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NUMERICAL ANALYSIS OF STRESS DISTRIBUTIONS FOR MULTIPLE BACKFILLED STOPES

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Dr. Zach Agioutantis, Director of Graduate Studies
NUMERICAL ANALYSIS OF STRESS DISTRIBUTIONS FOR MULTIPLE BACKFILLED STOPES

DISSERETATION

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the College of Engineering at the University of Kentucky

By

Christopher Richard Newman

Lexington, Kentucky

Director: Dr. Zach Agioutantis, Professor of Mining Engineering

Lexington, Kentucky

2018.

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Abstract

NUMERICAL ANALYSIS OF STRESS DISTRIBUTIONS FOR MULTIPLE BACKFILLED STOPES

Over the past three decades, technological innovations with respect to cemented paste backfill (CPB) as a means of ground support has allowed for increased production within the mining industry, management mine waste costs, as well as the improvement of the overall health and safety of underground mining operations. Despite the extensive use of this relatively new ground support material, many fundamental factors affecting the design of safe and economical CPB structures are still not well understood. Recently, a significant amount of academic and industry research has been conducted to better understanding the distribution of stress with respect to primary-secondary extraction sequencing for stope-and-fill mining operations. While current, as well as past research, as provided a wealth of knowledge on the distribution of stress through the fill material itself, it lacks in providing an examination into the mechanism by which stress is able to redistribute itself through the backfill material as well as within the surrounding rockmass.

The scope of this work is to optimize stope-and-fill extraction sequencing through the analysis of stress distributions as well as local and global stability of multiple narrow vertical fully-drained backfilled stopes. Scientific investigations into the behavior of the CPB material and surrounding rockmass will result in an improved understanding of how to better implement engineered paste-fill materials as a means of ground support for underground mining operations. Numerical simulations (FLAC3D and RocScience) were utilized in analyzing hypothetical (literature) as well as site-specific (field) case studies. While these simulations confirm generalized stress behaviors within the backfill material for single and adjacent stopes, stress redistributions within the surrounding rockmass as well as the rock-pillar indicated the development of tensile and compressive zones. From these results, one is able to better approximate ground and CPB instability with respect to site-specific conditions, geometries, and material properties. These simulations have been validated with respect to published analytical solutions, numerical simulations, and site-measurements for single (isolated) and adjacent narrow vertical fully-drained backfilled stopes.

Keyword: Mining, Stope, Backfill, Stress Distribution, Numerical Modeling

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June 7, 2018
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June 7, 2018
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To my daughters Elizabeth and Eloise. For three months I sat between your incubators and read you stories, prayed, and then read more stories. There, in the hospital, we met a Prince from a faraway planet, an Emu who just wanted a job, a mouse who really likes cookies, and all the inhabitants of the Hundred Acre Wood. Listening to all the beeps and whirls and watching doctors and nurse scurry about, I remember being scared. Terrified actually. But I will always remember, and keep close to my heart, an adventurous young boy and his bear telling us,

“You are braver than you believe, stronger than you seem, and smarter than you think”

Christopher Robin, Winnie the Pooh
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While everyone will recognize the hard work and dedication taken by the PhD student, I believe it is our partners who are often underrepresented in this accomplishment. I would like to acknowledge my best friend and wife, Maggie Richardson. You were there every single day, through every single model encouraging me, believing in me, and sacrificing your own career for the benefit of our family. I cannot thank you enough but I will love you forever.
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1 Introduction

As mining operations continue to produce at deeper depths and in more geologically and geometrically complex conditions, the application of ground support materials has become essential in ensuring the stability of underground mine works. Over the past decade, the mining industry has seen an increase in the application of cemented paste backfill (CPB) material in conjunction with the stope-and-fill mining method. The stope-and-fill mining method is a cost-effective, productive, and safe mining technique for high recovery and low dilution mining of narrow or irregular ore bodies where localized stability of the mine working is of concern (Darling, 2011). The application of engineered fill material in North American stope-and-fill mining operations dates back to the 1950’s with the introduction of hydraulic backfill material (De Souza, et al., 2003). As the ground control advantages of backfill material became more apparent, industry engineers sought to develop more effective and economical fill materials. The backfill material utilized in underground stope-and-fill mining operations are limited to either hydraulic, rock, or cemented paste backfill (Hassani and Archibald, 1998). Past experiences with hydraulic and rock backfill materials have found problems in material handling at large depths as well as water drainage issues. To remedy these concerns, Robinsky (1975) introduced cemented paste backfill for not only the support of underground excavations but also the disposal of mill tailings from the surface using pipeline reticulation. Through the utilization of engineered backfill material in conjunction with stope-and-fill mining, one is able to provide localized ground support to the stope walls and back horizon for the prevention of caving/roof falls as well as rock bursts (Coates, 1981).

Modern technological innovations within the mineral, aggregate, and cement processing industries as well as the incorporation of chemical additives has provided the mining industry with a ground support material which, if employed appropriately, greatly reduces mine waste costs (tailings) while increasing production and improving stability of the underground working environment. Today, CPB is typically composed of mill tailings (75%-85% by weight) mixed with cementitious binder additives (3%-7% by weight) such as Portland cement (T10 or T50), fly-ash, and smelter slag prior to fill placement in the excavated stope (Benzaazoua et al., 2004; Fall and Nasir, 2010; and Landriault, 1995). The purpose of these binding agents is to allow for the development of cohesion within the backfill material such that exposed faces will be self-supporting during the extraction of adjacent or secondary stopes (Mitchell et al., 1982). To maintain material flow properties, the cemented paste backfill contains at least 15% of particles smaller than 20 μm acting as a lubricant in the pipeline. A sufficient amount of water must be added to obtain a slump less than 230 mm (Potvin, et al., 2005) as well as enough water to ensure proper hydration of the binding agents (Benzaazoua et al., 2010). The water content of the backfill can also greatly influence the unit weight and strength of the material (Hassani and Archibald, 1998). While physical properties often define the material, the mechanical properties of cemented paste backfill ensure its effectiveness as a ground control material.

Due to the accessibility to and versatility of CPB, many stope-and-fill mining operations employ paste fill materials within a primary-secondary excavation-support sequencing allowing for significant increase in reserve recovery. As shown in Figure 1-1, the primary stopes (Stope A and Stope B) are excavated and backfilled in two phases; plug and final pours. The “plug” is initially placed at the bottom of the stope with a CPB material of increased cementitious content.
providing a strong foundation on which to build the rest of the CPB structure as well as ensuring the stability of the barricade against material breakthrough (Li and Aubertin, 2009). Once the “plug” has been allowed to cure, a less cementitious “final” pour material is used in backfilling the rest of the excavated stope. With the excavation and backfilling of all the primary stopes within a given mining district, a similar excavation-support sequencing is utilized in the extraction of the secondary stopes where the backfilled primary stopes become adjacent artificial pillars.

Figure 1-1: Primary-secondary excavation-support sequencing of mining events for stope-and-fill operations

Despite the extensive use of CPB as a means of ground support within the mining industry, it is often the case that the design of backfill structures are simplistic in nature and therefore do not effectively utilize stress redistribution mechanisms with respect to reserve economics, projections, and optimizations. For example, the vertical stress at the floor of the backfilled stope is often approximated as the gravity load of the CPB material at the given point. However, academic research (Aubertin, et al., 2003) and site-specific measurements (Helinski, et al., 2011; Thompson, et al., 2012) suggest that vertical and horizontal stress within the backfill structure is significantly less than the overburden stress (gravity loading).

While initially developed to estimate the loads on buried conduits, the methodology outlined by Marston (1930) has been modified for the evaluation of stresses within narrow backfilled stopes (Aubertin et al., 2003). For the purposes of backfilled stope, the Marston theory provides an approximation of the stress concentrations acting across the floor of the stope following the general concept of stress transfer by taking into account the weight of the backfill material as well as the shearing forces along the backfill-rockmass interface (Aubertin et al., 2003). The original Marston’s equations have been modified for the evaluation of stress distributions in single narrow vertical backfilled stopes (Aubertin, et al. 2003; Li et al., 2005; Falaknaz, 2014) as well as single narrow inclined backfilled stopes (Caceres, 2005; Ting, et al., 2011; Li, et al., 2013). With the increase in computational capacities, numerical modeling is a commonly utilized approach in the analysis of underground material behaviors. Numerical codes, such as FLAC and RocScience, have been used to evaluate the stress state within the CPB material as well as verifying analytical solutions for CPB structures (Li, et al., 2005). These numerical simulations
allow one to further evaluate the influence of geometric and material parameters on the
distribution and redistribution of stress for single and multiple backfilled stopes.

The main purpose of this dissertation is to develop a numerical modeling approach which will aid academic, operations, and regulatory professionals within the mining industry in more realistically approximating the distribution and redistribution of stress through the CPB material as well as the surrounding rockmass. In better approximating the behavior of and interactions between underground materials, one is able to better design ground support to enhance and optimize underground production while ensuring the stability of the local working section as well as the global stability of the mine works. The numerical models presented have been developed from more than 200 numerical simulations investigating the local and global stress development and distributions. Numerical modeling results for single narrow vertical fully-drained backfilled stopes as well as adjacent vertical fully-drained backfilled stopes showed good agreement between existing numerical and analytical solutions as well as site-specific measurements of the stress state within the CPB material for an isolated (single) backfilled stope. Measurements reported within the literature (Helinski et al., 2011) were used to validate numerical results. These models were further utilized for the analysis of stress distributions within the surrounding rockmass. Results indicate the development of significant tensile and compressive stress zones impacting the stability of the surrounding rockmass as well as the CPB structure(s).

1.1 Statement of Work
With a growth in industry application and knowledge of cemented paste backfill as a means of ground support, stope-and-fill mining operations are increasingly seeking a cost effective and safe means of achieving total extraction of the mining reserve. Literature suggests that in attempting maximum extraction of the mining reserve, operators employ a primary-secondary excavation-support sequencing for stopes. This mining method therefore requires the backfill material to be self-supporting and able to remain stability when the cemented paste backfill structure loses its confinement during the excavation of the adjacent secondary stope. Confinement of the backfill material is only regained once the secondary stope has been backfilled.

Therefore, the overall scope of this work is to aid in the optimization of stope-and-fill mine sequencing through the analysis of stress distributions and the stability of multiple narrow vertical fully-drained backfilled stopes. Scientific investigations into the behavior of the cemented paste backfill as well as the surrounding rockmass will result in a better understanding of stress concentrations and distributions within these materials as well as stress transfer between materials. The net result of this effort is expected to not only provide the mining industry with knowledge of cemented paste backfill material and its interaction with the surrounding rockmass for the efficient and economical extraction of mining reserve but also to enhance underground safety through a more comprehensive understanding of material behavior(s) and stress distributions with respect to the application of cemented paste backfill. The specific objectives proposed for this research effort have been designed such that they fully investigate the important analysis and application aspects of cemented paste backfill as a means of primary ground support within single and multiple narrow vertical fully-drained stopes. Each objective has been linked together such that the material and research results culminate into
the development of the final objective investigating the application of cemented paste backfill as a ground support system utilized in multiple stope-and-fill sequencing.

1.2 Objectives

**Objective One:** the development of a two-dimensional numerical model for the approximation of stress distributions through the backfilled stope as well as within the surrounding rockmass with respect to a single narrow vertical fully-drained backfilled stope. Numerical results are to be validated with respect to the published literature and site-specific measurements and/or observations.

**Objective Two:** numerically investigate the behavior of the backfill-rockmass interface with respect to stress transfer between the backfill material and the surrounding rockmass for a single narrow fully-drained vertical backfilled stope.

**Objective Three:** numerical investigations into the distribution and redistribution of stress through the backfill material and within the surrounding rockmass with respect to excavation and backfilling of an adjacent primary narrow vertical fully-drained backfilled stope.

**Objective Four:** numerical investigations into stress distributions through the backfill material and within the surrounding rockmass as well as stability analysis of the cemented paste backfill structure with respect to excavation of a secondary stope immediately adjacent to a single narrow vertical fully-drained backfilled primary stope.

**Objective Five:** numerical investigations into the distribution of stress through the backfill material and within the surrounding rockmass as well as stability analysis of the cemented paste backfill structure with respect to the excavation of a secondary stope in-between two adjacent narrow vertical fully-drained backfilled primary stopes.

1.3 Structure of Dissertation

The following dissertation is composed from multiple published and submitted technical papers. Therefore the chapters within this dissertation are structured as follows;

**Chapter 2** presents a review of current literature related to the application of cemented paste backfill material in stope-and-fill mining operations.

**Chapter 3** presents the development of a two-dimensional numerical model for the analysis of global stress distributions and stability with respect to a single (isolated) narrow fully-drained vertical backfilled stope.

**Chapter 4** presents a detailed analysis of stress distributions and redistributions through the backfilled stope and within the rockmass with respect to a single (isolated) narrow fully-drained backfilled stope. Numerical results are compared to site-specific stress measurements taken during the backfilling of a stope.

**Chapter 5** investigates the impact of interface elements defined along the backfill-rockmass contact area on the distribution of stress through the backfilled material as well as within the surrounding rockmass with respect to a single narrow fully-drained vertical backfilled stope.
Chapter 6 presents a detailed analysis of stress distributions and redistributions through the backfilled stopes and within the surrounding rockmass with respect to the excavation and backfilling of an adjacent primary stope.

Chapter 7 presents a detailed analysis of the stress distribution and redistribution as well as cemented paste fill stability through the backfilled stope and within the surrounding rockmass. Furthermore, the stability of a single side exposed primary backfilled stope was evaluated upon the excavation of an immediately adjacent secondary stope.

Chapter 8 investigates stress distributions and redistributions as well as cemented paste fill stability within two primary backfilled stopes and within the surrounding rockmass. Furthermore, the stability of multiple side exposed primary backfilled stopes were evaluated upon the excavation of a secondary stope in-between the two backfilled primary stopes.

Given that the following dissertation is composed from a series of technical publications coupled with dissertation formatting, there may be a repetition of information and overlap in analysis. Furthermore, stress is generally referred to in MPa, while distances and displacements are shown in terms of meters [m]. The interpretation of the results presented in these chapters are context dependent and differences between these results and existing publications were only considered substantial if it had an impact on the engineering design or decision making. The final chapter included in this work contains conclusions, discussions, and recommendations for the entire body of work. Furthermore, an Appendix of numerical modeling parameters and comprehensive references section concludes the body of work.

1.4 References


2 Literature Review
The following article was submitted to the 51st US Rock Mechanics / Geomechanics Symposium held in San Francisco, California, USA. This article was accepted for presentation at the symposium by an ARMA Technical Program Committee based on technical and critical review of the paper by a minimum of two technical reviewers.

Stress Redistribution in Stope-and-Fill Mining Operations with respect to Cemented Paste Backfill Material

Christopher Newman, University of Kentucky; Lexington, Kentucky; United States of America
Zach Agioutantis, University of Kentucky; Lexington, Kentucky; United States of America

Full Citation:

2.1 Synopsis
Over the past decade, the mining industry has seen an increase in the application of the stope-and-fill mining method as conventional underground deposits have been depleted and operations have been forced to produce at deeper depths and in more challenging ground conditions. Through the utilization of cemented paste backfill (CPB) material for localized ground support, modern stope-and-fill mining operations have been able to increase productivity, effectively manage mine waste costs, as well as provide a safer mining environment. While the application of CPB has allowed for an increase in ore recovery, it is important that engineering and operations personnel have a clear understanding of the fill material as well as the limitations of the fill design to provide the most efficient, cost-effective, and safe extraction of underground reserves. Despite extensive use of CPB in mines around the world, many fundamental factors affecting the design of safe and economical fill structures are still not well understood. A critical issue in the design of backfilled stopes is the determination of the stress state within the fill material and surrounding rockmass.

Recently work has been conducted further investigating stress distributions within engineered fill material as well as the stress interactions between the fill and the rockmass. While these works, as well as past research, have provided a wealth of knowledge on stress developments within the fill material itself, there is much room for further development of a more accurate understanding of the ability and mechanism by which the material is able to redistribute the stress around the excavation and through the fill material. This paper provides and overview of current research with respect to stress distributions for stope-and-fill mining operations and suggests areas in which further research is needed to fully comprehend the effectiveness of this newly developing ground support material.
2.2 Introduction and Background

Technological innovations with respect to cemented paste backfill (CPB) material as a means of ground support have promoted a global increase in the application of the stope-and-fill mining method for the excavation of reserves at large depths and in more challenging geological conditions. The utilization of CPB in stope-and-fill mining has led to reductions in mine waste costs while increasing both mining productivity and the overall health and safety of the underground working environment. Modern underground stope-and-fill operations utilize a primary-secondary excavation-support sequence in an attempt for total extraction of the mining reserve. Primary stopes are initially excavated and then backfilled in a two-stage pour; plug pour and final pour. Common applications of the two-stage pour implement backfill material with an increased cement content for the plug pour allowing for a stronger base which protects mine workings from material breakthrough as well as allowing the possibility of underhand mining activity while a lighter, less cementitious material is used to backfill the rest of the stope in the final stope pour. With primary stopes supported with CPB, the extraction of secondary stopes can commence utilizing the backfilled primary stopes as artificial pillars. While the application of CPB allows for an increase in reserve recovery, it is important for engineers to have a clear understanding of the material behavior as well as the limitations of material design to allow for the most efficient, cost-effective, and safe extraction of underground deposits.

Despite the extensive use of this relatively new technology, many fundamental factors affecting the design of safe and economical CPB structures are still not well understood (Fall and Nasir, 2010). A critical issue in the design of backfilled stopes is the determination of stress within the backfill material as well as the surrounding rockmass. Recently, work has been conducted investigating stress distributions within the backfill material (Li and Aubertin, 2010; Ting et al., 2014; Falaknaz et al., 2015; etc.) as well as the stability of the side exposed backfilled stopes (Mitchell et al., 1982; Dirige et al., 2009; Li et al.; 2014; etc.) for primary-secondary stope extraction. While current, as well as past, research has provided a wealth of knowledge on the backfill material itself, it lacks in providing an examination into the mechanism by which the material is able to redistribute the stress around the excavated and supported areas. By furthering the understanding of the behavior of CPB and the redistribution of stress within the rockmass as well as the CPB material itself, industry engineers will be provided with the means to further optimize production sequencing for single and multiple stope mining operations.

