http://dx.doi.org/10.17159/2411-9717/2015/v115n7a11

Large-scale deformation in underground hard-rock mines

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Synopsis

In some underground hard-rock mines, squeezing compressive ground conditions are influenced by the presence of rock foliation and high stress. In these cases, the orientation of the foliation with respect to the drift direction has a considerable impact on the magnitude of the resulting deformation. Irrespective of the reinforcement and support strategy, keeping drives developed sub-parallel to the rock foliation operational is difficult, and often requires excessive rehabilitation during the lifetime of the excavation. This study uses field observations and convergence measurements at the LaRonde and Lapa mines of Agnico Eagle Mines Ltd to provide guidelines of the anticipated squeezing levels at these operations.

Keywords

Squeezing ground conditions, large deformations, foliation, angle of drift interception, design guidelines.

Introduction

Squeezing ground conditions are encountered in several underground hard-rock mines and can result in large-scale deformation and ground instability. The International Task Force on Squeezing Rock in Australian and Canadian Mines reported that 'in a mining environment squeezing ground conditions were identified as closure larger than ten centimeters over the life expectancy of a supported drive' (Potvin and Hadjigeorgiou, 2008). Mine drives are usually in operation from 18 months to two years. Squeezing ground conditions in mines are associated with considerable failure of ground support and require significant rehabilitation work. This may cause a slowdown in development and can have severe economic repercussions.

In deep and high-stress mines, squeezing ground conditions are driven by the presence of inherent foliation and the orientation of the drift walls with respect to the foliation. Failure in bedded rock masses has been studied though physical modelling by Lin *et al.* (1984), and analytical methods by Kazakidis (2002). Potvin and Hadjigeorgiou (2008) reviewed ground support strategies used to control large-scale rock mass deformation under squeezing conditions in mines. Despite certain differences in the support philosophies between Australian and Canadian mines, it was evident that an effective support system makes use of both reinforcement elements and surface support. A successful system reinforces the rock mass around the excavation and mitigates the rate of deformation. Experience has shown that ductile surface support is an essential part of a successful ground support system.

In a mining environment, squeezing ground conditions are defined as those that exhibit strain higher than 2%. Potvin and Hadjigeorgiou (2008) observed that large deformations are generally associated with the presence of a prominent structural feature such as intense foliation, a dominant structural feature or a shear zone, and high stress in weak rock. The presence of joint alteration and mineralogy further increases the severity of squeezing.

Mercier-Langevin and Hadjigeorgiou (2011) presented a 'hard rock squeezing index' for underground hard-rock mines based on several mining case studies in Australia and Canada and calibrated against *in-situ* observations at the LaRonde mine in Quebec. The authors proposed the use of the index as a preliminary indicator of the squeezing potential in hard-rock mines with similar ground conditions.

Case studies in underground hard-rock mines

While many hard-rock mines around the world face problems associated with squeezing ground conditions, there are only a few case studies documented (Struthers *et al.*, 2000; Beck and Sandy, 2003; Potvin and Slade, 2007; Sandy *et al.*, 2010; Mercier-Langevin

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 Paper received Nov. 2014 and revised paper received Apr. 2015.

and Hadjigeorgiou, 2011; Mercier-Langevin and Wilson, 2013; Hadjigeorgiou *et al.*, 2013). Karampinos *et al.* (2014) presented a methodology for modelling the behaviour of foliated rock masses under high stress conditions using a 3D distinct element code. The resulting models addressed explicitly the effect of foliation and reproduced the observed buckling mechanism. Vakili *et al.* (2012) used a 3D distinct element code as a prelude to a 2D analysis using a finite difference code.

Table I summarizes the reported level of deformation from several hard-rock mines. The LaRonde and Lapa mines report some of the highest deformations in hard-rock mines. This necessitates excessive rehabilitation of affected drifts. This study focuses on the LaRonde and Lapa mines as they also experience a large spectrum of squeezing ground conditions. Both mines are situated in the Abitibi region of northwest Quebec, within 11 km from each other, and are operated by Agnico Eagle Mines Ltd.

