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Drainage characteristics and behaviour of hydraulically placed mine fill and fill barricades

Les caractéristiques de drainage et le comportement de mine hydrauliquement placée remplissent et remplissent des barricades

Kirralee J. Rankine & Nagaratnam Sivakugan
School of Engineering, James Cook University, Townsville Australia

ABSTRACT
To efficiently remove valuable minerals from large scale underground mining operations, the orebody is often divided into a series of stopes. The stopes are blasted, the rock removed for processing, and the large void created is backfilled with a slurry made from the by-product of the mineral processing activity. Underground failures have occured as a result of poor drainage of excess water from the backfill. The permeability of hydraulic fill is typically between 10-30 mm/hr (much less than industry specification), and yet many mines using these fills have operated successfully for many years. Hydraulic fill typically settles to a porosity value between 37% and 48%, and the dry density may be approximated as 0.56 times the specific gravity. This paper discusses current developments in drainage analysis of hydraulically placed mine fill and fill barricades from four Australian mines.

RÉSUMÉ
Obtenir la plupart d'enlèvement efficace de minéraux valables du grand métro à l'échelle extrait des opérations, le orebody est souvent divisé en un feuilleton de prismes arrêts appelés. Les arrêts sont explosés, les fragments ont enlevé pour traiter, et le très grand vide créé est rechargé avec un gâchis fait du dérivé des minéraux traitant. Les échecs souterrains sont arrivés à la suite du drainage pauvre d'eau supplémentaire du stope pendant les étapes remblayant de l'opération. La perméabilité d'hydraulique remplit est typiquement entre 10-30 mm/hr (beaucoup spécification moins que d'industrie), et pourtant beaucoup de mines utilisant remplit ceux-ci a fonctionnés avec succès pour beaucoup d'années. Hydraulique remplir typiquement règle à une valeur de porosité entre 37% et 48%, et la densité sèche peut être rapprochée comme 0,56 fois la gravité spécifique. Ce papier discute des développements actuels dans l'analyse de drainage de mine hydrauliquement placée.

1 INTRODUCTION

A common method of ore extraction from deep, metalliferous deposits across Australia and world-wide involves the orebody being divided into rectangular parallelepipeds called stopes. These stopes may extend up to two hundred meters in length. The stopes are blasted in slices, and the ore is extracted for processing through drawpoints off haulage drives that run below the stopes . On completion of extraction, the stopes, are backfilled with the by-products of the minerals processing activity called tailings. The mining industry is the largest generator of solid wastes in Australia (Boger 1998) and refilling these excavations with tailings provides an effective means of waste disposal. It also provides ground support to allow for removal of the ore adjacent to the previously excavated stope..

There are several types of backfill materials based on combinations of tailings, development waste or quarried rock. This paper deals with the placement of one particular type of backfill, called hydraulic fill, which has been used extensively since the 1980's (Thomas and Holtham, 1989). Hydraulic fill can be classified under the Unified Soil Classification System as silty sands or sandy silts with negligible clay fraction, and is produced using hydroclones to deslime and dewater the tailings.

Hydraulic fill is placed underground as a slurry, generally using gravitational methods. Historically, the slurry typically had a pulp density of 65%-75% solids by weight, but there has been a steady increase in pulp density over the past decade in an attempt to reduce the quantity of water that must be removed from the fill and to increase the proportion of solids placed. Rheological restrictions associated with the transportation of the slurry limit the solids content of hydraulic fills, but current industry specifications suggest that the density should exceed 70% solids by weight (Grice 1998).

To contain the slurry during placement, barriers, or barricades as they are commonly called in Australia are constructed in each of the drawpoints (Fig. 1). Drawpoints are of sufficient size to allow for machinery to access the stope and remove the ore for processing and the size, and the number and location of these drawpoints varies between stopes. Depending on the size and geometry of the stopes, filling may take from several days to several months. During this time, the fill settles under its own weight and excess water drains from the stope, either through the fill and barricades, or by decanting through upper barricades (Fig. 1).

