



An investigation of mechanisms involved in backfill-rock mass behaviour in narrow vein mining

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Synopsis

Today, mine backfilling has become an integral part of mining operations, both from a local and overall ground control point of view, and as regards mining techniques and environmental considerations. During the past decade, substantial research has been carried out to contribute to the better understanding of the mechanisms involved in mine backfill behaviour. This work involved analytical, experimental and numerical studies at different scales. Accordingly, this work has been aimed at developing backfill design guidelines for actual working conditions. Backfill design for deep mining conditions is complex and requires understanding of various elements. The most important of these elements are: backfill inherent strength parameters, backfill placement method, stope geometry and interaction between backfill and host rock. The mobilization of backfill strength parameters controls the backfill behaviour and thus, its failure mode. It is believed that the governing boundary conditions and backfill-rock interaction influence the backfill strength mobilization significantly. Accordingly, the interaction between backfill and host rock is an influential factor in overall backfill behaviour under applied loads. The focus of this research is to investigate the backfill-rock interaction, considering a nonlinear behaviour for both backfill and rock mass. Assuming typical stope geometry, the FLAC code was used to model the complex boundary condition associated with narrow vein mining conditions and to simulate the backfill behaviour. A comprehensive numerical study was conducted and the results obtained were compared against field observations. The analysis of findings provides qualitative results, which can be used for backfill design.

Keywords: Numerical modelling, backfill, deep mining, non-linear behaviour, rock mechanics, backfill behaviour, narrow vein mining.

Introduction

The history of application of backfill in North America goes back to the 1950s when hydraulic backfill was first introduced. De Souza *et al.* (2003) gave a summary of developments in backfill and backfilling as a ground control technique. Hassani and Archibald (1998) described different types of backfill employed in underground mining conditions. Cemented rock and paste backfill were developed in 1980s and enabled the use of more efficient mining methods. As a major ground control element, mechanical behaviour

of backfill has been studied by many authors. Hassani and Archibald (1998) provided typical values of mechanical properties for various types of backfills. Mitchell (1991) investigated the sill mat behaviour experimentally. William *et al.* (2001) looked at cemented backfill employed at the Lucky Friday mine from a geomechanics design point of view. The arching phenomenon observed in backfill was discussed by many authors (Marston, 1930; Terzaghi, 1943; Blight, 1986; Iglesia *et al.*, 1999; Take *et al.*, 2001). Aubertin *et al.* (2003) further explored the arching concept and looked at the backfill and rock mass interaction using analytical and numerical approaches. Assuming an elastic rock mass, the stress distribution within the backfill was examined analytically (Marston theory) and numerically (employing the Phase2 finite element code). They showed the strength of a numerical approach over existing analytical methods; however, material models used for backfill and rock mass were not suitable to represent the actual field condition.

As regards the complexities associated with mining at depth and under high stress conditions, analytical solutions mentioned above are not capable of describing the governing boundary condition in backfilled spaces in underground openings. Moreover, the behaviour and interaction of backfill and rock mass are non-linear and the governing differential equations cannot be solved analytically. On the other hand, powerful numerical methods capable of considering these complexities are developed.

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In this study, the FLAC code was used to investigate the mechanisms involved in backfill-rock mass behaviour. The concept presented in this paper has been used in a simplified manner in backfill design. As an example the work published by Rankine *et al.* (2007) uses a simplified approach to design backfill for BHP Cannington Mine in Australia. Additionally, in the modelling of the underground stability of cemented hydraulic fill (CHF) at Mount Isa Mine (Bloss, 1993) a similar concept was employed. However, in all these studies simplifications such as assuming vertical stope geometry or an elastic host rock behaviour were considered. Moreover, in previous works complexities such as the backfill-rock mass interface and its role in the backfill-rock interaction were not considered explicitly and in detail. In the presented work nonlinear material models were used for both backfill and host rock. Interface elements were employed in backfill-host rock contacts to capture the mechanisms involved. Comparison of field data against numerical results published by other authors is satisfactory. This work is a comprehensive numerical study, which includes the complexities associated with backfill design in deep mining condition; however, it is believed that more verification of the proposed concept is required. In the following sections the results of the conducted numerical analysis are presented.

Numerical investigation of backfill behaviour

Modelling strategy and input data

A 2D FLAC model of a typical stope of 50 m (height) by 6 m (width) was constructed. Assuming that the orebody has sufficient extension along strike, a plain strain condition was considered. The stope is dipping at 65 degrees and the model dimensions selected were large enough (200 m × 150 m) to avoid boundary effects. This was assured by examining the pattern and extent of induced stresses within the model after the excavation of the stope. Furthermore, it was assumed that the stope is located at a depth of 500 m and the ratio of horizontal to vertical *in situ* stress (σ_h / σ_v) is 2, typical of the Canadian shield. The rock mass was considered as a homogenous and isotropic material and a strain-softening material model was used to simulate the rock mass behaviour. To simulate the backfill-rock mass interface behaviour, Mohr-Coulomb's constitutive model was used. Figure 1 shows an overall view of the FLAC model of stope and its surrounding boundaries. In order to measure the stress and displacement around and within the stope, a series of measuring points was placed within the model. Figure 2 shows a magnified view of the model indicating the location of these points.

The assumed physical, mechanical and strength properties of backfill and rock mass are presented in Table I. Once the boundary condition was applied, the model was stepped to equilibrium (before excavation of stope). Both vertical and horizontal *in situ* stress gradually increase with depth, according to the stress ratio of $\sigma_h / \sigma_v = 2$. Once the *in situ* stresses were established within the model, the stope was excavated upward by consecutive cuts of 3 metres height, simulating the actual mining conditions. The simulated results are presented in the following sections.

