Geotechnical Issues of Mining with Hydraulic Backfills

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ABSTRACT
This paper presents the state of the art of geotechnical engineering issues involved in mining. Of the two methods of extracting ores from the ground, open cut mining and underground mining, this paper concerns itself with the latter: it gives a broad overview of the salient issues related to underground mining with special emphasis on hydraulic backfilling approach.

KEYWORDS: mining, open cut mining, underground mining, backfilling, hydraulic fill.

INTRODUCTION
Mining is one of the major export industries in the resource rich countries such as Australia, Canada, South Africa, Brazil, Chile, China, etc. (Figure 1). Open cut mines and underground mines are two major types of mines, where the difference is mainly in the way the ore is removed from the ground. When the ore deposits lie shallow, open cut mining (Figure 2a) is common where one can see large open pits on the ground. When there is substantial overburden present above the ore body, they can only be accessed through tunneling into the earth, and these mines are known as underground mines (Figure 2b).
Figure 1: Mining and exploration countries world-wide (http://www.infomine.com)

The underground mines are located mainly in Canada, USA, South Africa, Australia, Brazil, Sweden, Mexico, Ireland, Peru and Bulgaria. When the ore is removed from underground, very large voids are created which have to be backfilled to improve the stability of the underground excavations in the surrounding region. The common practice is to backfill the voids with the waste product from the crushed ore, after the minerals are extracted. This is also seen as an effective way of disposing the millions of tonnes of mine waste produced worldwide every year. This paper gives a broad overview of the salient issues related to underground mining with hydraulic backfills.

Figure 2: (a) Open cut mine (b) Underground mine
MINEFILLS

Minefills can vary from boulder-size aggregates to very fine clay fractions. Sometimes, a small dosage (e.g. 3-5%) of pozzolanic binder such as cement, fly ash, gypsum or slag is added to the minefill to improve stability. Hydraulic fills and paste fills are the most common types of backfills used worldwide and Australia, and hence this paper deals specially with these two fill types. James Cook University, Australia, has carried out substantial work on paste fills and hydraulic fills from most of the major mines in Australia. This includes characterization of the mine fills and barricade bricks through extensive laboratory and field tests, and numerical modeling using FLAC3D, FLAC and Abaqus. This paper summarizes the major findings from these studies. A more general coverage of different minefills, their applications and case studies is given by Potvin et al. (2005).

The backfilled voids can be approximated as rectangular prisms, known as stopes, with base dimensions of 20-60 m and heights as much as 200 m or even more. There are sublevel horizontal access drives at various levels, typically at vertical spacing 20-25 m. These drives provide access to vehicles and machinery and have typical dimensions of about 4-5 m horizontally and vertically. Sometimes the walls have slight inclination to the vertical; hanging wall is the one above the stope and footwall is the one below the stope. The hydraulic fill, cemented hydraulic fill and paste fill are generally placed within the stopes in the form of slurry at 65-80% solid content by weight (i.e. 25-54% water content). They are mixed at a plant far away and are transported through pipes and bore holes. The flowability of the fill slurry is measured by yield stress or slump tests. The schematic diagram of an idealized hydraulic fill stope is shown in Figure 3a. The flownet obtained using FLAC (Itasca 2005) in a 2-dimensional hydraulic fill stope is shown in 3b.

Due to the presence of traces of heavy metals, the specific gravity of the minefills can be significantly higher than the inorganic soils. It can vary in the range of 2.70-4.50. Drainage is one of the main concerns in the design and implementation of hydraulic and cemented hydraulic fill stopes, where every attempt should be made to remove the drainable water as quickly as possible from the stope. Drainage is never a concern in paste fills where there are substantial fines that will absorb the water and the remaining water is used in the hydration process.

Aggregate fills, rock fills, sand fills, cemented rockfills, cemented aggregate fills, and rocky paste fills are some of the other fill types that are currently being used for backfilling underground mine stopes.

BARRICADES OR HYDRAULIC FILLS

During filling, each horizontal access drive is blocked by a wall (Figure 4) to prevent any in-rush of the slurry into the drive and the other regions where the miners and the machinery are present. The failure of such barricades can be catastrophic, claiming lives and machinery, and such accidents have been reported world-wide. Therefore, it is necessary to understand the stresses within the minefills, the loadings on the barricades and the strength characteristics of the minefills and barricade bricks.
Barricades for hydraulic fill stopes were traditionally made of specially made porous bricks that are free draining. Berndt et al. (2007) reported a comprehensive study on the strength and stiffness of the porous barricade bricks. The variability of uniaxial compressive strength (UCS) and Young’s modulus (E) among the bricks was quite high, with average values being UCS = 7 MPa and E = 0.7 GPa. There was 25% reduction in UCS on wetting the bricks for 7 days or more, and some noticeable reduction in Young’s modulus as well. Since the brick barricades are wetted in service, reduced values of strength and stiffness must be used in the designs. Lately, impermeable shotcreted barricades with drainage pipes are being used in place of porous brick barricades.