In utilizing CPB as a means of ground support, it is imperative that engineers have an understanding of the stress concentrations within and around the supported stope. While the vertical stress within the backfilled stope is often simplistically determined as the overburden weight, academic research, (Aubertin et al., 2003; Pirapakaran and Sivakugan, 2007) and site-specific stress measurements (Helinski, et al., 2011) suggests the vertical stress state at a given point within the backfill material is significantly less than the overburden stress due to a phenomenon known as, “arching.” Stress transfer between the backfill and the surrounding rockmass is extremely beneficial since it effectively reduces the stress acting upon the CPB. Initially, when stope is excavated, far-field stresses are redistributed around the opening concentrating load along the stope wall as shown in Figure 2-1(a). The stope is then filled with CPB as a means of supporting the stope wall. Given that the backfill material is less rigid than the surrounding rockmass, CPB will begin to consolidate under load and transfer a portion of the
overburden weight onto the rigid abutments due to the frictional interface between the backfill and adjacent rockmass as seen in Figure 2-1(b). Due to the development of shear stress (shown in blue) along the backfill-rockmass interface, the vertical stress within the backfill material is reduced transferring vertical stress to the adjacent rockmass (shown in green). Several academic studies have been conducted to further evaluate stress transfer within backfilled stopes with respect to analytical equations as well as physical and numerical modeling. From the results of these investigations, one finds that stress concentrations at the backfill-rockmass interface are typically lower than those along the vertical center line (VCL) and that both vertical and horizontal stresses are less than the overburden stress. This paper will strictly be concerned with stress “arching” due to interactions along the backfill-rockmass interface as depicted in Figure 2-1(b).

Figure 2-1: a) Stress redistribution around excavated stope b) Backfilled stope with associated vertical stress transfer to surrounding rockmass

2.3 Review of Ground Control Research for CPB in Stope-and-Fill Mining

As the mining industry continues to utilize CPB it is becoming more imperative that engineers require a more thorough understanding on how the material transmits stress to the surrounding rockmass and around the stope as well as the materials ability to support the stope walls and immediate back. Current academic investigations into backfilled stopes primarily focus on the mechanism of stress distribution through the CPB with respect to a transfer of stress from the backfill to the surrounding rockmass as previously explained. This concept of stress transfer between two materials of significantly different stiffness has been employed by engineers in the analysis of many different design scenarios such as silo wall pressures (Blight, 1986), vertical stress and support requirements above tunnels (Terzaghi, 1943), earth pressure on retaining walls (Spangler and Handy, 1984), overburden weight on conduit pipe in ditches (Marston, 1930), etc.

The solution provided by Marston (1930) has become the primary stress transfer method applied to CPB for narrow stopes. While initially developed to estimate the overburden load on buried conduits, the methodology has been modified for the evaluation of the two-dimensional
stress distribution in vertical narrow backfilled stopes (see Aubertin et al., 2003 in Table 1-1) given an instantaneously backfilled stope in a fully drained condition (Table 1-2) with a cohesionless backfill material (see Table 1-3). Assuming that the internal friction of the backfill material [φ] is equal to the internal friction of the backfill-rockmass interface [δ], Aubertin et al. (2003) propose the following equation for the vertical (Eq. 2-1) and horizontal (Eq. 2-2) stress across the width of the backfilled stope at a depth h into the backfill material.

\[
\sigma_{vh} = \frac{\gamma B}{2K \tan(\delta)} \left[ 1 - \exp \left( - \frac{2K \tan(\delta)}{B} h \right) \right] \\
\sigma_{hh} = \frac{\gamma B}{2 \tan(\delta)} \left[ 1 - \exp \left( - \frac{2K \tan(\delta)}{B} h \right) \right]
\]

(Eq. 2-1)

(Eq. 2-2)

where B is the stope width (m); δ (°) is the friction angle of the backfill-rockmass interface; γ (kN/m³) is the unit weight of the backfill and the earth pressure coefficient (K) can be expressed as:

\[
K = K_0 = 1 - \sin(\phi) \quad \text{At rest condition} \quad (\text{Eq. 2-3})
\]

\[
K = K_a = \tan^2 \left( 45 - \frac{\phi}{2} \right) \quad \text{Active condition} \quad (\text{Eq. 2-4})
\]

\[
K = K_p = \tan^2 \left( 45 + \frac{\phi}{2} \right) \quad \text{Passive condition} \quad (\text{Eq. 2-5})
\]

Table 2-1: Compilation of modern literature on the development of stress analysis for backfilled stopes

<table>
<thead>
<tr>
<th>Reference Source</th>
<th>Backfilled Stope Stress Analysis</th>
<th>Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Aubertin et al., 2003)</td>
<td>2D Analytical &amp; Numerical</td>
<td>Single Stope</td>
</tr>
<tr>
<td>(Li et al., 2005)</td>
<td>2D Analytical &amp; Numerical</td>
<td>Single Stope</td>
</tr>
<tr>
<td>(Li et al., 2005)</td>
<td>3D Analytical &amp; Numerical</td>
<td>Single Stope</td>
</tr>
<tr>
<td>(Li and Aubertin, 2008)</td>
<td>2D Analytical &amp; Numerical</td>
<td>Single Stope</td>
</tr>
<tr>
<td>(Li and Aubertin, 2009a)</td>
<td>3D Analytical &amp; Numerical</td>
<td>Single Stope</td>
</tr>
<tr>
<td>(Li and Aubertin, 2010)</td>
<td>2D Analytical</td>
<td>Single Stope</td>
</tr>
<tr>
<td>(Falaknaz et al., 2015)</td>
<td>2D Numerical</td>
<td>Single Stope</td>
</tr>
<tr>
<td>(Caceres, 2005)</td>
<td>2D Analytical &amp; Numerical</td>
<td>Single Stope</td>
</tr>
<tr>
<td>(Li and Aubertin, 2009b)</td>
<td>3D Numerical</td>
<td>Single Stope</td>
</tr>
<tr>
<td>(Ting et al., 2011)</td>
<td>2D Analytical</td>
<td>Single Stope</td>
</tr>
<tr>
<td>(Ting et al., 2014)</td>
<td>2D Analytical &amp; Numerical</td>
<td>Single Stope</td>
</tr>
</tbody>
</table>
Table 2-2: Sequencing assumption made within modern stress analysis literature for backfilled stopes

<table>
<thead>
<tr>
<th>Reference Source</th>
<th>Backfilling Sequence</th>
<th>Backfill Material</th>
<th>Water Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Aubertin et al., 2003)</td>
<td>Instantaneous</td>
<td>Homogeneous</td>
<td>Drained</td>
</tr>
<tr>
<td>(Li et al., 2005)</td>
<td>Instantaneous</td>
<td>Homogeneous</td>
<td>Drained</td>
</tr>
<tr>
<td>(Li et al., 2005)</td>
<td>Instantaneous</td>
<td>Homogeneous</td>
<td>Drained</td>
</tr>
<tr>
<td>(Li and Aubertin, 2008)</td>
<td>Instantaneous</td>
<td>Homogeneous</td>
<td>Drained</td>
</tr>
<tr>
<td>(Li and Aubertin, 2009a)</td>
<td>Instantaneous</td>
<td>Homogeneous</td>
<td>Submerged</td>
</tr>
<tr>
<td>(Li and Aubertin, 2010)</td>
<td>Instantaneous</td>
<td>Homogeneous</td>
<td>Submerged</td>
</tr>
<tr>
<td>(Falaknaz et al., 2015)</td>
<td>4 Layers</td>
<td>Homogeneous</td>
<td>Drained</td>
</tr>
<tr>
<td>(Caceres, 2005)</td>
<td>Instantaneous</td>
<td>Homogeneous</td>
<td>Drained</td>
</tr>
<tr>
<td>(Li and Aubertin, 2009b)</td>
<td>4 Layers</td>
<td>Homogeneous</td>
<td>Drained</td>
</tr>
<tr>
<td>(Ting et al., 2011)</td>
<td>Instantaneous</td>
<td>Homogeneous</td>
<td>Surcharge</td>
</tr>
<tr>
<td>(Ting et al., 2014)</td>
<td>Instantaneous</td>
<td>Homogeneous</td>
<td>Surcharge</td>
</tr>
</tbody>
</table>

Table 2-3: Material assumptions made within modern analytical stress analysis Literature for backfilled stopes

<table>
<thead>
<tr>
<th>Reference Source</th>
<th>Backfill Material</th>
<th>Rock-Fill Interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Aubertin et al., 2003)</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>(Li et al., 2005)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>(Li et al., 2005)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>(Li and Aubertin, 2008)</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>(Li and Aubertin, 2009a)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>(Li and Aubertin, 2010)</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>(Caceres, 2005)</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>(Ting et al., 2011)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>(Ting et al., 2014)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

To investigate the validity of the results produced by these analytical equations, numerical models were developed by Aubertin et al. (2003) using Phase2 (see Figure 2-2) as well as Li et al. (2003) using FLAC. The results from these numerical investigations found that while a significant portion of the stress within the backfill can be transferred to the surrounding rockmass across the backfill-rockmass interface, the magnitude of the load transfer is overestimated by the Aubertin et al. (2003) analytical solution and therefore underestimates the stress magnitude residing within the CPB. It should also be noted that the Aubertin et al. (2003) solution does not take into consideration the influence of sequenced backfilling on the distribution of stress within and around the backfilled stope (Li et al., 2003). By not taking into consideration the sequencing of the backfill process, the wall convergence due to elastic straining of the rockmass is not imposed on the backfill material which would increase the mean stress. Similarly, Aubertin et al. (2003) assumes a homogeneous backfill material and does not take into consideration the effect of the plug or final pours on the distribution of stress through the backfilled stope.
The modified Marston’s solution for narrow backfilled stopes developed by Aubertin et al. (2003) was further expanded upon by Li et al. (2005) providing an analytical solution for a cohesive CPB material. While both analytical solutions provided by Aubertin et al. (2003) and Li et al. (2005) assumed a uniform stress distribution through the backfill material, numerical investigations found that the assumption of a uniform horizontal stress across the width of the stope is acceptable, however the consideration of a uniform vertical stress distribution is not valid. Therefore, in 2008, Li and Aubertin proposed an alternative modified Marston’s solution for narrow backfilled stopes which incorporates a distribution factor (DF). Expansion of the modified Marston’s solutions was carried out by Caceres (2005), Li and Aubertin (2009) and Ting et al. (2011) for determining the distribution of stress in narrow backfilled stopes with non-vertical parallel walls and were further validated by numerical modeling. Moreover, Ting et al. (2014) built upon previous work to provide an analytical solution for the stress distribution through a narrow backfilled stope for which the hanging wall and footwall lean in the same direction but are not parallel.

Through the development of analytical solutions and further numerical investigations into the distribution of stress through singular narrow vertical backfilled stopes has increased basic industry knowledge and understanding of backfill with respect to its behavior as a ground support material. This increase in knowledge has led to an industry push towards the efficient, economic, and safe extraction of the mining reserve. With the adoption of primary-secondary sequencing in modern underground stope-and-fill mining operations, there is a current need for academic investigations into the stress distributions through and around the backfilled stopes as well as the stability of the CPB during the extraction of the secondary stope. Building upon the previous work of Aubertin et al. (2003) and Li et al. (2005), Falaknaz et al. (2015) numerically

---

Figure 2-2: Modeling of a vertical narrow backfilled stope given a 1 to 2 vertical to horizontal insitu stress ratio: a) stope schematic; b) distribution of induced horizontal stress; c) distribution of induced vertical stress (from Aubertin et al., 2003)
investigates stress distribution within the backfill material of two adjacent primary vertical stopes. The modeling approach utilized by Falaknaz et al. (2015) assumed that each stope was excavated instantaneously allowing convergence of the stope walls to take place before backfilling the stope in four homogenous layers. Results from the two-dimensional FLAC model indicate that the reduction of stress within the backfill material due to “arching” occurs in both stopes, however each stope maintains very different stress states. The stress distribution within the second primary backfilled stope is similar to that obtained through numerical simulations of a singular narrow vertical backfilled stope. As shown in Figure 2-3, the stress distribution within the first primary backfilled stope increases up to 40% after backfilling of the second primary stope occurs.

Figure 2-3: Modeling of adjacent backfilled stopes: a) stope schematic of backfilled stopes; distribution of horizontal (b) and vertical (c) stress in adjacent stopes at the end of filling the second stope (from Falaknaz, 2014)

Figure 2-4: Stope and fill layout (a) before and (b) after excavation of adjacent secondary stope; c) schematic of planar failure for side-exposed backfill (adapted from Li, 2014)

The extraction of the secondary stopes adjacent to a given backfilled stope (see Figure 2-4) is outside the scope of the previously discussed analytical solutions and numerical investigations.
The stability of the side exposed backfilled vertical stope was investigated by Mitchell et al. (1982) with respect to a limit equilibrium analysis of a planar failure (Table 2-4). Building upon the solution proposed by Mitchell et al. (1982), Li (2014) most recently modified Mitchell’s solution such that it takes into consideration the non-homogeneity of the two staged pour for backfilled stopes; plug and final pours (see Table 2-5).

Table 2-4: Compilation of Modern Literature on the Development of Stability Analysis for Side-Exposed Backfilled Stopes

<table>
<thead>
<tr>
<th>Reference Source</th>
<th>Backfilled Stope Stress Analysis</th>
<th>Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Mitchell et al., 1982)</td>
<td>3D Analytical &amp; Experimental</td>
<td>N/A</td>
</tr>
<tr>
<td>(Dirige et al., 2009)</td>
<td>3D Analytical</td>
<td>N/A</td>
</tr>
<tr>
<td>(Li et al., 2014)</td>
<td>3D Analytical</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 2-5: Sequencing Assumption made within Modern Stability Analysis Literature for Backfilled Stopes

<table>
<thead>
<tr>
<th>Reference Source</th>
<th>Backfilling Sequence</th>
<th>Backfill Material</th>
<th>Water Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Mitchell et al., 1982)</td>
<td>Instantaneous</td>
<td>Homogeneous</td>
<td>Fully Drained</td>
</tr>
<tr>
<td>(Dirige et al., 2009)</td>
<td>Instantaneous</td>
<td>Homogeneous</td>
<td>Water Surcharge</td>
</tr>
<tr>
<td>(Li et al., 2014)</td>
<td>2 Layer Pour</td>
<td>Non-homogeneous</td>
<td>Fully Drained</td>
</tr>
</tbody>
</table>

Table 2-6: Material Assumptions made within Modern Stability Analysis Literature for Backfilled Stopes

<table>
<thead>
<tr>
<th>Reference Source</th>
<th>Backfill Material</th>
<th>Rock-Fill Interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Mitchell et al., 1982)</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>(Dirige et al., 2009)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>(Li et al., 2014)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Therefore the stability analysis of the backfill material given the extraction of the secondary stope has been developed with respect to two failure scenarios; a sliding plane within the plug pour and a sliding plane intersection the top surface of the plug. The solutions proposed by Li (2014) can be used for either the design of the backfill material utilized in the plug and final pours as well as a stability analysis of the exposed backfill. According to Li (2014) the stability of the backfill material is a function of the materials cohesive strength. Therefore, it is suggested that the backfill material design be performed with respect to the following steps;

1. Determining the minimum required cohesion of the final pour with respect to the cohesive ratio between the backfill-rockmass interface and final pour backfill material 

\[ r_{ij} \] ranging from 0 to 1:

\[ 2c = \frac{\gamma \left[ H_f - \frac{B \tan(\alpha)}{2} \right]}{\left( (FS - \frac{\tan(\phi)}{\tan(\alpha)}) \sin(2\alpha) \right)^{-1} + r_{ij} \left( H_f - \frac{B \tan(\alpha)}{2} \right)} \]  

(Eq. 2-6)
II. Determining the optimal plug pour to final pour cohesive ratio \( (r_p) \) with respect to the cohesive ratio between the backfill-rockmass interface and the final pour backfill material \( (r_{ff}) \), and the cohesive ratio between the backfill-rockmass interface and plug pour backfill material \( (r_{ip}) \) ranging from 0 to 1:

\[
r_p = \frac{\left( y - \frac{2r_{if}c}{L} \right) H_f + y_p \left( H_p - \frac{B \tan(\alpha)}{2} \right)}{\left( y - \frac{2r_{if}c}{L} \right) \left( H_f - \frac{B \tan(\alpha)}{2} \right) + 2r_{ip}c \left( H_p - \frac{B \tan(\alpha)}{2} \right)}
\]  \hspace{1cm} (Eq. 2-7)

III. Calculating the minimum required cohesive strength of the plug pour \( (c_p) \) as follows:

\[
c_p = r_p c
\]  \hspace{1cm} (Eq. 2-8)

Similarly, Li (2014) developed an analytical equation for evaluating the stability of the side exposed backfilled stope (FS) by analyzing failures with respect to a sliding plane within the plug \( (FS_1) \) and a sliding plane intersecting the top of the plug \( (FS_2) \).

\[
FS = \min \left\{ \frac{FS_1}{FS_2} \right\}
\]  \hspace{1cm} (Eq. 2-9)

\[
FS_1 = \tan(\phi) \left( y - \frac{2r_{if}c}{L} \right) H_f + y_p \left( H_p - \frac{B \tan(\alpha)}{2} \right) \sin(2\alpha) \]  \hspace{1cm} (Eq. 2-10)

\[
FS_2 = \frac{\tan(\phi)}{\tan(\alpha)} + \left( y - \frac{2r_{if}c}{L} \right) \left( H_p - \frac{B \tan(\alpha)}{2} \right) \sin(2\alpha) \]  \hspace{1cm} (Eq. 2-11)

where \( c \) is the cohesive strength (kPa) of the final pour; \( y \) (kN/m\(^3\)) is the unit weight of the final pour; \( H_f \) is the height (m) of the final pour material; \( \phi \) is the angle of friction (\(^\circ\)) of the final pour material; \( y_p \) (kN/m\(^3\)) is the unit weight of the plug pour; \( H_p \) is the height (m) of the plug pour material; \( B \) is the width (m) of the stope and \( \alpha \) is the angle (\(^\circ\)) between the sliding plane and the wall which is also equal to 45\(^\circ\) + \( \phi/2 \).

