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A 2-D numerical study of the effects of anisotropy, ancillary drainage and geometry on flow through hydraulic fill mine stopes

Une etude numérique de 2 D des effets de anisotropy, le drainage et la géométrie subordonnées sur le flux par hydraulique remplissent les arrêts de mine

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ABSTRACT
This paper utilises the two-dimensional finite difference package FLAC to investigate various factors affecting mine drainage including the effects of anisotropy, ancillary drainage and geometry on flow through hydraulic fill mine stopes. The numerical modelling carried out using FLAC shows that the horizontal ancillary drain provided at the bottom of the stope reduces the pore water pressure at all points within the fill substantially, however large the stope is, with the reduction being proportional to the length of the drain. For the case of stopes with horizontal ancillary drains at the bottom, a simple expression was developed to predict the maximum pore water pressure that always occurs at the bottom corner of the stope. The ancillary drain increases the hydraulic gradient and thus the rate of flow, resulting in quicker drainage of the stope. It was also shown that anisotropy in permeability of the fill material could also lead to a substantial reduction in pore water pressure. An increased knowledge of the factors affecting drainage will provide an increased level of confidence in design, more efficient mining procedures to be developed, and safer filling practices to be undertaken.

RÉSUMÉ
Ce papier utilise le FLAC de packet de différence fini à deux dimensions pour examiner de divers facteurs affectant le drainage de mine y compris les effets de anisotropy, le drainage et la géométrie subordonnées sur le flux par hydraulique remplissent les arrêts de mine. Le modelage numérique a exécuté utilisant les spectacles de FLAC que l'égout subordonné horizontal fourni au fond du stope réduit la pression d'eau de pore à tous points dans le remplit substantiellement, cependant grand le stope est, avec la réduction est proportionnel à la longueur de l'égout. Pour le cas d'arrêts avec les égouts subordonnés horizontaux au fond, une expression simple a été développée pour prédire la pression d'eau de pore maximum qui toujours arrive au coin inférieur du stope. L'égout subordonné augmente la pente hydraulique et ainsi le taux de flux, avoir pour résultat le drainage plus rapide du stope. Il a été aussi montré que anisotropy dans la perméabilité du remplit le matériel pourrait mener aussi à une réduction substantielle dans la pression d'eau de pore. Une connaissance augmentée des facteurs affectant le drainage fournira un niveau augmenté de confiance dans la conception, plus efficace extraire des procédures être développées, et le prac-tices de garniture plus sûr être entrepris.

1 INTRODUCTION

The disposal of mine tailings underground not only reduces the environmental impact but also provides the base of an engineering material that can be used to improve both the ground conditions and the economics of mining. Recent failures in Australia and worldwide have warned authorities of the acute need for proper understanding of underground filling practices, and, in particular, the use of hydraulic filling. Backfill refers to any waste material that is placed into voids mined underground for purposes of either disposal, or to perform some engineering function. This paper is concerned with one particular backfill material, called *hydraulic fill*, which can be defined as deslimed mine tailings, with no clay fraction and a D_{10} value in excess of 10 µm.

One method of obtaining ore from underground metalliferous mines is by a process known as open stoping. In a simple open-stoping mining operation, the 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. The application of such processes underground provides a number of advantages including: increased local and regional rock stability; improvement in ore recovery; reduced environmental impacts and an effective means of tailings disposal. This paper investigates the effect of anisotropy, ancillary drainage and geometry on flow through hydraulic fill mine stopes.

2 ANCILLARY DRAINAGE

Upon discharge into a stope, hydraulic fill generally consists of a material with a solids density of approximately 70-80% solids by weight and, because of its liquid nature, possess no shear strength. Before it can satisfactorily perform its function in the mining operation as an engineered backfill, it must go through a process of dewatering. Even at 75% solid content, assuming specific gravity of 3.00 for solid grains, 50% of the slurry volume is water. Therefore, there is a substantial amount of water that has to be drained from the hydraulic fill stope. To expedite the drainage, there have been recent attempts to use prefabricated drains in vertical, horizontal and inclined positions within the stope, thus reducing the length of the drainage paths (Kuganathan 2001, Neindorf 1983). Through the use of a two-dimensional model, developed in FLAC, this paper illustrates that the prefabricated drains are effective in accelerating the drainage process and reducing the pore water pressures within the stope. Previously, prefabricated drains have been successfully used in consolidation of clays. However, this is the first numerical modeling study that looks at the effects of prefabricated drains on drainage through hydraulically filled mine stopes, where the material is granular and the prefabricated drains are used simply to shorten the drainage paths. Although, it would be premature to regard the two-dimensional model developed here as a proven design tool, it will provide a better understanding of the effect of using ancillary drainage in effectively draining a hydraulically filled stope.

