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Investigation of surface subsidence due to sublevel caving

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Abstract

Mining with a sublevel caving induces the progressive failure of the hangingwall and in minor proportion the failure of the footwall. Surface subsidence is a consequence of the large deformation experienced by the rock mass. Monitoring displacement and fracture mapping are normally carried out in a regular basis especially when the mine is surrounded by civil and mining infrastructure. Since 1967, at Kiirunavaara mine, subsidence monitoring information has been obtained and used to calibrate predictive models. In this paper the monitoring data collected in Kiirunavaara mine is presented as time-displacement curves to analyse the pathway of the hangingwall and to predict displacements in short term. The results influenced by the quality of the rock mass, structural geology and stress conditions, shows different time-displacement behaviour along the hangingwall.

1 Introduction

Large scale subsidence has been induced on the hanging wall at the Kiirunavaara iron ore mine since 1967 when sublevel caving was implemented after an open pit operation. The mine is located in the North of Sweden about 180 km north of the Arctic Circle. The tabular orebody is 4 km long and its average thickness is 80 m dipping 60° to the east towards the City of Kiruna. Two deformation zones have been recognised on the hangingwall surface — a continuous deformation zone and a discontinuous deformation zone — as is shown in Figure 1.

Figure 1 Hangingwall deformation zones (Villegas and Nordlund, 2008)

The discontinuous deformation zone is characterised by large surface disturbances affecting limited regions. Features such as tension cracks, steps and chimney caves normally appear in this zone. Tension cracks are formed by extension strain with a tendency to develop along a joint set which is sub-vertical and strikes parallel to the orebody. Steps, which started as tension cracks, define the limit of the failure. Chimneys form in the failed rock mass under stress relaxation where individual rocks move vertically through flow channels after ore draw. The continuous deformation zone is characterised by a smooth lowering of the ground surface due to elastic or continuous non-elastic deformation detected by periodic survey.

Today, the railway is in the limit of the continuous subsidence zone and a predictive method is required for planning future adjustments of the railway until a new one is constructed. This paper presents the empirical method obtained by analysing surveying data.

2 Monitoring system

At the initial stage of the underground operation only visual inspection and fracture mapping were carried out on the hangingwall. In 1975, a formal monitoring system that covered only some sections of the mine was implemented. Transit, theodolite and cloth measuring tape were used with an estimated resolution of 0.01 m (Lupo, 1996). Since 2003 the measurements have been annually carried out using a GPS system with an accuracy of 5 mm in horizontal direction and 20 mm in vertical direction. Today, a network of 236 stations, which are marked bars mounted in cylindrical concrete bases buried 0.5 m into the ground, are distributed along the hangingwall in ten surveying lines oriented east–west (B, C, D, F, H, L, N, S, T) and two more (G, U) oriented north–south (see Figure 2). During crack mapping, a metric tape to measure crack aperture is used.

Figure 2 Location of the surveying lines in a map with the mine coordinate system

3 Deformation behaviour

3.1 Displacement curves

Because the hangingwall in sublevel caving mines resembles a rock slope where the toe is undercut during mining, it is reasonable to assume similar deformation behaviour to that observed in open pits. Thus, the Kiirunavaara hangingwall displacement prediction model was inspired from open pit mine slope failure prediction models. Plotting time versus displacement rate, two principal failure stages, a regressive stage and a progressive stage, were identified by Broadbent and Zavodni (1982). The point at which the slope changes from regressive to progressive was termed the onset-of-failure point (OOF). Recently, a more comprehensive time and event dependent deformation model has been proposed by Mercer (2006) who pointed out that the pre-collapse deformation rate behaviour is largely independent of the slope failure mechanism and mode. He concluded that the real potential for prediction is based on changing deformation rate patterns rather than identifying modes of instability or making comparisons of instantaneous deformation rates. Mercer's model is characterised, both in terms of horizontal and vertical displacement and displacement rates, by five distinct stages of deformation behaviour: primary rock mass creep modes, secondary rock mass creep modes, post-onset-of-failure to collapse behaviour modes, post-collapse behaviour modes and post-mining/recovery behaviour modes. This approach was used to analyse the hangingwall deformation behaviour.

3.2 Hangingwall behaviour

To generate the model, displacements were only analysed in the vertical and in the horizontal X direction (perpendicular to the ore body or east–west). In the horizontal Y direction (north–south) the movement is erratic and does not follow a clear pattern. It seems that it is influenced by the differential rate of extraction between production areas in the mine. Therefore, line C (Figure 2) was not included this study. The overall deformation behaviour is shown in Figure 3.

