Journal of Rock Mechanics and Geotechnical Engineering 9 (2017) 490–501

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full Length Article

Numerical investigation of the stresses in backfilled stopes overlying a sill mat

Mohamed Amine Sobhi, Li Li*

Research Institute on Mines and the Environment, Department of Civil, Geological and Mining Engineering, École Polytechnique de Montréal, Montréal, Canada

ARTICLE INFO

Article history:
Received 12 July 2016
Received in revised form
28 January 2017
Accepted 30 January 2017
Available online 13 May 2017

Keywords:
Mine depth
Backfill
Sill mat
Stresses
Numerical modeling

ABSTRACT

Backfill is commonly used in underground mines to help increase the ore recovery rate and reduce the ore dilution. The use of a part of mine waste as underground backfill material also helps reduce the environmental impact of mining operations. After all, backfill is used to provide a working platform or safer working space. Its primary and most important role is to improve the rock mass stability around mine openings. However, most available solutions to stress analyses were developed for an isolated stope, without taking into account the influence of mine depth, or of adjacent stopes. In this paper, results from a numerical study carried out to evaluate the stresses in backfilled stopes overlying a sill mat are presented. Mine depth and excavation of the underlying stope below the sill mat (horizontal pillar) are both taken into consideration. The influence of stope geometry, backfill, sill mat and rock properties on the stresses is also evaluated. Compared with the case of a single isolated backfilled stope, the numerical results show that the stress magnitudes in the overlying backfill are considerably increased due to the excavation of the underlying stope. In general, the stresses also increase with mine depth and backfill stiffness, while these tend to decrease with an increase in the surrounding rock mass stiffness. These results suggest that existing solutions for backfill design may need to be revised.

1. Introduction

Backfilling has become very common in underground mines around the world because it helps improve ground stability. It can also reduce the environmental impact of mining operations by utilizing a part of mine waste as underground backfill material (e.g. Aubertin et al., 2002; Bussière, 2007; Benzaazoua et al., 2008).

Several mining methods can involve the use of backfill. For instance, sill mats made of cemented backfill are commonly used to recover sill pillars in sublevel stoping methods. In the case of the underhand cut-and-fill mining method, ore is mined out by horizontal layers (cuts) from a higher level, followed by the construction of sill mats (horizontal pillars) made of cemented backfill. These man-made pillars are designed to provide a safer working space during the mining operations of underlying stopes (Hartman, 1992; Darling, 2011).

A main concern for the design of these sill mats is the minimum required strength of the cemented backfill used for their construction. The only available solutions to determination of the required strength of cemented backfill for sill mats are those of Mitchell (1991) who considered four failure mechanisms by sliding, flexion, rotation, and caving. An equation has been presented for each failure mechanism. The determination of the vertical stress σ_v (kPa) due to the overlying backfill on the cemented backfill sill mat is required in the first three failure modes. Mitchell (1991) proposed the following equation to calculate this stress:

$$\sigma_v = \frac{\gamma B}{2K \tan \phi} \quad (1)$$

where γ and ϕ are the unit weight (kN/m^3) and friction angle of the overlying backfill, respectively; B is the width (m) of the stope (or span of the sill mat); and K is the lateral earth pressure coefficient of the overlying backfill. This equation has been obtained by considering the arching solution for the case of a vertical stope with an

* Corresponding author. Fax: +1 514 340 4477.
E-mail address: li.li@polymtl.ca (L. Li).
Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

http://dx.doi.org/10.1016/j.jrmge.2017.01.001

infinite backfill thickness. Following the approach of Terzaghi (1943) for the case of an excavation within a cohesive soil (known as the "trap-door" problem), Mitchell (1991) has assumed $K = 1$.

1.1. Stresses in backfilled stopes

The stress distribution in a backfilled stope has been investigated extensively over the last decade or so. A few analytical solutions have been proposed for evaluating the stresses within two-dimensional (2D) and three-dimensional (3D) vertical (Aubertin et al., 2003; Li et al., 2005; Pirapakaran and Sivakugan, 2007a; Sobhi et al., 2017) and inclined (Caceres, 2005; Ting et al., 2011, 2014; Jahanbakhshzadeh et al., 2017) backfilled stopes. The non-uniform distribution of the stresses along the width of backfilled stopes has also been taken into account (Li and Aubertin, 2008, 2010), as well as the pore water pressure (Li and Aubertin, 2009a,b, 2010). All of these solutions are extensions from the approach of Marston (1930) who made use of Janssen's (1895) arching theory for estimating the loads on buried conduits in trenches. Arching in backfilled openings has been confirmed by numerical modeling (Li et al., 2003; Pirapakaran and Sivakugan, 2007a; Li and Aubertin, 2009c; Veenstra et al., 2014a, b; Widisinghe et al., 2014) and experimental results (Take and Valsangkar, 2001; Belem et al., 2004; Grabinsky, 2010; Pirapakaran and Sivakugan, 2007b; Thompson et al., 2012; Ting et al., 2012; Widisinghe et al., 2013, 2014; Li et al., 2014).

