The effect of stope inclination and wall rock roughness on back-fill free face stability

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ABSTRACT: In order to maximize the recovery of ore in variably dipping ore zones of moderate width, cemented backfill is normally placed to serve as structural support. With the intention of saving on costs, backfill of low cement content can be used, which are often supported by a sillmat of higher strength. The stability of the low cement backfill face, exposed during adjacent mining, must be carefully studied to provide very effective, safe and economic mining operations. Improper design of these stope support structures may result in fill mass failure resulting in relaxation and failure of the stope walls, with consequent losses of production, ore dilution, and in safety problems.

This paper presents a study conducted to assess fill performance during adjacent pillar mining and to provide a comprehensive understanding of backfill behaviour, the failure modes that may occur and the consequences to production, ore dilution and to safety problems, and accurately predict their stability. The design study investigated the effects of stope width and height, orebody geometry and inclination, and wall roughness on the stability of cemented backfill during adjacent pillar mining. Fill properties used were based on paste fill specimens cured for 28 days. Paste fill performances were assessed based on analytical and numerical modeling studies for the different mining conditions. Analytical modeling was carried out using limiting equilibrium analysis and numerical modeling was carried out using FLAC^{3D}. The modeling results suggested that, for stopes that are inclined with smooth wall rock conditions, backfill failure, driven by the fill self-weight, has minimum dependency on the binder content and is reduced by resisting forces developed on the footwall-fill contact. For inclined stopes with rough wall rock conditions, wall roughness contributes significantly to the stability of the backfill during adjacent pillar mining.

The analytical modeling approach was demonstrated to be useful in providing some approximate parameters for predicting the behaviour of paste fill exposed faces during adjacent mining, but cannot predict the mode or mechanisms of failure. Numerical modeling not only assess the stability behaviour of paste fill free faces, but also is able to provide a better idea of paste fill failure modes and possible failure mechanisms. The depth of failure and the potential for instability for a simulated stope filled with paste fill can be predicted, and may be useful in estimating the mass of material that could possibly fail and ore dilution levels.

1 INTRODUCTION

Backfilling is conducted for reasons that include ground control, economics, environmental considerations, and the need to prepare working floors in cut-and-fill operations (Archibald and Hassani, 1998). For ground control, the critical roles of backfill are for wall support in blasthole and cut-and-fill stoping, and as sillmats in undercut mining. The stability of the paste fill exposed face during adjacent mining and of sillmats when exposed by undercut mining is a prime concern due to the high costs associated with maintaining stable paste fill structures.

This paper presents results of a study conducted to assess fill performance during adjacent pillar mining and to provide an understanding of backfill behaviour, the possible failure modes that may occur and the consequences to production, ore dilution and to safety problems, and accurately predict their stability. The design study investigated the effects of various parameters such as stope width and height, orebody geometry and inclination, and wall roughness on the stability of cemented backfill during adjacent pillar mining. In most cases, stability analysis was based on paste fill prepared at 80% pulp density using unclassified tailings mixed with Type 10 Normal Portland cement (NPC) and Type C fly ash (FA), and cured for 28 days, since this corresponds to the cycle time used at the mine. Binder content used were 7% NPC/FA combination for the sillmat and 2.5% NPC/FA combination for the overlying low binder content paste fill.

Analytical and numerical modeling studies were used for the different conditions to asses paste fill performance. Analytical modeling was carried out using limiting equilibrium analysis adapted from a method introduced by Mitchell *et al* (1982). Numerical modeling was carried out using FLAC^{3D} (Fast Lagrangian Analysis of Continua), a powerful three-dimensional elastic plastic-finite difference code capable of solving a wide range of complex problems in mechanics. Models were prepared to simulate two different stope conditions of a mine: stopes 3 m wide, 15 m long, and 30 m high and stopes 7.5 m wide, 15 m long, and 40 m high. Stope walls were inclined at 90°, 75° and 60°. Smooth and rough rock wall conditions were established for simulating typical boundary modes in analytical and numerical modeling.

While the analytical modeling approach was demonstrated to be useful in providing some approximate parameters for predicting the behaviour of paste fill exposed faces during adjacent mining, it cannot predict the mode or mechanisms of failure. Numerical modeling not only assesses the stability behaviour of paste fill free faces, but also able to provide a better idea of paste fill failure modes and possible failure mechanisms. The depth of failure and the potential for instability for a simulated stope filled with paste fill can be predicted, and may be useful in estimating the mass of material that could possibly fail and ore dilution levels.

Based on the modeling results, some general recommendations can be made concerning the overlying paste fill binder content required to avoid instability. Stable fill free face exposure conditions exhibited by the modeling results using analytical and numerical approaches when the orebody is inclined no more than 75° in any of the simulated boundary conditions indicated the appropriateness of adding 2.5% binder content at 1.5% T-10 NPC and 1% T-C FA to the paste fill recipe. Recipes with higher cement contents would result in unnecessarily high operational costs. For exposure in narrower stopes (3 m wide), a lower than 2.5% binder content paste fill recipe may be appropriate. For exposure in 7.5 m wide stopes that is vertically inclined in any of the simulated boundary conditions, the 2.5% binder content paste fill recipe may not be appropriate. The design process, illustrated in case studies performed for establishing stable free vertical fill faces of a mine, demonstrates the effectiveness of the approach not only in describing or predicting the support performance of backfills during mining, but also in assessing arching effects, failure modes and fracture mechanics involved in fill mass failure. The analytical and numerical modeling procedures and results are presented in the following sections.