LaRonde exploits a world-class Au-Ag-Cu-Zn massive sulphide lens complex. The ore reserves extend from surface to 3110 m and are still open at depth. The mine, which has been in operation since 1988, uses two mining methods – longitudinal retreat with cemented backfill, and transverse open stoping with cemented and unconsolidated backfill. The deepest production horizon is currently at 2930 m, established after the construction of an 832 m internal shaft. The mine is operating in a variety of ground conditions. At different levels of the mine the observed rock mass behaviour can be hard and brittle or squeezing. The mine reports that the total wall convergence in certain areas can be in excess of 1 m, with fracturing extending up to 6 m into the rock mass.

Lapa is a high-grade gold mine and has been in operation since 2009. Access to the mine is provided by a 1369 m deep shaft and production is by two mining methods – longitudinal retreat with cemented backfill, and locally transverse open stoping with cemented backfill. The mine operates under challenging squeezing ground conditions. Hadjigeorgiou *et al.* (2013). Mercier-Langevin and Wilson (2013) provided an interpretation of the squeezing mechanisms at Lapa and the support strategies aimed at controlling large deformations.

Mitigating the degree of squeezing

Ground support

Significant differences in the ground support strategies followed by Australian and Canadian hard rock mines in squeezing ground conditions were reported by Potvin and Hadjigeorgiou (2008). Australian mines often use soft reinforcement elements such as split sets, complemented with fibre-reinforced shotcrete. The shotcrete increases the stiffness of the support system and can initially delay the rock mass degradation. However, as shotcrete can accommodate only limited rock mass deformation and can crack, it is often necessary to install screen over shotcrete. This results in a stiff liner early in the squeezing process, followed by a ductile surface support after the installation of the screen. Canadian mines, on the other hand, use a high density of bolts with yielding capability (such as Swellex or hybrid bolts) and weldmesh, often accompanied with mesh straps.

In the past, frictions bolts were used at LaRonde with partial success. The split sets 'lock up' between the foliation planes when buckling occurs and fail at the contact between the bolt and the plate when deformation surpasses a certain level. Mercier-Langevin and Turcotte (2007b) reported limited success in the use of cemented grouted cable bolts, yielding cable bolts, and modified cone bolts in squeezing conditions, as they either did not yield sufficiently or lost their ability to yield early in the squeezing process. The mine has been more successful using the hybrid bolt (Mercier-Langevin and Turcotte, 2007b) as part of its ground support strategy. The advantages of the hybrid bolt were presented by

Table I

Squeezing ground conditions reported in hard-rock mines

Mine site	Strain range % (defined as total wall deformation over the drift width)		Magnitude of deformation
	Lower bound	Upper bound	
LaRonde (Hadjigeorgiou *et al.*, 2013)	2.5%	41%	2.1 m (total wall convergence)
Lapa (volcanics and ultramafics) (Mercier-Langevin and Wilson, 2013)	1%	>40%	
Wattle Dam (Marlow and Mikula, 2013)	1%	5%	
Westwood (Armatys, 2012)		Up to 8.5%	0.34 m (total wall convergence)
Perseverance (Gabreau, 2007) (Potvin and Slade, 2007) (Struthers *et al.*, 2000)			2.5 m total wall convergence Wall convergence > 2 m 3 m total sidewall closure, over 1 m of floor heave
Yilgarn Star (Potvin and Slade, 2007)			Up to 2 m in the hangingwall
Black Swan (Potvin and Slade, 2007)			Up to 1.5 m in one wall
Maggie Hayes (Mercier-Langevin and Hadjigeorgiou, 2011)	1%	2.5%	
Casa Berardi (Mercier-Langevin and Hadjigeorgiou, 2011)	1%	5%	
Waroonga (Mercier-Langevin and Hadjigeorgiou, 2011)	1%	5%	
Bousquet (Mercier-Langevin and Hadjigeorgiou, 2011)	1%	10%	
Doyon altered zone (Mercier-Langevin and Hadjigeorgiou, 2011)	2.5%	10%	

Turcotte (2010) and include a setup that prevents the resin from escaping into the fractured rock. Furthermore, the hybrid bolt has a high resistance to shear and frictional resistance as compared to split sets. The *in-situ* behaviour of the hybrid bolt is characterized by a stiff early reaction at low displacements and almost perfectly plastic behaviour when subjected to high load (approximately 15 t). The current standard employed at the LaRonde mine was presented by Hadjigeorgiou *et al.* (2013) and consists of friction sets and screen in the sidewalls and rebars and screen in the back, complemented by hybrid bolts in the sidewalls and meshed straps installed 12 m away from the face.