Figure 3: (a) An idealized hydraulic fill stope (b) Flownet within a 2-dimensional stope
DRAINAGE THROUGH HYDRAULIC FILLS

In spite of the wide range of specific gravity (Gs) values, all hydraulic fill slurries have about the same void ratio at placement. However, the solid content or water content can be quite different depending on Gs. Grice (1998) suggested that the hydraulic fills should be placed at a target density of $47.5 \pm 2.5\%$ by volume of solids. At 47.5% volume of solids, the slurry density in terms of solids by weight can be written as:

$$solid\ content\ (by\ weight) = \frac{47.5G_s}{47.5G_s + 52.5} \times 100$$

where $G_s$ is the specific gravity. This shows that larger the specific gravity, larger is the solid content of the fill slurry at placing.

Grice (1989), Cowling et al. (1988) and Bloss and Chen (1998) have investigated the mechanisms associated with the barricade failure. “Erosion piping” appears to be the most plausible explanation for most failures. It starts by some hydraulic fill grains being washed out through the barricade, which leads to the development of an “erosion pipe” which progresses towards the top of the fill surface to meet the free decant water. This makes the loading conditions at the barricade hydrostatic, as opposed to the original K0-condition where the vertical stresses are substantially reduced by arching. This “erosion piping” mechanism discussed in mining literature is quite different to the piping mechanism associated with seepage in geotechnical context.

Adequate drainage is an absolute necessity in the design and operation of hydraulic fill mine stopes. Most barricade failures have been attributed to problems associated with lack of drainage. These failures generally take place during the early hours of filling, due to problems associated with the build up of excess pore water pressure. Therefore, it is desirable to remove the drainable water as quickly as possible.

Figure 4: Brick barricade blocking a drive (Photo: Courtesy Ms. A. Brady)
from the stope. Traditionally it was believed that if the permeability of the settled hydraulic fill is greater than 100 mm/hour, the stope would perform satisfactorily (Herget and de Korompay 1978). Nevertheless, recent studies show that hydraulic fill mine stopes with significantly lower permeability values have operated satisfactorily, without any problems (Rankine et al. 2006).

Drainage through hydraulic fill mine stopes has been studied extensively, particularly with reference to Australian mines, by Sivakugan et al. (2005, 2006a) and Rankine et al. (2006). They discussed the laboratory studies carried out to assess the geotechnical characteristics of the minefills and barricade bricks. It was shown that the grain size distribution curves for more than 25 different hydraulic fills tested fall within a narrow band. The hydraulic fills are classified as silty sands (SM) or sandy silts (ML). Based on laboratory studies, it was reported that the slurry settles to about 40-45% porosity with relative density of 50-80%, which agrees with the field measurements from Pettibone and Kealy (1971). Sivakugan et al. (2006b) carried out constant head and falling head permeability tests on full size barricade bricks and reported that their permeability is 2-3 orders of magnitude greater than those reported for hydraulic fills. Therefore, the fill-barricade interface shown in Figure 3 can be assumed to be free-draining.

A stope is rarely filled continuously, due to limitations in the fill processing plant, build-up of decant water etc. Cowling et al. (1988) suggested that it is a good practice to ensure that there is minimal free water present above the fill in the form of decant water. A simple guideline for fill pouring and resting times proposed by Cowling et al. (1988) is given in Table 1. The hydraulic filling of a mine stope takes place over several days (e.g. 12 hours fill and 12 hours rest per day) and it is necessary to know the fill height and water height throughout the filling operation and to know when the drainage will stop. Isaacs and Carter (1983) developed the first computer program simulating hydraulic filling of a 2-dimensional mine stope. The program gives flow rates through the barricades, pore water pressures, water height and fill height during any stage of filling. This was later extended to 3-dimensional stopes by Traves & Isaacs (1991). Sivakugan and Rankine (2006) showed from simple mass balance, that ensuring permeability value of the settled hydraulic fill to be greater than the value given in Eq. 2 will see that there is no decant water present above the fill.

$$k \geq \frac{W_s}{\rho_w A i_{entry}} \left[ \frac{w_{slurry} - \frac{n}{(1-n)G_s}}{w_{exit}} \right]$$  \hspace{1cm} (2)

Here, $W_s = \text{solids filling rate (t/h)}$; $A = \text{plan area of the stope (m}^2\text{)}$; $i_{entry} = \text{hydraulic gradient at the top of water level}$; $w_{slurry} = \text{water content of the slurry}$; $n = \text{porosity of the settled fill}$; and $\rho_w = \text{density of water (t/m}^3\text{)}$. For 2-dimensional stopes, $i_{entry}$ can be estimated from the approximate equation suggested by Sivakugan and Rankine (2006):

$$i_{exit} = 0.2(H_w / B)^{0.75}$$  \hspace{1cm} (3)

where $B$ is the width of the stope and $H_w$ is the height of water within the stope.