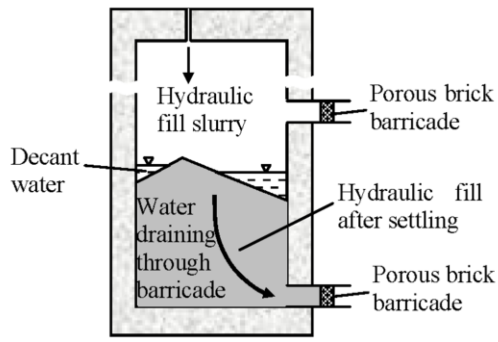

Figure 1. Schematic diagram of a stope

Ideally, hydraulic fill should be free draining to enable the excess water to be removed as quickly as possible, so that the pore water pressure within the stope is minimised and adjacent works can commence without delay. Many techniques aiming to achieve optimal barricade drainage are used throughout the industry including, pipes and valves through the barricades, internal drainage in the form of ancillary drainage pipes, and most commonly in Australia specially manufactured porous bricks, which have permeability comparable to coarse gravels.

Barricade failure in underground hydraulic fill mines have considerable financial ramification, and due to the catastrophic nature of failure also carry considerable risk to the safety of underground workers. Extreme cases have resulted in multiple fatalities (e.g., Bronzewing mine disaster in Western Australia in 2000).

Based on a thorough investigation of over 15 separate hydraulic fill samples from several of the larger underground metalliferous mines across Australia, permeability, settlement and strength characteristics of typical Australian hydraulic fills are summarized, and details of specialized laboratory test procedures for assessing these characteristics are explained. This paper also describes the subsequent development of empirical relations which may be utilized to predict the properties of hydraulic fill.

The one-dimensional drainage path through the porous barricade bricks was simulated in the laboratory, and the permeability values were determined using constant head and falling head permeability tests in a specially designed permeability cell (Rankine et al. 2004). The permeability values and flow characteristics of the bricks are summarized in this paper.

Finally, a three-dimensional numerical model developed using $FLAC^{3D}$, which simulates the filling and drainage of a typical stope, is described and some interesting findings are discussed.

2 HYDRAULIC FILLS

Hydraulic fill is produced by passing the by-product from mineral processing through hydroclones to deslime and dewater the tailings. The level to which the tailings is ground is dependent on individual mine processing techniques. However the results of grain size distribution tests on over 20 hydraulic fill samples across Australia showed that with the fine material (fines or slimes) removed, the grain size distribution curves for typical Australian hydraulic fills, fall within a narrow band (Rankine et al. 2004).

Hydraulic fills are placed as slurries at a solids content of approximately 70% (Thomas and Holtham, 1989). For this reason, the specific gravity of the fill will have a significant influence on the quantity of water that is also placed underground, and subsequently drained from the stope. Unlike typical soils, the specific gravity values for hydraulic fills vary significantly with values found to range from 2.8 to 4.4. This factor has a considerable influence on the drainage characteristics of a stope.

2.1 *Permeability of hydraulic fills*

In the laboratory, hydraulic fills were prepared as slurries with solids densities corresponding to the values typically used at the respective mines. The water contents was between 30% and 35%. The slurries were placed in a 153 mm diameter, 306 mm high permeameter and allowed to settle under self weight. The reconstituted hydraulic fill sample typically resulted in relative densities of between 50% and 80%, which is typical of hydraulic fills. Field measurements reported by Pettibone and Kealy (1971) taken in hydraulic fill stopes in US mines were in good agreement with these laboratory results. Therefore, this preparation technique provided a sedimented hydraulic fill sample that was representative of in situ hydraulic fill.