Simulation results

After complete stope excavation through consecutive cuts, some displacement was allowed within the rock mass (within elastic limit) and changes in stress and displacement as well as the development of failure zone around the stope were examined. Accordingly, once some deformation occurred within the rock mass, backfill was placed and analysis was

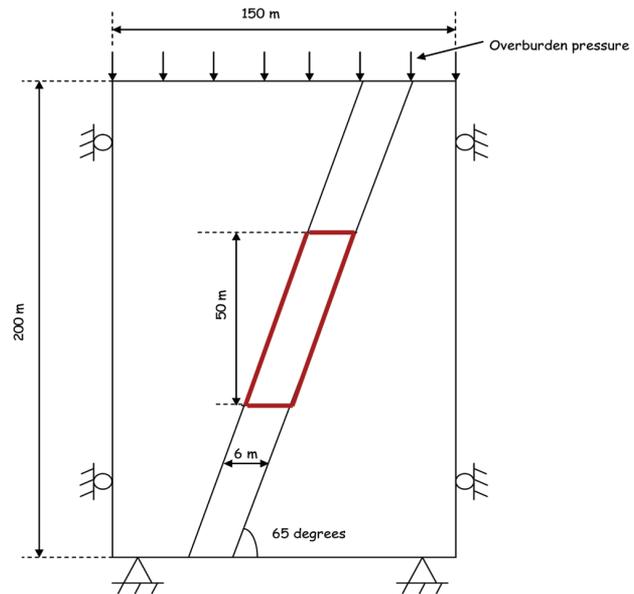


Figure 1—Overall view of the FLAC model and imposed boundary condition

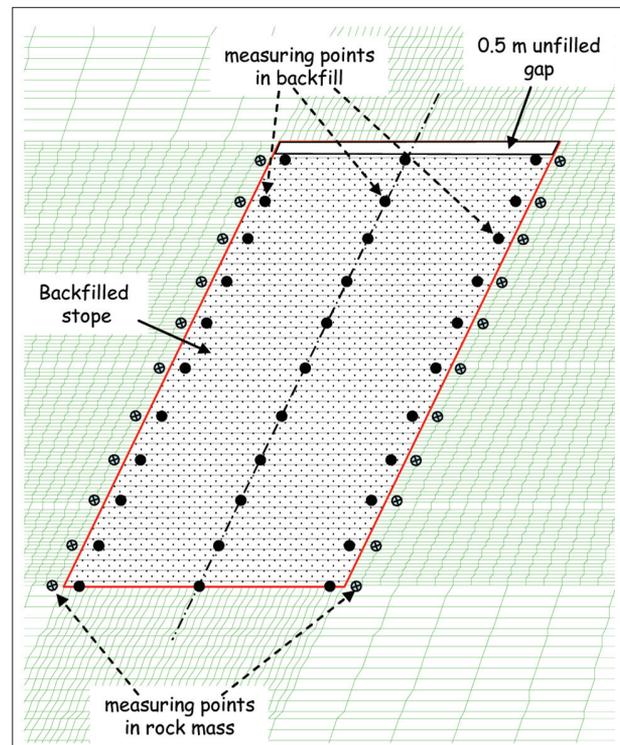


Figure 2—Magnified view of the stope model showing the measuring point locations

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Table 1

Backfill and rock mass properties used in the numerical modelling

Description	Rock mass		Back fill	Interface	
	Parameter	Value	Value	Parameter	Value
Elastic	K	25 GPa	0.167 GPa	Kn	0.167 GPa
	G	11.5 GPa	0.083 GPa	Ks	0.04 GPa
Elast-perfect plastic	c	12.5 MPa	0	C	0
	ϕ	45°	30	f	30
Strain softening	e_p	0.0025 m/m	0.02	-	-
	c_r	5.8 MPa	0.01 MPa	-	-
	ϕ_r	30°	40	-	-

carried out until the final equilibrium state of the backfilled stope and rock mass was achieved. In actual mining conditions, it is not possible to backfill the stope immediately and some deformation occurs in rock prior to backfilling. It should be realized, however, that in practice backfill is placed soon enough to prevent major rock deformation and stope failure. Figure 3 illustrates the change in vertical and horizontal stresses after stope excavation.

Figure 3 indicates that since the major stress is acting horizontally, high stress concentration is formed in the stope floor and back regions. Stress magnitudes of more than 90 MPa in the roof, well beyond the rock mass strength, makes the roof region burst prone and poses risk of violent rock failure. The same argument holds for the floor as well, but since the stope bottom is filled tightly, the stress concentration in the stope floor would not be problematic. For a given *in situ* horizontal stress magnitude, the stress concen-