2 ANALYTICAL MODEL

The analytical solution is adapted from a three-dimensional analytical solution developed by Mitchell *et al* (1982) for the stability analysis of exposed vertical fill faces. The two models differ in orebody geometry, width to length (W/L) and width or length to height (W or L/H) ratios, and therefore are based on a number of different design assumptions. The three-dimensional critical operational stage for paste fill in an inclined orebody after the adjacent ore zone is removed is shown in Figure 1. Besides the shear resistance of a failure plane within the fill, it can be noted that a portion of the block weight is resisted by shear along the footwall contact; insignificant or no shear resistance is expected at the hanging wall contact due to the orebody inclination. The footwall shear resistance is assumed constant and equal to the fill cement bond shear strength, approximated by two strength parameters, cohesion, c, and friction angle, ϕ. The weight of the potential sliding block is reduced by an amount equal to the cohesion and frictional resistance at the fill-footwall rock interface. Depending on the roughness condition of the wall rock, two shearing resistance forces may occur. For wall rock that is generally rough in nature, failure at the fill-rock interface is assumed to occur as shearing through the fill by the rock asperities. Thus, shearing resistance is assumed to be mobilized by both the fill cohesion and friction angle. For relatively smooth wall rock conditions, failure is assumed to occur by shearing within the actual fill-footwall rock interface. Thus shearing resistance is assumed to be mobilized by just the fill friction angle.

For vertically inclined orebody, when both the hanging wall and footwall rocks are smooth, shear resistance is only expected at the failure plane within the fill; no shear resistance is expected at the hanging wall/footwall rock – fill interface. Shear resistance is however, expected at the hanging wall/footwall rocks – fill interface when the wall rocks are rough.

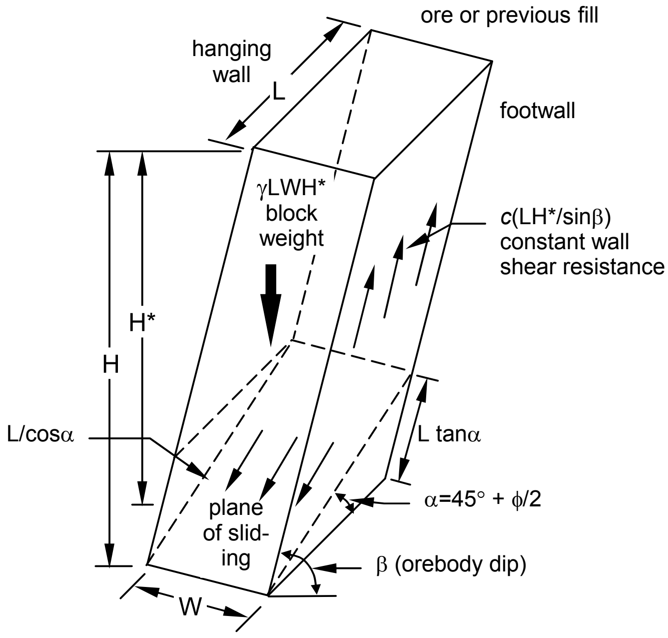


Figure 1. Confined block mechanism (adapted from Mitchell *et al*, 1982).

Using the strength parameters for the cemented backfill material, the optimum paste fill recipe to be used for a given stope dimension can be determined. It is assumed that a paste fill recipe which can provide a factor of safety of more than one for a given stope free-standing height can be considered to be stable.

For an orebody inclined less than 90°, the factor of safety against failure is estimated by balancing the total driving forces acting on the fill plane of sliding (failure plane) with the shear resistance acting along the fill failure plane and with the shear resistance at the fill-footwall rock wall contact. The shear resistance at the footwall interface is a function of the degree of roughness of the rock wall. For smooth rock wall surfaces, the factor of safety against failure is given as:

$$F.S. = \frac{\tan\phi}{\tan\alpha} + \frac{c \text{ x } \dfrac{\text{L}}{\cos\alpha} \text{ x W}}{F_V \text{ x } \sin\alpha} + \frac{\cos\beta \tan\phi}{\sin\alpha} \quad (1)$$

where F_V = vertical force applied by the weight of the potential sliding block, kN; α = angle of the failure plane within the fill = 45 + ϕ/2, degrees; ϕ = fill friction angle, degrees; β = hanging wall/footwall dip, degrees; c = fill cohesion, kN/m^2; W = stope/backfill width, m; and

$$F_V = (\gamma \text{ x W x L x H}^*) - ((\gamma \text{ x W x L x H}^*)\cos\beta \tan\phi) \quad (2)$$

where γ = fill unit weight, kN/m^3 and H* = H – (L tanα)/2, m where H is the fill height, m.

For rough rock wall surfaces, the factor of safety against failure is given as:

$$F.S. = \frac{\tan\phi}{\tan\alpha} + \frac{c \text{ x } \dfrac{\text{L}}{\cos\alpha} \text{ x W}}{F_V \text{ x } \sin\alpha} + \frac{\cos\beta \tan\phi}{\sin\alpha} + \frac{c \text{ x L x } \dfrac{\text{H}^*}{\sin\beta}}{F_V \text{ x } \sin\alpha} \quad (3)$$

where the vertical force, F_V, is given as:

$$F_v = (\gamma \text{ x W x L x H*}) - \left(\left(c \text{ x L x } \frac{\text{H*}}{\sin\beta}\right) + (\gamma \text{ x W x L x H*})\cos\beta\tan\phi\right) \quad (4)$$

