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International Journal of Rock Mechanics & Mining Sciences 45 (2008) 538–553
International Journal of Rock Mechanics and Mining Sciences
www.elsevier.com/locate/ijrmms

Interaction of shotcrete with rock and rock bolts—A numerical study

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Received 28 August 2006; received in revised form 29 June 2007; accepted 16 July 2007
Available online 27 September 2007

Abstract

The shotcrete–rock interaction is very complex and is influenced by a number of factors. The influence of the following factors was investigated by a series of numerical analyses: the surface roughness of the opening, the rock strength and Young's modulus, the discontinuities, the extent and properties of the excavated disturbed zone, the mechanical properties of the interface between shotcrete and rock, and the thickness of the shotcrete lining and the rock bolts. The study was carried out as a sensitivity analysis. The results showed that the rock strength and the surface roughness had significant impact on the number of failures at the rock–shotcrete interface and in the shotcrete lining. Furthermore, the behaviour of the lining is sensitive to small amplitudes of the surface roughness. In all the cases investigated, a high interface strength was favourable. The results indicate that if a thick shotcrete lining is dependent on the bond strength. The benefit of using a thicker lining can be doubtful. The analyses showed that for an uneven surface the extent of the EDZ had a minor effect on the behaviour of the shotcrete lining. Furthermore, if rock bolts were installed at the apex of the protrusion instead of at the depression, the number of failures decreased both at the interface and in the lining.

Keywords: Numerical analyses; Shotcrete; Excavated disturbed zone (EDZ); Rock strength; Surface roughness; Shotcrete–rock interface; Rock bolt; Rock stress

1. Introduction

In underground mining and tunnelling, shotcrete is often used as an important support element. The main design principle for rock support is to help the rock to carry its inherent loads. The shotcrete–rock interaction, however, is very complex and is influenced by a number of important factors (see Fig. 1), such as the roughness of the walls and roofs of the opening [1–3], the mechanical properties of the rock, the rock stress, the disturbed or damaged zone around the opening (excavation damaged zone—EDZ) [4–9], the discontinuities [2,10–12], the rock bolts [13,14], the mechanical properties [15–17], and the thickness of shotcrete and the interface between shotcrete and rock [11,18–20]. The influence of all these factors is almost impossible to analyse using analytical or experimental models. Empirical methods are therefore often used in the design of shotcrete linings.

To improve the understanding of the interaction of shotcrete and rock, a number of numerical analyses were carried out. All analyses were based on the conditions at LKAB's underground mine in Kiruna, in northern Sweden. Therefore, the mine is briefly described in Section 2. The rock properties in the present work, the mining-induced rock stresses, the geometry of the drift, etc., are presented in Sections 2 and 3. Mechanical properties of rock and shotcrete are presented in Section 4, results in Section 5, discussions and conclusions in Sections 6 and 7.

2. Kiirunavaara mine

The mining company Luossavaara Kiirunavaara AB, (LKAB), has been mining iron ore for more than 100 years in the mines in Malmberget and Kiruna in northern Sweden. The Kiirunavaara mine (in Kiruna) has an annual production of 23 million tonnes of iron ore. The ore body strikes nearly north–south, and dips 60° to the east. It is more than 4000 m long (of which 3800 m is currently being mined) and 80 m wide on average. The depth of the deposit

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doi:10.1016/j.ijrmms.2007.07.024

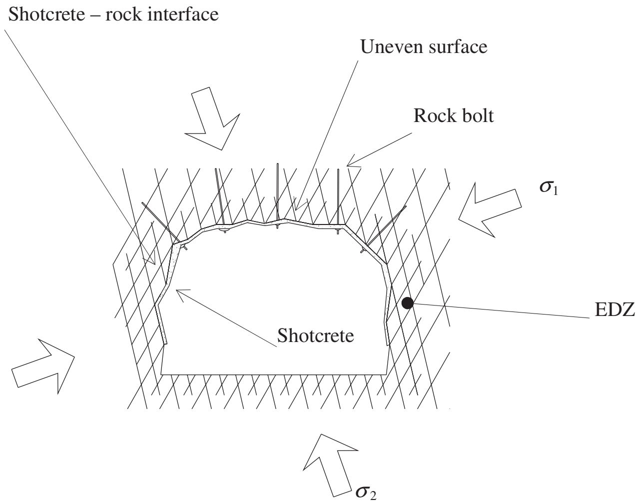

Fig. 1. Shotcrete–rock interaction, tunnel section with irregular shape.