A light-weight and portable permeability apparatus was designed specifically for on-site use. The apparatus is predominantly constructed of stainless steel, and is capable of performing both constant head and falling head permeability tests with reproducible results on a reconstituted hydraulic fill sample. Both constant head and falling head tests can be carried out with the sample in the same position thereby eliminating sample disturbance that can occur if the sample must be disturbed between test types. The fill permeability apparatus was capable of applying constant head values in excess of 2.5 m.

A summary of the permeability results, and reconstituted sample properties from an extensive study of 17 different fill samples from four separate Australian hydraulic fill mines, is given in Table 1. The table also provides the specific gravity and D_{10} values for the fills.

The preferred unit for fill permeability in the mining industry is mm/hr (1cm/s = 36000mm/hr), and this unit is used throughout this paper. The constant head and falling head test results compared well for all samples tested. Industry specifications suggest that the permeability of hydraulic fill should be at least 100mm/hr to ensure good drainage (Grice 1998, Herget and De Korompay, 1978). However, as shown in Table 1, the permeabilities of the hydraulic fills tested was substantially lower than the recommended value. Most (but not all?) of the mines have however operated satisfactorily for many years with backfills having the lower values.

Table 1: Fill permeability test summary

Fill ID	G_s	D_{10} (μm)	Porosity (%)	Dry density (t/m^3)	Average permeability (mm/hr)
A1	2.79	19.1	40.1	1.67	10.2
A2	2.80	23.4	40.8	1.66	19.1
B1	2.88	13.3	39.8	1.73	2.1
B2	2.88	23.4	48.5	1.43	0.6
C1	4.35	20.3	43.8	2.44	21.5
C2	3.45	18.6	38.3	2.13	17.9
C3	3.69	12.1	38.7	2.26	17.8
C4	3.02	19.2	37.1	1.90	22.5
D1	3.42	27.1	36.8	2.16	20.7
D2	3.71	37.7	39.9	2.23	24.0
D3	3.53	36.5	41.2	2.08	53.7
D4	3.50	32.8	41.9	2.03	20.4
D5	3.50	35.0	41.2	2.06	25.3
D6	3.53	42.9	39.8	2.13	30.8
D7	3.32	29.4	40.4	1.98	20.5
D8	3.12	30.9	41.9	1.81	31.5
D9	3.42	40.6	42.0	1.98	26.8

Evidence has been presented to suggest that the grains finer than 10μm contribute most to hydraulic fill permeability (Thomas 1978). There is a rule-of-thumb (Cowling 1998) within the industry that suggests hydraulic fills should be limited to a maximum of 10% passing 10μm to ensure effective drainage . Herget and De Korompay (1978), quote 35μm as the typical D_{10} value, and other researchers have quoted typical hydraulic fill D_{10} values in excess of 10μm (Kuganathan 2002, Brady and Brown 2002). The D_{10} range for the fill samples tested for this research fell between 12μm and 43μm. The relationship between permeability and grain size has been widely explored in soil mechanics. Most commonly, D_{10}, also known as the effective grain size, is used to relate grain size to flow through granular soils using Hazen's (1930) equation. Preliminary estimations of fill permeability in mm/hr, can be made using Hazen's (1930) empirical relationship is given in Equation 1, with the constant C in the range of 0.03 – 0.05, and the fill D_{10} in mm (Rankine et al. 2004).

$$k=CD_{10}^2 \quad (1)$$

2.2 *Placed properties of hydraulic fills*

Unlike typical soils where the specific gravity tends to fall within a narrow range between approximately 2.6 and 2.9, as shown in Table 1, the specific gravity range for hydraulic fills varies considerably. The fills tested in this research varied from