The ground support system employed at Lapa was inspired by the successful performance of the hybrid bolt at LaRonde (Mercier-Langevin and Wilson, 2013). The support strategy recognizes and accounts for the presence of weak schist zones (ultramafic) prone to squeezing. In areas where squeezing is anticipated, hybrid bolts are installed instead of split set bolts.

When the sidewalls are subject to excessive deformation, the drives can become narrow and inadequate for the mining equipment. Under these circumstances, the walls are 'purged' using a scoop to remove excess material. This is a costly and time-consuming process, and is conducted only when necessary and under the close supervision of ground control personnel. Following purging of the excavation, additional support such as cable bolts supplemented with screen and straps is installed to further stabilize the walls. Turcotte (2010) reported a considerable reduction of purging since the introduction of the hybrid bolt in LaRonde.

Mining under extreme squeezing ground conditions has demonstrated that it is not a realistic aim to completely arrest ground deformation. This can result in early failure of the support and necessitate frequent rehabilitation. Current practice aims to control the resulting deformation under squeezing conditions. Management of drive closure can be improved through an understanding of the factors that define and control the squeezing phenomenon.

Mercier-Langevin and Turcotte (2007a) demonstrated that modifying the mining layout by driving drifts in a more favourable direction with respect to the foliation resulted in less purging and rehabilitation. Although this necessitated longer development drives per level, it significantly reduced rehabilitation and production delays. This practice reduced the likelihood of major ground instability in the drive.

Influence of drift orientation

The influence of drift orientation on the observed degree of squeezing is evident in several places at both Lapa and LaRonde. This was quantified from the angle of interception, defined as the angle between the normal to the foliation planes and the normal to the sidewall (Figure 1). This is illustrated by three drifts that were driven at 2150 m depth at LaRonde (Figure 2). There is no evidence of squeezing for a drift developed perpendicular to the foliation, only minor squeezing when driven at 45 degrees, and severe squeezing for a drift oriented parallel to the foliation.

The angle of interception had a direct impact on the performance of the ground support systems used at the LaRonde mine. An investigation of the effect of the orientation of the drift on the degree of squeezing was initially made by Mercier-Langevin (2005). It was based on 23 field observations from drifts at the LaRonde mine. The original database reported the observed squeezing level, the damage to the support, the difference between the orientation of the drift and the foliation, and the influence of stress on the resulting deformation. For the cases where the drifts were developed sub-parallel to the foliation, regardless of the support system employed, it was difficult to keep the drifts in operation unless they were subjected to regular rehabilitation work (Mercier Langevin and Hadjigeorgiou, 2011). The degree of squeezing varied for drifts driven at different angles with respect to the foliation.

This orientation phenomenon is supported by mechanistic analysis. Auto-confinement of foliation planes is greater when the angle between the normal to the free face and the normal to the foliation increases (Hadjigeorgiou *et al.*, 2013). It has been shown analytically that even a small confining pressure is sufficient to prevent buckling failure (Kazakidis, 2002).

Updated database for investigating the influence of drift orientation

In this work, the original database was extended using quantitative data for drift closure from 57 new case studies at LaRonde and 87 from Lapa. For every case study the following parameters were recorded: the dip and dip direction of foliation; the orientation of the drift; the observed damage; the development date; the stress effect due to mining activity; the support system used; the additional support installed; and the presence of water. Any intervention such as rehabilitation or purging was also recorded.

The cavity monitoring survey (CMS) instrument CMS V400 (Optech Incorporated, 2010) was used to capture the wall profile. Figure 3 shows an example of multiple CMS readings in a drift at Lapa. 3D surveys, showing the initial drift dimensions after the development of every drift, are also available for both mines. These surveys are made by surveying one point at the back, the floor, and each sidewall immediately after the development of a drift.

