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# An improved method to assess the required strength of cemented backfill in underground stopes with an open face

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ABSTRACT

Backfill is increasingly used in underground mines to reduce the surface impact from the wastes produced by the mining operations. But the main objectives of backfilling are to improve ground stability and reduce ore dilution. To this end, the backfill in a stope must possess a minimum strength to remain self-standing during mining of an adjacent stope. This required strength is often estimated using a solution proposed by Mitchell and co-workers, which was based on a limit equilibrium analysis of a wedge exposed by the open face. In this paper, three dimensional numerical simulations have been performed to assess the behavior of the wedge model. A new limit equilibrium solution is proposed, based on the backfill displacements obtained from the simulations. Comparisons are made between the proposed solution and experimental and numerical modeling results. Compared with the previous solution, a better agreement is obtained between the new solution and experimental results for the required cohesion and factor of safety. For large scale (field) conditions, the results also show that the required strength obtained from the proposed solution corresponds quite well to the simulated backfill response.



## 1. Introduction

Backfill is increasingly used in underground mines around the world. There are many environmental and economical benefits associated with underground backfilling for the mining industry [1,2]. Nonetheless, the primary objective of stopes backfilling is to provide a safe working space for miners and to increase mineral recovery by reducing ore dilution [3–6].

Many mines operate with primary and secondary stopes. The primary stopes are mined and then backfilled with a cemented fill, which must possess certain characteristics so that it can stand on its own during the mining of adjacent secondary stopes. The solution proposed by Mitchell et al. is commonly used to calculate the required strength for the cemented backfill in stopes with an open face [7]. A simple modification of this solution was proposed by Zou and Nadarajah, who took into account an overlying load (surcharge) [8]. Dirige et al. also proposed an analytical solution (inspired by, but distinct from that of Mitchell et al.) for estimating the required strength of backfill in stopes with inclined walls [7,9]. However, the latter may lead to an overly conservative design as it considers the hanging wall of the backfill as a free surface (without normal stresses); this assumption does not correspond to numerical modeling results, which show that non-negligible contact stresses may exist along the fill-hanging wall interface, depending upon the wall inclination, stope geometry and backfill properties [10]. The authors also proposed a modification of the Mitchell solution that is largely based on similar assumptions as those adopted by Mitchell et al.; the modified solution is typically (but not always) less conservative than the latter [7,11].

Mitchell et al. developed their original solution based on a limit equilibrium analysis [7]. To validate their solution, these authors conducted a series of box stability tests in the laboratory. These same test results will be used below to validate (in part) the solution proposed here, and to make a comparison with the original Mitchell solution.

In this paper, the solution proposed by Mitchell et al. is first recalled [7]. Some of the main assumptions behind the underlying wedge model are examined. Three dimensional numerical simulations are then presented to assess the mechanical response of the backfill upon exposure due to removal of a vertical (supporting) wall. A new analytical solution is proposed for the exposed backfill strength, taking into account the simulation results regarding the displacement and apparent failure mechanism. This improved solution is compared with experimental data for validation purposes.

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## 2. Wedge block model

### 2.1. Original solution

Fig. 1 shows the wedge block model used by Mitchell et al. to develop an analytical solution for estimating the factor of safety (*FS*) of a stope upon exposure of the unsupported backfill [7]. The corresponding values of *FS* can be formulated as:

$$FS = \frac{\tan\phi}{\tan\alpha} + \frac{2cL}{H^*(\gamma L - 2c_b)\sin 2\alpha} \tag{1}$$

where $B$ and $L$ are the stope length and width, respectively; $\alpha$ the assumed angle between the sliding and horizontal planes at the base of the wedge; $c$ and $\phi$ the cohesion and internal friction angle of the backfill (based on the Coulomb failure criterion), respectively; $c_b$ the bond cohesion (adherence) along the interface between the side walls and backfill; and $H^*$ (=$H - (B\ \tan\alpha)/2$, where $H$ is the actual height) is an equivalent height of the wedge block.

Assuming $c_b = c$, Eq. (1) can be used to evaluate the required backfill strength (cohesion); this leads to the following equation:

$$2c = \frac{(FS - \frac{\tan\phi}{\tan\alpha})\gamma H^* L \sin 2\alpha}{(FS - \frac{\tan\phi}{\tan\alpha})H^* \sin 2\alpha + L} \tag{2a}$$

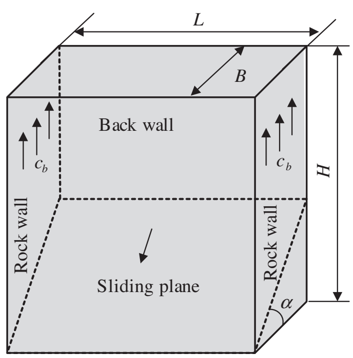


**Fig. 1.** Wedge block model [7].

By further considering $H \gg B$ (thus $H^* \approx H$), Mitchell et al. expressed the required backfill cohesion as follows (for $FS = 1$) [7]:

$$c = \frac{\gamma H}{2(H/L + \tan\alpha)} \tag{2b}$$

where the sliding plane angle $\alpha$ is dependent on the fill friction angle $\phi$ (i.e. $\alpha = 45° + \phi/2$, for the commonly used assumption).