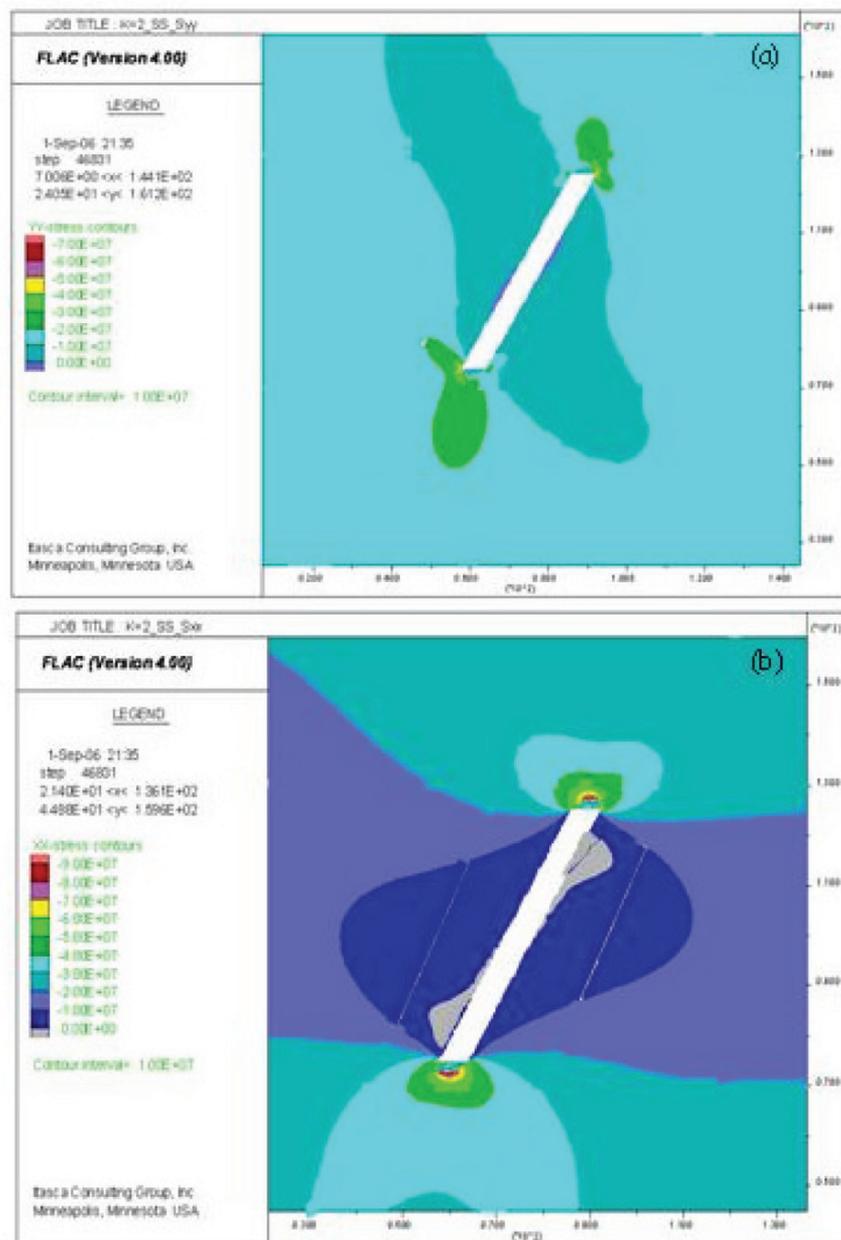


Figure 3—Distribution of major (a) vertical and (b) horizontal stress around the excavated stope

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tration at the back depends on stope width, orebody dip, and amount of gap left at the stope back. With increase in orebody thickness (stope width) more deformation is allowed in the roof and this reduces the stress concentration.

In narrow orebodies, the stress concentration increases significantly, leading to a highly burst-prone condition at stope back. Another cause of stress concentration is the change (increase) in orebody dip in the stope back area. Numerical results show that changes in orebody thickness and dip significantly increase the magnitude of stress concentration and potential of violent failure at sill locations. Figure 3b demonstrates that a tensile stress zone and a large stress shadow region are formed in the stope wall areas. These areas, particularly the hangingwall zone, are potential failure zones depending on rock mass condition. Figure 4 illustrates the extension of the failed zone around the stope. With regard to the extension of failed and distressed zones around the stope, the use of tight filling will become important. Figure 5 shows the distribution of vertical and horizontal stress after backfilling the stope.

Comparing the results presented in Figures 4 and 5, the confining effect offered by backfill significantly reduces the stress concentrations at the stope back. Moreover, placement of backfill prevents the development of a tensile zone in footwall and hangingwall areas. Additionally, backfill controls the wall deformation and, consequently controls the extent of the distressed zone in footwall and hangingwall areas. The extent of the distressed zone can greatly influence the success of underhand cut and fill method in deep orebodies; this becomes more pronounced in low dipping orebodies. In mildly dipping orebodies (less than 45°), if backfilling is not done properly, the extent of the distressed zone may extend beyond one mining level and include 2–3 consecutive mining levels leading to highly stressed sill pillars. In a worst scenario, this could lead to caving in of the hangingwall. Figure 6 shows displacement vectors demonstrating the displacement direction around the stope and in backfill. It is clear that the 0.5 m gap left unfilled

above the stope significantly affects the rock and backfill displacement in the upper mid-height of the stope. Therefore, under high horizontal stress conditions, the tight filling of stopes must be included in design.

In order to further illustrate the interaction between backfill and rock mass, a series of measuring points was placed within the model (see Figure 2). Accordingly, stress and displacement along backfill-rock mass interface and in stope inclination direction were measured. Figure 7 shows the distribution of horizontal, vertical, and shear displacements along backfill-rock interface. In Figure 8, variation of horizontal and vertical stresses within backfill and rock mass is shown.

As expected, maximum displacement occurred at stope mid-height (Figure 7). With regard to the inclination of the stope and lack of geometrical symmetry, variations of horizontal displacement in the footwall and hangingwall are slightly different. Occurrence of maximum displacement at stope mid-height is indicative of high interaction between backfill and rock at this elevation. The large distressed zone developed in the hanging wall (Figure 3b) causes the maximum shear and normal interaction between backfill and rock at stope mid-height elevation. The obtained results show the elevation at which the arching may occur. As shown in Figure 7b, the direction of vertical displacement (both in rock and backfill) also changes at stope mid-height elevation in the footwall. This is mainly due to the gap left above the stope and shows the shear interaction happening at the footwall interface. The upward movement in the footwall rock reduces to zero at the stope top, while backfill shows vertical deformation due to the gap. In the hangingwall interface, both rock and backfill demonstrate downward deformation as expected.