2.4 Assumptions Made

Since its introduction by Robinksy in 1975, CPB have provided the mining industry with an effective and economical ground control material for the support of stope walls and the immediate back. Over the past three decades, technological innovations with respect to CPB as a means of ground support has allowed for an increase in the overall health and safety of the mining operations as well as increases in productivity through the application of primary-secondary stope extraction sequencing. Therefore current academic research, not limited to those previously mentioned, has been focused on better understanding the behavior of the CPB...
and its ability to redistribute stress with the means to further optimize backfill materials as well as production sequencing for single and multiple stope mining operations. However, much of the research being conducted has made large assumption in the development of analytical solutions, numerical models, and stability analyses (see Table 2-2).

The analytical solutions previously discussed in this paper all assumed that the backfilled stope was instantaneously excavated and instantaneously backfilled with a homogenous CPB material. Similarly, the numerical models utilized to validate the developed analytical solutions utilize a homogeneous backfill material which is often instantaneously placed (excluding Li and Aubertin (2009a) and Falaknaz et al. (2015) as shown in Table 2-1 and Table 2-2). With respect to industry operations, it is known that the backfilling process is done as a series of lifts and includes two main phases; plug and final pour. The plug pour is the initial phase of the backfilling process and utilizes a backfill with increased amounts of cementitious material proving a solid foundation for the backfilled stope as well as preventing any potential of material breakthrough inundating other areas of the mine workings. Once the Plug Pour has been completed through a series of lifts, the backfilling process continues with the Final Pour phase which consists of a much lighter and less cementitious backfill material.

While the analytical solutions were developed in an attempt to accurately estimate the transfer of stress from the backfill material to the surrounding rockmass with respect to a phenomenon previously defined as stress “arching”, many assumptions have been made in defining the backfill-rockmass interface (see Table 2-3 and Table 2-6). From the numerical models conducted to validate these analytical solutions, parametric analyses highlight the enormous effect the backfill-rockmass interface properties have on the stress distribution within and around the backfilled stope area. Increasing the friction angle of the backfill-rockmass interface resulted in an increase in stress transfer therefore contributing to a reduction of stress concentrations in the backfill material while increasing the cohesion of the backfill also resulted in a reduction of stress concentration in the backfill material. Similarly, stability analyses for a backfilled stope with an open face assumed that the cohesion of the backfill-rockmass interface was equal to the cohesion of the backfill material, and completely neglected the shear strength (cohesion and angle of friction) along the back wall as well as the angle of friction for the two adjacent side walls. By more accurately defining the properties along the backfill-rockmass interface, industry engineers will be provided with a more realistic representation of stress redistribution by the backfill material as well as backfill stabilities during the excavation of the adjacent secondary stope.

2.5 Summary and Future Work

With a growth in industry application and knowledge of cemented paste backfill (CPB) as a means of ground support, stope-and-fill mining operations are increasingly seeking a cost effective and safe means of achieving total extraction of the mining reserve. Literature suggests that in attempting maximum extraction of the ore reserve, operators employ a primary-secondary sequenced stope panel. Here, primary stopes are initially removed and backfilled with a cemented paste backfill material. This backfill must be self-supporting and able to remain stable when the backfill material loses its confinement during the excavation of the adjacent secondary stope. Confinement of the backfill material is only regained once the secondary stope has been backfilled. While this seems to be commonly utilized within the mining industry, there
is conflicting literature in its application. There is little published literature documenting successful/unsuccessful implementation of the primary-secondary stope sequencing method or investigations into the behavior, stress distributions, or optimization of multiple stope and fill operations. In fact, research and in situ testing conducted by Cai (1983) suggests that the backfill material is incapable of supporting the total weight of the overburden and therefore can only be considered as a secondary support system.

Research is currently being conducted at the University of Kentucky in an attempt to optimize stope and fill mining sequences through the analysis of stress distributions and stability of multiple narrow vertical backfilled stopes. Analytical investigations are seeking to more realistically approximate stress redistributions within CPB with respect to staged backfill sequencing as well as time-dependent curing behaviors. Similarly, laboratory investigations are to be conducted further clarifying the cohesive and frictional behavior of the backfill-rockmass interface. Utilizing numerical modeling to validate the results of these analytical and laboratory investigations, the net result of this research effort is expected to not only provide the mining industry with knowledge of cemented paste backfill material for the efficient and economical extraction of mining reserves but also to enhance underground safety through a more comprehensive understanding of the behavior and ground control application of cemented paste backfill.

2.6 References


3 Development of Numerical Model for the Analysis of Stress Distributions for a Single Narrow Vertical Backfilled Stope

The following article was submitted to the 2018 Society of Mining Engineering (SME) Annual Conference and Exposition held in Minneapolis, Minnesota, USA. This article was accepted for presentation at the conference by an SME technical review committee based on the technical and critical review of the papers synopsis.

Stability Assessment for Stope-and-Fill Mining Operations

Christopher Newman, University of Kentucky; Lexington, Kentucky; United States of America
Zach Agioutantis, University of Kentucky; Lexington, Kentucky; United States of America

Full Citation:

3.1 Synopsis
Over the past decade, as conventional underground deposits have been depleted, mining operations have been forced to produce at greater depths and in more geologically and geometrically challenging conditions. As such, there has been a global increase in the application of cemented paste backfill (CPB) in tabular deposits utilizing open stope mining method with a delayed backfill placement. Despite the extensive use of CPB, many fundamental factors affecting the design of safe and economical fill structures are still not well understood. A critical issue in the design of backfilled stopes is the determination of stress states within the fill material itself as well as the surrounding rockmass.

Analytical equations provide a means of quickly evaluating the effectiveness of a given design. However, in developing these equations large assumptions are implemented to simplify the design problem. It is important that one understands these simplifications as well as their effect on the overall design. This paper investigates common analytical equations utilized in the evaluation of single vertical backfilled stopes and their assumptions through comparisons to numerical modeling results.

3.2 Introduction and Background
As the mining industry continues to produce at greater depths and in more geometrically and geologically complex conditions, cemented paste backfill (CPB) has gained traction as a means of providing localized ground support in modern stope-and-fill mining operations. The application of CPB in stope-and-fill mining as a ground support material has led to the reduction of mine
waste costs, while increasing both mine production and stability. In an attempt to achieve total extraction of the mining reserve, stope-and-fill mining operations often employ a primary-secondary excavation-support sequence (see Figure 3-1). In this practice, primary stopes are initially excavated and then backfilled in a two-stage pour; plug and final pours. During the first stage (plug), a CPB material with increased cementitious content is placed at the bottom of the stope providing a strong base from which to build a backfill structure as well as protect mine works from material breakthrough. Following placement, the backfill plug is allowed to cure to a given strength as designated by the mine design. Upon achieving the required cure strength, a less cementitious CPB material is used to backfill the remaining stope area. This is referred to as the final pour stage. With all primary stopes excavated and supported using backfill, the extraction of the secondary stopes commences as primary stopes are utilized as artificial pillars. While the application of CPB in a primary-secondary extraction-support mining sequence allows for a substantial increase in reserve recovery, it is imperative the mining personnel and planning engineers have a clear understanding of the material’s behavior and stress interaction with the surrounding rockmass to ensure the most efficient, cost-effective, and safe extraction of underground deposits.

Due to modern technological innovations with respect to CPB, many academics, industry professionals, and regulatory agencies have begun to reevaluate the fundamental factors concerning the safe and economical design of CPB underground structures. With respect to single and multiple stope-and-fill mining operations, a critical design issue has, and continues to be, the determination of the stress state within the backfill material and the surrounding rockmass. Recently, contributions from Li and Aubertin (2009), Ting et al. (2014), Falaknaz et al. (2015), etc. have provided new insights into stress distributions around single vertical, inclined, and adjacent backfilled stope respectively. From these numerical, physical, and analytical investigations as well as field measurements, one finds that given the backfill material is less ridged than the surrounding rockmass, CPB material will consolidate under load and transfer a portion of the overburden weight onto the rigid abutments due to frictional interfaces between that backfill and adjacent rockmass. As described in Newman and Agioutantis (2017), vertical stress within the backfill material is reduced due to the development of shear stress along the backfill-rockmass interface and is commonly referred to as stress “arching” (Figure 3-2).
The concept of stress transfer has been utilized in a wide swath of engineering designs such as stress conditions around buried conduit pipe (Marston, 1930), vertical stress and support requirements for tunneling (Terzaghi, 1943), wall pressures within grain silos (Blight, 1986), etc. In evaluating the stress condition within a single vertical narrow backfilled stope in a fully drained condition, Aubertin et al. (2003) proposed the following equations for vertical and horizontal stress at a depth $h$ into the backfill material:

$$\sigma_{vh} = \frac{\gamma B}{2K \tan(\delta)} \left[ 1 - \exp\left( -\frac{2K \tan(\delta)}{B} h \right) \right]$$
(Eq. 3-1)

$$\sigma_{hh} = \frac{\gamma B}{2 \tan(\delta)} \left[ 1 - \exp\left( -\frac{2K \tan(\delta)}{B} h \right) \right]$$
(Eq. 3-2)

where $B$ is the stope width (m); $\delta$ (°) is the friction angle of the backfill-rockmass interface; $\gamma$ (kN/m$^3$) is the unit weight of the backfill and the earth pressure coefficient ($K$) can be expressed as:

$$K = K_0 = 1 - \sin(\phi)$$
At rest condition
(Eq. 3-3)

$$K = K_a = \tan^2 \left( 45 - \frac{\phi}{2} \right)$$
Active condition
(Eq. 3-4)

$$K = K_p = \tan^2 \left( 45 + \frac{\phi}{2} \right)$$
Passive condition
(Eq. 3-5)
where $\phi$ is the internal friction angle of the CPB material. The work initially proposed by Aubertin et al. (2003) has been further expanded to incorporate cohesive soils, non-linear stress distributions, non-vertical geometries, etc., as outlined in Newman and Agioutantis (2017).

While the significant amount of research and field monitoring of narrow backfilled stopes has increased our knowledge of how stress redistributes itself with respect to stope-and-fill mining operations, several assumptions have been made in the development of both analytical equations and numerical models. This paper presents preliminary investigations into the stress transfer mechanism along the backfill-rockmass interface with respect to a single narrow vertical backfilled stope.

3.3 Numerical Model

Previously, various authors have utilized both the two- and three-dimensional FLAC code (Itasca, 2002) in analyzing stress distributions with respect to stope-and-fill mining operations. Therefore, to maintain consistency with proceeding literature, a preliminary two-dimensional single narrow vertical stope has been developed using FLAC3D (version 4.01). Imposed boundary conditions, geometry, and material properties are shown in Figure 3-3. The representative stope is located at a depth of 300 m (to the stope floor), a total width of 6 m, and a total height of 45.5 m. The CPB structure is modeled as five backfill lifts for a total fill height of 45 m. A 0.5 m void space is left at the top of the stope to represent the poor contact between the roof and backfill material as well as the self-consolidating properties of CPB materials. Under the assumption that a smaller element size will provide the most accurate result and to easily match the dimensions of the stope, 0.5 m square brick elements were implemented in the representation of the stope area and rockmass. Model boundaries (eastern and western) were placed a distance of 197 m from the edge of the stope area while the northern boundary extend to a representative surface (elevation of 0 m).
Figure 3-3: Model schematic of boundary conditions and geometries

The bottom of the model is fixed in both the x-, y-directions while the western boundary is fixed in the x-direction. The western boundary has been defined as a line of symmetry (fixed in x-direction) such half the model can be solved about the y-axis. The northern boundary (surface) has been defined as free or not fixed. Given that this is a three-dimensional representation of a two-dimensional problem, the z-direction has been fixed throughout the model.

To obtain a 1:2 vertical-to-horizontal insitu stress condition, gravity (grav) was set to -10 in the y-direction, while a vertical stress (syy) gradient of -0.027 and a horizontal stress (sxx) gradient of 0.027 were initialized in the y-direction. This insitu stress condition is representative of the stress regime encountered in the Canadian Shield (Aubertin et al. (2003), Li and Aubertin (2009), Falaknaz et al. (2015), Sivakugan et al. (2014)).

Model properties were assigned as stated within the literature. All CPB material was defined as a homogeneous, isotropic, elastic plastic material with respect to the mechanical Mohr-Coulomb material model (mech mohr) given a bulk (bulk) modulus of 166.7 MPa, a shear modulus (shear) of 125 MPa, a density (den) of 0.00183549 *10^{-6} kg/m^3, a cohesion (coh) of 0 kPa, an angle of internal friction (fric) of 30 degrees, and a dilatancy angle (dil) of 0 degrees (see Appendix I). The rockmass material has been defined as a homogenous, isotropic, linear elastic material (mech elastic) given a bulk modulus of 29412 MPa, a shear modulus of 11278 MPa, and a density of 0.00275323 *10^{-6} kg/m^3. It should also be stated, that interface elements were not defined at backfill-rockmass or backfill-backfill interfaces.

The progression of numerical simulations within the model was orchestrated as to be representative of actual mine production sequencing. As illustrated in Figure 3-4, Step 1 simulates the insitu stress condition within the rockmass. Step 2 simulates the stress conditions
following the instantaneous excavation of the stope area. Steps 3 through 7 simulate the backfilling process as material is placed in lifts until the stope has been backfilled. Each numerical simulation within the model was determined with respect to a mechanical ratio (mech ratio) of $10^{-8}$ allowing all elements to settle to significantly insignificant velocity magnitudes.

Figure 3-4: Event sequencing within model

3.4 Results & Discussion

The vertical and horizontal distributions of within the backfill material are shown along the VCL (Figure 3-5) and stope wall (Figure 3-6). From both graphs, one finds that the stress within the backfill material is less than the gravity loads signifying the presence of a stress transfer mechanism between the backfill material and surrounding rockmass. Figure 3-5 and Figure 3-6 both indicate large compressive stress concentrations within the first backfill layer caused by a combination of floor heave and wall closure. As one progresses farther away from the influence of the heaving floor, stress magnitudes are reduced as the backfill material is loading solely by wall convergence eventually reaching 0 MPa at the top of the CPB structure. Furthermore, as shown in Figure 3-7 and Figure 3-8, one finds that the stress distributed around the backfilled stope returns to far-field stress conditions.
Figure 3-5: Distribution of vertical and horizontal stress along the VCL of a single vertical narrow backfilled stope

Figure 3-6: Distribution of vertical and horizontal stress along the walls of a single vertical narrow backfilled stope
Given the homogenous, isotropic, and elastic rockmass material, the distribution of stress about the stope is similar in behavior to stress distributions about a circular opening as described by Kirsch (1898). For example, in Figure 3-7, one finds that the horizontal stress along the vertical center line (VCL) greatly increase from far-field conditions upon entering and exiting the backfilled stope analogous to the increase in tangential stress along the vertical axis of the Kirsch circle. Similarly, in Figure 8, the vertical stress along the VCL rapidly decreases in magnitude upon entering and exiting the backfilled stope. With respect to the Kirsch circle, the radial stress should be zero at the edge of the excavation. However, it is important to note that because of insitu stress conditions (1:2 vertical-to-horizontal stress ratio) as well as the concentration of high horizontal stress concentrations along the roof and floor of the stope, there is an increase in the vertical stress due to the Poisson’s effect of the rock.

Furthermore, to ensure stability, all models were evaluated with respect to velocities in the x- and y-directions. Although results indicate that elements are still in motion, magnitudes in the
range of \(10^{-08}\) to \(10^{-09}\) are deemed as insignificant and therefore the one can state that all elements have settled to their final position upon completion of the numerical simulation.

3.5 Conclusion and Future Work

As the knowledge of cemented paste backfill (CPB) as a means of ground support continues to grow, one’s ability to accurately predict stress distributions around a backfilled stope is imperative in the design of cost effective and safe extraction of the mining reserve. While multiple publications within the literature indicate stress distribution results for single and multiple backfilled stope, frequently the input parameters and sequencing of numerical simulations do not represent real world conditions often citing that models have been adapted to obtain a given set of data or results. The preliminary model discussed within this paper is a first step in developing a means of predicting backfill material behavior as well as backfill-rockmass stress interaction with respect to operationally accurate production sequencing.

Work currently being conducted at the University of Kentucky seeks to better optimize stopes-and-fill mining sequence through a thorough understanding of stress distribution and material stability in narrow backfilled stopes. Analytical and numerical investigations are being conducted to more realistically approximate stress distributions through and round backfilled stopes with respect to CPB staged sequencing and time-dependent curing properties. Similarly, laboratory testing is to be conducted examining the cohesive and frictional behavior of the backfill-rockmass interface as well as the backfill-backfill interface. Building upon this preliminary model, the net result of this work is to validate analytical results and laboratory investigations providing the mining industry with a numerical design methodology for the efficient and cost-effective extraction of mining reserves while maintaining underground stabilities and enhancing mine safety.

3.6 References


4 Numerical Investigation into the Distribution and Redistribution of Stress for a Single Narrow Vertical Backfilled Stope

The following article was submitted to the 2018 International Conference on Ground Control in Mining held in Morgantown, WV, USA. This article was accepted for presentation at the conference by an ICGCM technical review committee based on technical and critical review of the paper by a minimum of two technical reviewers.

