Underground Mine Backfilling and Stress Distributions

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ABSTRACT: Australian mining industry uses substantial quantities of mine backfills in underground mining. The access drives at different levels of the underground mines are barricaded so that the void can contain the mine fill slurry and allow it to consolidate. Failure of the barricades can be catastrophic and several accidents and fatalities are reported worldwide annually. Therefore, it is necessary to understand the stress developments within the mine fills and to ensure that the barricades are not overloaded. The focus of the paper is to discuss in detail the analytical studies, laboratory characterisation of the mine fills, laboratory model tests, and numerical simulations carried out using FLAC^{3D}. The laboratory model tests and the numerical simulations clearly show that there is substantial arching taking place within the fill due to wall friction, which reduces the barricade loading. The findings improve the current state-of-the-art and would contribute towards ensuring a safer environment within the mines.

1 INTRODUCTION

Underground mining is the process of extracting mineral ore deposits. The massive ore bodies are divided into blocks or stopes, and the ore is mined from those stopes sequentially. The processed mineral waste is called tailings and the disposal of tailings in a safe, stable and economical manner is very important and beneficial to all stakeholders. The valuable minerals make only a very small fraction of the ore and the rest of the unwanted crushed waste rock is returned to the underground voids as backfills. Hydraulic fills (HFs) and paste fills are two of the most common backfills used in underground mining. Hydraulic fills have no clay fraction and paste fills have substantial clay content with a small dosage of cement. Hydraulic fills and paste fills are placed in the underground voids in the form of slurry for the ease of transport through pipelines and boreholes over a long distance.

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2 STRESS DEVELOPMENTS WITHIN THE BACKFILL

2.1 *Analytical and numerical approaches*

Understanding the stress development within the backfilled mine stopes is necessary for estimating the loads on the barricade. The barricade stress variation is analytically expressed after assuming elastic behaviour and considering a vertical layer element along the drive. Also numerical modelling has been carried out for studying the stress developments within the stope as well as the loads acting on the barricade (Helinski et al. 2010). When a granular material is placed in rigid containers or behind retaining walls, the shear stress, between the wall and the granular material interface, leads to arching and results in lower vertical stresses at any depth. Arching is beneficial to engineers since it reduces the effective stress acting on the structure (Take and Valsangkar 2001).

The vertical stress (**σ_v**) within a square stope of width **B** and height ***z*** can be analytically estimated from Janssen's equation,

$$\sigma_v = \frac{\gamma B}{4K \tan\delta}\left[1 - e^{-4K\tan\delta\left(\frac{z}{B}\right)}\right] \tag{1}$$

where γ is the unit weight of the fill, δ is the interfacial friction angle and K is lateral pressure coefficient.

2.2 *Hydraulic fills (HF)*

The hydraulic fills are the coarse fraction from mine tailing streams. Removal of finer fraction, desliming, leads to a major characteristic of hydraulic fills as "less than 10% to be finer than 10 µm". This implies that D_{10} of a HF is expected to be greater than 10 µm. The median grain diameter (D_{50}), effective grain size (D_{10}), coefficient of uniformity (C_u) and coefficient of curvature (C_c), are tabulated in Table 1. According to USCS, the sand would be classified as poorly graded uniform sand, with symbol of SP, and the HF can be categorised as silty sand with symbol of SM.

Table 1. Material properties of HF and sand

Property	HF	Sand
Median grain diameter, D_{50} (mm)	0.13	0.33
Effective grain size, D_{10} (mm)	0.02	0.11
Coefficient of uniformity (C_u)	7.71	3.43
Coefficient of curvature (C_c)	1.69	1.08
Minimum dry density (kg/m^3)	1540	1430
Maximum dry density (kg/m^3)	2175	1676
Specific gravity	3.12	2.58
Peak friction angle, φ (°)	39.3	38.2
Interfacial friction angle, medium rough walls, δ (°)	23.1	22.9
Interfacial friction angle, rough walls, δ (°)	38.8	37.5