For a vertically inclined orebody with smooth fill-rockwall interface, the factor of safety against failure is estimated by balancing the total driving forces acting on the fill plane of sliding (failure plane) with the shear resistance acting along the fill failure plane. There is no shear resistance at the fill-rock wall contact. When the fill-rock wall contacts (hanging wall and footwall) are rough, the shear resistance at the fill-rock wall interface is included in the equation. For smooth rock wall surfaces, the factor of safety against failure is given as:

$$F.S. = \frac{\tan\phi}{\tan\alpha} + \frac{c \text{ x } \frac{\text{L}}{\cos\alpha} \text{ x W}}{F_V \text{ x } \sin\alpha} \quad (5)$$

where the vertical force, F_V, is given as:

$$F_V = (\gamma \text{ x W x L x H*}) \quad (6)$$

For rough rock wall surfaces, the factor of safety against failure is given as:

$$F.S. = \frac{\tan\phi}{\tan\alpha} + \frac{c \text{ x } \frac{\text{L}}{\cos\alpha} \text{ x W}}{F_V \text{ x } \sin\alpha} + \left(\left(\frac{\cos\beta\tan\phi}{\sin\alpha}\right) * 2\right) + \left(\left(\frac{c \text{ x L x } \frac{\text{H*}}{\sin\beta}}{F_V \text{ x } \sin\alpha}\right) * 2\right)$$

(7)

where the vertical force, F_V, is given as:

$$F_v = (\gamma \text{ x W x L x H*}) - \left(\left(\left(c \text{ x L x } \frac{\text{H*}}{\sin\beta}\right) + (\gamma \text{ x W x L x H*})\cos\beta\tan\phi\right) * 2\right) \quad (8)$$

2.1 *Analytical Model Development*

The limit equilibrium analysis assumed that the paste fill free-standing height is stable when the factor of safety against failure is more than 1. For smooth rock wall conditions, the rock wall and fill interface was assumed to have a very low frictional or shearing resistance. For rough rock wall conditions, the shear resistance at the rock wall-fill interface was assumed to be equal to the fill shear strength. Application of the model described by equations 1 - 8 was based on a series of parametric calculations. The fill shear strength parameters, obtained from uniaxial and triaxial compression tests, are shown in Table 1. The paste fill/stope dimensions are listed in Table 2.

Table 1. Fill properties.

Paste Fill Properties	**Paste Fill Recipe (% binder content)**	
	2.5%	**7%**
Friction Angle, ϕ	29.00	35.00
Cohesion, c (kPa)	44.95	305.10
Uniaxial Compressive Strength, (kPa)	168.00	1,235.00
Unit Weight, γ, (ρg) (kN/m^3)	18.98	19.03
Density, ρ (g/cm^3)	1.94	1.94
Plane Failure Angle, α ($\alpha = 45^0 + \phi/2$) (degree)	59.50	62.50
Hanging wall/Footwall Dip, β (degree)	75.00	75.00

Table 2. Fill dimensions.

Dimensions		**Paste Fill Recipe (% binder content)**			
		2.5%		**7%**	
Stope Height (m)		30.00	40.00	30.00	40.00
Stope Width, W (m)		3.00	7.50	3.00	7.50
Block Height, H (m)					
Sillmat Thickness (m)	*Whole Column*	30.00	40.00	30.00	40.00
	1W Sill	27.00	32.50	-	-
	2W Sill	24.00	25.00	-	-
Effective Height, H* (m) = H - (L/tanα)/2					
Sillmat Thickness (m)	*Whole Column*	25.58	35.58	26.10	36.10
	1W Sill	22.58	28.08	-	-
	2W Sill	19.58	20.58	-	-
Strike Length, L (m)		15.00	15.00	15.00	15.00
Sliding Plane Length, ℓ (m) = L/cosα		29.55		32.49	

2.2 *Analytical Model Results*

Results of the limit equilibrium trial calculations for paste fill free-standing heights are shown in Table 3.

Table 3. Factor of safety calculation results.

Stope Width, Height, and Paste Fill and Sill Thickness (m)	**2.5% Binder**						**7% Binder**					
	90°		**75°**		**60°**		**90°**		**75°**		**60°**	
	S	***R***	***S***	***R***	***S***	***R***	***S***	***R***	***S***	***R***	***S***	***R***
3 m Wide and 30 m High Stope												
Full Stope Height	0.54	5.68	0.74	30.05	0.94	∞	1.89	∞	2.44	∞	3.11	∞
27 m (1W Sill)	0.57	5.82	0.77	30.76	0.98	∞	2.10	∞	2.69	∞	3.43	∞
24 m (2W Sill)	0.60	5.99	0.82	31.7	1.03	∞	2.36	∞	3.01	∞	3.83	∞
7.5 m Wide and 40 m High Stope												
Full Stope Height	0.48	1.08	0.67	1.50	0.86	2.25	0.53	∞	0.77	∞	1.01	∞
32.5 m (1W Sill)	0.52	1.14	0.72	1.57	0.91	2.37	0.57	∞	0.82	∞	1.07	∞
25 m (2W Sill)	0.59	1.25	0.80	1.71	1.01	2.56	0.64	∞	0.91	∞	1.19	∞

Note: *S* = smooth and *R* = rough

Results indicated that, for smooth rock wall conditions (where the shear resistance at the rock wall-fill interface is mobilized by the fill friction resistance), the 2.5% paste fill blend in most of the simulated stope widths, orebody inclination, and free face heights, except for the stopes inclined at 60° with 2W sill, would become unstable (Table 3). When placed in stopes with rough wall rock conditions, the analytical equation indicated that the 2.5% paste fill blend in any of the simulated free face heights and stope widths would become stable.

For the 7% binder content paste fill in any of the simulated 3 m stopes, the analytical equation indicated stable conditions. For the wider stope (7.5 m), unstable conditions are indicated when the orebody inclination is more than 60° and with smooth rock wall-fill interface. Model results indicated that the 7% paste fill blend free standing faces in any of the simulated stope widths with rough rock wall condition would become stable. The infinite factor of safety results suggest stable conditions or the equation do not work for the given conditions. When the equations is used in stopes with dimensions of 15 m strike length and 30 - 40 m height, and input parameters (cohesion and friction angle) from a 7% paste fill blend, results suggest the following: the factor of safety equation using the net weight of sliding block would be applicable when the stope width, W, is ≥ 0.667*H, and inclined at 75°. Widths lower than 0.667*H would result in a condition where the resisting force is higher than the vertical force applied by the weight of the potential sliding block, and therefore indicating stable conditions.