1.2. Limitations of existing solutions

It is noted that all of the previous numerical, analytical and laboratory experimental investigations were performed without considering the excavation (and filling) of neighboring stopes, except for Hill et al. (1974), Pariseau et al. (1976), Beruar et al. (2013) and Falaknaz et al. (2015a, b). Hill et al. (1974) and later Pariseau et al. (1976) conducted a few finite element analyses to investigate the effect of backfilling on the stope closure and stresses in a sill pillar separating two stopes. They indicated that the stope closure and pillar stresses can be decreased significantly by using a stronger backfill. Beruar et al. (2013) investigated the influence of sill pillar geometry and addition of backfill on the rockburst potential of pillars. Their results did not include the stresses in the backfill. Falaknaz et al. (2015a,b) investigated the stresses in multiple backfilled stopes laying side by side (at the same level). Their results showed that the stress distributions within a backfilled stope can be quite different when a new stope is created nearby.

In this paper, the stress distribution along the vertical central line (VCL) of a backfilled stope overlying a sill mat made of cemented backfill is investigated before and after the excavation of a stope underneath. The focus is placed on the influences of the stope depth and geometry and of the mechanical properties of the backfill, sill mat and rock mass on the induced stresses.

2. Numerical modeling

2.1. Numerical model

The numerical study was carried out using the finite element software PLAXIS 2D (Brinkgreve et al., 2014). The validation process before its application to the present investigation can be found in Sobhi (2014).

Fig. 1 shows the model of a sill mat with an overlying uncemented backfill and an excavation underneath. B is the stope (and sill mat) width, H is the height of the overlying backfill, and e is the thickness of the sill mat. The backfill, sill mat and rock mass are considered as homogeneous and isotropic materials obeying the elasto-plastic law with Coulomb criterion.

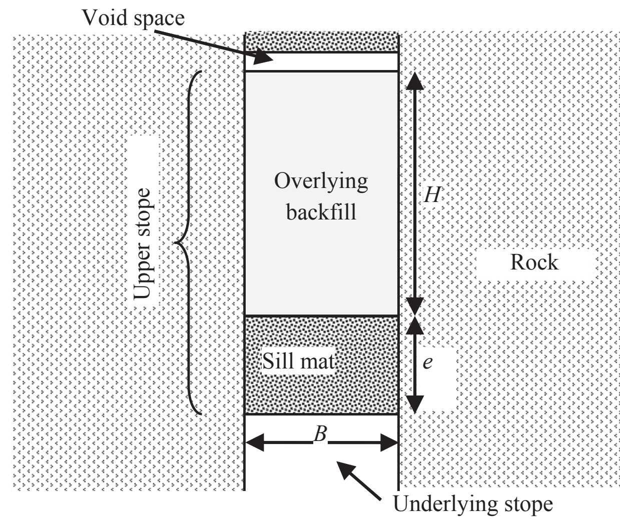

Fig. 1. Model of a sill mat with an overlying uncemented backfill of height H and an underlying excavation.

Parameter sensibility analyses were performed with a reference configuration. It consists of a 6 m wide and 3 m thick sill mat and an overlying vertical stope filled with a cohesionless backfill characterized by H = 10 m (height), E = 300 MPa (Young's modulus), μ = 0.3 (Poisson's ratio), γ = 18 kN/m^3 (unit weight), ϕ = 35° (friction angle), and ψ = 0° (dilation angle). For the sill mat, the Young's modulus E_s = 5 GPa, Poisson's ratio μ_s = 0.3, unit weight γ_s = 20 kN/m^3, cohesion c_s = 1500 kPa, friction angle ϕ_s = 35°, and dilation angle ψ_s = 0°. As for the surrounding rock mass, the Young's modulus E_r = 42 GPa, Poisson's ratio μ_r = 0.25, unit weight γ_r = 27 kN/m^3, cohesion c_r = 9400 kPa, friction angle ϕ_r = 38°, and dilation angle ψ_r = 0°. A void space of 0.5 m is left between the top surface of the backfill and the back of the stope to simulate the poor contact between the backfill and stope roof. The sill mat is located at a depth z = 200 m from its mid-height to the ground surface. A typical stress regime of the Canadian Shield is applied to the rock mass (Herget, 1988; Arjang, 2004), where the vertical in-situ stress is calculated based on the overburden and the horizontal natural stress is twice the vertical in-situ stress (i.e. with a lateral earth pressure coefficient of the rock mass K_r = 2).

Fig. 2 shows the typical numerical model built with PLAXIS 2D for a vertical backfilled stope overlying the sill mat. The vertical symmetry axis has been taken into account by using only half of the full model. The outer boundary is free along the upper face to simulate the ground surface, fixed in the horizontal direction but free in vertical direction along the lateral face, and fixed in both the vertical and horizontal directions along the lower face. The input data for the reference case are also presented in Fig. 2. Other simulations have been conducted by changing one parameter at each time to see its influence on the stress distribution within the backfilled stope and the sill mat.

The numerical simulations have been conducted by following the five steps shown in Fig. 3. The first step is to obtain an initial stress state in the model before any opening exists. The second step consists of excavating the upper stope. In step 3, a sill mat is added using a cemented backfill. A cohesionless backfill material is added (in one layer) above the sill mat in step 4. The last step (step 5) is the creation of a stope below the sill mat.