2.1 *Case Studies*

The effects of ancillary drains on the pore water pressures and discharge were studied through a two dimensional numerical model developed in FLAC. Most of the analysis runs were made on a 50 m wide stope containing hydraulic fill with a water level at 80 m height and with a 5 m x 5 m drain (Fig.1). The ancillary drain is placed horizontally at the bottom of the drain. The first few trials were run with the above stope dimensions whilst varying the length of the ancillary drain. Later, a few more runs were made for stopes with different dimensions and drain lengths, to verify the findings.

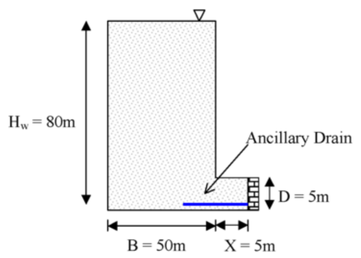

Figure 1. Geometry of Stope with Ancillary Drainage

2.2 *Numerical Model*

The numerical modelling undertaken in this research utilised FLAC, a two-dimensional, explicit finite difference computer program specifically designed for solving complex geotechnical problems. The inbuilt programming language FISH was also used to write simple subroutines for functions that were not available in FLAC. The program written for this research simulated a flow-only analysis for a two-dimensional stope of specific geometry. The input parameters required in the model were determined from extensive laboratory testing carried out on hydraulic fills at James Cook University (Rankine et al, 2004). The assumptions made during the modelling are outlined below:

Assumptions

1. The hydraulic fill mass was treated as an incompressible soil skeleton, thus the numerical runs were modelled as "flow-only" simulations. It is assumed that the permeability remains the same at all depths and the effects of consolidation are insignificant.
2. The flow rate, and thus the seepage velocity through the hydraulic fill, is very small therefore the flow can be assumed to be laminar and Darcy's law is valid
3. Permeability of the porous brick barricades are three orders of magnitude greater than that of the hydraulic fill (Rankine et al. 2004). Therefore, it is assumed that the porous brick barricades are free draining and hence the pore water pressure at the fill-barricade interface is zero. Typical flow rate is in the order of 10-30 litres/minute which is significantly less than the flow capacity of the drain.
4. Water enters at the top of the fill and exits through the drains. All other boundaries (see Fig. 1) are assumed to be impervious
5. Ancillary drain was modelled located 1 m above the bottom of the stope, to avoid interference with the impervious bottom boundary. In reality, it is placed on the ground, at the bottom of the stope.

2.3 *Interpretation of Results*

2.3.1 *Pore Water Pressure*

Sivakugan et al. (2005) showed that the maximum pore water pressure (u_{max}) within a two dimensional hydraulic fill stope occurs at the corner of the stope and proposed the following expression to estimate it, using the method of fragments.

$$u_{\max} = \left[h_L \left(\frac{\alpha\Phi_2 + \Phi_3}{\Phi_1 + \Phi_2 + \Phi_3} \right) + D \right] \gamma_w \qquad (1)$$

Here, Φ_1, Φ_2, and Φ_3 are dimensionless form factors that are functions of the geometry of the stope. D is the drain height, h_L is the head loss across the stope, γ_w is the unit weight of water, and α is a factor less than 1, which is a function of D/B. It was shown that the predictions of the maximum pore water pressures from the above equation were within 2% of the values computed through FLAC.

The FLAC runs showed that, for all analysed values of ancillary drain lengths, pore water pressure is still the maximum at the corner of the stope. For the 50 m wide stope described above (Fig. 1), the maximum pore water pressure, which occurs at the corner of the stope, decreases linearly with the drain length as illustrated in Fig 2.