In general, fill stability increases with decreasing stope width and height, and orebody inclination, and increasing binder content and wall roughness.

3 NUMERICAL MODEL

Numerical modeling was carried out using FLAC^{3D}. FLAC^{3D} offers a wide range of capabilities to solve complex problems in mechanics. Three-dimensional elastic-plastic models were constructed and, since closure strains and pore pressure development were not considered in the study, the stope walls were modeled as fixed boundaries. First, a geometrically-similar model was formed using a refined grid to ensure that a failure plane would be well defined within the fill. The fill-rock wall interfaces were then created to simulate distinct planes along which slip and/or separation can occur. Because the stability of the paste fill free face is dependent on the strength of the fill and fill-wall rock interface, the interface strength was simulated in two of the scenarios found underground. Smooth rock wall conditions were established by setting the friction angle of the interface equal to the fill friction angle and the interface cohesion was assumed to be zero. Rough rock wall conditions were simulated by setting the interface strength equal to the fill cohesion and friction angle.

3.1 *Numerical Model Development*

A series of three-dimensional elastic-plastic models were constructed using FLAC^{3D}. An inclined stope 3-D geometry and long section are illustrated in Figure 2(a) and (b). The fill was discretized into cube elements each with a volume of 0.125 m^3, to ensure that a failure plane would be well defined within the fill, while the wall rock representing the boundary was discretized into larger cube elements each with a volume of 1 m^3. The fill was modeled as a Mohr-Coulomb material using effective shear strength parameters obtained from consolidated-undrained triaxial tests while the boundary (wall rock) was modeled as an elastic material. The backfill properties were measured from paste with 2.5% and 7% binder contents, cured for 28 days. The model input parameters are shown in Table 4.

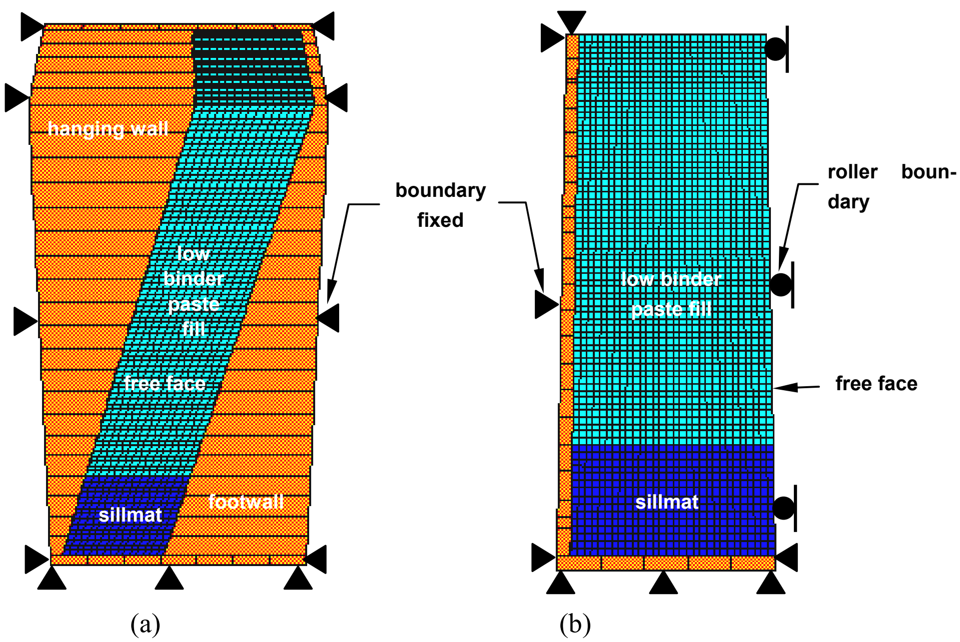


Figure 2 (a). 3-D paste fill free-standing height geometry. (b). Long section.

Two-dimensional interface elements were placed between the fill and the fixed stope wall boundaries to represent the frictional properties of the fill-rock interface. In this case, the interface allowed for the grids, representing the fill and rock mass, to move by sliding and/or opening relative to one another. The elastic stiffness of the interface may not be of importance but the friction and cohesion played an important role on stability characterization. It was recommended by Itasca Consulting Group (Electronic User's Manual) that the lowest stiffness, consistent with the smallest interface deformation, be used. It was also suggested, as a good rule-of-thumb, to set the normal stiffness, k_n, and shear stiffness, k_s, to ten times the equivalent stiffness of the stiffest neighboring zone. The apparent stiffness (expressed in stress-per-distance) of a zone in the normal direction was given by the equation:

$$\max\left[\frac{\left(K+\frac{4}{3}G\right)}{\Delta z_{\min}}\right] \quad (6.4) \quad (9)$$

where K and G are the Bulk and Shear Moduli, respectively, and $\Delta z_{\min}$ is the smallest width of the adjoining zone in the normal direction.

Table 4. Material properties of the fill and rock.

Parameters	Sillmat	Paste Fill	Rock
	7% Binder Content	2.5% Binder Content	
Density (ρ)	1,940 kg/m^3	1,935 kg/m^3	2,700 kg/m^3
Bulk Modulus (K)	85.81 MPa	18.66 MPa	310 MPa
Shear Modulus (G)	53.97 MPa	13.82 MPa	230 MPa
Effective Cohesion (c')	0.305 MPa	0.045 MPa	-
Effective Internal Friction Angle (ϕ')	35°	29°	-
Tensile Strength ($c/tan\phi$)	0.436 MPa	0.081 MPa	-
Compressive Strength	1.235 MPa	0.168 MPa	-

The max [ ] notation indicates that the maximum value over all zones adjacent to the interface should be used. In the modeling, the minimum zone size adjacent to the interface was 0.5 m. The friction angle of the interface was set equal to the fill friction angle, and the interface cohesion was assumed to be zero for models with smooth walls and equal to the fill cohesion for models with rough walls.