The distance between the two sidewalls was extracted from the CMS, and recorded at heights of 1.5 and 2.5 m from the drift floor. The back–to-floor distance was estimated at the centre of each drift and at 1 m on each side from the centre. In cases where a CMS profile was not available, measurements were made using a laser measuring device. It

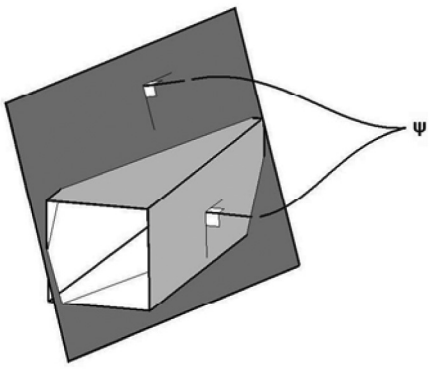

Figure 1 – Definition of angle of interception (ψ) (after Mercier-Langevin and Hadjigeorgiou, 2011)

Figure 2 – Variations in squeezing severity in three locations less than 100 m apart at 2150 m depth, LaRonde mine. (a) Perpendicular – no squeezing; (b) 45 degrees – minor or no squeezing; (c) parallel – severe squeezing (after Mercier-Langevin and Hadjigeorgiou, 2011)

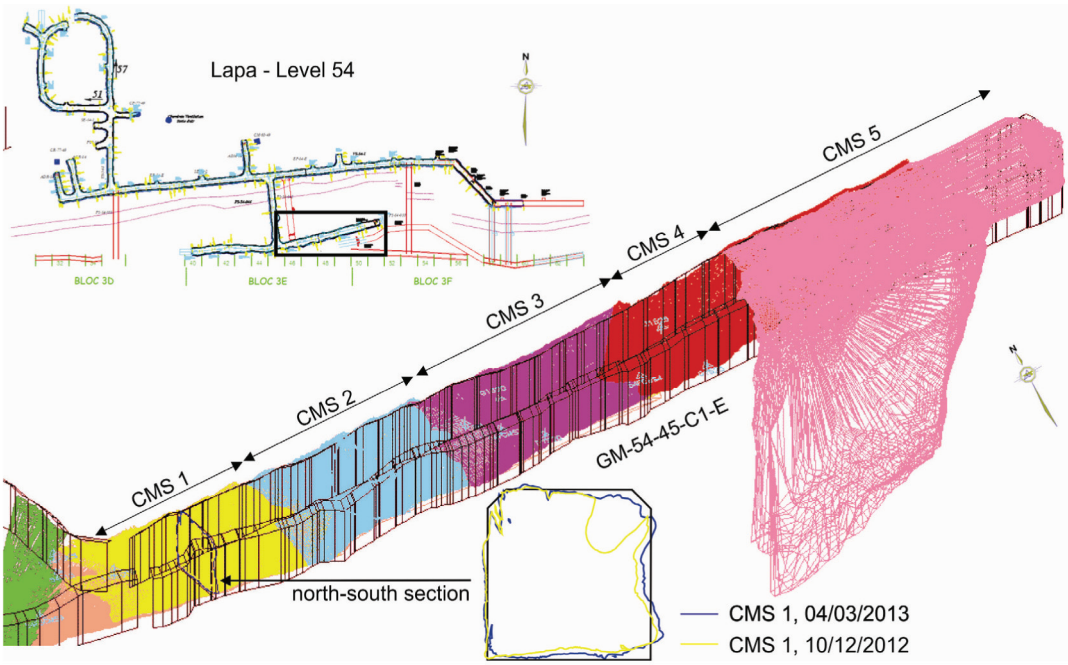

Figure 3 – Example of multiple CMS in a longitudinal drift at Lapa, 540 m depth

was thus possible to determine the total sidewall and total back–to-floor convergence for each case study.

The greatest convergence was derived from CMS readings for 35 case studies at LaRonde and 73 case studies at Lapa. The convergence was determined by comparing the initial 3D survey results during development and the CMS profile after a time interval. Data collection was complicated by the frequent presence of muck on the side of each drift. Figure 4 shows the various methods used to identify the convergence in each case study and the reference points along the drift.