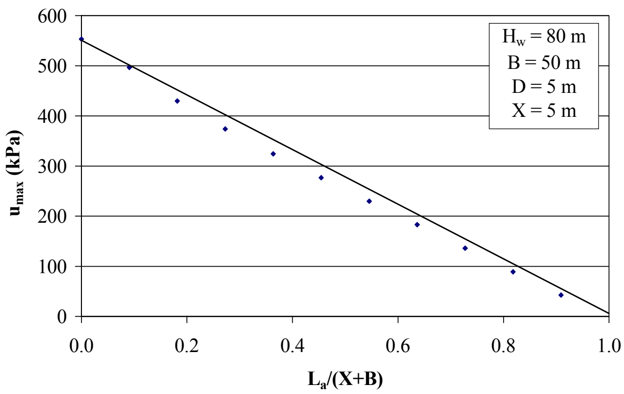

Figure 2. Effects of Ancillary Drain on Pore water Pressure Measurements

When the ancillary drain extends to the full width of the stope (i.e., L_a = X+B), the maximum pore water pressure is zero. Therefore, for a given length of ancillary drain the maximum pore water pressure can be simply interpolated, and can be expressed as:

$$u_{\max} = \left(1 - \frac{L_a}{B+X} \right) \left[h_L \left(\frac{\alpha\Phi_2 + \Phi_3}{\Phi_1 + \Phi_2 + \Phi_3} \right) + D \right] \gamma_w \qquad (2)$$

Equation 2 is used to calculate the maximum pore pressure for any given stope geometry with an ancillary drain being placed along the stope base. As shown in Fig. 2 and Fig. 3, the results for the given geometry in this paper illustrate a small error between the maximum pore pressure obtained from FLAC and that calculated using equation 2. This is a result of the drain being modeled 1 m above the stope base in FLAC.

Figure 3 illustrates the comparison between the maximum pore pressures calculated using Equation 2 and those obtained from FLAC for varying geometries and ancillary drain lengths.

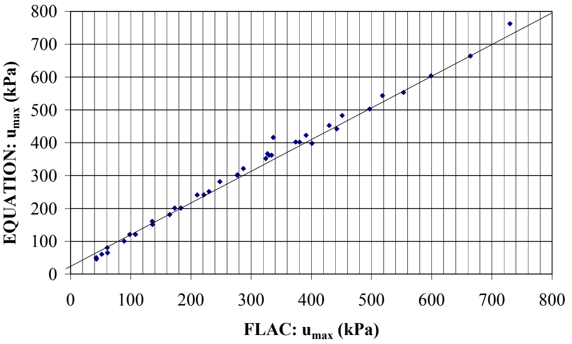

Figure 3. Comparison between Maximum Pore Pressures Obtained from FLAC and those Calculated using Equation 2.

2.3.2 *Discharge*

The values of discharge (Q) were computed for a number of simulations with varying ancillary drain lengths in FLAC. These results are illustrated in Fig. 4.

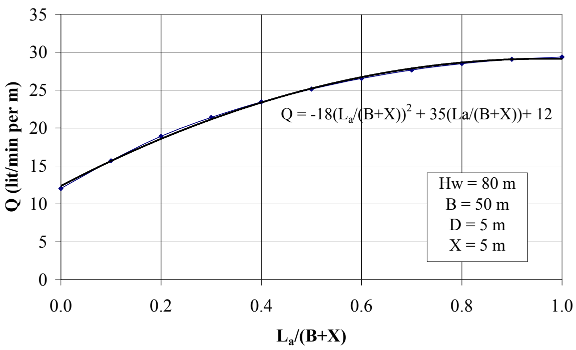

Figure 4. Effect of Ancillary Drain on Discharge Results

From this figure it is clear that as the ancillary drain length is increased, the discharge also increases thus reducing pore pressure build-up behind the barricades. However, the cost and difficulty of installation is increased as the drain length increases, therefore it is important to reach a compromise between the two factors.