**Table 1:** Pour and rest times for hydraulic filling at Mount Isa mine  
(Cowling et al. 1988)

<table>
<thead>
<tr>
<th>Stope plan area (m$^2$)</th>
<th>Pour time (hours)</th>
<th>Rest time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 400</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>400-1000</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>1000-1600</td>
<td>16</td>
<td>8</td>
</tr>
<tr>
<td>&gt; 1600</td>
<td>No restrictions</td>
<td>Not required</td>
</tr>
</tbody>
</table>
Recognising the fact that the flow is one dimensional within the horizontal drain and the upper region of the stope, Sivakugan et al. (2006c) proposed a simple technique based on method of fragments to compute the flow rate and pore water pressures within a 2-dimensional stope. Rankine et al. (2007) extended this to 3-dimensional stopes.

STRESSES WITHIN MINEFILLS

Before attempting to understand the stresses within the horizontal drives and on the barricades, it is necessary to fully understand the stress developments within a mine stope. Marston’s (1930) 2-dimensional plane strain theory was extended by Terzaghi (1943) to present an expression for the vertical stress at depth $H$ within the fill in a narrow stope of width $B$ as:

$$\sigma_v = \frac{\gamma B - 2c}{2K \tan \delta} \left[ 1 - \exp \left( -\frac{2KH \tan \delta}{B} \right) \right]$$

(4)

where $\gamma$ = unit weight of the fill, $\delta$ = fill-wall friction angle, $c$ = cohesion, and $K$ = lateral earth pressure coefficient. Comparing the estimates of $\sigma_v$ from Eq. 4 with those obtained from numerical modeling and laboratory model tests, Pirapakaran and Sivakugan (2007) showed that the fill within the stope is close to at-rest state and hence $K = K_0 = 1 - \sin \phi$. They extended Eq. 4 to rectangular stopes as:

$$\sigma_v = \frac{\gamma B - 2c}{2K \tan \delta} \left[ 1 - \exp \left\{ -2 \left( \frac{L + B}{LB} \right) KH \tan \delta \right\} \right]$$

(5)

For a square stope, Eq. 5 becomes:

$$\sigma_v = \frac{\gamma B - 2c}{4K \tan \delta} \left[ 1 - \exp \left\{ -\frac{4KH \tan \delta}{B} \right\} \right]$$

(6)

and this equation can be used for a circular stope as well. Circular stope has a purpose in numerical modeling due to its simplicity for being modeled as axisymmetric problem, but it is not common in practice. In the case of hydraulic fills $c = 0$. The variation of vertical normal stress along the vertical centre line of a 10 m wide and 50 m high stope, as modeled in FLAC, is shown in Figure 5. It can be seen that the vertical stresses are significantly less than what is given by the product of the depth and unit weight of the fill. The effect of arching is more pronounced in circular or square stope than in a narrow stope.
SUMMARY AND CONCLUSIONS

Hydraulic fills are one of the most popular mine fill types for backfilling the large voids created in the underground mining. When they are placed in the form of slurry, they impose significant loading on the barricades that are used for blocking the drives. Failure of barricades can result in sudden in-rush of large quantities of wet tailings into the drives and adjacent areas, endangering the safety of the miners. Several accidents involving fatalities have been reported world-wide in the recent past, and hence it is necessary to fully understand the drainage and stress developments within the hydraulic fills.

One of the primary objectives in the design of hydraulic fill stopes is to remove all drainable water as quickly as possible. This is often achieved by controlling the grain size distribution and limiting the fines which ensures that the permeability is large enough to facilitate adequate drainage. Presences of significant quantities of decant water above the fill heights can be seen as a sign of potential problems. These can be checked through computer simulation models that are being used in the mining industry.

The analytical expressions (Eqns. 4, 5 and 6) proposed in the literature for estimating the average vertical normal stress at any depth within the minefill give reasonable estimates provided the appropriate values are used for the wall friction angle and the lateral earth pressure coefficient. These analytical expressions and numerical models clearly demonstrate that there is significant arching taking place within

Figure 5: Vertical stress variation within a 10 m x 50 m hydraulic fill stope
the mine stopes. The degree of arching is much greater for square stopes than narrow stope, due to the presence of the walls in all four sides.

REFERENCES