Quantifying observed convergence

Previous analysis of the data at the time it was collected focused on a qualitative interpretation. As more quantitative data was collected and more case studies were documented, it became possible to provide a preliminary quantitative interpretation (Hadjigeorgiou *et al.*, 2013). The work presented in this paper includes more case studies and further information that reports on back-to-floor convergence, wall-to-wall convergence, and sidewall deformation. The recorded convergence in the case studies presented in the past was also updated.

For the purposes of this investigation the total wall-to-wall convergence (δ_{total}) was estimated from the difference between the surveyed width (L) and the lowest sidewall distance measured. Similarly, the total back-to-floor convergence was derived from the lowest back-to-floor distance and the height of the drift. The total wall-to-wall and back-to-floor convergences were expressed as percentages of the total strain (ε_{total}):

$$\varepsilon_{total} = \frac{\delta_{total}}{L} * 100 \qquad [1]$$

It is recognized that operational restrictions can influence the data collection process. In particular, when the wall-to-wall closure is close to 3.5 m, the drift becomes non-operational for equipment and therefore it is purged. Consequently, a value of 3.5 m was used as the lowest wall-

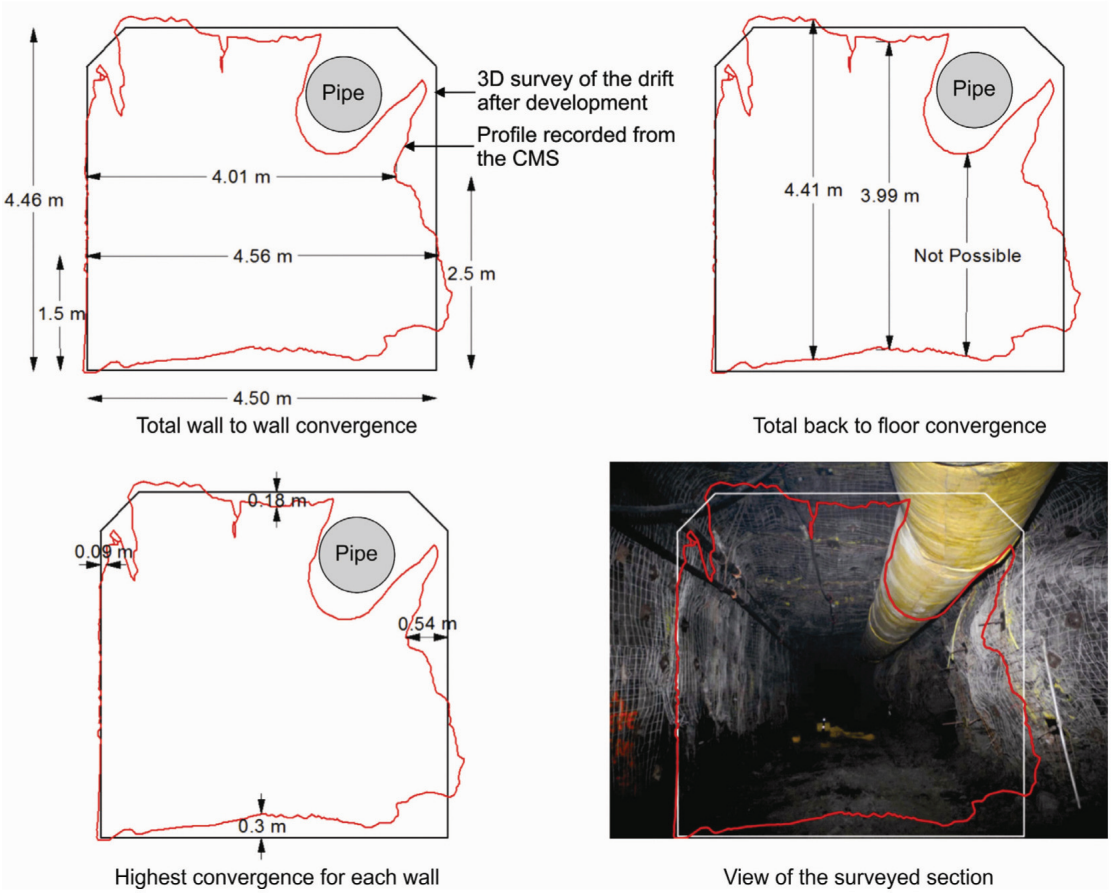

Figure 4 – Estimation of drift convergence

to-wall distance measured in these cases. A revised classification scheme for quantifying squeezing in hard-rock mines is proposed:

- No or low squeezing (0% < ε < 5%)
- Moderate squeezing (5% < ε < 10%)
- Pronounced squeezing or rehabilitated drifts (10% < ε < 35%)
- Extreme squeezing (35% < ε).