3 ANISOTROPY

Hydraulic fill materials, produced by crushing the waste rocks, have very angular grains. When settling from the slurry, they produce an anisotropic fill. Therefore, it is necessary to incorporate the directional variation in permeability when numerically modeling the drainage through hydraulic fills. All the present numerical models (Isaacs and Carter 1983; Traves and Isaacs 1991; and Rankine et al. 2003) assume permeability of the hydraulic fills to be isotropic. Previous laboratory testing carried out on tailings (Fourie 1988) records the presence of anisotropic ratios in permeability in the order of 1 to 10. Therefore, these values provided the limits for the input parameters for the anisotropic permeability ratios in the numerical modeling. Anisotropic permeability has also been recorded by various other authors including Pettibone and Kealy 1971; however these authors have no experimental results to back up their values of horizontal and vertical permeability.

3.1 *Numerical Modeling*

A combination of the finite difference program FLAC, EXCEL and the method of Fragments (Sivakugan et al 2005) was used to numerically investigate the effect of anisotropic permeability on maximum pore pressure and discharge within a two dimensional hydraulic filled stope with a single drain at the base. Results from previous laboratory testing were used as input parameters for the model and the assumptions made for the ancillary drain numerical simulations, were also applied to the anisotropic modeling. To incorporate the anisotropic permeability, inbuilt functions (k11, k22) in FLAC were applied to the model.

3.2 *Method of Fragments*

Sivakugan et al (2005) used the method of fragments to develop simple expressions to compute the discharge (Equation 3) and the maximum pore water pressure (Equation 1) within a two-dimensional hydraulic filled stope with a single drain at the stope base. They showed that the stope could be divided into three fragments, whereby the flow is one-dimensional within the upper region and within the drain of the stope. The permeability coefficient *k* in Equation 3 is equal to $k_{equiv}=(k_h k_v)^{0.5}$ for anisotropic permeability. The discharge was given by:

$$Q = \frac{kh_L}{\Phi_1 + \Phi_2 + \Phi_3} \quad (3)$$

and the maximum pore water pressure is given by Equation 1. Also, the above expressions are only valid when the height of water (H_w) is greater than the width of the stope (B) and the drain length (X) is greater than half the drain height (D).

When the fill is anisotropic, with the ratio of horizontal permeability to vertical permeability greater than 1, the standard procedure is to rescale the flow region and transform it into an equivalent "isotropic" region. This can be done by rescaling the horizontal dimensions by $(k_h/k_v)^{0.5}$ while maintaining the same scale vertically (Das 1985).

Wherever possible, the computations of the discharge and pore water pressures were made using the above equations. Only in cases where, after the transformation, the drain length was shortened and was less than half the drain height, it was necessary to use FLAC.

3.3 *Interpretation of Results*

3.3.1 *Pore Water Pressure*

The change in permeability for an isotropic fill material has little effect in the pore pressures developed (Isaacs and Carter 1982). However, if the fill material contains anisotropic permeability, the effect on pore pressure is quite significant. Figures 5 and 6 illustrate the results.

These figures illustrate the effect of geometry and anisotropy in permeability on the maximum pore pressure measurements. It is interesting to note that, whilst the absolute magnitude of permeability has no influence on the pore water pressures within the stope, the presence of anisotropy in permeability reduces the pore water pressures quite significantly for a specific height of water.

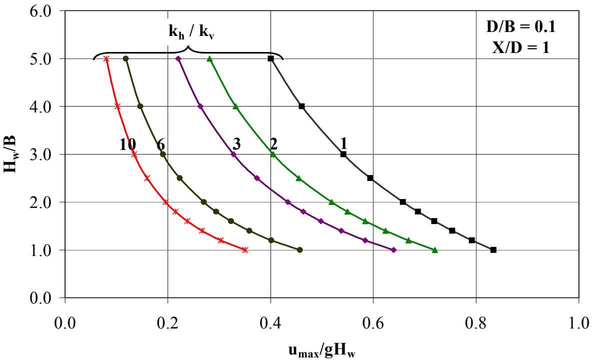

Figure 5. Design Chart for Pore Pressure Measurements for Anisotropic Fill Material: D/B = 0.1; X/D = 1