Development of a Numerical Model for the Approximation of Stress Distribution for a Single Vertical Backfilled Stope

Christopher Newman, University of Kentucky; Lexington, Kentucky; United States of America
Zach Agioutantis, University of Kentucky; Lexington, Kentucky; United States of America

Full Citation:

4.1 Synopsis
As conventional underground deposits are continuing to be depleted, mining operations have been forced to produce at greater depths and in more geologically and geometrically challenging conditions. Over the past decade there has been a global increase in the application of cemented paste backfill (CPB) material as a means of ground support in open stope mining operations. Although CPB has been extensively used within the industry, there are many fundamental factors affecting the design of safe and economical fill structures that are still not well understood. A critical design issue with respect to backfilled stopes is determining the stress state within the fill material as well as the surrounding rock.

This paper details the development of a reliable numerical model for the simulation of stress distributions around the excavated stope area as well as through the backfill material. Through discussions on modeling parameters and output results, one is provided with insights into the mechanisms of stress redistribution allowing for further accuracies in simulating the behavior of the CPB material as well as its interaction with the surrounding rockmass.

4.2 Introduction and Background
Modern technological innovations with respect to material processing, cementitious composition and chemical additives, and material transportation have provided the mining industry with a ground support material which greatly reduces mine waste costs while, when
used appropriately, increases reserve production and mine stability. As mining operations continue to produce in more complex geologic and geometric conditions, cemented paste backfill (CPB) has become commonly employed within primary-secondary excavation-support sequencing allowing for total extraction of the mining reserve. As shown in Figure 4-1, primary stopes are initially excavated and then backfilled in a two-staged pour - plug and final pours. The “plug” (initial pour), is initially placed at the bottom of the stope with a CPB material of heightened cementitious material. While the “plug” provides a strong foundation on which to build the rest of the CPB structure, it also provides protection against barricade breakthroughs (Li and Aubertin, 2009), as well as providing operations a means of underhand stope-and-fill mining through the utilization of an artificial sill pillar (Hughes, et al., 2011). Following its placement, the “plug” is allowed to cure to a designated design strength. Upon completion of the “plug,” a less cementitious “final” pour material is used to backfill the rest of the excavated area.

![Figure 4-1: Primary-secondary excavation-support sequencing for stope-and-fill mining operations.](image)

Once all primary stope areas have been excavated and backfilled, excavation-support sequencing is initiated within the secondary stope areas utilizing backfilled primary stopes as adjacent artificial pillars. As described above, the primary-secondary extraction-support sequencing for stope-and-fill mining operations provides a means of significantly increasing reserve recovery while maintaining the stability of the underground working environment. Through the utilization of engineered backfill material in conjunction with the stope mining techniques, one is able to provide localized ground support to the stope walls and back horizon for the prevention of caving/roof falls as well as rock bursts (Coates, 1981). With a better understanding of stress distributions in the excavated area as well as through the backfill material, modern stope-and-fill mining operations are provided with the means of better evaluation of pressures at the stope barricade, optimization of backfill mixes for site-specific conditions, and more accurate analysis of single- and multiple-stope mining conditions and behaviors. Due to the intricacies involved in developing an economical, efficient, and safe stope-and-fill mine design, it is imperative that planning engineers and operational personnel have a
clear understanding of the material behavior and interaction with the surrounding rockmass to ensure the safe extraction of underground mine reserves.

Dating back to the 1950s, the mining industry has a long history in the application of backfill within stope-and-fill mining operations, providing cost-effective, productive, and safe mining techniques for high recovery and low dilution mining of narrow or irregular reserve bodies where localized stability of the mine environment is of concern (Darling, 2011). As the ground control advantages of CPB materials became more apparent, academic, industry, and regulatory professionals have begun to reevaluate the fundamental factors concerning the design of underground backfill structures. With respect to single- and multiple-stope mining operations, a critical design issue has been, and continues to be, the approximation of stress states within the backfill material and the surrounding rockmass (Fall and Nasir, 2010). It is often the case that the analysis and/or design of underground CPB structures for stope-and-fill mining operations are simplistic in nature. For example, stress approximations are made with respect to the gravitational loading of the backfill material and do not effectively utilize stress behaviors stemming from the actual geometry and configuration of the each excavation opening.

However, as summarized by Newman and Agioutantis (2017), given a backfill material that is less rigid than the surrounding rockmass, once placed in the stope the CPB material will begin to settle under its own weight transferring a portion of the gravity load from the backfill material onto the more rigid abutments (stope walls) due to the frictional interface between the backfill and the adjacent rock wall. Load transfer within the backfill material has been observed through numerical investigations (Li et al., 2005; Ting et al., 2014; Falaknaz et al., 2015; etc.) as well as through site-specific measurements (Helinski et al., 2011; Thompson, et al., 2012).

Despite the extensive amount of research and field work conducted on better understanding the impact of CBP on narrow backfilled stopes, the mining industry is still lacking a thorough knowledge base on the behavior of CPB as well as the mechanism of stress redistribution with respect to stope-and-fill mining operations (Fall and Nasir, 2010). While the literature contains numerous publications on the approximation of stress distributions within the backfill material, these analytical and numerical methods have been developed given significant assumptions with respect to model boundaries and material properties, as outline in Newman and Agioutantis, 2017. The following paper presents a simple two-dimensional model which has been defined to further investigate load transfer within the backfilled stope as well as the distributions and re-distribution of stress about the excavated stope area providing industry professionals with a means by which to more design stopes and pillars, evaluate underground stabilities as well as further optimizing reserve recovery with respect to stope-and-fill mining operations.

4.3 Numerical Modeling
Numerical models provide a flexible and versatile tool for solving complex problems through the application of input parameters, boundary conditions, loading scenarios, and material models that describe site-specific conditions and behaviors. In maintaining consistency with the literature, a two-dimensional numerical model has been developed using RocScience2D (RocScience, 2018) for the analysis of stress distributions for a single, vertical, fully-drained backfilled stope given an x-(width), y-(height), and z-(length) coordinate system (Figure 4-2). The geometry of the surrounding rockmass was selected such that stress within the overburden will
return to far-field conditions a given distance away from the excavated stope. Discretization and meshing of the model was performed based on the automated process within RocScience2D (RS2) allowing for a coarse mesh defined within surrounding rockmass and a fine mesh for the backfill material and immediate stope area. Boundary conditions have been applied to each edge of the model. The southern boundary of the model is fixed in the x- and y-directions while the east and west boundaries are fixed in the y-direction. The northern model boundary represents a flat surface and, therefore, is defined with respect to a free surface boundary condition. The excavated area has been defined at a depth of (-) 300 from the surface to the stope floor.

![Figure 4-2: Schematic of modeling geometry and boundary conditions (not to scale).](image)

**Table 4-1: Stope geometry and material properties for numerical Model A and Model B**

<table>
<thead>
<tr>
<th>Numerical Model</th>
<th>Material Type</th>
<th>Material Model</th>
<th>Density ([10^3 \text{kg/m}^3])</th>
<th>Bulk Modulus ([\text{MPa}])</th>
<th>Shear Modulus ([\text{MPa}])</th>
<th>Cohesion ([\text{kPa}])</th>
<th>Angle of Friction ([\text{degrees}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model A</td>
<td>Backfill</td>
<td>Mohr-Coulomb</td>
<td>0.0018</td>
<td>167</td>
<td>125</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>Model B</td>
<td>Backfill</td>
<td>Mohr-Coulomb</td>
<td>0.0018</td>
<td>1460</td>
<td>560</td>
<td>125</td>
<td>30</td>
</tr>
<tr>
<td>Model A &amp; B</td>
<td>Rockmass</td>
<td>Linear Elastic</td>
<td>0.0027</td>
<td>29412</td>
<td>11278</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
The rockmass was defined such that it is represented as a homogeneous, isotropic, linearly elastic material with a Young’s Modulus \( (E_R) \) of 30 GPa, a Poisson’s ratio \( (\nu_R) \) of 0.33, and a unit weight \( (\gamma_R) \) of 27 kN/m\(^3\). The CPB material is represented as a homogeneous elastic-plastic material with respect to a Mohr-Coulomb failure criterion. Details on backfill material parameters are presented in Table 4-1 and have been adapted for numerical modeling (Aubertin et al., 2003; Li et al., 2005; Falaknaz, 2014) from laboratory testing results (Belem et al., 2000; Veenstra, 2013). The backfill material implemented in Model A (hypothetical) is a conservative representation of a soft paste material with no cohesive strength and a low internal friction angle, as similarly implemented within the literature, while the backfill of Model B (case study) represents a cemented paste (3.1% cementitious content) developed from tailings (75% by weight) at the Kanowna Belle (KB) gold mine with an ultimate compressive strength of 433 kPa.

Loading of the model was defined with respect to gravity and utilizes a 1:2 vertical-to-horizontal far-field stress ratio. Interface material along the planes of contact between the backfill material and the rock wall were not defined within this model. Loading of the rockmass material was defined with respect to both far-field stress and body forces, and the backfill material was defined with respect to body forces only.

The sequencing of mining events within the numerical model can have significant impacts on the results of the simulation (Li and Aubertin, 2007). In this model, the sequencing of underground stope-and-fill production stages was defined as detailed by Li et al. (2005) and Falaknaz (2014). As outlined in Table 4-2 and illustrated in Figure 4-3, initially the rockmass is solved for the insitu stress condition followed by the instantaneous excavation of the stope area. In RS2, the excavation of the rockmass material was simulated with respect to an “Excavate” material model which applies no material properties within a defined material boundary while allowing the material boundary to deform with respect to solution results. Upon excavation, the rockmass is allowed to deform until force equilibrium is achieved. Following the excavation, backfilling of the stope is initiated. Each backfill layer \( (\text{BF}_i) \) contains 8m of material and progresses from bottom to top. The placement of the fifth (top) backfill layer \( (\text{BF}_5) \) completes the backfilling of the stope area. The model is allowed to equilibrate after each sequencing stage defined within the model.

<table>
<thead>
<tr>
<th>Numerical Sequencing of Stope-and-Fill Mining Events</th>
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<tbody>
<tr>
<td><strong>Sequencing Stage</strong></td>
</tr>
<tr>
<td>Stage 1</td>
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<td>Stage 2</td>
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<td>Stage 3</td>
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<td>Stage 4</td>
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<td>Stage 5</td>
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<td>Stage 6</td>
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<tr>
<td>Stage 7</td>
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</tbody>
</table>
Two models are presented in this paper. The first, Model A, is a simplistic hypothetical case study representative of previously published numerical investigations that will aid in the discussion of mechanistic behaviors within the CPB material as well as the surrounding rockmass. A second model, Model B, has been adapted from Model A to simulate the Kanowna Belle (KB) case study as published by Helinski et al. (2011). Stope geometries and material properties (Table 4-2) were defined with respect to published literature (Falaknaz, 2014; Helinski et al., 2011) while rock properties were defined to represent a rockmass which is significantly stiffer than the backfill material.

4.4 Results of Numerical Modeling
The numerical results presented in this paper were obtained at three specific modeling stages within the simulated stope-and-fill operational sequencing - pre-mining (insitu condition), post-mining (excavation of the stope), and backfill (completed). Analysis of pre-mining results confirmed insitu stress conditions for a given model while post-mining results provided indication of stress distribution in the excavated stope area.

4.4.1 Numerical Model A: Hypothetical Case Study
Model A is a simplistic, hypothetical case study representative of previously published numerical investigations within the literature (Falaknaz, 2014; Li et al., 2005). These publications and others focus exclusively on the behavior of the CPB material and do not take into consideration the behavior of the surrounding rockmass. After the excavation of the stope area (height-to-width ratio > 4), stresses around the opening are distributed to accommodate the disturbance in the stress field; however, the vertical and horizontal stresses return to their far-field conditions a distance of 197 m (> 30 opening widths) away from the edge of the excavation (Figure 4-4). Furthermore, the radial stress at the wall of the excavation is zero and gradually increases to its far-field stress state, while the vertical stress distribution indicates the development of a tensile stress near the stope wall, transferring to compression 5m into the surrounding rockmass where it peaks a distance of 40 m (or ~ 7 opening widths) away from the excavated stope. Checking whether stresses away from the opening return to insitu conditions, is an important step in the validation of any numerical model for underground openings which (a) can be used to...
determine the effective boundaries of the mesh and (b) ensures that stress redistribution values close to the opening are not affected by boundary conditions.

Figure 4-4: Distribution of stress in surrounding rockmass progressing from the wall of the excavation to the edge of the model.

The distribution of stress within the rockmass was further evaluated with respect to varying vertical-to-horizontal far-field stress conditions. In comparing the results of these model runs, one finds that the distance by which the peak stress is displaced into the rockmass is significantly affected by the magnitude of the far-field horizontal stress or by the magnitude of the vertical-to-horizontal stress ratio (Figure 4-5). Furthermore, these results find that the development of tensile stress along the walls of the excavation are a function of stope geometry.
Figure 4-5: Distribution of vertical stress within the surrounding rockmass for varying insitu stress ratios.

Backfilling of the excavated stope was achieved through the application of five (5) consecutive backfill layers. The backfilling process was numerically simulated by applying backfill material models and properties with respect to “stage” boundaries. The model is allowed to equilibrate after each backfilling step. Stress distributions within the backfill material were evaluated following the placement and numerical solution for a given backfill (BF) layer. As shown in Figure 4-6 and supported by the literature, the vertical and horizontal stress distributions within the backfill material signify a load transfer mechanism between the backfill and surrounding rockmass as the stress at a given point within the CPB structure is significantly less than the (expected) gravitational load at the same point. Modified Marston’s (Aubertin et al., 2003) equation and published numerical simulations (Falaknaz, 2014) indicates that this model accurately replicates material conditions and behaviors with respect to our current knowledge and understanding of CPB as a ground support material.
Due to the importance of maintaining the stability of the backfill barricade with respect to material breakthrough, the distribution of stress in the vicinity of the stope floor was further analyzed. As previously shown in Figure 4-6, there is a slight increase in stress within the initial backfill (BF$_1$). To investigate the development and distribution of stress within backfill layer one and the immediate floor material, Figure 4-7 provides a detailed view of the results presented in Figure 4-6. Here, one finds that the increase in stress is a result of stress continuity within the numerical model. Insitu loading of the rockmass is represented by the solid black (linear) line beginning at the stope floor (distance of 45m) and continuing into the immediate floor material while the dashed black line represents the gravity loading of the backfill material in the vicinity of the stope floor. Upon placement of the initial backfill layer, stress is transferred from the surrounding rockmass to the fill material. Backfill loading within the vicinity of the stope floor gradually increases as subsequent backfill layers are placed. These numerically observed behaviors within the backfill were not significantly impacted by varying the horizontal stress magnitude or the magnitude of the vertical-to-horizontal ratio. Furthermore, modifications to the elastic modulus of the backfill material does not have a significant effect on the distribution of stress as similarly observed by Li and Aubertin (2009).
4.4.2 Numerical Model B: Kanowna Belle (KB) Mine

The backfilling of a given stope at the Kanowna Belle mine, located in Western Australia, was instrumented to obtain a better understanding of stress concentrations within the backfill material and at the backfill barricade (Helinski et al., 2011). For the purposes of this paper, backfill stress monitoring data collected at the floor of a 15m x 40m (width x height) will be utilized for validating the discussed numerical model. Utilizing similar modeling techniques and procedures as previously outlined and discussed in Model A, Model B (height-to-width > 2) provides a simplistic two-dimensional model for the analysis of stress distributions within the backfill material as well as the surrounding rockmass for a stope at the KB mine. After the instantaneous excavation of the stope, similar to the results of Model A, the horizontal stress returns to its far-field stress state 197m from the wall of the excavation. While the peak vertical stress is located a distance of 28m (or 1.75 opening widths) the stress returns to is far-field state 150m (or ~ 10m) from the edge of the stope wall. In accordance with the stress redistribution behavior observed in Model A, the displacement of peak stress into the rockmass is affected by the magnitude of the vertical-to-horizontal stress ratio and the development of tensile stress along the walls of the excavation are a function of stope geometry.

Following the excavation of the KB stope, backfilling of the stope was numerically simulated through the application of “stage”d backfill material. The model is allowed to equilibrate after each backfilling step. Stress distributions within the CPB structure were evaluated following the placement and numerical solution for the fifth backfill (BF\textsubscript{5}) layer. Analogous to the results presented in the Model A, the vertical and horizontal stress distributions within the backfill material indicate a similar load transfer mechanism (Figure 4-8). In comparing the end-of-filling vertical stress measurement at the stope floor 200 hours after the backfilling of the stope was initiated, represented by the data point, to the results of Model B, one finds a discrepancy between the numerical results and field observations. Further investigating the development and distribution of stress within the initial backfill layer and the immediate floor material, Figure 4-7: Vertical stress development and distribution at the vicinity of the stope floor where distance has been defined from the top of the backfill structure to 0.5 meters into the stope floor rockmass material.
4-9 provides a detailed view of the results presented in Figure 4-8. Similar to the behavior observed in Model A, one finds that the increase in stress is a result of stress continuity within the numerical model. Insitu loading of the rockmass is represented by the solid black line beginning at the stope floor (distance of 45m) and continuing into the immediate floor material. The gravity loading of the backfill material in the vicinity of the stope floor is outside the viewport of this chart. Upon placement of the initial backfill layer, stress is transferred from the surrounding rockmass to the fill material. Backfill loading within the vicinity of the stope floor gradually increases as subsequent backfill layers are placed. The discrepancy between numerical results and the measured data can be attributed to the requirement of stress continuity throughout the model as previously discussed in Model A.

Furthermore, it should be noted that the numerical results presented in this paper are calculated with respect to stress equilibrium and are, therefore, representative of final stress conditions and cure properties while the data provided by Helinkski, et al. (2011) are time dependent.