2.8 to 4.4. As shown in Table 1, all fill samples settled to porosity values between approximately 37% and 48%, and therefore it can be inferred that the dry density is proportional to the specific gravity of the fill. Figure 2 shows dry density in terms of specific gravity (Fig. 2) for the 15 sedimented samples detailed in Table 1, as well as five in situ measurements taken by Pettibone and Kealy (1971) from US mines and in situ results for fills from three Australian mines. The relationship between the parameters can be approximated by the equation:

$$\rho_d\ (\text{g/cm}^3) \approx 0.56G_s \qquad (2)$$

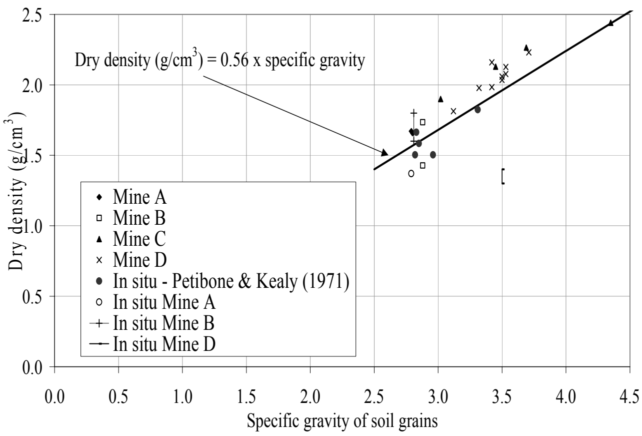

Figure 2. Dry density versus specific gravity

Friction angle is an important parameter for both static and dynamic stability analyses of hydraulic fills. Underestimating the friction angle may under estimate the arching potential and therefore the stability of the fill (Mitchell 1975). The very angular particle geometry typical of hydraulic fills (Pettibone and Kealy, 1971; Thomas and Holtham, 1989) would suggest that the friction angle would be greater than that for common granular soils. Limited direct shear testing has confirmed that for relative densities of greater than 35%, the friction angle and relative density can be related for fill sample D6, by the equation:

$$\phi = 19D_r^2 + 33 \qquad (3)$$

Minimum and maximum dry density tests were performed on many of the fills tested for this research, and it was found that the relative densities were in the range of 50% to 80% (Rankine et al. 2004). Similar relative densities were reported by Pettibone and Kealy (1971) for in situ fills.

3 POROUS BARRICADE BRICKS

Barricade failure in underground mining operations is of significant concern to the industry, because the potential for the outcome to be catastrophic is very high. This section summarizes some findings with regard to permeability and strength characteristics of the porous barricade bricks commonly used to contain the fill within the stope during filling and drainage.

3.1 *Permeability of porous barricade bricks*

Flow through an underground mine brick is essentially one-dimensional (Fig. 1), and therefore it is necessary to ensure that flow through the brick is tested in the single, longitudinal direction. A specialized pressure testing chamber was designed and constructed to test the permeability of porous barricade bricks through adaptations of constant head and falling head methods, and also determine the variation of flow with applied pressures as high as 350kPa (Fig. 3).

Figure 3. Porous brick pressure testing chamber

The constant head permeability results compared well with the falling head results. A method to extrapolate the permeability of the porous barricade bricks from the pressure testing was determined and the results also compared well with those obtained from constant and falling head tests. The permeability values for over 17 porous bricks tested, ranged from 1800mm/hr to over 10,000mm/hr. This result confirms industry perceptions that manufacturing procedures for these porous bricks are not of an adequate standard to allow the barricade flow properties to be adequately predicted. The sizeable difference in permeability value (2 to 3 orders of magnitude) between the hydraulic fill, and the porous brick barricades suggests, that provided the barricades are built from the bricks in such a way that the construction does not impede the drainage performance, it may be assumed that the barricade does not contribute to the development of excess pore pressures within the fill, and hence the drainage of the system is not hindered by the permeability of the bricks.