During the modeling sequence, gravity stresses due to self-weight were first allowed to develop in the fill and the model was allowed to reach gravity equilibrium. This simulation was performed elastically so that the fill would not yield. At equilibrium, displacements were reset to zero, the cohesion and friction material properties were set to the proper values, and adjacent mining activity was simulated by freeing the y-direction, which was initially fixed at the free face of the fill. At this simulation stage, the program was set in 'large strain mode' to allow appropriate deformations of the grid to develop. Both y-displacement and unbalanced force histories were used to evaluate whether the system was coming to equilibrium at each step. Increased steps were continued until active collapse of the fill occurred or the model reached equilibrium. The history of horizontal displacements at the fill free face was also recorded. The state of plasticity, stress contours, and displacement contours and vectors were also used to evaluate paste fill deformation behaviour and failure modes.

3.2 *Numerical Model Results*

Results of the numerical modeling for paste fill free-standing heights are shown in Table 5. Modeling results representing stopes with sillmats (using 7% binder content paste fill) of varying thicknesses overlain by 2.5% binder content paste fill cured at 28 days in 3 m wide, 30 m high and 7.5 m wide, 40 m high stopes, are presented to illustrate the range of responses observed. Figures 3 to 9 show the plastic state, displacement vectors, displacement contours and horizontal displacement (y-displacement) histories for stopes with varying sillmat heights overlain by a 2.5% paste fill blend. The plots of plastic state, displacement vectors and displacement contours are taken from a long section parallel to the orebody strike length, midway between the hanging wall and footwall. The largest vector in the plane representing horizontal (y-) displacement is scaled to facilitate visual observation of deformation. The plots of horizontal (y-) displacement perpendicular to the vertical free face (shown in Figures 3b, 4b, 5b, 6b, 7b, 8b and 9b) are monitored from points at the center of the stope, midway between the footwall and the hanging wall, at heights of 5, 14, 23 and 30 m from the base for the 3 m wide, 30 m high stopes, and 10, 20, 30 and 40 m from base for the 7.5 m wide, 40 m high stopes. The presented results apply to models with rough and smooth rock wall conditions.

Table 5. Stability conditions for paste fill blends cured for 28 days placed in stopes of different dimensions predicted by FLAC^{3D} models.

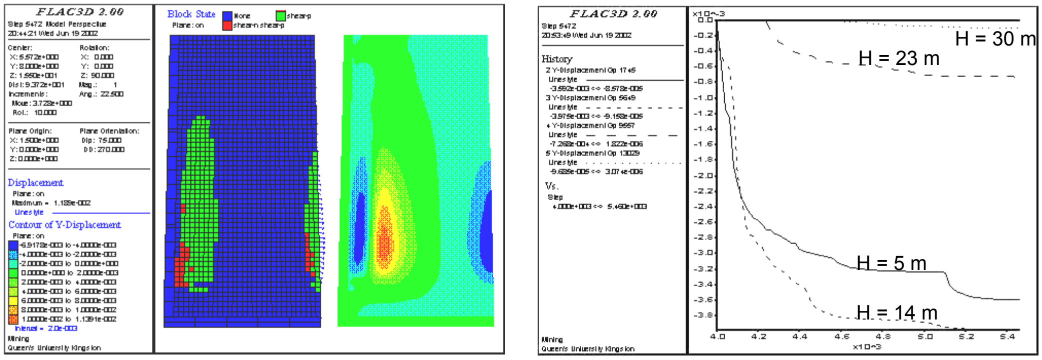
Stope Width, Height, and Paste Fill and Sill Thickness (m)	**2.5% Binder**						**7% Binder**					
	90°		**75°**		**60°**		**90°**		**75°**		**60°**	
	S	***R***	***S***	***R***	***S***	***R***	***S***	***R***	***S***	***R***	***S***	***R***
3 m Wide and 30 m High Stope												
Full Stope Height	Ustbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl
27 m (1W Sill)	Ustbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl
24 m (2W Sill)	S	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl
7.5 m Wide and 40 m High Stope												
Full Stope Height	Ustbl	Stbl	Ustbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl
32.5 m (1W Sill)	Ustbl	Stbl	Ustbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl
25 m (2W Sill)	Ustbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl	Stbl

Note: *S* = smooth, *R* = rough, Ustbl = unstable, and Stbl = stable.

Numerical modeling results showed that, in any of the simulated mining conditions (3 and 7.5 m wide stopes, and 30 and 40 m high, respectively, and rough boundary conditions), stable fill free face conditions were achieved. Each model scenario differed in various aspects, such as the number of time steps to reach equilibrium, plastic state, displacement vectors and contours, unbalanced forces, and horizontal displacements at the free-face.