3 LABORATORY MODEL

A simple laboratory model stope is developed at James Cook University (JCU) geomechanics laboratory to study the effects of arching and vertical stresses within the granular fill by Pirapakaran and Sivakugan (2007). A container of uniform cross section, referred to as 'the stope' from here onwards, was made out of Perspex. The stope was held vertically by three equally spaced supports (Fig.1). The supports were attached to a load cell (Revere Transducers, type 9363-D3-100kg_20T1; precision 0.001 kg), which was connected to the frame. Therefore, the load of the model stope and bracings was measured with the load cell. The model was lowered until it just touches the balance, without registering any load on the electronic balance (maximum reading 60 kg, precision 0.005 kg). There was a tiny gap (less than a grain size) between the bottom of the model walls and the balance. When the model stope was partially filled, a part of the fill mass is carried by the base (i.e., the balance) and the rest is transferred to the wall (i.e. the load cell). These two were monitored throughout the filling process.

4 NUMERICAL SIMULATIONS

FLAC, a finite difference numerical package was used to simulate the laboratory scale model filling, in order to compare with model test results.FLAC uses an explicit, Lagrangian calculation scheme and a mixed-discretization zoning technique and is well recognised in simulations with geomechanical applications. Since the numerical modelling approach discussed herein is for a continuum, which does not consider grain size, the simulation results applicable to other cohesionless fill types too.

Axisymmetric configuration was used to model cylindrical containments in FLAC. Dimensions of the FLAC models were the same as those of the model containments tested in the laboratory, where the outer diameters of 100 mm and 150 mm with a wall thickness of 3 mm. The model consisted of 1 mm × 1 mm grid. Most of the geotechnical properties of HFs were chosen with literature and the material parameters used for modelling are tabulated in Table 1. The model walls were fixed for both y and x-displacement. Y-displacement was fixed at the bottom of the model. The interface stiffness parameters K_n and K_s were empirically calculated as suggested by FLAC users guide.

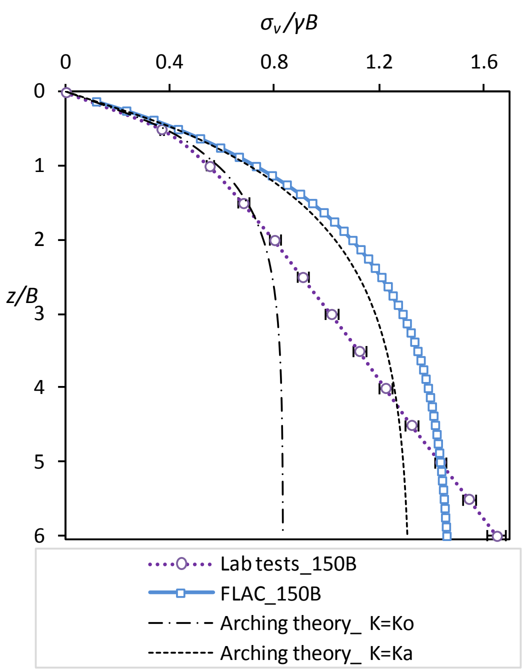

Fig. 1. Vertical stress variation after the 150 mm square container filled with sand as obtained with laboratory tests and numerical simulations

5 RESULTS

The variation of the vertical stress with depth, for square stopes of width 150 mm, is presented in Fig. 1. The depths upto 3B is denoted as the upper section and the depths after 3B is denoted as the lower section, herein. The dashed lines show the variation of the average vertical stress, with $K = K_o$ and $K = K_a$ depth based on Equation (1), where the vertical stress is substantially reduced with arching. The vertical stress reaches an asymptotic value relatively quickly, at depths of lower section with arching theory. The vertical stress estimated with FLAC^{3D} also reaches an asymptote at a lower section of the stope. The vertical stress variation from laboratory tests follows analytical equation ($K = K_o$) in upper section, but then deviates and shows a linear increase in lower section (Fig. 1).