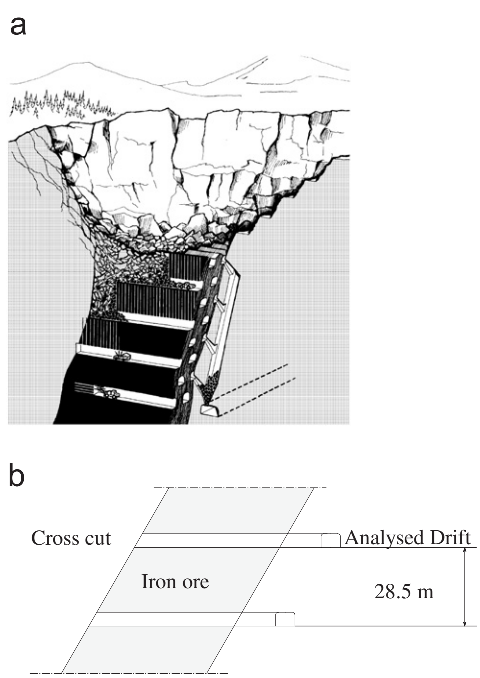

Fig. 2. Large-scale sublevel caving in the Kiirunavaara mine: (a) large-scale sublevel caving, principles, after [23] and (b) schematic section.

is unknown, but proven reserves are found to a depth equal to 1360 m. The mining method used at the Kiirunavaara mine is large-scale sublevel caving (Fig. 2). Important features of large-scale sublevel caving in the Kiirunavaara mine are described in [21].

Tables 1 and 2 present some mechanical properties of the rock at the Kiirunavaara mine. Rock mass classification according to the *RMR* or the *Q*-system is not performed on a regular basis at the mine. Hence, the values presented in Table 2 have been determined as part of special projects in the mine.

The change of the stress state caused by the mining is shown in principle by stress trajectories in Fig. 3.

Table 1
Mechanical properties of intact rock at Kiirunavaara mine, mean values

	E (GPa)	ν	ρ (kg/m^3)	σ_{ci} (MPa)	σ_t (MPa)	m_i[a]
Hangingwall	70	0.22	2700	184	12	18
Iron ore	65	0.25	4700	133	10	28
Foootwall	70	0.27	2800	200	11	16

[a]Constant in Hoek–Brown failure criterion [24].

Table 2
Rock mass classification, *RMR* [25] and *Q* [26]

	RMR mean	*RMR* min–max	*Q* mean	*Q* min–max
Hangingwall	51	–	–	–
Iron ore	58	21–85	3.3/8.2	0.1–25
Footwall	60	49–68	–	–
Contact footwall–iron ore	22	–	–	–

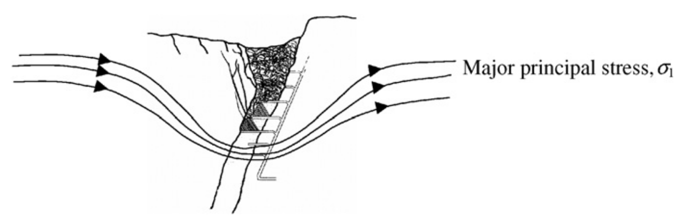

Fig. 3. Schematic section of the sub level caving, after [27].

Numerical analyses of the whole mine has shown [22] that the stress perpendicular to the ore body increases as a function of the vertical distance from the mining level and reaches a maximum (at the footwall drift position), 35–60 m below the mining level. This implies that if the drift is excavated two or more levels below the production level, the stress perpendicular to the ore body will initially increase and then decrease as mining progresses downwards. On the other hand, if the drift is excavated less than two levels below the production level, the stress will only decrease.

At LKAB's underground mines, shotcrete is an important support element together with rock bolts. To improve the understanding of the behaviour of shotcrete, an extensive failure mapping was carried out. Fig. 4 shows two examples where the lining has been over-stressed and where cracks, possibly caused by bending, have occurred. Fig. 5 shows a shear failure in the shotcrete lining in an area of the mine where the rock was heavily fractured due to high compressive stresses.

3. Introduction to the numerical analyses

Most of the infrastructure in the mine such as the accesses to the ore body, electrical supply and equipment, radio communication, water and the mine ventilation are