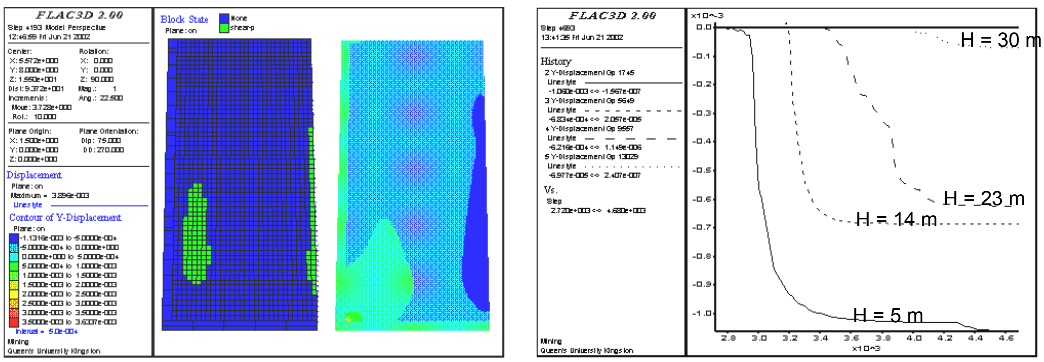
The 3 m wide, 30 m high vertically inclined stope with rough rock wall condition and sillmat thickness equivalent to the stope width (Figure 3 (a)), showed failure to be restricted to a 1.5 m thick zone at the exposed face, as indicated by the plastic state and displacement contour. The failed zones were indicated to have undergone shear failure at the earlier stages of the simulation (shear in the past, shear-p), except for a number of elements in the 1 width sillmat model, which indicated active shear failure (shear-n) at 0.5 to 1.5 m from the fill face above the sillmat. The shear failures in the past (shear-p) are a result of initial plastic flow conditions that occurred at the earlier stages of the simulation. Subsequent stress redistribution during further simulation had relaxed the yielding elements so that their stresses could no longer satisfy the yield criterion. Only the active yielding elements (shear-n, tension-n) are important to the detection of a failure mechanism. It can be noted that, for the models with 2.5% overlying paste fill blend, the failed zones increase in height with increasing fill column and stope inclination, and decreasing rock wall roughness. This is an indication of the significance of the fill self-weight on the stability of paste fill exposed faces. In spite of the existence of some elements which indicated active shear failure, total failure is not expected to occur because of the lack of a continuous plane that joins two surfaces. All the 3 m wide models with varying orebody inclination are therefore considered stable (Figures 4 (a) and 5 (a). This are supported by the horizontal (y-) displacement histories from the exposed fill faces in Figures 3 (b), 4 (b) and 5 (b) which show the displacements levelling out as the solution proceeded. The maximum horizontal (y-) displacement vector of the vertical fill face for the model with sillmat thickness equivalent to the stope width is around 8.65 x 10^{-3} m.

In the 7.5 m wide, 40 m high vertically inclined stope, the depth of failure extends to 3.5 m (Figure 6 (a)) from the fill free face. While it can be noted that many of the zones have failed in the past (shear-p), and are no longer undergoing active yield (shear-n), there are still a few zones in active shear. Active shear extends at a depth of 2 to 3.5 m from the fill free face, just above the sill and extends to a height of around 11.5 m. Nonetheless, lack of a continuous plane of active plastic zone joining the two surfaces of the fill is evident. It may be possible that the active yield zone remained constant in size until the system reached equilibrium or that these elements may be simply sitting on the yield surface without any significant plastic flow taking place. The stable condition of the fill free face is supported by the horizontal (y-) displacement histories observed from the exposed fill faces shown in Figure 6 (b) which levelled out as the solution proceeded. The results are consistent with those of the 3 m wide stope. The maximum horizontal (y-) displacement vector of the vertical fill face for the model is around 3.063 x 10^{-2} m.



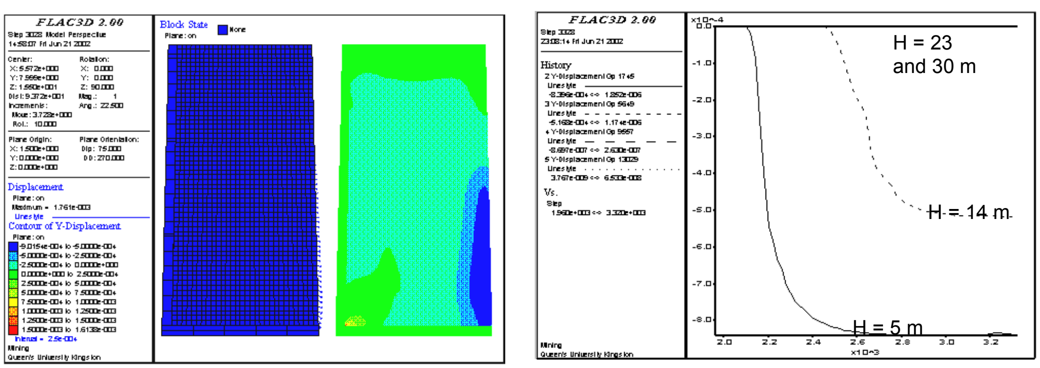
(a) (b)

Figure 3 (a). Plastic state, displacement vectors and displacement contours in a long section for sillmat thickness equivalent to the stope width overlain by 2.5% paste fill blend cured for 28 days in a 3 m wide vertically inclined stope with rough rock walls (shear-n=shear yielding now, shear-p=shear yielding in past); and (b). History of horizontal displacements (y-displacement) of the vertical fill face versus time step at heights 5, 14, 23 and 30 m from fill base.



(a) (b)

Figure 4 (a). Plastic state, displacement vectors and displacement contours in a long section for sillmat thickness equivalent to the stope width overlain by 2.5% paste fill blend cured for 28 days in a 3 m wide stope inclined at 75° with rough rock walls (shear-n=shear yielding now, shear-p=shear yielding in past); and (b). History of horizontal displacements (y-displacement) of the vertical fill face versus time step at heights 5, 14, 23 and 30 m from fill base.