For the specific case (considered by Mitchell et al. [7]) where $\phi = 0$ (or $\alpha = 45°$), $c_b = c$, and $H \gg B$, Eq. (1) reduces to the following:

$$FS = \frac{2cL}{H(\gamma L - 2c)} \tag{3}$$

The required unconfined compressive strength, UCS (=$2c$, for $\phi = 0$) can then be expressed from Eq. (2b) or Eq. (3) as follows (for $FS = 1$):

$$UCS = 2c = \frac{\gamma H}{1 + H/L} \tag{4}$$

Eq. (4) was proposed by Mitchell et al. to define the minimum strength of cemented backfills in stopes with an unsupported (open) face [7].

To validate this solution (Eq. (4)), Mitchell et al. performed a series of box stability tests conducted using a laboratory physical model [7]. Their main experimental results are summarized in Table 1. Fig. 2 shows a comparison of the required cohesion obtained from the experimental and predicted results. These tend to indicate that this solution often overestimates the required strength of the backfill, especially for stopes having a relatively low (height to length) aspect ratio ($H/L < 3.5$), leading to uneconomic design. The relatively poor correlation between this solution and the experimental results is further illustrated in Fig. 3 in terms of *FS*; this figure indicates that the analytical solution often tends to underestimate the factor of safety (i.e. $FS < 1$), particularly in the case of low (height to length) aspect ratio openings.

The Mitchell et al. solution presented above was developed based on following hypotheses [7]:

(i) The potential sliding surface near the base of the stope makes an angle $\alpha$ with the horizontal, which is assumed to be $\alpha = 45° + \phi/2$ (corresponding to the Rankine active case).

**Table 1**
Physical model test results of backfilled stopes after removal of the front wall [7].

| Test No. | $L$ (m) | $B$ (m) | $H$ (m) | $\gamma$ (kN/m[c]) | $\alpha$ (°) | Average direct shear strength, $c_b$ (kPa) | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Samples[a] | Control[b] | Corrected[c] |
| S13 | 0.8 | 0.2 | 0.8 | 19.5 | 68 | 3.1 | 3.00 | 3.30 |
| S15 | 0.8 | 0.2 | 0.8 | 19.4 | 69 | 2.9 | 3.40 | 3.40 |
| S7 | 0.8 | 0.4 | 0.9 | 19.7 | 60 | 2.7 | 2.70 | 2.70 |
| T10 | 0.8 | 0.4 | 0.9 | 18.7 | 63 | 2.8 | 3.00 | 3.00 |
| S14 | 0.8 | 0.2 | 1.0 | 19.3 | 66 | 4.0 | 4.00 | 4.00 |
| S18 | 0.6 | 0.2 | 0.8 | 19.4 | 66 | 3.2 | 3.20 | 3.20 |
| S16 | 0.6 | 0.2 | 0.8 | 19.3 | 70 | 2.7 | 3.00 | 3.00 |
| S4 | 0.4 | 0.2 | 0.6 | 19.7 | 60 | 2.2 | 2.00 | 2.20 |
| S17 | 0.6 | 0.2 | 0.9 | 19.6 | 56 | 2.5 | 3.25 | 3.00 |
| S8 | 0.8 | 0.4 | 1.3 | 18.8 | 60 | 3.8 | 3.50 | 4.00 |
| T9 | 0.8 | 0.4 | 1.4 | 19.0 | 72 | 3.0 | 3.50 | 3.50 |
| T11 | 0.8 | 0.4 | 1.6 | 18.9 | 65 | 4.2 | 5.00 | 4.40 |
| T6[d] | 0.8 | 0.4 | 1.8 | 19.5 | 62 | 4.4 | n.a. | 4.90 |
| T12[d] | 0.8 | 0.2 | 1.8 | 18.9 | 65 | 4.0 | n.a. | 4.50 |
| S27 | 0.6 | 0.2 | 1.5 | 18.3 | 78 | 3.5 | 3.50 | 3.60 |
| S28 | 0.6 | 0.2 | 1.5 | 18.1 | 66 | 3.6 | 3.75 | 3.85 |
| S20 | 0.6 | 0.4 | 1.8 | 18.5 | 60 | 3.4 | 3.50 | 3.60 |
| S1A | 0.4 | 0.2 | 1.4 | 20.0 | 61 | 3.2 | 3.10 | 3.20 |

[a] Measured values from direct shear tests done on samples taken from either the intact parts of a failed block or from the material left in the formwork after each test was completed.
[b] Measured values from control direct shear tests, carried out just before fill exposure.
[c] Back calculated values based on the average normal stress on the observed sliding surface for each failure [7].
[d] Failure with a surcharge of 450 N (45 kg in mass).