Figure 8a shows the variation of vertical stress along the stope height. At mid-height stope elevation, where maximum displacement occurs, rock and backfill reach equilibrium. At stope top and bottom, stresses increase significantly in rock due to concentration of horizontal stress at stope corners.

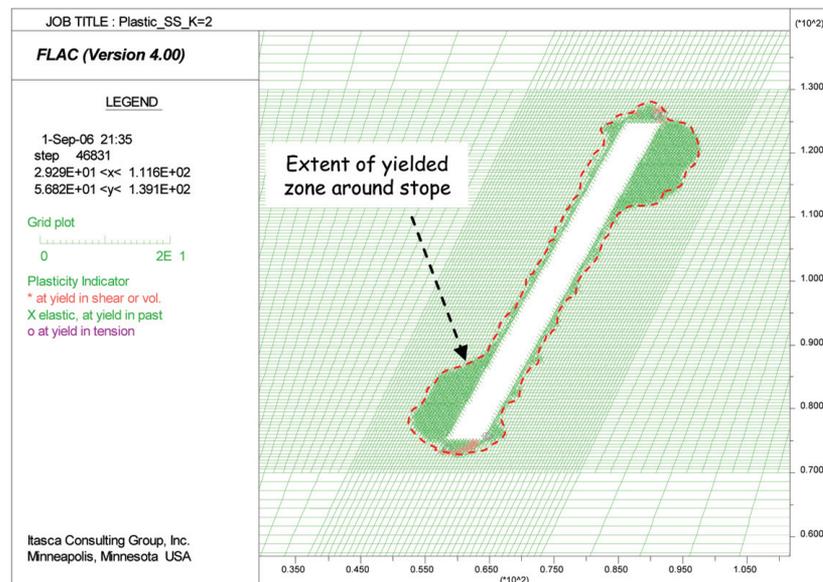


Figure 4—Development of yield zone around the stope

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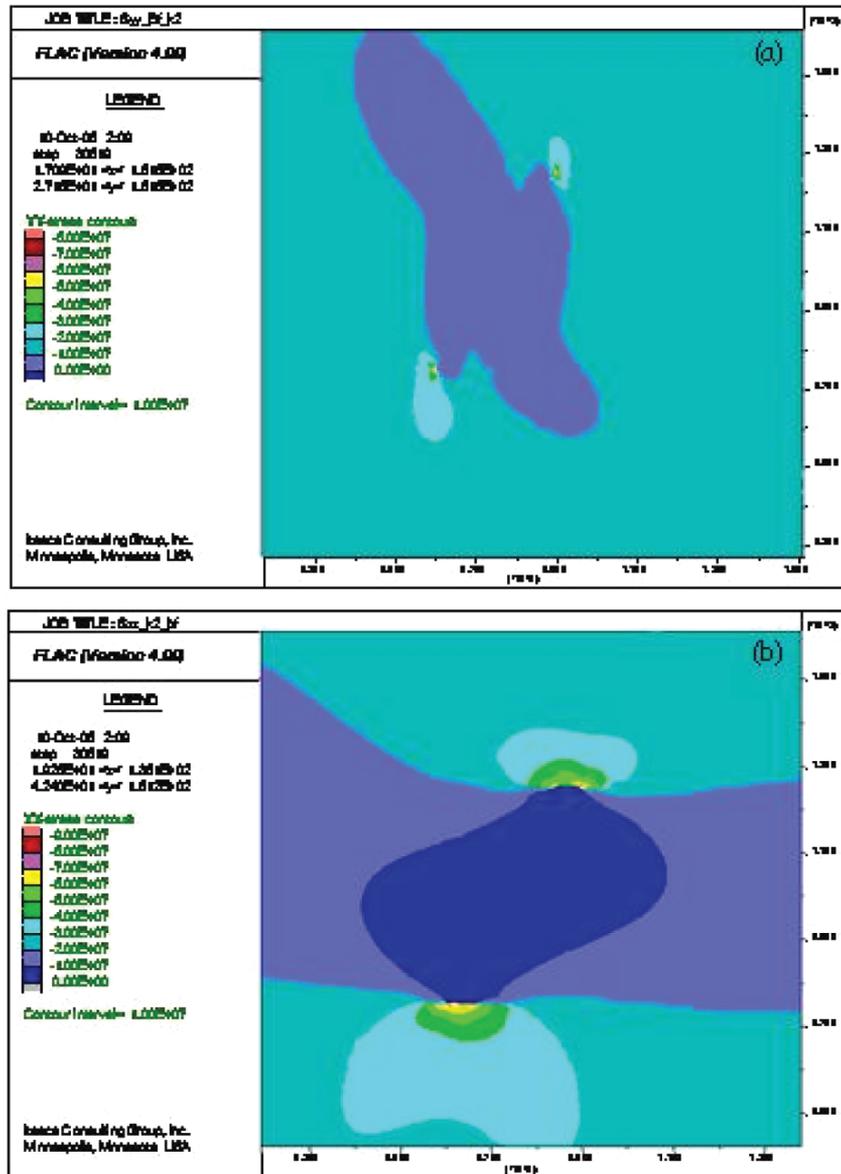


Figure 5—Distribution of (a) vertical, and (b) horizontal stress after backfilling