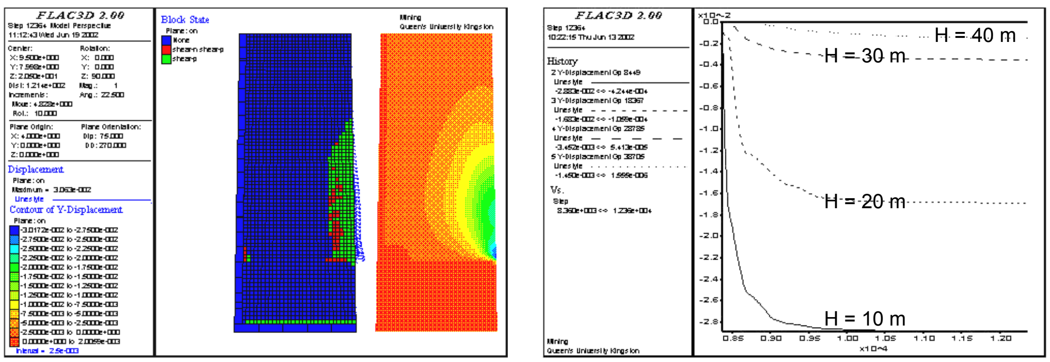


(a) (b)

Figure 5 (a). Plastic state, displacement vectors and displacement contours in a long section for sillmat thickness equivalent to the stope width overlain by 2.5% paste fill blend cured for 28 days in a 3 m wide stope inclined at 60° with rough rock walls (shear-n=shear yielding now, shear-p=shear yielding in past); (b). History of horizontal displacements (y-displacement) of the vertical fill face versus time step at heights 5, 14, 23 and 30 m from fill base.

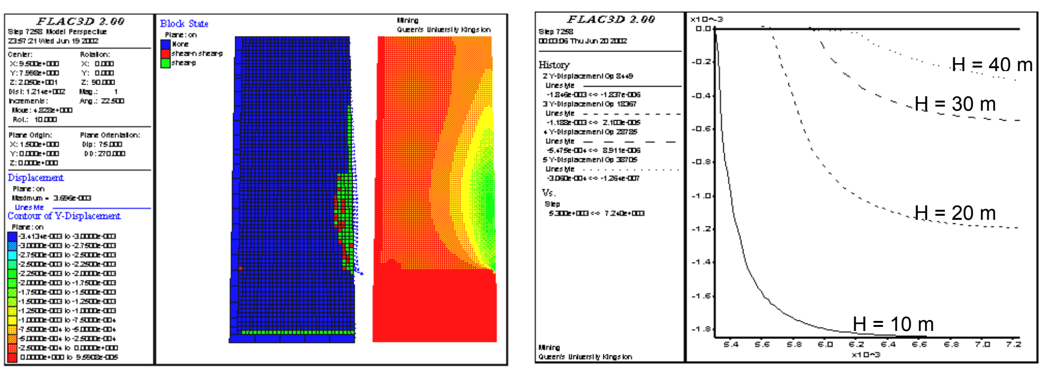
Figures 7 and 8 show results for a 7.5 m wide, 15 m long and 40 m high stope with sillmat thickness equivalent to the stope width and orebody inclination of 75° and 60°, respectively. The plastic state and displacement contour in Figure 7 (a) indicated failure to be restricted to a 2.5 m thick zone at the exposed face. The model shows that most of the zones have failed in the past and are no longer under active yield, and that only a few zones were in active shear. However, no significant plastic flow took place in the active shear zones and they may have remained constant until the system reached equilibrium. Figure 8 (a) indicated stable condition. The stable condition of the fill free face for both models is supported by the horizontal (y-) displacement histories from the exposed fill face shown in Figures 7 (b) and 8 (b). The maximum horizontal (y-) displacement vector of the vertical fill face for the model in Figure 7 (a) is around 1.16×10^{-2} m.

Displacement at the fill free face also indicated an increasing trend with increasing overlying paste fill height, stope width and orebody inclination, and decreasing rock wall roughness. Numerical model simulations for stopes with rough footwall boundary conditions showed better stability indicating the effect of wall roughness on the free-standing height stability of paste fill faces exposed during adjacent mining.



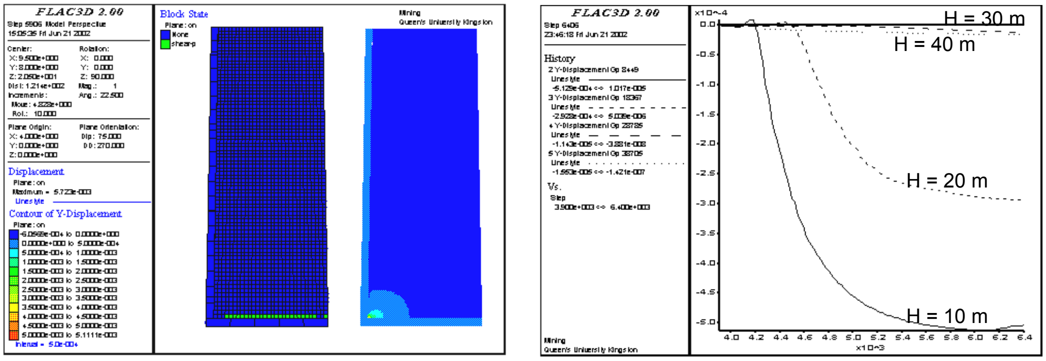
(a) (b)

Figure 6 (a). Plastic state, displacement vectors and displacement contours in a long section for sillmat thickness equivalent to the stope width overlain by 2.5% paste fill blend cured for 28 days in a 7.5 m wide vertically inclined stope with rough rock walls (shear-n=shear yielding now, shear-p=shear yielding in past); and (b). History of horizontal displacements (y-displacement) of the vertical fill face versus time step at heights 10, 20, 30 and 40 m from fill base.