Published work in civil engineering tunnelling applications summarized by Potvin and Hadjigeorgiou (2008) reported considerably lower ranges than those proposed here. This is a result of the higher tolerance of rock mass failure in a mining environment. Typical squeezing examples observed in LaRonde and Lapa mines are presented in Figure 5. The influence of the angle of interception (ψ) on the resulting total wall-to-wall and back-to-floor strain is shown in Figure 6.

For comparison purposes, the convergence was also examined for each wall separately. This was defined as the ratio of the highest recorded convergence (δ) for each wall to half of the surveyed width (L) for the sidewalls or to half the surveyed height for the back and the floor. The convergence for each wall was expressed as percentage strain (ε):

$$\varepsilon = \frac{\delta}{L/2} * 100 \qquad [2]$$

The influence of the angle of interception (ψ) on the resulting strain for each wall at the LaRonde and Lapa mines is presented in Figure 7 for the sidewalls and in Figure 8 for the back and the floor. These diagrams capture only a part of the behaviour of a rock mass under squeezing ground conditions. There are further factors that can influence the resulting strain, such as the time of measurement, the foliation spacing, the stresses, the strength of the rock, and the condition of the joints. In addition, operational constraints do not allow for a drive with a wall-to-wall distance less than 3.5 m.

Figures 6 to 8 include a threshold of the highest expected strain for a given angle of interception. It is noted, however, that there is limited data for an angle of interception less than 10 degrees in extreme squeezing conditions. The observed trend is supported by recent numerical modelling work by the authors. Nevertheless, the field data clearly indicates that an increase in the angle of interception between the drift and the inherent foliation will invariably reduce the resulting level of squeezing.

The south walls demonstrated the highest strain, exceeding 50% in certain case studies. These values are also higher than the total sidewall strain recorded. The difference between the convergence on each sidewall (north walls and south walls) at Lapa was identified by Mercier-Langevin and Wilson (2013). Higher strain, resulting in frequent rehabilitation, was linked with the presence of ultramafics, whereas lower strain, easily managed, was associated with relatively

Figure 5 – Examples of drifts subjected to squeezing at the LaRonde and Lapa mines (Hadjigeorgiou *et al.*, 2013)