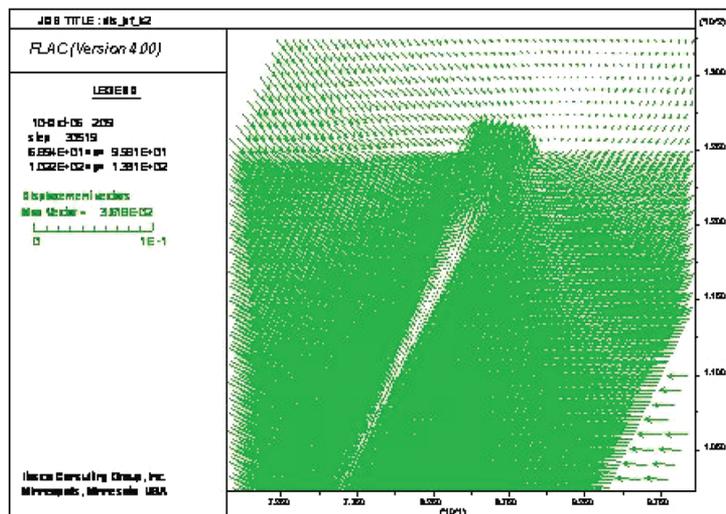


Figure 6—Distribution of displacement vectors around the stope

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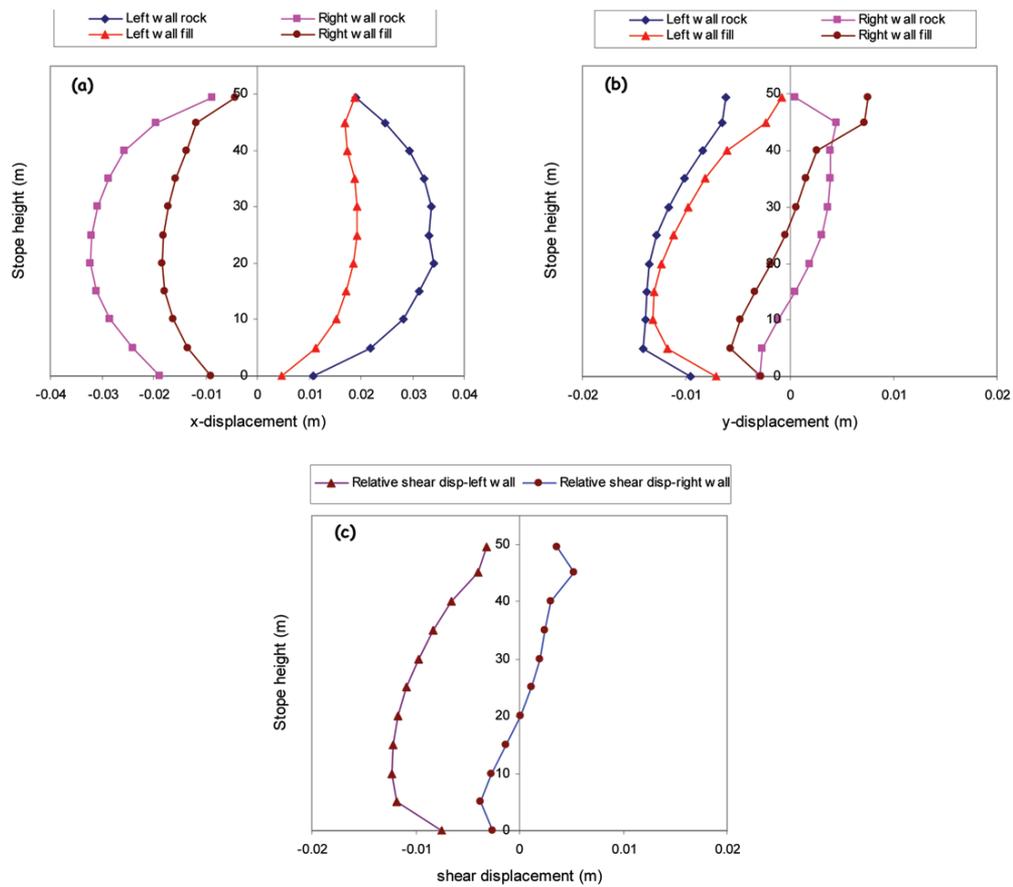


Figure 7—Distribution of (a) horizontal, (b) vertical, and (c) shear displacements along backfill-rock interface

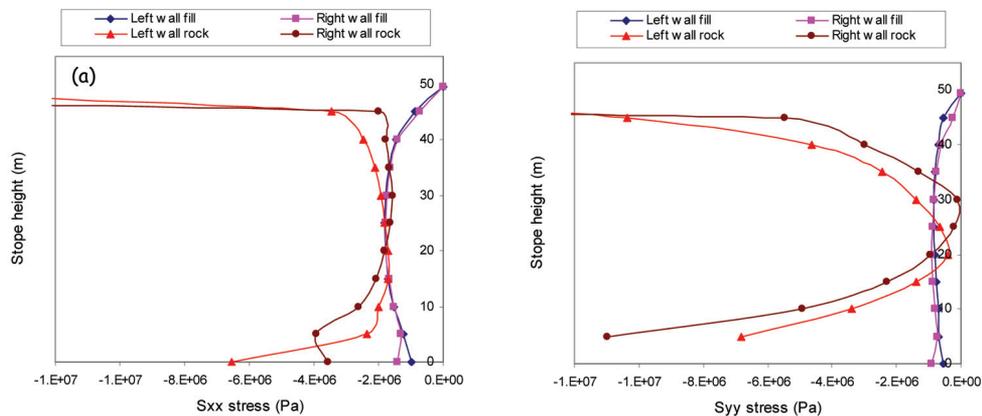


Figure 8—Distribution of (a) horizontal, and (b) vertical stress along backfill-rock interface

On the other hand, backfill absorbs a fairly uniform amount of horizontal stress tending to zero at top due to the gap. The vertical stress drops significantly at stope mid-height (Figure 8b). This is more noticeable for the footwall, where the displacement direction changes because of upward movement of footwall interface due to the gap. Additionally, backfill does not offer enough confinement and maximum wall displacement occurs at stope mid-height, leading to maximum relaxation of vertical stress. Accordingly, at stope top and bottom, wall displacement/relaxation decreases, leading to stress build-up at these points.