(a) (b)

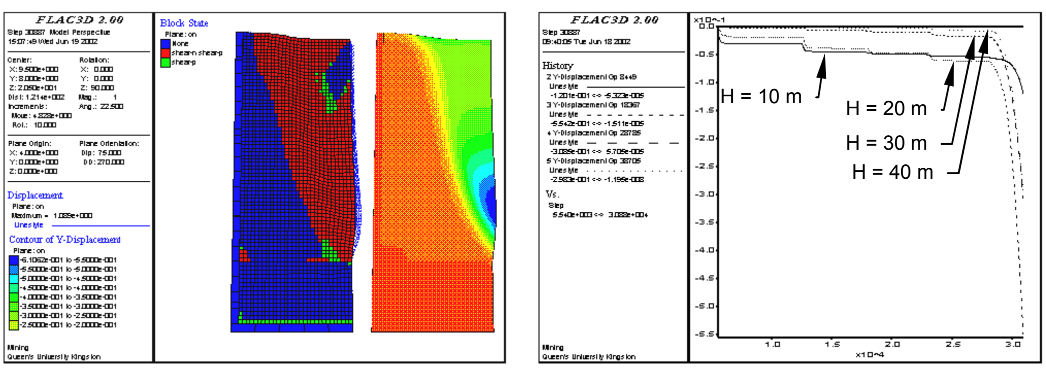
Figure 7 (a). Plastic state, displacement vectors and displacement contours in a long section for sillmat thickness equivalent to the stope width overlain by 2.5% paste fill blend cured for 28 days in a 7.5 m wide stope inclined at 75° with rough rock walls (shear-n=shear yielding now, shear-p=shear yielding in past); and (b). History of horizontal displacements (y-displacement) of the vertical fill face versus time step at heights 10, 20, 30 and 40 meters from fill base.



(a) (b)

Figure 8 (a). Plastic state, displacement vectors and displacement contours in a long section for sillmat thickness equivalent to the stope width overlain by 2.5% paste fill blend cured for 28 days in a 7.5 m wide stope inclined at 60° with rough rock walls (shear-n=shear yielding now, shear-p=shear yielding in past); and (b). History of horizontal displacements (y-displacement) of the vertical fill face versus time step at heights 10, 20, 30 and 40 meters from fill base.

Results of FLAC^{3D} simulations of a filled stope 7.5 m wide, 15 m long and 40 m high (sillmat thickness equivalent to the stope width), with smooth rock wall condition is shown in Figures 9 (a) and (b). The plastic state, total displacement and displacement contours are shown in Figure 9 (a). The horizontal displacement histories are shown in Figure 9 (b). Significant shear failure occurred and the fill collapsed as a sliding block, somewhat resembling a circular slip. The long section of the plastic state in Figure 9 (a) shows a wide band of zones in active shear (shear-n) extending from the base of the overlying paste fill free face up towards the back wall. The failure surface seems to be slightly concave with an angle approximating 60 – 65° from the horizontal which agrees very closely to the failure plane convention of 45 + $\phi/2$. This failure shape is more pronounced in the displacement contour shown in Figure 9 (a). The horizontal displacement histories shown in Figure 9 (b) illustrate the slow failure mode attained before a run-away failure.



(a) (b)

Figure 9 (a). Plastic state, displacement vectors and displacement contours in a long section for sillmat thickness equivalent to the stope width overlain by 2.5% paste fill blend cured for 28 days in a 7.5 m wide vertically inclined stope with smooth rock walls (shear-n=shear yielding now, shear-p=shear yielding in past); and (b). History of horizontal displacements (y-displacement) of the vertical fill face versus time step at heights 10, 20, 30 and 40 meters from fill base.

4 CONCLUSIONS

The analytical and numerical modeling results indicated comparable modeling results in any of the simulated stope dimensions (3 m wide, 15 m long and 30 m high, and 7.5 m wide, 15 m long and 40 m high stopes) with rough stope rock wall conditions in any of the simulated orebody inclinations. However, numerical modeling results do not agree with the analytical modeling results which indicated that, for all the simulated stope sizes and orebody inclination with smooth boundary conditions which were filled with 2.5% overlying paste fill, the factor of safety against failure would be less than 1. Agreement of modeling results was only achieved when the footwall rock conditions were considered rough.

Increasing the binder content of the overlying paste fill to 7% placed in the same stope sizes and with smooth boundary conditions, would increase the stability of the paste fill exposed face compared with the 2.5% paste fill blend. All models with smooth boundary conditions indicated stable conditions in both modeling techniques. With rough wall conditions, all the simulated stope widths would become stable. The paste fill free-standing height analysis also indicated that, when the stope walls are inclined, failure, driven by the fill self-weight, is dependent on the binder content and is reduced by resisting forces developed on the footwall-fill contact and fill failure plane. The case is not the same for vertically inclined orebodies. Failure, which is also driven by the fill self-weight, is dependent on the binder content and is reduced only by the resisting forces developed on the fill failure plane.

While the analytical modeling approach was demonstrated to be useful in providing some approximate parameters for predicting the behaviour of paste fill exposed faces during adjacent mining, it cannot predict the mode or mechanisms of failure. Numerical modeling not only assess the stability behaviour of paste fill free faces, but also is able to provide a better idea of paste fill failure modes and possible failure mechanisms. The depth of failure and the potential for instability for a simulated stope filled with paste fill can be predicted, and may be useful in estimating the mass of material that could possibly fail and the resultant ore dilution levels.

Based on the modeling results, some general recommendations can be made concerning the overlying paste fill binder content required to avoid instability. Stable fill free face exposure conditions exhibited by almost all of the modeling results using the two engineering approaches in any of the simulated mining conditions indicated the appropriateness of adding 2.5% binder content at 1.5% T-10 NPC and 1% T-C FA to the paste fill recipe when the orebody is inclined and with rough rock wall conditions. Recipes with higher cement contents would result in unnecessarily high operational costs. For exposure in narrower stopes (3 m wide) with rough rock wall conditions, a lower than 2.5% binder content paste fill recipe may be appropriate.

5 REFERENCES

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