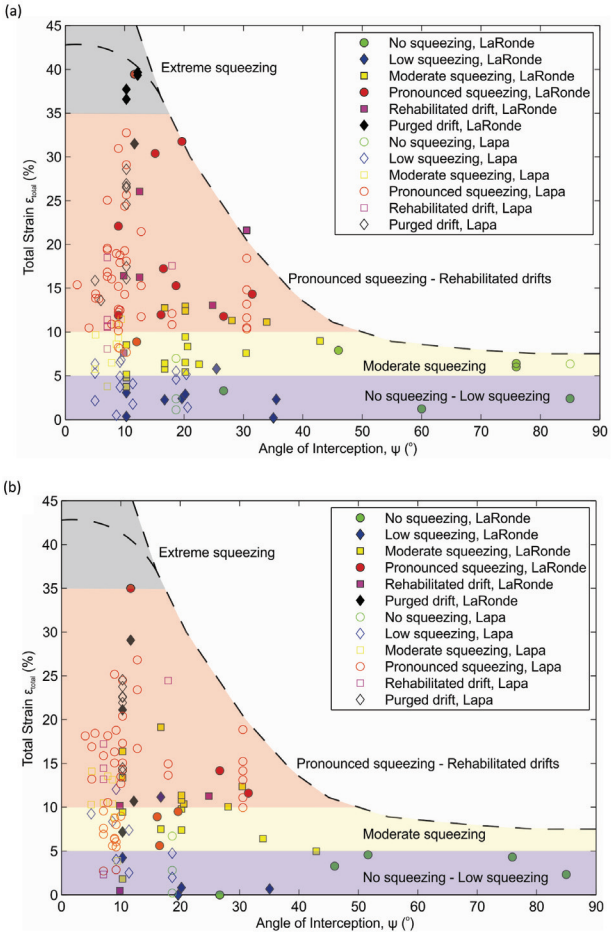

Figure 6 – Influence of angle of interception (ψ) on resulting total strain at the LaRonde and Lapa mines. (a) Total wall-to-wall strain, (b) total back-to-floor strain

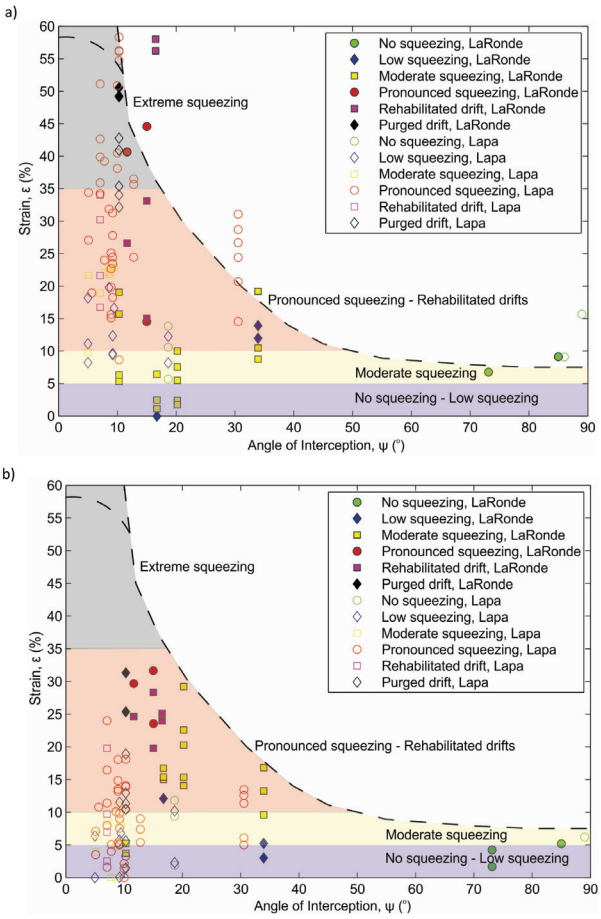

Figure 7 – Influence of angle of interception (ψ) on resulting sidewall strain at the LaRonde and Lapa mines. (a) South wall strain, (b) north wall strain