Summary and discussion

From a backfill design point of view in deep mining conditions, stope boundary conditions, in particular stope inclination and backfill gap, are important issues. It is understood that stiffness and strength properties of backfill are also important design aspects, but the effect of these parameters were not considered in this study. The focal point of this study was to take into account the complex boundary conditions associated with deep mining situations and delve into the mechanisms involved in backfill-rock mass interactions. A typical stope geometry in narrow vein mining



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condition was simulated. For rock mass strain softening and for backfill strain hardening, material models considering the post-peak behaviour were used. Moreover, interface elements were employed along backfill-rock mass contacts (walls and floor) to describe the normal and shear displacement in critical areas. Contours of stress and displacement distribution were calculated and presented before and after backfilling. The numerical findings align closely with practical observations. The proposed analytical solutions (Mitchell, 1991; Marston, 1930; Caceres, 2005) are given for vertical stope geometries and are not suitable for describing backfill behaviour and calculating backfill design load. Moreover, because of the inclination of the stope, the application of proposed analytical solutions has major limitations.

The arching phenomena discussed by many authors were also numerically investigated in detail. The numerical results

show that the inclination of the stope has a significant effect on stress distribution around the stope and in backfill. The formation of arching in vertical stopes, as described by Li *et al.* (2003) has a different scenario in inclined stopes. Figure 9 shows a magnified view of normal and shear stress distributions within backfill. A fairly non-uniform and complex stress distribution can be seen within the backfilled stope. In order to look at the arching formation, the numerical values of vertical stress were extracted from modelling results and compared against recorded field data (Figure 10).

Results presented in Figure 10 were measured at stope left boundary, right boundary, centre line and along the stope height. These data were plotted against overburden pressure and *in situ* data recorded in a vertical stope by Barrett and Cowling (1980).

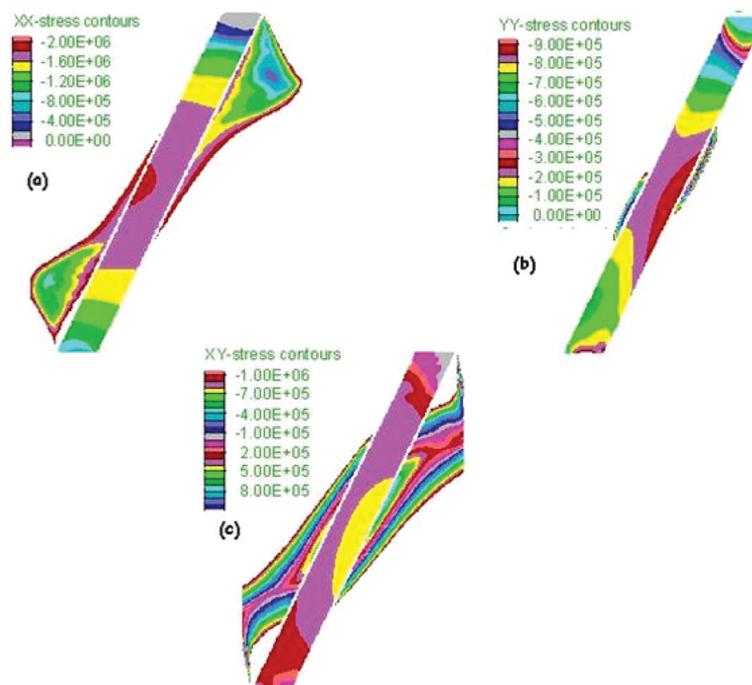


Figure 9—Contours of (a) S_{xx} , (b) S_{yy} , and (c) S_{xy} stress distribution within backfill

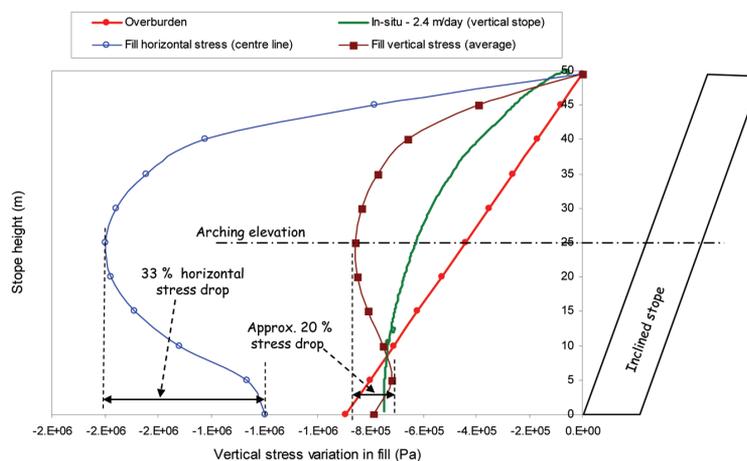
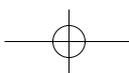


Figure 10—Vertical stress distribution within backfill indicating the formation of arch



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The results show that the inclination of stope causes arching to form at about stope mid-height elevation. In an inclined stope, vertical stress in backfill (from top to bottom) increases at a slower pace compared to vertical stress distribution recorded in vertical stopes. At a depth of about 10 m (from top) away from the gap, confining stress (from rock and backfill weight) affects the rate of vertical stress build-up in backfill and at stope mid-height elevation, maximum vertical stress is measured in backfill.

