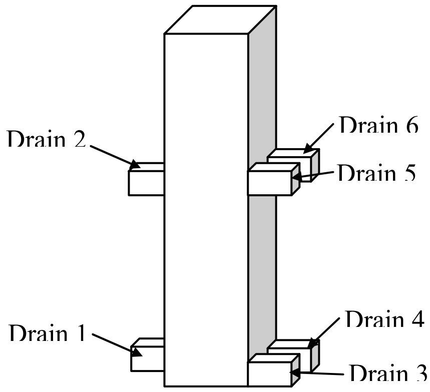

Figure 5. Diagramatic representation of the model stope construction

3.2. Scaled Model Barricade Design

In actual stopes, barricades are generally made of very porous concrete bricks which have a much larger permeability than the tailings they contain. Values of permeabilities of the barricades can be as high as that of coarse gravels. In other words, the barricade can be assumed to be free draining for all practical purposes.

A free draining barricade consisting of a 2 mm thick square hollow section (SHS), 2 mm steel mesh and geo-fabric drainmat was constructed for each of the outlets (Fig. 5). To produce a free draining barricade, it was imperative that the drainmat be completely saturated before testing commenced. If the drainmat was not completely saturated, the entrapped air gave resistance to the flow in the early stages of the drainage. The drainmat enabled water to seep through the barricade without incurring any head loss while preventing the hydraulic fill from being carried away through the pores of the drainmat.

4. DRAINAGE MODEL – INTERPRETATION OF RESULTS

This section summarises the results from the laboratory model studies, and compares them with the newly developed FLAC^{3D} numerical model. The primary objective of the research undertaken here was to investigate the effect of drain numbers, distance of drains within the drives and location on the efficiency of the drainage of excess water used for the hydraulic fill placement.

In general, the FLAC^{3D} model replicated the trends of the observed drainage, but substantially underpredicted the flow. This discrepancy is attributed to the permeability value used as the input parameter for the FLAC^{3D} model. This value was obtained through perolation tests, where the fill was in the form of a consolidated cake. However, during the sedimentation process, the fill is in the form of a slurry, therefore the permeability coefficient used within the modeling should be much higher.

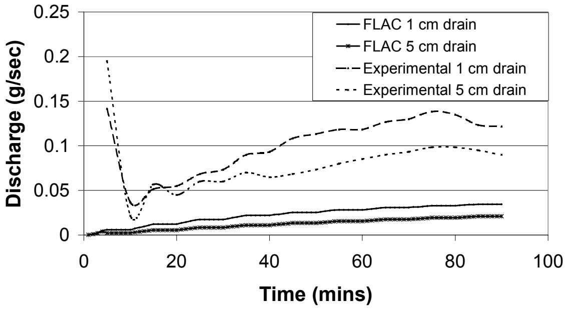

Figure 6. Discharge comparison for 1 drain FLAC^{3D} simulation and experimental results.

The large discharge rates measured experimentally during the first 10 minutes (Fig. 6) of filling were the result of the method of drain preparation. Barricades were designed to be 'free-draining' and thus it was necessary to ensure complete saturation of the barricades before testing commenced. Unless the barricades were fully saturated, they were not free-draining, and the entrapped air provided resistance to the flow.

The FLAC^{3D} predicted discharge from the stope, was approximately equal for both the one drain and two drain simulations. This is because over 99% of the water discharged for each of the cases regardless of drain length or location, exited the stope from the bottom drains. Although based on simple flow principles, the discharge from the bottom drain was predicted to be substantially higher than that from the drain located higher up the stope, the degree to which the program has predicted this to occur invites the need for more research in this area.

The trends observed for the one drain simulation (Fig. 6) from both the numerical and experimental results are also shown with the two drain simulation results in Fig. 7.

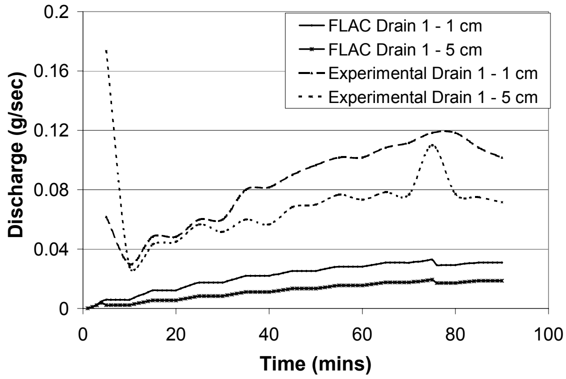

Figure 7. Discharge comparison for base drain of two drain FLAC^{3D} simulation with experimental results.

By increasing the drain length from 1 cm to 5 cm in both the one and two drain simulations, the FLAC^{3D} predicted discharge is reduced by an average of 45%. The experimental results show a 25% and 21% reduction for the one drain and two drain cases respectively.

Substantial head loss occurs within the drain compared to the stope. As a result, the hydraulic gradient decreases significantly with increased drain length and this leads to reduction in discharge.

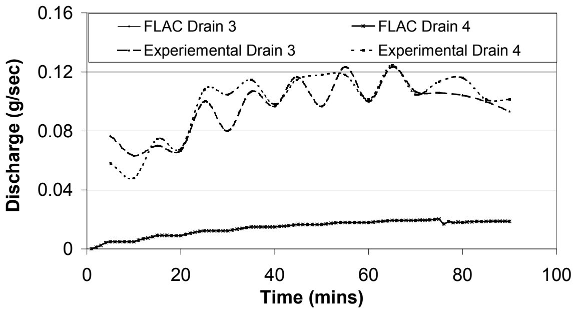

Figure 8. Discharge comparison for drains 3 and 4 of four drain FLAC^{3D} simulation with experimental results.

As expected, the predicted discharge (Fig. 8) from drains 3 and 4 (Fig. 5) using the FLAC^{3D} program were identical. There was a slight difference in the experimental values.

For the one and two drain simulations, the numerical model results showed a 35% reduction in individual drain efficiency when located at the corner of the stope as opposed to the central location used. Despite this drop in individual efficiency, there is an overall increase in predicted base drain discharge of 30% when the one central drain is substituted for two drains located at the corners (Fig. 5).

5. CONCLUSION

Both numerical and scale modelling can play a vital role in stope planning of hydraulic fill mines. The effects of drain numbers, drain location and drain length can be studied using either numerical modeling or scale modeling techniques, prior to backfilling.

The following conclusions could be developed using the application of the numerical modeling program described in this paper:

- The drain outlets at the base of the stope dictate the quantity of discharge from the stope.
- The three-dimensional analysis of drain discharge, provides a larger estimation of the quantity of outflow than that calculated applying Darcy's law to the simplified two-dimensional problem.
- Increasing the drain length reduces the discharge.
- The number and location of outlets significantly influences the discharge rate from the stope.

Although only trends were replicated by the model stope, this exercise has proven very valuable in developing the following conclusions:

- Simple percolation tests are not suitable in determining a representative input value for permeability constant. The average permeability during sedimentation is higher.
- Model stope test procedure and measurement needs to be extremely particular to obtain quantitative results.
- The model stope is very valuable in obtaining preliminary quantitative results for stope drainage characteristics.

The underground mine safety is dependent on accurate stope drainage analysis. The three-dimensional numerical simulation described in this paper, provides a valuable prediction tool for studying the drainage of excess water through hydraulic fills and barricades. By varying input parameters and model geometries, the drainage regime of a mine may be optimised and accurately predicted, ultimately leading to safer mine operation. It is suggested that the program be extended to accommodate all fill and drainage scenarios by the inclusion of partially saturated flow regimes into the numerical calculation.

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