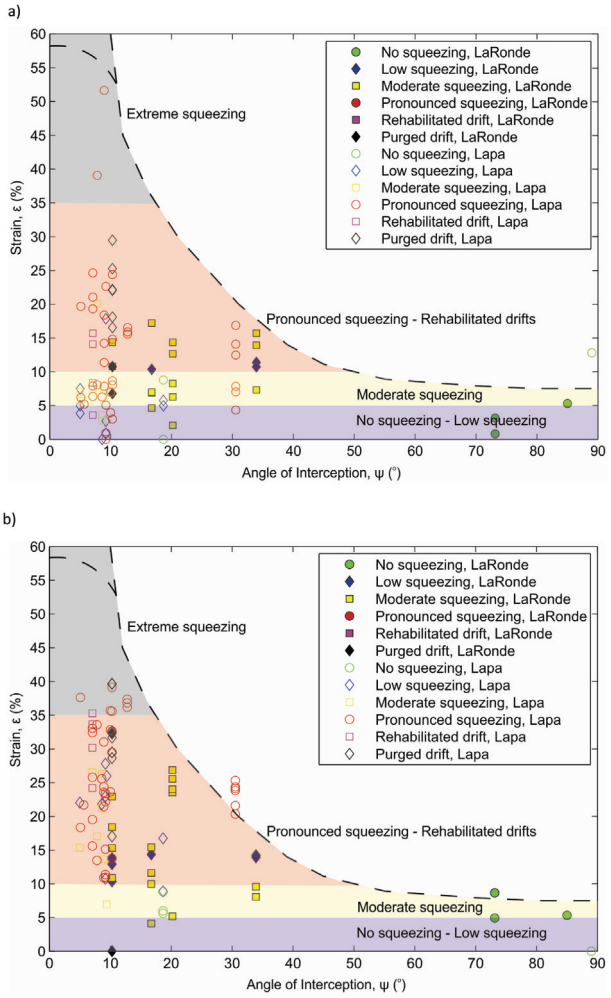

Figure 8 – Influence of angle of interception (ψ) on resulting back and floor strain at the LaRonde and Lapa mines. (a) Back strain, (b) floor strain

competent sediments and volcanics. The ultramafics have typically much smaller foliation spacing and talc-chlorite alteration is usually present. The examined south walls at Lapa were comprised of ultramafic formations while the north walls were mostly driven in sediments.

Visual observations suggest that the strain in the north walls at Lapa is lower than that recorded in many cases. The strain may be overestimated as sometimes the walls in sediments follow the dip of the foliation (approximately 85°), which was not considered in the 3D survey. Higher strain can also be a result of errors in the positioning of the CMS or any shape irregularities on the wall, as the 3D survey considers the wall as a plane surface.

The reported total sidewall and total back-to-floor strain has significant practical implications for the functionality of the drifts and the need for rehabilitation to maintain them in operation. The determination of the strain for each individual wall can allow for a more representative consideration of the geological and mineralogical conditions that can influence the squeezing level. Consequently, the influence of other factors controlling the degree of squeezing, such as the foliation spacing, the alteration, intact rock strength, and the stress can be explored in greater detail.

Currently there is a lack of a ground support system that can fully control pronounced and extreme squeezing ground conditions. Consequently, exploring changes in the orientation of development can be an effective strategy in mining under such conditions. While this has been an opportunity in LaRonde, it is more difficult at Lapa, due to the lower flexibility allowed by the mining method.

Hoek and Marinos (2000) used the ratio of the uniaxial compressive strength (σ_{cm}) of the rock mass to the overburden stress (p_o) to predict the extent of squeezing in tunnelling, using a similar method to estimate the wall strain. This approach does not consider the anisotropic behaviour of the rock mass and the presence of any dominant structure. A successful classification system for the prediction of the level of squeezing at LaRonde and Lapa should take into account the influence of foliation and the angle of interception (ψ).

This study has demonstrated the need to better define and capture the transition between the various squeezing zones. This can potentially be attained by combining field observations with numerical studies.

Conclusions

The LaRonde and Lapa mines exhibit large-scale deformation in a range of ground conditions. The estimation of the total sidewall and the total back-to-floor strain indicated the problems encountered in the functionality of the drifts and the need for rehabilitation work when pronounced and extreme squeezing conditions are faced. An analysis of the reported strain for each drive wall revealed a strong correlation between the squeezing level and the geology. Variations in the geology at each side of a drift can result in significantly more pronounced squeezing conditions. Under these circumstances it is optimal to implement a different ground support standard for each wall.

Acceptable squeezing levels in a mining environment are considerably higher than in civil engineering tunnelling operations. Although this allows more flexibility, mining operators have to work under greater economic constraints in terms of support. Squeezing ground conditions in mining applications often involve considerable failure of ground support and necessitate significant rehabilitation work.

The LaRonde and Lapa mines follow similar ground support strategies for developing excavations in squeezing ground conditions. The support systems aim to control the extreme deformation rather than prevent it, which is not a realistic objective in a mining context. This paper has presented the results of extensive field work in the quantification of the influence of the angle of interception between the drift and the foliation. The choice of a favourable angle of interception can result in a more manageable squeezing level and increase the performance of an appropriate support system for squeezing ground conditions. The results from this study are in agreement with the squeezing index proposed by Mercier-Langevin and Hadjigeorgiou (2011) and contribute towards its validation and extension.

Acknowledgements

The support of Agnico Eagle Mines Ltd, Division LaRonde and Lapa, and the Natural Science and Engineering Research Council of Canada is gratefully acknowledged.

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