To further illustrate the issue, the distribution of horizontal stress was also plotted on Figure 10. It is visible that the maximum wall deformation occurring at stope mid-height, compresses the backfill at this elevation. Accompanied by increase in vertical stress, this causes the full mobilization of backfill-rock interface shear strength. This is also reflected in Figure 7c, which demonstrates the shear displacement distribution at interface. It is noticeable from Figure 7c that at about mid-height stope elevation in footwall, there is no shear displacement whereas in the hangingwall, some downward shear displacement occurs as a result of hangingwall displacement. With regard to the results presented, in the case of a vertical stope, from top to bottom, backfill stress increases initially and after a certain depth, no significant stress increase is observed. This can be seen from *in situ* field data given by Barret *et al.* (1980) and also shown numerically by Li *et al.* (2003). As shown in Figure 10, the effect of arching in inclined stopes is more pronounced and below the arch elevation, backfill vertical stress drops by about 20%. This indicates that some portion of the vertical load is carried by the backfill arch. At stope floor elevation, backfill stress is increased slightly. The reason for this is the failure of a large portion of the hangingwall at this location (see Figure 4).

In addition to the study of backfill-host rock interaction and formation of arching, a ground reaction curve (GRC) analysis was also carried out. The intention was to determine the relation between the internal stabilizing pressure supplied by backfill and amount of stope boundary deformation. The GRC concept is typically applied to tunnels in weak rock, but it can be useful here in that it demonstrates the general function for backfill under simulated boundary conditions and also the deformation condition that the support must be

designed to accommodate. To implement the GRC analysis, the original *in situ* stresses were first applied to the interior surfaces of the stope, then these interior stresses (representing backfill pressure) were gradually reduced to zero (i.e. unsupported excavation) in consecutive steps. For each of these increments, the final values of support pressure and corresponding displacement were recorded. Figure 11 illustrates the GRC analysis results for various locations on stope roof, floor and walls.

The GRC analysis results show that surface instability will occur at all stope boundaries. The walls (especially the left wall) deforms more than the back. This occurs due to stope inclination, as the horizontal stress is significantly higher than the vertical stress. In the GRC analysis presented in Figure 11, full relaxation was allowed in stope walls. In reality, once backfill is placed, it interacts with rock and after a certain amount of deformation, an equilibrium state is reached between rock mass and backfill. Numerical results show that this equilibrium is achieved in different fashions at various locations around the stope. Parameters affecting this equilibrium state are stope inclination, ratio of horizontal to vertical stress, unfilled gap amount, rock mass, and backfill properties. Once backfill-rock equilibrium is achieved at a given location, rock mass and backfill act in a unified manner and demonstrate equivalent stiffness behaviour against applied loading. At these locations, backfill becomes part of the rock mass and it would be difficult to distinguish it as an independent support system. In Figure 12 the maximum principle stress (horizontal) variations in backfill and rock were plotted against horizontal displacement at various elevations in the hangingwall and footwall. Based on Figure 12, it is obvious that backfill behaviour differs significantly as a function of stope boundary conditions.

At 45 m elevation (5 m below gap) backfill demonstrates a perfectly plastic behaviour. In the hangingwall area there is not much interaction between backfill and rock whereas in the footwall, backfill interacts completely with rock. At this elevation, there is not much rock failure in the hangingwall (see Figure 4) while a large portion of rock failed in the footwall area. The hangingwall rock mass, which did not fail, stores most of the induced stress and a small portion of induced stress is transferred to backfill. On the other hand, in