3.2 *Strength assessment of porous barricade bricks*

A thorough uniaxial compressive strength testing program on longitudinal and lateral cores, whole bricks and specially cast brick cylinders provided a comprehensive database of strength and stiffness properties of barricade bricks used in Australian hydraulic fill mines. The results of these investigations indicated that the strength and stiffness of the bricks vary considerably between bricks. From the data obtained through this research, current industry perception overestimates the actual value for brick strength. It was also found that the strength of the bricks decrease with wetting; an undesirable feature considering the conditions the bricks are subjected to. The E/UCS value for porous barricade bricks was found to be between approximately 100 and 400. Clays typically have E/UCS values between 250 and 750, and concrete typically about 1000.

4 FLAC^{3D} STOPE FILLING SIMULATION

The drainage behaviour of a typical hydraulically filled stope was simulated numerically in three dimensions using FLAC^{3D}. The model incorporated various filling sequences, stope geometries and drain locations. The results of the simulation predicted the pore water pressure developments and discharge through the drains. These predictions were compared to those obtained in a two--dimensional model of Isaacs and Carter (1983) which has previously been verified against in situ data. Good agreement was observed between the two simulations.

Drain length has a significant influence on stope discharge and pore pressure distribution (Rankine, 2003). A stope having the geometry shown in Figure 4 was used to demonstrate the effect of this length on discharge rate and pore pressure development during filling. The stope was 20 m x 20 m in plan and 100 m in height. The drain had cross-sectional dimensions of 4 m x 4 m, and 2 m, 4 m and 8 m drain lengths were investigated.

The model was designed in such a way that the water height remained at or below the fill height during the entire filling process. At no stage was decant water allowed to pool on the surface of the fill during continuous filling of the stope. The variation in discharge with water height for each of the drain lengths is plotted in Fig. 5.

As expected, the discharge rate decreases and the maximum pore pressure increases with drain length. Previously, the two-dimensional approximations to this problem used Darcy's law to estimate the effect of drain length. This method suggests a drain of 2 m would have twice the discharge of the 4 m drain, and four times the discharge of the 8 m drain. This study shows this method underestimates the performance of the drain.

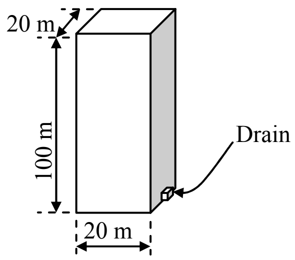

Figure 4. Diagrammatic representation of FLAC^{3D} simulation

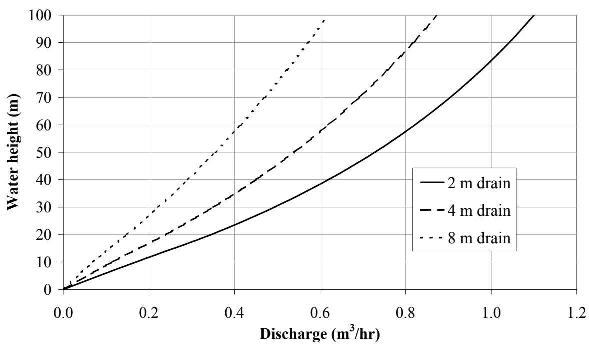

Figure 5. Effect of drain length on discharge rate

5 CONCLUSION

Hydraulic fill is placed underground at approximately 70% solids content. Unlike typical granular soils, hydraulic fills can have specific gravity values anywhere from approximately 2.8 to 4.5, and therefore the quantity of water placed, and in turn requiring removal, can vary considerably between different operations. A comprehensive program of laboratory testing on the barricade bricks commonly used underground has shown that the permeability and strength of these bricks varies considerably. However, the permeability of the bricks is 2 to 3 orders of magnitude greater than that of the hydraulic fill, which is typically between 10 to 30mm/hr (much less than industry specification) as measured in the laboratory. Hydraulic fills typically settle to a porosity value between 37% and 48%, and the dry density may be approximated as 0.56 times the specific gravity. A three-dimensional numerical model has been developed to predict discharge rates and pore pressures within a stope during filling and draining, and this model has been demonstrated to be effective for investigating the effect of stope geometry and fill properties on the drainage characteristics of a stope.

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