Figure 4-8: Load transfer within KB backfill compared to end of fill site measurements (red)
Summary and Conclusions

The numerical simulations presented in this paper provided detailed analysis of the behavior and mechanism by which stress distributes itself in the excavated stope as well as through the backfill material. Numerical investigations presented in the international literature focus solely on the distribution of stress within the cemented paste backfill (CPB) material and do not allow for the consideration of stress interactions between the paste fill material and the surrounding rockmass. Numerical results indicate that stress distributions within the surrounding rockmass follow the generalized behavior of the redistribution of stress in an excavation, validating these models for detailed investigations of rockmass behaviors with respect to stope-and-fill mining operations. Due to the slender stope geometries, tensile stress zones developed along the stope walls and transferred to a compressive stress state where the peak vertical stress resides. Furthermore, in agreement with published literature and site measurements, both numerical models indicate the presence of a load transfer mechanism within the backfill material. While the results presented in this paper are validated by those of Falaknaz (2014) and Helinski et al. (2011), both numerical models show a slight discrepancy in the vicinity of the stope floor. As previously discussed, this increase in stress may be a result of stress continuity within the numerical model. In placing the initial backfill layer and making contact with the stope floor, stress is allowed to transfer between the materials with respect to the loading state defined within the model.

Work will continue in the development of an appropriate model for the simulation of stress distributions with respect to single- and multiple-stope mining operations by incorporating more appropriate material models and parameters with respect to the backfill material as well as the backfill-rockmass interface. Laboratory testing conducted by Kaklis et al (2018) indicates that the properties of cemented paste are not constant and change with the depth of the backfill layer and curing time. These results were further confirmed by the work of Chen et al (2017). Similarly, laboratory test results with respect to the backfill-rockmass interface suggest that shear stress along the interface is a function of roughness, cure time, and chemical decomposition (Manaras, 2009; Fall and Nasir, 2010; Koupouli, et al., 2016). The models
presented in this paper are able to provide further insights into the behavior and mechanism by which stress distributes itself in stope-and-fill mining operations. These models are simplistic in their nature and through the incorporation of more accurate representations of field conditions and material behaviors, will provide the mining industry with the means of evaluating global stability of stope-and-fill operations for the total extraction of the mining reserve.

4.6 Acknowledgements
The authors of this paper would like to acknowledge Dr. Essie Esterhuizen of NIOSH for his advice and expertise with respect to numerical modeling. His help was instrumental in the development of the presented numerical models as well as providing further insights into the distribution of stress about the excavated stope as well as through the backfill material.

4.7 References


Application of the Backfill-Rockmass Interface for the Numerical Analysis of Stress Distributions for Single Narrow Vertical Backfilled Stopes

The following article will be submitted for publication in a peer-reviewed journal or conference proceedings by the authors.

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Zach Agioutantis, University of Kentucky; Lexington, Kentucky; United States of America

5.1 Introduction and Background

Modern technological improvements in material processing has left many mining operations with an abundance of fine mill tailings. Initially developed as a means of disposing of waste underground, cemented paste backfill (CPB) engineering materials are now commonly utilized as ground support greatly reducing mine waste costs, increasing reserve recovery as well as stope stability. As mining operations continue to produce in more complex geologic and geometric conditions, cemented paste backfill (CPB) has become commonly employed within an excavation-support sequencing allowing for high extraction of the mining reserve.

As the advantages of CPB as a ground support material became more apparent, academic, industry, and regulatory professionals have begun to reevaluate the fundamental factors concerning the design of underground backfill structures. With respect to single- and multiple-stope mining operations, a critical design issue has been, and continues to be, the approximation of stress states within the backfill material and the surrounding rockmass (Fall and Nasir, 2010). It is often the case that stope-and-fill designs are simplistic in nature as stress within the backfilled stope is commonly approximated with respect to gravity loading of the CPB structure. However, as summarized by Newman and Agioutantis (2017), given the CPB material is significantly less stiff than the surrounding rockmass, when placed within the stope the backfill material will begin to settle under its own weight transferring the gravity load from the backfill to the stiffer adjacent rockmass. The load transfer from the CPB material to the surrounding rockmass is a function of shear stress development along the backfill-rockmass interface and has been observed within the backfilled stope numerically (Li et al., 2005; Falaknaz et al., 2015; Newman and Agioutantis, 2018) as well as through site-specific measurements (Helinski et al., 2011; Thompson et al., 2012).

While the literature contains multiple numerical investigations into the stress distributions within single vertical backfilled stopes, there are only six publications (to the author’s knowledge) which investigate the CPB-rockmass interface. Of these six publications, four are laboratory investigations (Nasir and Fall, 2008; Manaras, 2009; Koupoli et al., 2016; Koupoli et al., 2017) and two are numerical investigations (Liu et al., 2016; Liu et al., 2017). This paper investigates the distribution of stress along the vertical center line (VCL) of a single vertical fully-drained backfilled stope using the RocScience2D finite-element (FE) numerical code. In
comparing the stress results obtained by numerical models with and without consideration of the backfill-rockmass interface, one finds that the inclusion of the backfill-rockmass interface does not significantly affect the stress state within the backfilled stope.

5.2 Numerical Modeling

Numerical methods have provided the mining industry with a flexible and versatile tool for solving complex, modern problems through the utilization of model geometries and boundary conditions, material loading and models, as well as event sequencing for the approximation of site-specific conditions and behaviors. The model presented in this paper builds upon the numerical model previously introduced in Chapter 4. Here, a two-dimensional finite-element model (RocScience, 2018) was developed for the analysis of single and multiple vertically-drained backfilled stope with interfaces defined along the backfill-rockmass contact given an x-(width), y-(height), and z-(length) coordinate system (Figure 5.1). Model geometry and boundary conditions were defined such that vertical and horizontal stress returned to far-field conditions a given distance away from the stope area. The auto-discretization and auto-meshing utilities within RocScience2D (RS2) were utilized in the development of a coarse mesh within the surrounding rockmass with a finer mesh applied to the backfilled stope as well as the immediate back, floor, and walls.

Stope-and-fill operational sequences were defined with respect to a series of “stage”s within RS2. As outlined in Table 5-1 initially the model is solved for insitu conditions followed by the instantaneous excavation of the stope.

Figure 5-1: Schematic of modeling geometries and boundary conditions
Table 5-1: Numerical Sequencing of Mining Events

<table>
<thead>
<tr>
<th>Stage</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Insitu Stress Condition</td>
</tr>
<tr>
<td>2</td>
<td>Excavation of Stope A</td>
</tr>
<tr>
<td>3</td>
<td>Stope A, Backfill Layer 1</td>
</tr>
<tr>
<td>4</td>
<td>Stope A, Backfill Layer 2</td>
</tr>
<tr>
<td>5</td>
<td>Stope A, Backfill Layer 3</td>
</tr>
<tr>
<td>6</td>
<td>Stope A, Backfill Layer 4</td>
</tr>
<tr>
<td>7</td>
<td>Stope A, Backfill Layer 5</td>
</tr>
</tbody>
</table>

Figure 5-2: Numerical simulation of stope-and-fill operational sequencing while considering the backfill-rockmass interface

The stope has a width of 6m and is backfilled to a height of 45m with a 0.5m void space between the top of the backfill and the immediate stope back which allows for the self-consolidating behavior of the CPB material. The stope has been defined at a depth of 300m measured from the surface to the stope floor. The rockmass material has been defined as a homogeneous, isotropic, linearly elastic material with a Young’s Modulus (E_R) of 30GPa, Poisson’s ratio (ν_R) of 0.33, and a unit weight (γ_R) of 27 kN/m³. The backfill material has been defined as a homogeneous elastic plastic material with respect to a Mohr-Coulomb failure criterion with a Young’s Modulus (E_B) of 300 MPa, Poisson’s ratio (ν_B) of 0.2, a unit weight (γ_B) of 18 kN/m³, an internal friction angle of 30-degrees, a cohesion of 50kPa, and a dilatancy angle of 0-degrees. The backfill material employed in this model is a conservative representation of a soft paste material with an arbitrary cohesive strength and internal friction angle as similarly utilized and outlined within the literature (Falaknaz, 2014; Liu et al., 2016).

As previously indicated, interface elements have been defined within the numerical model to provide a more representative analysis of stress redistribution around and through a single vertical backfilled stope. The present model utilizes a series of open-ended joints which are defined within the model between the surrounding rockmass and the staged backfill material. The backfill-rockmass (material-rock) interface behavior is simulated with respect to the shear (cohesion and angle of friction) and stiffness (normal and shear) properties of that interface surface (Table 5-2).
Table 5-2: Interface material properties for numerical cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Cohesion [kPa]</th>
<th>Friction Angle [degree]</th>
<th>Normal Stiffness [GPa/m]</th>
<th>Shear Stiffness [GPa/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Backfill-Rockmass Interface Not Considered</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>VAR</td>
<td>30</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>VAR</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>50</td>
<td>30</td>
<td>VAR</td>
<td></td>
</tr>
</tbody>
</table>

Due to the difficulty in obtaining site-specific measurements, the material properties for the backfill-rockmass interface have been defined with respect to generalized values available in the literature. However, within the literature, there are two numerical methodologies implemented for the analysis of stress distributions and redistributions with respect to stope-and-fill mining operations; finite-element and finite-difference. While these numerical methods both provide users with a reliable analyses and accurate results, one should ensure that input parameters defined within the model have been implemented in accordance to the numerical code utilized for analysis of the backfilled stope. In determining the numerical stiffness (normal and shear) properties of the backfill-rockmass interface for a finite-element solution, the backfill-rockmass interface is commonly represented as a joint where the normal and shear stiffness is approximated with respect to Barton (1972) as recommended by the RocScience user’s manual (Eq.1).

\[ \frac{E_m}{E_i} = \left[ \frac{k_n \times L}{(k_n \times L) + E_i} \right] \]

where \( E \) and \( E_m \) are the elastic moduli for the intact rock and rockmass, respectively, \( k_n \) is the normal stiffness, and \( L \) is the mean joint spacing perpendicular to the direction of loading.

While often utilized in conjunction with finite element codes, users should understand that this formulation was developed with respect to empirical equations derived from physical lab testing observations of rock-to-rock interfaces. Therefore, this methodology for the determination of normal and shear stiffness does not lend itself to a backfill-rockmass (material-to-rockmass) interface and should only be implemented for joints which reside within a single material.

For finite-difference models within the literature, it is common for the stiffness of the backfill-rockmass interface to be approximated with respect to Eq. 2 as recommended in the FLAC user’s manual (Itasca, 2012). Here, \( K \) is the bulk modulus, \( G \) is the shear modulus, and \( z \) is the size of the smallest backfill element along the backfill-rockmass interface.

\[ k_n = k_s = 10 \times max \left( \frac{K + 4G/3}{\Delta z_{min}} \right) \]

Given the discretization and meshing algorithms utilized within RocScience, the \( z \) value could not be accurately determined by the authors. Therefore, the normal and shear stiffness of the backfill-rockmass interface has been defined as a generalized value of 20 GPa/m in accordance to the published literature. While this methodology has been commonly utilized within the literature, the normal and shear stiffness magnitudes determined with respect to Eq. 2 do not
lend themselves to accurately describing the stiffness of the backfill-rockmass interface. Furthermore, laboratory testing conducted by Koupouli et al. (2016) found shear stiffness of the backfill-rock interface to range from 45-260 MPa/m. From the author’s review of the literature, publications with respect to the determination of rock joint stiffness is sparse (Kulhawy, 1975; Bandis et al., 1983).

5.3 Results and Discussion
Within the following section, stress distributions along the VCL of a single vertical backfilled stope have been evaluated with respect to varying the material properties of the backfill-rockmass interface. Table 1 presents three numerical cases as well as details on interface parameters. A given parameter’s influence on the distribution of stress within a single vertical backfilled stope was analyzed by varying the material properties of the backfill-rockmass interface (specifically interface cohesion, friction angle, and stiffness) while holding all other material properties (i.e. rockmass and backfill) as well as the sequencing of simulated mining events constant.

5.3.1 Cohesion of the Backfill-Rockmass Interface
While the general trend of the stress distribution through the backfilled stope is similar, the introduction of the backfill-rockmass interface saw a reduction in the stress within the backfill material (Figure 5-3). The stress within the backfill when the backfill-rockmass interface is not considered is only slightly larger (about 2kPa) than stress results obtained from those considering interfaces with a cohesive value of 25-100kPa. In varying the cohesive strength of the interface one finds that the model becomes insensitive to interface cohesion values larger than 25kPa when considering a stiffness of 20 GPa/m and friction angle of 30-degrees. This demonstrates that as the shear strength of a given interface decreases, the stress within the backfill increases as the load transfer mechanism between the backfill material and the surrounding rockmass is reduced. While this behavior is similarly documented by Liu et al. (2016), the difference determined with respect to these models find that the change in stress with and without considering the backfill ranges between 1-5kPa.
Furthermore, as the cohesive strength of the backfill-rockmass interface approaches zero, the stress within the backfill increases from 0.21MPa for a cohesion of 25kPa to 0.24MPa for a cohesion of 0kPa (Figure 5-4). While this results in a significant change in the stress state along the VCL of the backfill (30kPa), with a peak vertical stress of about 200kPa within the backfill itself, this results in a stress increases of 13%.

5.3.2 Friction Angle of the Backfill-Rockmass Interface

Varying the friction angle of the backfill-rockmass interface resulted in similar behaviors as previously described with respect to the interface cohesion. As shown in Figure 5-5, the introduction of the backfill-rockmass interface saw a reduction in the stress. However, the
overall stress distribution within the backfill is not significantly different from results which did not take into consideration the backfill-rockmass interface. Although values ranged from 21- to 45-degrees, modeling results are insensitive to modification to the interface angle of friction when considering a stiffness of 20GPa/m and a cohesion of 50kPa.

![Figure 5-5: Vertical stress distribution along the VCL of a single vertical backfilled stope with varying interface friction angle.](image)

However, as the angle of friction for the backfill-rockmass interface approaches zero, stress within the backfill material increases from slightly from 0.21MPa for a friction angle of 30-degrees to 0.218MPa for a friction angle of 0-degrees (Figure 5-6). As similarly indicated by the literature (Kouplouli et al., 2016; Kouplouli et al., 2017), as the interface is continually weakened, the shear strength of the interface is significantly impacted resulting in a stress increase in the backfill material as the stress transfer mechanism between the backfill material and the rockmass is reduced. However, this modification only results in a 2% stress increase within the backfill material.
5.3.3 Stiffness of the Backfill-Rockmass Interface

As previously stated, there are several methodologies utilized within the literature for approximating the normal and shear stiffness of the backfill-rockmass interface. In reviewing the derivation and implementation of these methodologies (rock-to-rock), it is the opinion of the authors that none should be considered appropriate for defining the stiffness of the backfill-rockmass (material-to-rock) interface. In accordance with the literature available, the normal and shear stiffness have been set equal to each other and defined as 20 GPa/m. The insensitivity of the model with respect to the shear strength (i.e. cohesion and angle of friction) of the backfill-rockmass interface indicates too large a stiffness magnitude for utilization within a FE numerical code. As shown in Figure 5-7, in reducing the normal and shear stiffness by an order of magnitude, the stress within the backfill material increased 5kPa.

Figure 5-6: Comparison of vertical stress distributions along the VCL of a single backfilled stope considering and not considering the friction angle of the backfill-rockmass interface.
Figure 5-7: Vertical stress distribution along the VCL of a single vertical backfilled stope with varying interface stiffness.

From these results one finds that as the stiffness of the interface is reduced, the stress within the backfill increases due to a weakened backfill-rockmass interface resulting in a reduction in the stress transfer mechanism from the backfill to the surrounding rockmass. While this similar in behavior to the literature (Liu et al., 2016), the stress difference between numerical results considering vs not considering interfaces is in the range of 1-5kPa (Figure 5-8). When taking into consideration a peak vertical stress of about 200kPa within the backfill itself, the correction provided by the introduction of interface elements does not provide significant increases in accuracy with respect to increased runtime.

Figure 5-8: Comparison of vertical stress distributions along the VCL of a single backfilled stope considering and not considering the backfill-rockmass interface.
5.4 Summary and Conclusion
As previously indicated by Newman and Agioutantis (2017), stress within the backfill material is transferred to the surrounding rockmass with respect to the development of shear stress along the backfill-rockmass interface. While numerical analyses commonly ignore stress influences with respect to the backfill-rockmass interface, a significant amount of academic and industry research is focused on more accurately simulating the behaviors of the material-to-rock interface. The backfill-rockmass interface model presented in this paper follows the general behaviors of those previously published within the literature. However, these results do not indicate a significant increase in stress within the backfilled stope when considering or not considering the backfill-rockmass interface. Although these results did not indicate any significant stress contribution from the inclusion of a backfill-rockmass interface, in reviewing the literature, there is a significant need to further evaluate the approximation of the normal and shear stiffness along a material-to-rock interface.

5.5 References


6 Numerical Investigations into the Distribution and Redistribution of Stress for Single and Multiple Narrow Vertical Backfilled Stopes

The following article was submitted to the 52nd US Rock Mechanics / Geomechanics Symposium to be held in Seattle, Washington, USA. This article was accepted for presentation at the symposium by an ARMA Technical Program Committee based on technical and critical review of the paper by a minimum of two technical reviewers.

Stress Redistribution Around Single and Multiple Stope-and-Fill Operations

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Zach Agioutantis, University of Kentucky; Lexington, Kentucky; United States of America

Full Citation:

6.1 Synopsis
As conventional underground deposits have been depleted, mining operations have been required to produce at deeper depths and in more complex geological conditions. Cemented paste backfill (CPB) is often utilized by mining operations as a means of ground support providing not only a safe working environment but also the ability to further enhance reserve extraction while effectively managing mine waste material. While CPB has been quickly established within the mining industry, there are many fundamental design factors with respect to the safe and economical design of backfill structures that are still not well understood. A critical design issue is the determination of stress distributions around the excavation and through the backfill material. This paper details the development of a reliable numerical model for the simulation of stress distributions and behaviors with respect to single and adjacent vertical backfilled stopes as well as through the CPB material. Through discussions on modeling parameters and output results, one is provided with insights into the mechanisms of stress redistribution allowing for further accuracies in simulating the behavior of the CPB material as well as its interaction with the surrounding rockmass. With a more thorough understanding of the stress distribution mechanisms, industry engineers will be provided with a better means of optimizing underground stope-and-fill mining operations for the total extraction of the mining reserve.