The load cell, which is attached to the laboratory test setup, provides data such that the shear stress exerted on walls can be calculated. The horizontal stress is calculated with shear stress and tanδ, and included in Fig. 2. The horizontal stress is normalised with the unit weight and the stope width and termed as horizontal stress hereafter. The horizontal stress variation obtained for HFs and sand filled stopes in laboratory tests are compared to the theoretical horizontal stress in Fig. 2.

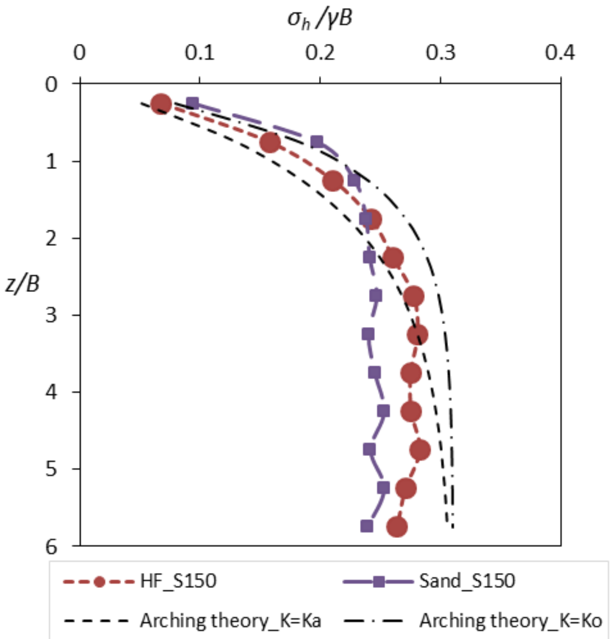

Fig. 2. The horizontal stress variation within HF and sand filled square stopes

5.1 *Calculated lateral pressure coefficient (K_{calc})*

The laboratory tests conducted for this study, enabled the vertical and horizontal stresses be measured independently and therefore, the lateral pressure coefficient could be calculated with depth and denoted as K_{calc}. The presented values of K_{calc} for HFs and sand in Fig. 3, K_{calc} shows a non-linear variation with depth for both HFs and sand. The maximum is K_o, but the minimum is shown to be less than the K_a within the lower section of the stope (Fig. 3).

6 DISCUSSION

When a stope is filled in layers, the added weight is transferred to the underlying layers, as well as to the wall. The mobilisation of friction along the wall controls the vertical stress variation felt at bottom. The vertical stress and shear stress variation in upper section can be explained by considering the soil/HF grain matrix. At lower depths, the soil matrix is capable of holding the self-weight, remains intact and acts like a continuum, and hence the stress variation follows the analytical equation (Figs. 1 and 2).

6.1 *Vertical and horizontal stress variation*

The horizontal stress, as obtained in laboratory tests, follows the analytical equation in upper section and reaches a maximum. Thereafter, horizontal stress does not increase in lower section. However, the maximum horizontal stress shown in laboratory tests is less than the expected with arching theory (Fig. 5).

When the horizontal stress variation with depth is considered, the horizontal stress reaches a maximum at a relatively shallow depth, within upper section, as seen in the laboratory tests (Fig. 2).