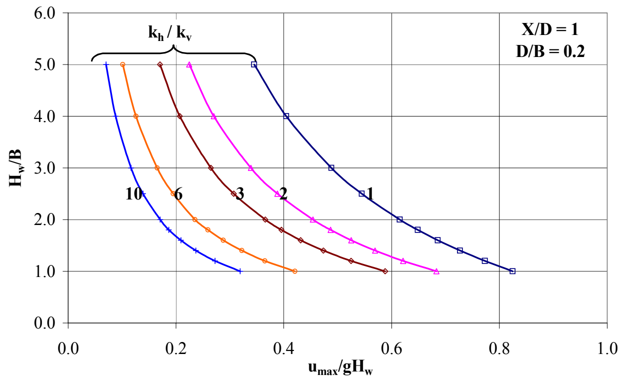

Figure 6. Design Chart for Pore Pressure Measurements for Anisotropic Fill Material: D/B = 0.2; X/D = 1

3.3.2 *Discharge*

The rate of drainage of water from the stope will be governed, to some extent, by the hydraulic properties of the fill material. It is obvious that materials of higher permeability will drain more quickly than those of lower permeability, however, the effect of anisotropic permeability on discharge of hydraulic fill material has previously had little attention. The results from this analysis are illustrated in Fig. 7.

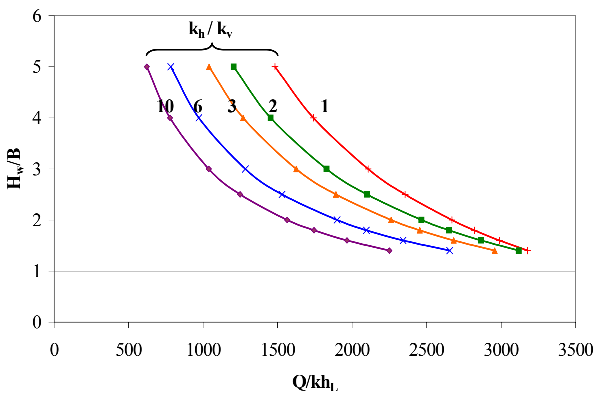

Figure 7. Design Chart: Effect of Anisotropic Permeability on Discharge D/B = 0.2; X/D = 1

Fig. 7 demonstrates the effect of varying anisotropic ratios on a stope with an X/D ratio of 1 and D/B ratio of 0.2. As shown in the figure, as the anisotropic permeability and the H_w/B ratios increase within the stope, the discharge decreases. If we look at Equation 4, that calculates discharge, we can break the effect of the anisotropic permeability into two specific terms: $k_{equiv} = (k_h k_v)^{0.5}$ and N_f/N_d equals the ratio of flow channels to equipotential drops in the flownet. As the anisotropic ratio increases, k_{equiv} increases and N_f/N_d decreases.

$$Q = k_{equiv} h_L \frac{N_f}{N_d} = \sqrt{k_h k_v} \times h_L \frac{N_f}{N_d} \tag{4}$$

However, these terms are not proportional to each other, and care must be taken when analysing the effect of anisotropic permeability on discharge as the discharge trends vary for differing geometries.

4 SUMMARY AND CONCLUSIONS

Through the use of a two-dimensional model developed in FLAC, this paper illustrates that the use of ancillary drainage behind barricades is effective in accelerating the drainage process within a hydraulically filled stope - consequently, reducing the build-up of pore pressure behind the barricades. It was shown that the horizontal ancillary drain, provided at the bottom of the stope, reduces the pore water pressure at all points within the fill, with the reduction being proportional to the length of the drain. A simple expression was developed to determine the maximum pore water pressure for the given stope and ancillary drain arrangement. The ancillary drain also increases the hydraulic gradient, and also the rate of flow, resulting in quicker drainage of the stope. This paper also illustrates the effect of anisotropic permeability in hydraulic fill material. From the results, it is evident that the anisotropic permeability has a significant effect on pore pressure development and discharge within the stope. As the anisotropy in permeability is increased there is a substantial reduction in pore pressure. A number of design charts were created to quantify the effect of varying anisotropic ratios and geometries on pore pressure and discharge within the stope.

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