6.2 Introduction and Background
As mining operations continue to produce at deeper depths and in more geologically and geometrically diverse conditions, the application of underground ground support materials has
become essential in ensuring the stability of underground mine works. Cemented paste backfill (CPB) materials has been utilized in North American underground mining operations since it was first introduced in 1975 by Robinsky. With the development of modern technological innovations within the mineral, aggregate, and cement processing industries as well as the incorporation of chemical additives has provided mining operations with a ground support material which, if employed appropriately, greatly reduces mine waste costs while increasing production and improving stability of the underground working environment. Due to the accessibility to and versatility of CPB, many stope-and-fill mining operations employ paste fill materials within a primary-secondary excavation-support sequencing allowing for significant increase to reserve recovery. As shown in Figure 6-1, the primary stopes (Stope A and Stope B) are excavated and backfilled in two phases; plug and final pours. The “plug” is initially placed at the bottom of the stope with a CPB material of increased cementitious content providing a strong foundation on which to build the rest of the CPB structure as well as ensuring the stability of the barricade against material breakthrough (Li and Aubertin, 2009). Once the “plug” has been allowed to cure, a less cementitious “final” pour material is used in backfilling the rest of the excavated stope. With the excavation and backfilling of all the primary stopes within a given mining district, a similar excavation-support sequencing is utilized in the extraction of the secondary stopes where the backfilled primary stopes become adjacent artificial pillars.

Despite the extensive use of CPB technology as a means of ground support within the mining industry, outlined in Newman and Agioutantis (2017), it is often the case that the design of backfill structures are simplistic in nature and therefore do not effectively utilize stress redistribution mechanisms with respect to reserve economic, projections, and optimizations. For example, the vertical stress at the floor of the backfilled stope is often approximated by the gravity load of the CPB material at a given point. However, academic research (Aubertin, et al., 2003) and site-specific measurements (Helinski, et al., 2011; Thompson, et al., 2012) suggest that the vertical stress within the backfill structure is significantly less than the overburden stress.

A significant amount of research has been conducted on the development of a reliable means of evaluating stress distributions and redistributions with respect to stope-and-fill mining
operations (Newman and Agioutantis, 2018). Numerical simulations as well as site-measurements both observe a significant reduction in the vertical and horizontal stress distributions within the backfill material signifying a load transfer mechanism between the backfill and surrounding rockmass as the stress at a given point within the CPB structure is significantly less than the (expected) gravitational load at the same point. Furthermore, due to the slender stope geometries, tensile stress develops along the stope walls and transferring to a compressive stress state where the peak vertical stress resides a given distance into the rockmass.

Although the literature contains multiple numerical investigations into stress distributions with respect to the sequenced backfilling of narrow backfilled stopes (Li, et al., 2005; Falaknaz, 2014), several assumptions have been made in the determination of numerical parameters as well as in the development of comparative analytical equations. Through the utilization of a two-dimensional finite-element model, this paper looks to further investigate the distribution and redistribution of stress within the surrounding rockmass and within the backfill material for single and multiple stope-and-fill mining operations.

6.3 Numerical Modeling
Numerical methods have provided the mining industry with a flexible and versatile tool for solving complex, modern problems through the utilization of model geometries and boundary conditions, material loading and models, as well as event sequencing for the approximation of site-specific conditions and behaviors. A two-dimensional finite-element model (RocScience, 2016) was developed for the analysis of single and multiple fully-drained vertical backfilled stope given a x-(width), y-(height), and z-(length) coordinate system (Figure 6-2). Model geometries were determined such that vertical and horizontal stress returned to far-field conditions a given distance away from Stope A and Stope B. The auto-discretization and auto-meshing utilities within RocScience2D (RS2) were utilized in the development of a coarse mesh within the surrounding rockmass with a finer mesh applied to the backfilled stope as well as the immediate back, floor, and walls. Boundary conditions have been applied to each edge of the model. The bottom edge of the model have been fixed in the x- and y-directions while the east and west edges have been fixed in the y-direction. The top edge of the model represents the surface and therefore is defined as a free surface.
Both stopes evaluated within this model, Stope A and B, have a width of 6m and are filled to a height of 45m with a 0.5m void space between the backfill material and the immediate roof strata to allow for the self-consolidating behavior of the backfill material. Both stopes have been defined at a depth of 300m measured from the surface to the stope floor. The rockmass material has been defined as a homogeneous, isotropic, linearly elastic material with a Young’s Modulus \( (E_R) \) of 30GPa, Poisson’s ratio \( (\nu_R) \) of 0.33, and a unit weight \( (\gamma_R) \) of 27 kN/m\(^3\). The backfill material has been defined as a homogeneous elastic plastic material with respect to a Mohr-Coulomb failure criterion with a Young’s Modulus \( (E_B) \) of 300 MPa, Poisson’s ratio \( (\nu_B) \) of 0.2, a unit weight \( (\gamma_B) \) of 18 kN/m\(^3\), an internal friction angle of 30-degrees, a cohesion of 0kPa, and a dilatancy angle of 0-degrees. The backfill material employed in this model is a conservative representation of a soft paste material with no cohesive strength and a low internal friction angle and has been similarly utilized and outlined within the literature (Falaknaz, et al., 2015).

Stope-and-fill operational sequences were defined with respect to a series of “stage”s within RS2. As outlined in Table 1, initially the model is solved for insitu conditions followed by the instantaneous excavation of Stope A.
Table 6-1: Numerical Sequencing of Mining Events

<table>
<thead>
<tr>
<th>Stage</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Insitu Stress Condition</td>
</tr>
<tr>
<td>2</td>
<td>Excavation of Stope A</td>
</tr>
<tr>
<td>3</td>
<td>Stope A, Backfill Layer 1</td>
</tr>
<tr>
<td>4</td>
<td>Stope A, Backfill Layer 2</td>
</tr>
<tr>
<td>5</td>
<td>Stope A, Backfill Layer 3</td>
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<td>6</td>
<td>Stope A, Backfill Layer 4</td>
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<tr>
<td>7</td>
<td>Stope A, Backfill Layer 5</td>
</tr>
<tr>
<td>8</td>
<td>Excavation of Stope B</td>
</tr>
<tr>
<td>9</td>
<td>Stope B, Backfill Layer 1</td>
</tr>
<tr>
<td>10</td>
<td>Stope B, Backfill Layer 2</td>
</tr>
<tr>
<td>11</td>
<td>Stope B, Backfill Layer 3</td>
</tr>
<tr>
<td>12</td>
<td>Stope B, Backfill Layer 4</td>
</tr>
<tr>
<td>13</td>
<td>Stope B, Backfill Layer 5</td>
</tr>
</tbody>
</table>

The excavation of the stope area is simulated with respect to an “Excavate” material model within RS2, which applies no material properties within a defined boundary while allowing the material to deform with respect to solution results. Upon excavation of Stope A, the rockmass is allowed to deform until force equilibrium is achieved. Next, the backfilling of the Stope A is initiated with the placement of the first backfill layer (BF1). Each backfill layer (BFi) contains 9m of material and progresses from bottom to top. Following the backfilling of Stope A, Stope B is instantaneously excavated leaving a 4m wide rock-pillar between the two adjacent primary stopes. Backfilling of Stope B is simulated by the same means as previously discussed for Stope A. The model is allowed to equilibrate after each sequencing stage defined within the model.

Stope geometries, material properties, and sequencing of mining events were defined with respect to the literature (Aubertin, et al., 2003; Li et al., 2005; Falaknaz, 2014).

6.4 Results and Discussion

Modeling results, presented here, focus on the distribution of stress around and through two adjacent fully-drained vertical narrow backfilled stopes. For information on the analysis of the single vertical narrow backfilled stope (Stope A) see Newman and Agioutantis (2018). Numerical results were obtained at three specific events within the stope-and-fill mine sequencing as previously discussed above; post-backfill of Stope A, excavation of Stope B, and post-backfill of Stope B. Furthermore, analysis of insitu stress results within the rockmass were utilized in the confirmation of the pre-mining stress condition while excavation and post-backfilling results provided indication of stress distribution about the excavated stope area. Following the backfilling of Stope A, stress distributions were numerically monitored within backfilled stope as well as the surrounding rockmass during the excavation and backfilling of the second stope (Stope B). From these analyses, one is provided with further insights into the material behaviors and interactions of the cemented paste backfill material as well as the surrounding rockmass.
Stress distributions within the cemented paste backfill of Stope A were initially analyzed with respect to the excavation and backfilling of an adjacent stope with a pillar width (D) of 4m. As shown in Figure 6-3, the stress distribution within the fill material of the fully backfilled Stope A is significantly lower than the gravity loading of the material indicating the presence of stress transfer from the backfill material to the surrounding rockmass. Furthermore, analysis of the rockmass indicates the development of tensile stress near the stope wall due to vertical stress distributions within the overburden as described in Newman and Agioutantis (2018). With respect to stope geometry, the proposed excavation area of Stope B is partially located within the tensile zone developed about the backfilled Stope A as illustrated by the stress contours within Figure 6-3. The transition between the tensile and compressive regime within the rockmass is identified with respect to the contoured “arch” which propagates into the surrounding overburden. Note that it is important for operators that utilize drilling and blasting for stope excavation to understand the development and location of these tensile zones as the tensile stress within the rockmass can create unfavorable ground conditions and often requires the utilization of installed ground supports such as bolts and cables. The backfill and rockmass behaviors observed within this model follow the general numerical and field measurements as discussed within the literature (Falaknaz, 2014; Helinski et al., 2011).
The distribution of stress within Stope A continued to be numerically monitored during the excavation and backfilling of Stope B. Initially, vertical stress along the VCL drops slightly upon the instantaneous excavation of Stope B. As Stope B is backfilled, simulated with the application of “stage”d fill material, vertical stress gradually increases with the placement of the subsequent layer (Figure 6-4). This behavior is similarly replicated with respect to the distribution of horizontal stress within the backfill of Stope A during the excavation and backfilling of the adjacent stope, Stope B (Figure 6-5). Additionally, the vertical and horizontal stress distributions within the backfill material of Stope B were monitored throughout the filling process. The development and distribution of stress within the backfill of Stope B followed a similar behavior of a single backfilled stope as illustrated in Figure 6-6. These numerically observed behaviors within the backfill were not significantly impacted by varying the horizontal stress magnitude or the magnitude of the vertical-to-horizontal ratio.
The excavation and backfilling of Stope B significantly changes the distribution of stress within the surrounding rockmass between the two stopes. As mentioned above, vertical stress distributions within the surrounding rockmass allowed for the development of tensile stress along the walls of the backfilled Stope A (Figure 6-3). As illustrated in Figure 6-7, in instantaneous excavation and “stage”d backfilling of Stope B, tensile stress develops about the backfill-rockmass interface of Stopes A and B, lines A’-A’ and B’-B’ respectively, while the rock-pillar is in a state of non-uniform compression. This behavior is further confirmed in evaluating the vertical stress distribution within the rockmass within the rock-pillar (Figure 6-8).
The non-uniformity in the compressive state of the rock-pillar is caused by the development of tensile stress within the rock-pillar back and floor vicinities (Figure 6-9). This behavior is further confirmed by transfer of horizontal stress into the top of the backfill for both Stopes A and B. Referring back to Figure 6-5, the horizontal stress distribution along the vertical center line (VCL) shows a slight initiation increase in horizontal stress as indicated by the y-intercept.

The distribution of stress within the rockmass was further evaluated with respect to varying rock-pillar widths. In comparing the results of these model runs, one finds similar stress distribution behaviors within the surrounding rockmass as well as through the rock-pillar (Figure 6-9).
6.5 Summary and Conclusions
The numerical model presented in this paper provides a detailed analysis of the behavior and mechanism of stress distributions within the backfilled stope, surrounding rockmass, and rock- pillar. Due to technological innovations within mineral, aggregate, and cement processing industries, there has been a recent surge in academic research with respect to cemented paste backfill (CPB). Unfortunately, a significant amount of literature is focused solely on the development and distribution of stress within the CPB material and do not allow for the consideration of global stress interactions and impacts within the surrounding rockmass. While numerical results within the backfill follow the generalized stress distributions within paste fill material and surrounding rockmass of a single backfilled stope (Aubertin, et al., 2003; Newman and Agioutantis, 2018) as well as backfill behaviors for adjacent stopes (Falakanz et al., 2015), stress redistributions within the rock-pillar indicate a non-linear compressive state. This non-linearity is caused by the development of tensile stress in the vicinity of the rock-pillar back and floor.

While this model allows for the evaluation of general material and stress distribution behaviors, it provides significant insights into the evaluation of global stability for stope-and-fill mining operations utilizing a primary-secondary extraction-support production sequence. An understanding of the stress distribution within the rockmass and redistribution within rock-pillar, industry engineers are provided with insights into the improvement of ground control and CPB mix design for the total extraction of the mining reserve while maintaining the stability of the underground working environment. Work will continue in the development of an appropriate model for the evaluation of stress distributions for stope-and-fill mining operations through the incorporation of improved material models and numerical parameters. Recent laboratory testing of cementitious paste materials suggest that material properties within the test specimens vary with depth into the sample (Kaklis, et al., 2018). Furthermore, research indicates that the stress transfer mechanism within the backfill material is a function of wall roughness, material curing behaviors and properties, as well as chemical decomposition (Manaras, 2009; Fall and Nasir, 2010, Koupouli, et al., 2016). In further investigating these conclusions and their adaption to numerical modeling input parameters and material properties, the model presented in this paper will provide the mining industry with a simplistic model for the evaluations of global stability in stope-and-fill mining operations.

Through the utilization of this model, industry engineers are provided with an understanding of the distribution and re-distribution of stress with respect to multiple adjacent vertical backfilled stope as well as the development of tensile stresses within the rockmass and rock-pillar due to slender stope geometries and insitu stress conditions. By appropriately adapting this model for site-specific conditions and behaviors, one is provided with a numerical tool for the improvement and optimization of CPB mix design, the proactive installation of ground support with respect to areas of instability caused by the development of tensile stress within the material, as well as pillar design.

6.6 Acknowledgements
The authors of this paper would like to acknowledge Dr. Essie Esterhuizen of NIOSH for his advice and expertise with respect to numerical modeling. His help was instrumental in the
development of the presented numerical models as well as providing further insights into the distribution of stress about the excavated stope as well as through the backfill material.

6.7 References


7 Numerical Investigations into the Distribution and Redistribution of Stress for a Side Exposed Single Narrow Vertical Backfilled Stopes

The following article will be submitted for publication in a peer-reviewed journal or conference proceedings by the authors.

Christopher Newman, University of Kentucky; Lexington, Kentucky; United States of America
Zach Agioutantis, University of Kentucky; Lexington, Kentucky; United States of America

7.1 Introduction & Background
Within the North American underground mining industry, it is common for stope-and-fill mining operations to utilize cemented paste backfill (CPB) within a primary-secondary excavation-support mining sequence allowing for high recovery rates while ensuring the integrity of the underground working environment. As shown in Figure 7-1, the primary stopes (Stope A and Stope B) are excavated and backfilled in two phases; plug and final pour. The “plug” is initially placed at the bottom of the stope with a CPB material of increased cementitious content providing a strong foundation on which to build the rest of the CPB structure as well as ensuring the stability of the barricade against material breakthrough (Li and Aubertin, 2009). Once the “plug” has been allowed to cure, a less cementitious “final” pour material is used in backfilling the rest of the excavated stope. With the excavation and backfilling of all the primary stopes within a given mining district, a similar excavation-support sequencing is utilized in the extraction of the secondary stopes where the backfilled primary stopes become adjacent artificial pillars.

Figure 7-1: Stope and fill layout (a) before and (b) after excavation of adjacent secondary stope; c) schematic of planar failure for side-exposed backfill (adapted from Li, 2014)
Within the stope-and-fill mining method, it is inherent that one will expose the face of a CPB structure within a primary stope upon the extraction of a secondary stope. Therefore, in designing multiple stope-and-fill mining operations it is critical that operations and planning personnel appropriately determine the minimum strength of the CPB structure. The stability of the side exposed backfilled vertical stope was initially investigated by Mitchell et al. (1982) with respect to a limit equilibrium analysis for an exposed CPB structure. It is assumed that failure will occur with respect to shear failure along a sliding plane forming a wedge of material (Figure 1c). Physical laboratory testing performed by Mitchell et al. (1982) related the shear strength properties of the cemented past material to stope geometries for the design of a stable CPB structure when a single side is exposed (Eq. 1).

\[
c = \frac{\gamma H}{2 \times \left(\frac{H}{L} + \tan \left(45 + \frac{\phi}{2}\right)\right)}
\]

where \(c\) is the cohesive strength of the backfill material, \(L\) is the stope length (assumed to be three time the width), and \(\phi\) is the internal angle of friction of the backfill material.

Within the literature (Falaknaz, 2014; Yang et al., 2017), several numerical simulations have been developed with respect to finite-difference numerical methods for the evaluating the stability of a side exposed backfilled stope. However, as identified in the previous chapters, these numerical models were developed with respect to modified parameters such that results reflected previously published analytical solutions. The following chapter presents a simple two-dimensional model has been developed to further investigate the distribution of stress around and through the backfilled stope as well as the overall stability of the side exposed backfilled structure.