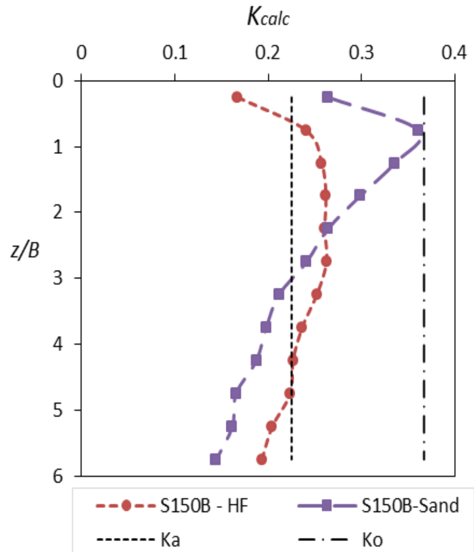

Fig. 3. The calculated lateral pressure coefficient from laboratory tests

As the horizontal stress is maximised, the shear stress also reaches the maximum. But, the maximum horizontal stress and shear stress in laboratory tests are less than what is estimated from analytical equations (Fig. 2). But theory predicts shear and horizontal stresses greater than the recorded in tests (Fig. 2). This implies that the shear forces have not fully developed as predicted with theory.

Theoretically, with Janssen's or Marston's equations, the additional load from the added backfill is totally balanced by shear forces, which leads to an asymptotic vertical stress in the lower section. The shear force is capable of carrying the weight from the added fill mass. However, the horizontal stress or shear stresses are not high as expected theoretically. Therefore, the additional load from added backfill is not fully balanced by shear forces at lower section in laboratory tests. Therefore, further down the stope, the addition of load from the top makes it difficult for the soil matrix to carry the entire load without slipping and some of the load from the added layer is transferred to the base. As this weight portion of the new layer transferred continuously to base, the vertical stress shows a linear increase, without reaching an asymptote, in lower section (Fig. 1).

6.2 *Granular material assumed as a continuum?*

In the laboratory setup or in a backfilled stope, the filled weight is partially taken by the walls and the rest is transmitted to bottom. However, the measured shear forces or horizontal stress reach a maximum value in laboratory tests and this maximum is less than the estimated value with the arching theory. Though the arching theory estimates an asymptotic vertical stress in lower stope, test results indicates an increase of vertical stress even at a depth of 6B.

Confinement between the grains in soil matrix develops in upper section, and enables the horizontal and shear stresses to increase. But in lower section, the wall friction is mobilized to the maximum, and therefore shear stress cannot increase further. Then the rest of the load is transferred to bottom, making the vertical stress to increase in a liner trend and not reaching an asymptote. The same pattern is observed by Ting (2011), where the vertical stresses do not reach an asymptote; rather they tend to increase with depth (Fig. 1).

Finite element or finite difference numerical simulations assume the material as a continuum over the considered element or zone. As seen in Fig. 3, FLAC^{3D} simulates a vertical stress variation, which shows a deviation from measured stress variation. This is considered as the major difference between the actual particulate behaviour shown in granular material and theoretical continuum approach. The Mohr-Coulomb constitutive model was used in the presented model, as the backfill is often modelled with Mohr-Coulomb model. However, it is understood that the FLAC overestimates the vertical stress variation when compared to laboratory tests. Therefore, hybrid discrete element and finite difference or element numerical simulations would be more appropriate for mine backfilling situations.

6.3 *Lateral pressure coefficient*

Arching theory uses a constant K (K_0, K_a or $K_{krynine}$) to estimate the stress variations. Additionally, in the arching theory it is considered that the lateral stress ratio is a constant such that the horizontal stress increased proportionally with the vertical stress along the depth. However, it was shown that the ratio of the horizontal stress to the average vertical stress is not a constant and varies with the depth. Therefore, the lateral pressure coefficient obtained with laboratory tests is not a unique curve with depth, and varies with the filling material (Fig. 3).

7 CONCLUSIONS

The arching theory gives a basis to estimate the vertical stresses in granular filled containments, but is not sufficient. The average vertical stress within the laboratory model does not reach an asymptote even at depths of 6*B*, whereas arching theory estimates that the vertical stress reaches the asymptote value at depths less than 6*B*. Therefore, it is advised to consider hybrid simulation including the discrete element models for reasonable stress estimates within backfills.

A 'varying lateral pressure coefficient', in which the K is taken as a function of depth, can be suggested as an alternative to match test results from this study with analytical equations.

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