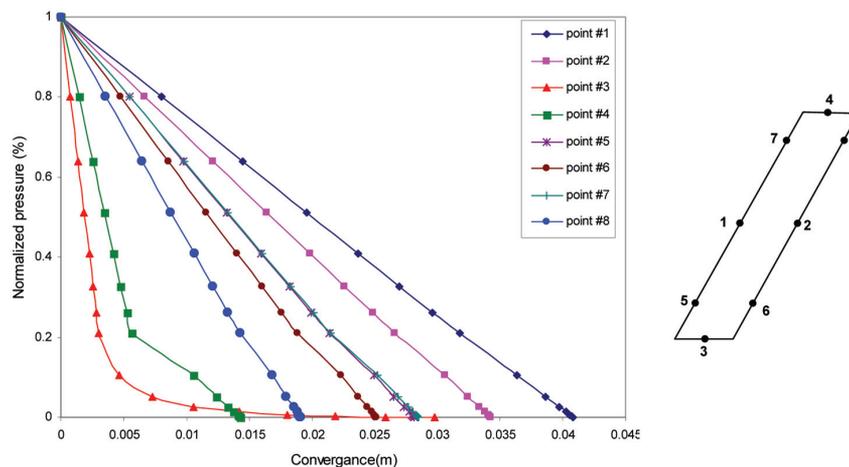


Figure 11—Comparison of ground reaction curve for stope back, floor and walls

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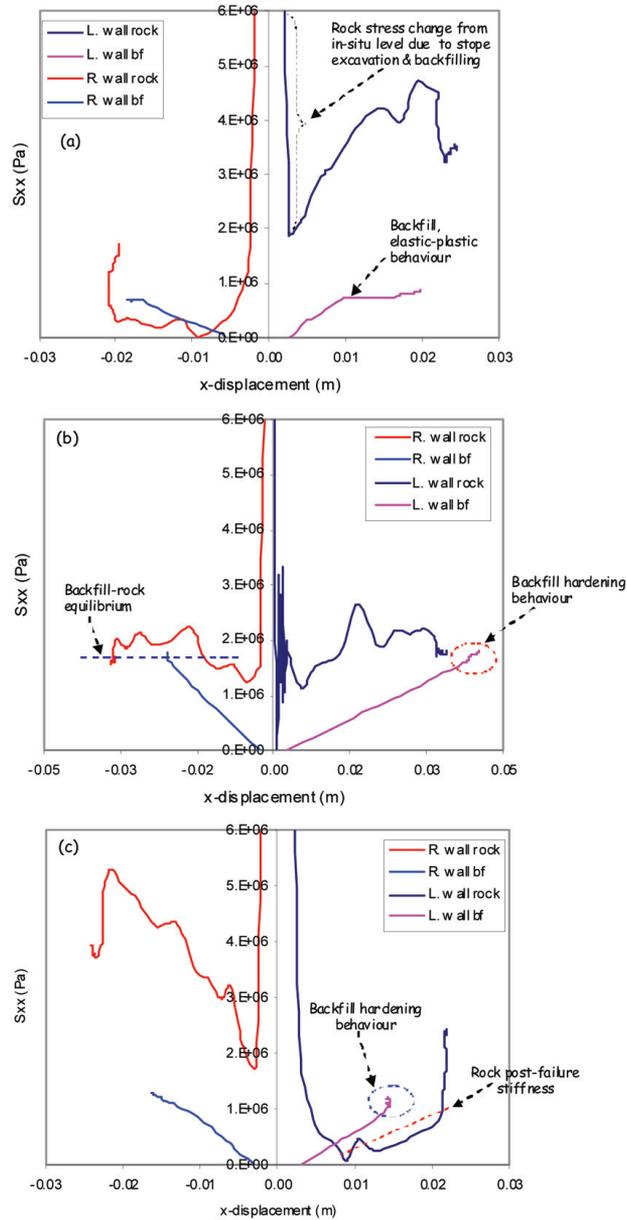


Figure 12—Rock mass-backfill interaction at (a) 45 m, (b) 25 m, and (c) 5 m from stope floor

the footwall side, rock mass fails significantly and from stiffness point of view, has degraded to a less stiff material. Looking at the final stress state and post-peak stiffness of backfill and rock mass (Fig 12a), it is visible that at a given elevation, backfill action in the hangingwall and footwall can be different. In Figure 12b, at midheight stope elevation, backfill demonstrates a hardening behaviour both in the hangingwall and footwall. Moreover, final stress levels in backfill and rock mass are almost the same; this indicates full interaction between rock and backfill. Figure 12c demonstrates the backfill-rock interaction at the bottom portion of the stope (5 m above floor). At this elevation, backfill interacts fully with rock in the hangingwall whereas in the footwall, interaction between backfill and rock is not very significant. In other words, in the footwall backfill provides confinement to a rock mass which has not failed

and still bears a load. Once again, looking at Figure 4, a large portion of rock mass has failed in the hangingwall, leading to reduction in rock mass stiffness and, thus, more interaction with backfill. Similarly, in the footwall rock mass has not failed significantly and its final stress state is different from that of backfill.

Comparing Figures 12a and 12c, backfill-rock interaction at the top and bottom portion of the stope, dominated by the extent of rock mass failure in the hanging wall and footwall, are almost mirror images of one another. However, due to full confinement at stope bottom portion, backfill demonstrates a hardening behaviour while the top, an elastic-perfectly plastic behaviour is seen. In Figure 13, the backfill stress-strain curves calculated numerically at various elevations are compared. With regard to the presented results, it is believed that the stope inclination, *in situ* stress ratio, extent of failure zone in the hangingwall and the footwall, as well as the gap left unfilled above the stope are the dominating factors causing different backfill behaviour.

Conclusions

A comprehensive numerical study was carried out to investigate the interaction between backfill and rock mass. A typical inclined stope was simulated and stress and displacement were calculated at various locations within backfill and stope boundaries. Interface elements were used at backfill rock interface to model the interaction of backfill and rock more accurately. The arching theory was investigated in detail. The numerical findings show that the available analytical solutions based on arching theory are not applicable to inclined stopes. Moreover, in inclined stopes stress distribution is very complex and arching formation has a different scenario from that of vertical stopes. Additionally, in inclined stopes the elevation in which arching forms is different from vertical stopes. In vertical stopes, arching occurs at the top portion of the stope. In inclined stopes arching occurs at about mid-height of the stope. Furthermore, in non-vertical stopes, backfill vertical stress drops by about 20% and horizontal stress by 33 % below the arch level, whereas in vertical stopes there is no significant change in

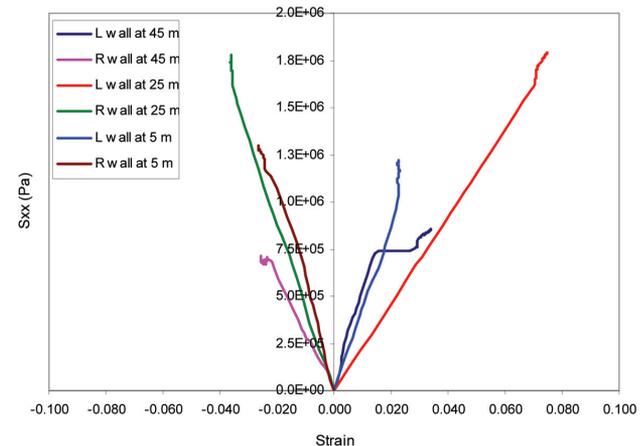


Figure 13—Comparison of backfill stress-strain curves at various elevations

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vertical stress below the arch level as illustrated by *in situ* measurements and numerical modelling. Therefore, use of backfill with varying strength properties in inclined stopes is a viable alternative. The amount of gap left above the stope has a significant influence on backfill-rock interaction. The results obtained show that even a small gap left unfilled at the top of the stope significantly influences the backfill-rock shear and normal interactions all the way up to the stope bottom portion. Therefore, for orebodies with varying dip and high stress condition, tight filling must be considered in the design.

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