### 7.2 Numerical Modeling

A two-dimensional finite-element model (RocScience) was developed for the analysis of single and multiple fully-drained vertical backfilled stope given an \(x\)-(width), \(y\)-(height), and \(z\)-(length) coordinate system (Figure 7-2). Model geometries were determined such that vertical and horizontal stress returned to far-field conditions a given distance away from the excavated stope area. The auto-discretization and auto-meshing utilities within RocScience2D (RS2) were utilized in the development of a coarse mesh within the surrounding rockmass with a finer mesh applied to the backfilled stope as well as the immediate back, floor, and walls. Boundary conditions have been applied to each edge of the model. The bottom edge of the model has been fixed in the \(x\)- and \(y\)-directions while the east and west edges have been fixed in the \(y\)-direction. The top edge of the model represents the surface and therefore is defined as a free surface.
Both the primary (Stope A) and secondary (Stope B) stopes have a width of 6m and are excavated and then backfilled to a height of 45m with a 0.5m void space between the backfill material and the immediate stope back to allow for the self-consolidating behavior of the backfill material. Both stopes have been defined at a depth of 300m measured from the surface to the stope floor. The rockmass material has been defined as a homogeneous, isotropic, linearly elastic material with a Young’s Modulus (E_R) of 30GPa, Poisson’s ratio (ν_R) of 0.33, and a unit weight (γ_R) of 27 kN/m³. The backfill material was defined as a homogeneous elastic plastic material with respect to a Mohr-Coulomb failure criterion with a Young’s Modulus (E_B) of 1340 MPa, Poisson’s ratio (ν_B) of 0.22, a unit weight (γ_B) of 18 kN/m³, a tensile strength of 200 kPa, a cohesion of 240kPa, an internal friction angle of 40-degrees, and a dilatancy angle of 0-degrees. The backfill material employed in this model was defined with respect to laboratory testing of cemented paste materials conducted by Kaklis et al. (2018).

**Figure 7-2: Schematic of modeling geometries and boundary conditions**

<table>
<thead>
<tr>
<th>Stage</th>
<th>Event Description</th>
</tr>
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<tbody>
<tr>
<td>Stage 1</td>
<td>Insitu Stress Condition</td>
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<tr>
<td>Stage 2</td>
<td>Excavation of Stope A</td>
</tr>
<tr>
<td>Stage 3</td>
<td>Stope A, Backfill Layer 1</td>
</tr>
<tr>
<td>Stage 4</td>
<td>Stope A, Backfill Layer 2</td>
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<tr>
<td>Stage 5</td>
<td>Stope A, Backfill Layer 3</td>
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<tr>
<td>Stage 6</td>
<td>Stope A, Backfill Layer 4</td>
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<tr>
<td>Stage 7</td>
<td>Stope A, Backfill Layer 5</td>
</tr>
<tr>
<td>Stage 8</td>
<td>Excavation of Stope B</td>
</tr>
</tbody>
</table>

**Table 7-1: Numerical Sequencing of Mining Events**
Stope-and-fill operational sequences were defined with respect to a series of “stage”s within RS2. As outlined in Table 7-1, initially the model is solved for insitu conditions followed by the instantaneous excavation of Stope A. The excavation of the stope area is simulated with respect to an “Excavate” material model within RS2, which applies no material properties within a defined boundary while allowing the material to deform with respect to solution results. Upon excavation of Stope A, the rockmass is allowed to deform until force equilibrium is achieved. Next, the backfilling of the Stope A is initiated with the placement of the first backfill layer (BF₁). Each backfill layer (BFᵢ) contains 9m of material and progresses from bottom to top. Following the backfilling of Stope A, Stope B is instantaneously excavated immediately adjacent to the primary stope, Stope A.

7.3 Results and Discussion

Modeling results, presented here, focus on the distribution of stress around and through a single vertical narrow fully-drained backfilled stope (Stope A) which has a single side exposed from the excavation of the immediately adjacent secondary stope (Stope B). For information on the analysis of the single vertical narrow backfilled stope (Stope A) see Newman and Agioutantis (2018). Numerical results were obtained during to numerically simulate mining events, the backfilling of Stope A and the immediate excavation of Stope B. Furthermore, analysis of insitu stress conditions within the rockmass were utilized in confirmation of the pre-mining stress state while the backfilling of Stope A and excavation of Stope B provide indication of the stress distribution around the excavated stope area. Utilizing these results, the stability of the CPB structure is evaluated and compared to the Mitchell solution for side exposed stope stability.

Figure 7-3: Vertical Stress distribution within the backfill of Stope A along the VCL post-backfilling of Stope A and prior to the excavation of Stope B
As shown in Figure 7-3, the stress distribution within the fill material of the fully backfilled Stope A, along A-A, is significantly lower than the gravity loading of the material indicating the presence of stress transfer from the backfill material to the surrounding rockmass. Furthermore, analysis of the rockmass indicates the development of tensile stress near the stope wall due to vertical stress distributions within the overburden as described in Newman and Agioutantis (2018). With respect to stope geometry, the proposed excavation area of Stope B is partially located within the tensile zone developed about the backfilled Stope A as by Figure 7-4. The transition between the tensile and compressive regime within the rockmass is identified with respect to the contoured “arch” which propagates into the surrounding overburden. The backfill and rockmass behaviors observed within this model follow the general numerical and field measurements as discussed within the literature (Falaknaz, 2014; Helinski et al., 2011).

![Figure 7-4: Stress distribution with the immediate surrounding rockmass of Stope A along the proposed VCL of Stope B following the excavation and backfilling of Stope A.](image)

The distribution of stress within Stope A continued to be numerically monitored during the excavation and backfilling of Stope B (Figure 7-5). Following the excavation of Stope B, stress within Stope A significantly increase as load is transferred from the excavated area to the immediately adjacent backfill material as well as the surrounding rockmass. However, while there is a significant increase in stress along the VCL (A’-A’), the stress within the backfill is still significantly less than insitu loading to the CPB structure.
In addition to monitoring the stress distributions through and around Stope A, displacements were monitored along the exposed face (C-C). From Figure 7 one is able to conclude that the side exposed CPB structure is stable with a maximum displacement of 2cm. However, with respect to the strength equation developed by Mitchell et al. (1982), a minimum cohesion of 120kPa is required to ensure the stability of a single side exposed CPB structure. As shown in Figure 7-6, the cohesive value determined with respect to Mitchell et al. (1982) is not only stable but mimics the displacements with respect to a backfill with a cohesive strength of 240kPa. Instability within the single side exposed CPB structure occurs at a cohesive strength of 78kPa, a cohesive value 35% less than that reported by the Mitchell et al. (1982) solution. Here, the exposed face (C-C) was displaced 2.2cm resulting in the development of a shear failure plane as indicated by the stress contours in Figure 7-6. These numerically observed behaviors within the backfill were not significantly impacted by varying the horizontal stress magnitude or the magnitude of the vertical-to-horizontal ratio.

Figure 7-5: Comparison of stress distributions within the backfilled Stope A during the Post-backfilling of Stope A and the Excavation of Stope B.

Figure 7-6: Displacement along the Stope A exposed backfill face (C-C)
7.4 Summary and Conclusions
In utilizing a primary-secondary excavation-support stope-and-fill mine sequencing, it is often the case that mine planning and geometries require operations to take a secondary stope immediately adjacent to a backfilled primary stope. With respect to the side exposed CPB structure, the critical design parameter is the cohesive strength of the backfill material. From the numerical models presented in this chapter, one finds that upon excavating the immediate secondary stope, there is a significant increase in stress within the backfilled primary stope. This increase in stress initiates movement within the backfill resulting in displacement of the CPB structure into the excavated area. Similar to behaviors documented within the literature (Mitchell et al., 1982; Falaknaz, 2014), as the cohesive strength of the backfill material is reduced, the CPB structure becomes unstable and subsequently drives a wedge failure within the backfilled stope. In determining the cohesive strength of the CPB for structural stability, results indicate that Mitchell’s solution overestimates the required cohesion by 35%. Utilizing this model allows one to better optimize their cemented paste design for the consideration of stress distribution and redistributions within the backfill material and surrounding rockmass.

7.5 References
8 Numerical Investigations into the Distribution and Redistribution of Stress for Two Side Exposed Narrow Vertical Backfilled Stopes

The following article will be submitted for publication in a peer-reviewed journal or conference proceedings by the authors.

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8.1 Introduction and Background
As the mining industry continues to produce at greater depths and in more geometrically and geologically complex conditions, cemented paste backfill (CPB) has gained traction as a means of providing localized ground support in modern stope-and-fill mining operations. The application of CPB in stope-and-fill mining as a ground support material has led to the reduction of mine waste costs, while increasing both mine production and stability. In an attempt to achieve total extraction of the mining reserve, stope-and-fill mining operations often employ a primary-secondary excavation-support sequence (see Figure 8-1). Here, primary stopes are initially excavated and then backfilled in a two-stage pour; plug and fill pours. During the first stage, CPB with high cementitious content is pumped into the stope and placed at the bottom of the stope providing a strong base from which to build a backfill structure as well as protect the mine works from material breakthrough. Following the placement and curing of the backfill plug, backfilling of the stope continues with a less cementitious paste fill material until the entire stope has been backfilled with material. With all primary stopes backfilled, the extraction of the secondary stopes begins as backfilled primary stopes are utilized as artificial pillars.

Figure 8-1: Primary-secondary extraction-support operational sequencing for underground stope-and-fill mining

Due to modern technological innovations with respect to CPB, many academics, industry professionals, and regulatory agencies have begun to reevaluate the fundamental factors concerning the safe and economical design of CPB underground structures. With respect to
single and multiple stope-and-fill mining operations, a critical design issue has, and continues to be, the determination of the stress state within the back fill material and the surrounding rockmass. Furthermore, in utilizing a primary-secondary excavation-support stope-and-fill operational mine sequence, the backfill material within the primary stopes needs to remain stable during the excavation and backfilling of the adjacent secondary stope. Recently, contributions from Chapter 7 have provided new insights into the distribution and redistribution of stress around and through multiple backfilled stopes in which the immediately adjacent stope has been excavated. Building upon the results of Chapter 7, this paper presents a preliminary investigation into the distribution and redistribution of stress with respect to the excavation of a secondary vertical stope in between two primary backfilled vertical stopes.

8.2 Numerical Modeling

A two-dimensional finite-element model (RocScience, 2018) was developed for the analysis of stress distributions and redistributions with respect to multiple fully-drained vertical backfilled stopes given a x-(width), y-(height), and z-(length) coordinate system (Figure 8-2). The dimensions of the model were defined such that the vertical and horizontal stresses return to their far-field conditions a given distance away from the stope area. Auto-discretization and auto-meshing utilities within RocScience2D (RS2) were utilized in the development of a coarse mesh within the surrounding rockmass with a finer mesh applied to the backfilled stope as well as the immediate back, floor, and walls. Boundary conditions have been applied to each edge of the model. The bottom edge of the model have been fixed in the x- and y-directions while the east and west edges have been fixed in the y-direction. The top edge of the model represents the surface and therefore is defined as a free surface.
All three stopes (Stope A, Stope B, Stope C) have a width of 6m, excavation height of 45.5m and a depth of 300m measured from the surface to the stope floor. Stope A and Stope B are excavated and backfilled with respect to stope-and-fill operational sequences. The sequence of mining events were defined with respect to a series of “stage”s within RS2. As outlined in Table 8-1, initially the model is solved for insitu conditions followed by the instantaneous excavation of the stope. The rockmass material has been defined as a homogeneous, isotropic, linearly elastic material with a Young’s Modulus (E_r) of 30GPa, Poisson’s ratio (ν_r) of 0.33, and a unit weight (γ_r) of 27 kN/m³. The backfill material has been defined as a homogeneous elastic plastic material with respect to a Mohr-Coulomb failure criterion with a Young’s Modulus (E_b) of 300 MPa, Poisson’s ratio (ν_b) of 0.2, a unit weight (γ_b) of 18 kN/m³, a cohesion of 240 kPa, and an internal angle of friction of 40-degrees. The backfill material employed in this model is a conservative representation of a soft paste material which utilizes a tensile cut-off value of zero as similarly implemented within the literature (Falaknaz, 2014; Liu et al., 2016).

Table 8-1: Numerical sequencing of stope-and-fill mining events

<table>
<thead>
<tr>
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<tbody>
<tr>
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<td>Stage 3</td>
<td>Stope A, Backfill Layer 1</td>
</tr>
<tr>
<td>Stage 4</td>
<td>Stope A, Backfill Layer 2</td>
</tr>
</tbody>
</table>
Stage 5 | Stope A, Backfill Layer 3  
Stage 6 | Stope A, Backfill Layer 4  
Stage 7 | Stope A, Backfill Layer 5  
Stage 8 | Excavation of Stope B  
Stage 9 | Stope B, Backfill Layer 6  
Stage 10 | Stope B, Backfill Layer 7  
Stage 11 | Stope B, Backfill Layer 8  
Stage 12 | Stope B, Backfill Layer 9  
Stage 13 | Stope B, Backfill Layer 10  
Stage 14 | Excavation of Stope C

Stope-and-fill operational sequencing was simulated with respect to a series of “stage”s within RocScience2D. As shown in Table 8-1, the model is initially solved for insitu stress conditions prior to any mining activity. Each stope is excavated (instantaneously) with respect to an “excavate” material model and subsequently backfilled in 9m lifts progressing from the bottom of the stope to the top. Each stage within the model is solved with respect to force equilibrium is achieved.

8.3 Results and Discussion
The modeling results, presented here, focus on the distribution and redistribution of stress through two primary adjacent fully-drained vertical backfilled stopes (Stope A and Stope B) prior to and following the excavation of an in-between secondary fully-drained vertical backfilled stope (Stope C). For information on the analysis of a single and multiple narrow fully-drained vertical backfilled stopes, please refer to Newman and Agioutantis (2018a). Numerical results were obtained at three specific events within the stope-and-fill mine sequencing as previously discussed above; post-backfill of Stope A, excavation of Stope B, post-backfill of Stope B, and excavation of Stope C. Furthermore, analysis of insitu stress results within the rockmass were utilized in the confirmation of the pre-mining stress condition while excavation and post-backfilling results provided indication of stress distribution about the excavated stope area. Following the backfilling of Stope A, stress distributions were numerically monitored within backfilled stope as well as the surrounding rockmass during the excavation and backfilling of the second stope (Stope B), as well as the excavation of the third stope (Stope C). From these analyses, one is provided with further insights into the material behaviors of the cemented paste backfill material as well as the surrounding rockmass.
Initially stress distributions were analyzed within the CPB material as well as the surrounding rockmass of a fully backfilled Stope A prior to the excavation to the second primary stope (Stope B). As shown in Figure 8-3, the stress within the backfill material of Stope A is significantly less than the gravity loading indicating the presence of stress transfer between the backfill material and the surrounding rockmass as described by Newman and Agioutantis (2018b). Similarly, the behavior of the cohesive backfill material is similar to the literature (Aubertin et al., 2003; Falaknaz, 2014). Furthermore, analysis of the rockmass indicates the development of tensile stress along the stope wall due to the distribution of vertical stress within the immediately surrounding rockmass as described in Newman and Agioutantis (2018a). Given stope geometries, this tensile zone intersect the proposed extraction area for Stope C while Stope B remains in a compressive stress state (Figure 8-3). Note that it is important for operators that utilize drilling and blasting for stope excavation to understand the development and location of these tensile zones as the tensile stress within the rockmass can create unfavorable ground conditions and often requires the utilization of installed ground supports such as bolts and cables. The backfill and rockmass behaviors observed within this model follow the general numerical and field measurements as discussed within the literature (Falaknaz, 2014; Helinski et al., 2011).

During the excavation and backfilling of Stope B, stress distributions and redistributions were continually monitored along the VCL of Stope A. Due to the inclusion of a cohesive material, upon the excavation of Stope B the stress within Stope A is significantly altered. As shown in Figure 8-3, the significant reduction in stress within the backfill material is due to an increase in stress transfer between the backfill and rockmass assuming stress is able to transfer across the backfill-rockmass contact area. This occurs in the upper 25-30m of the stope. However, as stress continues to be redistributed within the backfill of Stope A during the backfilling of Stope B, the lower 15-20m of backfill within Stope A shows a significant increase in stress.

Figure 8-3: Vertical stress distribution along the VCL of Stope A with respect to the extraction and backfilling of Stope B
In monitoring stress along the VCL of Stope B (Figure 8-4), the development and distribution of stress within the CPB material during the backfilling of Stope B is similar to the behavior observed with respect to a single vertical backfilled stope; Stope A.

![Figure 8-4: Comparison of stress distributions within the backfill for a single backfilled stope (Stope A) and Stope B following the excavation and backfilling of both Stopes A and B.](image)

Furthermore, the excavation and backfilling of Stope B significantly alters the stress distribution within the surrounding rockmass. Upon the excavation of Stope B, tensile stress zones develop along the backfill-rockmass interface of Stope A (A-A) and Stope B (B-B) while Stope C, the unexcavated in-between rock pillar, is in a state of non-uniform compression (Figure 8-5) as similarly observed by Newman and Agioutantis (2018a).

![Figure 8-5: Vertical stress distribution across Stope A and B where the cross-section is parallel to the x-axis and located at mid-stope as represented by the red dashed line.](image)
Following the instantaneous extraction of Stope C, stress distributions within Stope A and Stope B indicate failure of the backfill material resulting from further increases of in-stope stress (Figure 8-6). This is further validated by stope wall displacements results. As shown in Figure 8-7, the exposed backfill face for Stope A (A'-A') and Stope B (B'-B') was displaced 270cm and 250cm respectively. These results indicates that with respect to the given loading scenario, cemented paste backfill material is incapable of maintaining stability upon the excavation of Stope C, an adjacent secondary narrow vertical stope.

Figure 8-6: Vertical stress distributions along the VCL of Stopes A and B following the excavation of the in-between stope, Stope C.

Figure 8-7: Total displacement of the side exposed face for Stope A (A'-A') and Stope B (B'-B') where the cross-section is parallel to the x-axis.
8.4 Summary and Conclusion

The numerical results presented in this paper provide a detailed analysis of the behavior and mechanism of stress distribution and redistribution with respect to a multiple stope-and-fill mining operation utilizing primary-secondary extraction-support method of mining. Numerical results within the backfill follow the generalized stress distributions within paste fill material and surrounding rockmass of a single backfilled stope (Aubertin, et al., 2003; Newman and Agioutantis, 2018) as well as backfill behaviors for the adjacent primary stope (Falakanz et al., 2015). However, upon excavation of the second primary stope (Stope B), stress results along the VCL of Stope A indicate a transition into a tensile stress state. Given there is no tensile strength within the backfill, this resulted in model closure of 0.004 over a million iterations. While model closure was reduced to the benchmark 0.001 by defining the backfill material with a low tensile strength (200kPa as suggested by Kaklis et al. (2018)) the majority of the backfill within Stope A transitions to a tensile stress state as if the rockmass were imparting tensile stresses to the backfill. Furthermore, if interface elements are utilized as a means of controlling the stress transfer across the backfill-rockmass contact area, the behavior of the backfill is disconnected from the rockmass and pure gravity loading within the backfill. This is expected as typical interface elements do not transfer tensile stresses across the interface they represent. If interface elements are not used, then the backfill nodes and the rockmass nodes at the interface tend to be connected by the numerical models resulting in tensile stresses being transmitted across the interface. While it is assumed that actual mine site conditions lay somewhere between full and no attachment along the backfill-rockmass contact area, more site instrumentation is needed to evaluate stress and displacements with respect to stope-and-fill operational sequencing.

The results of this numerical investigation suggest that the material properties of the cemented paste backfill (CPB) material should be derived with respect to the transfer of stress across the backfill-rockmass contact area. Through the utilization of this model, industry engineers are provided with an understanding of the distribution and re-distribution of stress with respect to multiple vertical backfilled stope as well as the development of tensile stresses within the rockmass and backfill materials. By appropriately adapting this model for site-specific conditions and behaviors, one is provided with a numerical tool for the improvement and optimization of CPB mix design, the proactive installation of ground support with respect to areas of instability caused by the development of tensile stress within the material, as well as pillar design. However, with current technological innovations within mineral, aggregate, and cement processing industries as well as the application of chemical additives, research will continue in the development of a CPB material of increased stiffness and strength that could be utilized in such a stress scenario.

8.5 References


9 Discussion

The application of engineered fill material in North American stope-and-fill mining operations dates back to the 1950’s with the introduction of hydraulic backfill material (De Souza, et al., 2003). Over the past decade, the mining industry has seen an increase in the application of cemented paste backfill (CPB) material in conjunction with stope-and-fill mining method. The stope-and-fill mining method is a cost-effective, productive, and safe mining technique for high recovery and low dilution mining of narrow or irregular ore bodies where localized stability of the mine working is of concern (Darling, 2011). As mining operations continue to produce at deeper depths and in more geologically and geometrically diverse conditions, the ground control advantages of backfill material became more apparent. Through the utilization of engineered backfill material in conjunction with the stope mining, one is able to provide localized ground support to the stope walls and back horizon for the prevention of caving/roof falls as well as rock bursts (Coates, 1981).

Through the incorporation of modern technological innovations within the mineral, aggregate, and concrete processing industries as well as the incorporation of chemical additives has providing the mining industry with an accessible, cost-efficient, and versatile material which, if employed appropriately, greatly reduces mine waste (mill tailings) while increasing underground production and stability. CPB is composed of mill tailings (75%-85% by weight) mixed with cementitious binder additives (3%-7% by weight) such as Portland cement (T10 or T50), fly-ash, and smelter slag prior to fill placement in the excavated stope (Benzaazoua et al., 2004; Fall and Nasir, 2010). The purpose of the cementitious binding agents is to allow for the development of cohesion within the backfill material such that exposed faces will be self-supporting during the extraction of adjacent or secondary stopes (Mitchell et al., 1982). Furthermore, to maintain material followability, CPB materials must contain at minimum 15% of fines smaller than 20 μm, a sufficient amount of material slump, as well as water to ensure that the cementitious material is properly hydrated.

CPB is commonly utilized in underground stope-and-fill mining operations which utilize a primary-secondary excavate-support sequencing allowing for high reserve recovery while maintaining the integrity and stability of the mining environment. Although CPB is extensively used as a means of ground support within underground mining operations, it is often the case that designs of stope backfill structures are approximated with respect to gravity loading of the backfill material at a given point. Therefore, the purpose of this dissertation is the development of a numerical modeling approach which aims to aid academic, operations, and regulatory professionals in more realistically approximating the distribution and redistribution of stress within the surrounding rockmass as well as through the backfill material. By better approximating the behavior of and interactions between materials, one is able to better design ground support which enhance and optimize underground production while ensuring the stability of the local working section as well as the global stability of the mine works. The net result of this effort is expected to not only provide the mining industry with knowledge of cemented paste backfill material and its interaction with the surrounding rockmass for the efficient and economical extraction of mining reserves but also to enhance underground safety through a more comprehensive understanding of the behavior and ground control application of cemented paste backfill.
While the literature contains multiple numerical analyses with respect to backfilled stopes, these publications never expanded their investigations to consider the distribution and redistribution of stress within the surrounding rockmass and therefore the nature of stress transfer from the backfill material to the surrounding rockmass. This is important when excavation of multiple stopes is considered. Through the development and analysis of the models presented, a significant amount of knowledge has been obtained for appropriately defining parameters and mine sequencing with respect to the numerical approximation of stress distributions around and through both single and multiple stope-and-fill mining scenarios. The following section highlights several important aspects and points drawn from the entirety of the presented work.

9.1 Contributions to the Literature for Single Narrow Vertical Backfilled Stope
A significant amount of the literature currently available with respect to stress distributions within single backfilled stopes was contributed by and/or derived from Aubertin et al. (2003), Aubertin and Li (2009), and Falaknaz (2014). However, in replicating their numerical models there were significant limitations to the analysis due to their selection of modeling geometries, boundary conditions, and material properties. These limitations and their significance in the analysis of stress distributions around and through a single narrow vertical fully-drained backfilled stope.

a) It was determined that some of the model geometries presented in the literature do not allow vertical or horizontal stress to return to their far field condition and therefore they should not be utilized in the analysis of stress distributions within the rockmass or stress transfer between the rockmass and the backfilled stope. From the previously discussed numerical simulations, it was determined that for the specific stope geometry the model boundaries should be defined a minimum of about 33 times the stope width (D).

b) Models developed by and/or derived from the literature implemented a fixed boundary condition along the stope floor to rockmass interface. By fixing their displacements in the y-direction, all interactions between the backfill and surrounding rockmass in the vicinity of the stope floor is nullified. In utilizing this assumption, numerical results with respect to the distribution of stress within a single backfilled stope are similar in behavior to the Modified Marston’s analytical solution. However, this is not representative of actual site conditions or behaviors. By allowing a free boundary along the stope floor, floor heaving is observed (numerically) following the excavation of the stope. Furthermore, upon placement of backfill within the stope, there is a significant increase in stress within the vicinity of the stope floor due to the backfill material pushing back against the heaving floor impacting the overall stress distribution within the single narrow vertical fully-drained backfilled stope.

c) Within FLAC3D (v 4.0.1), analysis indicates that upon placement of backfill materials with a significant lower density than the surrounding rockmass, the numerical model modified all materials such that densities were redefined with respect to the density of the backfill material. This bug was brought to the attention of Itasca’s technical team, however this version of FLAC3D is no longer maintained by technical support. Therefore, it was determined by the authors that modeling within Itasca’s FLAC3D (v 4.0.1) does not provide the means for the analysis of single or multiple backfilled stopes.
Subsequent models were therefore developed with respect to the RocScience2D (RS2) numerical program.

d) Analysis of the surrounding rockmass indicates that, in the presence of a slender excavated stope, tensile stress develops along the stope wall transferring to a compressive stress state a given distance away from the stope wall. Backfilling of the stope does not have a significant impact on the location or distribution of stress within the surrounding rockmass.

e) Analysis of the Kanowna Belle (KB) gold mine suggests that the numerical simulation of a single narrow vertical fully-drained backfilled stope slightly over predicts the stress within the stope and therefore underrepresents the impact of stress transfer between the backfill and rockmass. Therefore, in accordance with the literature (Liu et al., 2017), interface elements were evaluated within RocScience2D (RS2) for their significance in the approximation of stress distributions through and around a single narrow vertical backfilled stope. While numerical simulations verified similar behaviors observed within the literature, results within RS2 indicate that there is no significant impact on the distribution of stress within the backfill or rockmass.

f) Further analysis of the numerically simulated backfill-rockmass interface within RocScience2D (RS2) as well as laboratory results within the literature (Manaras, 2009) suggest that the interface stiffness defined within the RS2 models are not indicative of site conditions. Furthermore, methodologies outlined within the literature (Liu et al., 2017; Itasca, 2002) as well as the RocScience2D (2018) take into consideration a rock-to-rock interface of similar properties and not a rock-to-material interface with drastically differing material characteristics and properties.

9.2 Contributions to the Literature for Multiple Narrow Vertical Backfilled Stope

Expanding upon the previously discussed single narrow vertical fully-drained backfilled stope model developed in RocScience2D (RS2), the developed multiple stope models allowed for the analysis of stress distributions within the backfill as well as in the surrounding rockmass.

a) As similarly observed by Falaknaz (2014), upon the backfilling of an adjacent primary stope numerical results indicated a significant stress increases within the backfill material of Stope A. Furthermore, stress development along the vertical center line (VCL) of Stope B maintain a distribution similar to that of a single narrow vertical fully-drained backfilled stope.

b) In line with the previously discussed single backfilled stope results, upon the excavation of Stope A, tensile stress develops along the stope wall transitioning to a compressive state a given distance away from the excavated stope. Similarly, upon the excavation of the adjacent primary stope, Stope B, tensile stress develops along the stope wall transitioning to a compressive stress state a given distance away from the stope area.

c) Upon the excavation of the adjacent primary stope (Stope B), a non-uniform compressive stress state is observed within the in-between rock pillar. This non-uniform compressive state within the rock pillar is a result of tensile development within the vicinity of the floor and back of the rock pillar.
9.3 Contributions to the Literature for Single and Multiple Narrow Vertical Backfilled Stopes with Side Exposure

Expanding upon both the single as well as the multiple narrow vertical fully-drained backfilled stope models previously discussed, models were developed for the analysis of backfill stability upon the excavation of the immediately adjacent secondary stope to a primary backfilled stope (single side exposure) as well as the excavation of the adjacent secondary stope in-between two primary backfilled stopes (multiple side exposures).

a) As similarly observed by Mitchell (1989), it was determined that the cohesive strength of the cemented paste backfill (CPB) material is the most significant parameter for evaluating the stability of a single side exposed backfilled stope. However, numerical results indicate that the solution proposed by Mitchell (1989) over predicts the required cohesion by 34% for the model geometry and material properties analyzed.

b) When considering a primary-secondary excavation-support sequence as implemented in stope-and-fill mining operations, numerical results indicate a transition from a compressive stress state within the backfill to a tensile stress state when utilizing a CPB material of a given cohesive strength. This transition, to the author’s knowledge, has not been documented within the literature and has not been observed by in-stope stress measurements. In an attempt to mitigate the transfer to tensile stress from the rockmass to the backfill material, a zero tension cutoff was utilized in defining the tensile strength of the material. However, this resulted in similar results although the model was unable to close over 1 million iterations. Similarly, interface elements were implemented, again as a means of mitigating the tensile stress imparted on the backfill by the surrounding rockmass. This results in the dislodgement of the backfill structure from the backfill-rockmass contact area allowing for pure gravitational loading of the backfill structure.

9.4 References


10 Conclusions and Recommendations
Detailed numerical models were developed for the analysis of the distribution and redistribution of stress around and through typical narrow vertical fully-drained backfilled stopes with respect to an elastic rockmass material and an elastic-plastic cemented paste backfill (CPB) material. Through the development and verification of these numerical models with respect to the literature and site-specific measurements, the models presented in this work will aid academic, operations, and planning personnel in better optimizing backfill mix designs, stope geometries, and/or extraction and backfill sequencing for the safe and efficient extraction of the underground mining reserve. The following conclusions and recommendations detailed within this section are only applicable for the geometries, material properties, and insitu stress conditions as simulated by the previously discussed numerical models.

10.1 Conclusions
Expanding upon discussions with respect to both single and multiple narrow vertical fully-drained backfilled stopes, the following section outlines conclusions drawn from multiple finite-element numerical models for the analysis of stress distributions and redistributions within the backfilled stope as well as the surrounding rockmass.

1. High horizontal stresses significantly impact stress distributions as tensile and compressive stress regions develop within the rockmass upon excavation of a single or multiple stopes.

2. Due to the slender geometry of the stope as well as high horizontal stress, tensile stress develops along the stope wall transitioning to a compressive stress state a given distance away from the excavated stope. Analysis indicates that backfilling of the stope has no significant impact on the magnitudes or locations of these tensile and compressive stress regions within the rockmass.

3. Numerical results indicate a stress increase within the initial backfill layer. While this was not identified within the literature, displacement of the immediate stope floor material is shown to significantly impact stress distributions within the backfill material due to the heaving behavior of the immediate stope floor.

4. In contrast to the literature, finite-element interface elements along the backfill-rockmass contact area were shown to have an insignificant impact on the distribution or redistribution of stress within the backfilled stope or within the surrounding rockmass.

5. In excavating the immediately adjacent secondary stope, Mitchell’s Solution over predicts the required cohesive strength of the cemented paste backfill material by 34%. It should be noted, that this value pertains to the specific model geometry and parameters as discussed within the dissertation.

6. Upon excavation of the subsequent adjacent primary stope, the in-between rock pillar transitions into a non-uniform compressive stress state.

7. Some numerical simulations for multiple stopes and with specific material properties, may not solve due to excessive displacements within the model(s).

10.2 Recommendations
In addition to the conclusions drawn from this body of work, detailed investigations into the behavior of CPB as well as the surrounding rockmass highlight areas in which further research
would provide better assessment of material behaviors as well as the distribution and redistribution of stress.

1. While the numerical models presented in this work slightly over predicted the stress measurement(s) taken within a single backfilled stope, more case studies need to be collected for validation of the numerical model. The case study used in this work only provides generalized information on the stope geometry and location with respect to neighboring stopes. By obtaining case studies which clearly document stope geometries, locations, as well as backfill material properties. In collecting more mine site data, one will be able to further validate these models.

2. Instrumentation of multiple stope-and-fill mining operations for the collection of stress and deformation data with respect to mine operations and the sequencing of mining events. This data could be further utilized in verifying or calibrating the numerical model to site-specific measurements.

3. Within the numerical models, heaving floor material had a significant impact on the distribution of stress within the vicinity of the stope floor. To better calibrate for the significance of displacements within the stope floor, site-measurements and/or observations are required in validating the behavior of the backfill and rockmass materials.

4. Investigations into the backfill-rockmass interface indicate further numerical and laboratory studies into accurately defining the normal and shear stiffness of the backfill-rockmass interface.

5. In the analysis of secondary stope extraction in-between two primary backfilled stopes, there was significant movement within the backfill. Further site-specific investigations with respect to the development of tensile stress within cemented paste materials are required in validating the behavior of the backfill and rockmass materials.

6. Within all numerical models presented, the rockmass has been modeled as a linear elastic material. Although the literature (Falaknaz, 2014) suggests that numerically representing the rockmass as an elastic-plastic material has no significant effect on the distribution of stress within the CPB material of multiple backfilled stopes, this would have a significant impact on the distribution and redistribution of stress within the rockmass as stope-and-fill mine operations continue.

10.3 References


Appendix
The following provides details on numerical parameters utilized within the analysis of stress distributions through and around single and/or multiple narrow vertical fully-drained backfilled stopes.

10.4 Single Narrow Vertical Backfilled Stope Model Developed in FLAC3D

Figure 11-1: Schematic of single vertical backfilled stope with model geometries and boundary conditions

Figure 11-2: Numerical sequencing of events within a stope-and-fill mining operation
Figure 11-3: Element mesh within vicinity of the backfilled stope

Figure 11-4: Loading condition as defined within the FLAC3D code

Table 11-1: Material properties as defined within the model

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10.5 Single Narrow Vertical Backfilled Stope Model Developed in RocScience2D

Figure 11-5: Schematic of single vertical backfilled stope with model geometries and boundary conditions within RocScience2D

Figure 11-6: Numerical sequencing of events within a stope-and-fill mining operation
Figure 11-7: Element mesh within vicinity of the backfilled stope

![Figure 11-7](image)

Figure 11-8: Loading condition as defined within RocScience2D

![Figure 11-8](image)

Table 11-2: Material properties as defined within the model

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10.6 Investigation into the Backfill-Rockmass Interface Developed in RocScience2D

Figure 11-9: Schematic of single vertical backfilled stope with model geometries and boundary conditions within RocScience2D

Figure 11-10: Numerical sequencing of events within a stope-and-fill mining operation with respect to the backfill-rockmass interface
Figure 11-11: Element mesh within vicinity of the backfilled stope

Figure 11-12: Loading condition as defined within RocScience2D
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10.7 Adjacent Primary Narrow Vertical Backfilled Stopes Developed in RocScience2D

Figure 11-13: Schematic of single vertical backfilled stope with model geometries and boundary conditions within RocScience2D

Figure 11-14: Numerical sequencing of events within a stope-and-fill mining operation with respect to the backfill-rockmass interface
Figure 11-15: Element mesh within vicinity of the backfilled stope

Figure 11-16: Loading condition as defined within RocScience2D

Table 11-4: Material properties as defined within the model

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10.8 Adjacent Secondary Narrow Vertical Backfilled Stope Developed in RocScience2D

Figure 11-17: Schematic of single vertical backfilled stope with model geometries and boundary conditions within RocScience2D

Figure 11-18: Numerical sequencing of events within a stope-and-fill mining operation with respect to the backfill-rockmass interface
**Figure 11-19: Element mesh within vicinity of the backfilled stope**

**Figure 11-20: Loading condition as defined within the RocScience2D**

**Table 11-5: Material properties as defined within the model**

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10.9 Secondary Narrow Vertical Backfilled Stope between Two Primary Narrow Vertical Backfilled Stopes Developed in RocScience2D

Figure 11-21: Schematic of single vertical backfilled stope with model geometries and boundary conditions within RocScience2D

Figure 11-22: Numerical sequencing of events within a stope-and-fill mining operation with respect to the backfill-rockmass interface
Figure 11-23: Element mesh within vicinity of the multiple stope area

Figure 11-24: Loading condition as defined within the RocScience2D

Table 11-6: Material properties as defined within the model
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List of References


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