Figure 3 Typical displacement curve of the hangingwall at the Kiirunavaara mine

Four different graphs for each surveying station showing cumulative displacement (horizontal and vertical) versus time and rate of movement (vertical and horizontal) versus time were obtained. Any point on the surface subsidence area experiences three different stages of time-dependent deformation behaviour: regressive, progressive and steady state. During the regressive stage the movement starts with dilation and relaxation of the rock mass due to changes in stresses. Following the initial response, the displacement-time curve shows linear behaviour but when the rate of extraction in the mine is low, shows short-term

decelerating displacement cycles. This type of decaying movement has also been observed in rock slopes and it could be the effect of increasing shear strength due to formation of oversteps and bends along cross-section of the failure surface. In the Kiirunavaara mine, the exploitation of a deeper sublevel produces a stress changes that displaces monitoring points at an accelerating rate. This behaviour is known as progressive. A steady state of movement is reached when the hangingwall continues to creep at constant velocity. Finite element analyses of the mine sections Y1500 and Y2300 showed that the failure surface was coincident with a critical vertical displacement (CVD) defined by the inflexion point in time-displacement curves (Villegas and Nordlund, 2008). This finding could indicate that, at this time, the failure surface is well defined. Because the hangingwall undergoes large displacements, it can be assumed that the failure surface reaches its residual strength. Finally, a transition from the steady-state behaviour to another progressive stage may take place as a result of the proximity to the caving area. During this second progressive stage, the hanging wall displaces at an accelerating rate to the point of collapse in a chimney or sinkhole.

The regressive stage in Figure 3 shows a decay deformation behaviour but in the overall deformation behaviour pattern its effect can be neglected and fitted with a polynomial function. For instance, the accumulated horizontal displacement of station S3 has been plotted in Figure 4.

Figure 4 Plot of horizontal displacement versus time of station S3

The station S3 is located above the mine block 25 and it is expected that mining of this block is influencing its behaviour. In the graph three acceleration points can be seen. During the year 2000 there is a small acceleration of the movement which is coincident with the initial extraction of block 25 in the mine level 820 m. The second acceleration moment during 2003 is also coincident with the extraction of block 25 at the mine level 849 m, and the third acceleration movement is during the year 2005 coincident with the opening of the mine level 878 of block 25. This point appears to be the onset of failure since the movement is accelerating which is characteristic behaviour of the progressive stage. The point of failure (POF) and the OOF can be seen more clearly by plotting the average rate of movement as shown in Figure 5. The rate of movement has a sharp drop in 2004 previous to the OOF. This behaviour is associated in Mercer's model with the formation of a tension crack where the rock mass behind the crack decelerates. The rate of movement curve was used to define the points OOF and POF, and the displacement curve to fit a continuous function for displacement prediction.

Figure 5 Plot of rate of horizontal movement versus time of station S3

4 Results

Based on the tendencies shown by the time-displacement behaviour of the surveying stations, the surveying lines (Figure 2) were divided into three groups:

- Group 1: surveying lines B and F
- Group 2: surveying lines H, N and S
- Group 3: surveying lines L, M T and D.

Group 1 is characterised by a significant displacement in the Y direction to the south. During the regressive stage, some stations experienced uplifting. The tilting of a large block could explain the uplifting effect experienced by these stations. The curves of time versus displacement in the X and Z directions were fitted with a polynomial function of third degree. Because these lines are located close to the end of the orebody, the stress condition likely affects the deformation behaviour.

Group 2 is characterised by a significant horizontal displacement during the steady state. The curves of the displacement versus time in the X and Z directions were fitted with polynomial functions of second degree. This group of lines is located above sections of the mine with lower extraction rates and higher rock mass quality.

Group 3 is located above the areas of the mine with higher extraction rates and lower rock mass quality. Although they can show larger horizontal displacement than vertical displacement during the regressive stage, they show higher rate of movement in the vertical direction than the horizontal during the steady state. The time versus displacement curves of the X direction were fitted with polynomial functions of second degree. With the exception of line L, the curves for vertical displacement follow a linear relationship. Table 1 summarises the relevant values of time and displacement for each surveying line.

Table 1 Critical displacements and periods of time for the regressive and progressive stage

Line	Station	OOF (m)	POF (m)	Regressive Stage (Time in Years)	Progressive Stage (Time in Years)
B	B4	0.65		10	
D	D8	0.62		10	
F	F2	0.87		10	
L	L6	1.08	3.65	11	2
M	M4	1.33		12	
N	N29	0.65	1.73	9	2
S	S3	1.14	2.17	11	2
T	T5	0.64	2.59	11	2

The values shown in Table 1 were estimated from displacements and rates of movement in the horizontal direction. It can be seen in Table 1 that the regressive stage covers a period of 10–11 years ending with a horizontal displacement magnitude in the range of 0.6–1.3 m which is the onset-of-failure point (OOF). On the other hand, the progressive stage takes only two years ending in the point of failure (POF) with a wider range of displacement magnitudes 1.7–3.7 m. Table 1 does not show values for Line H because it shows different deformation behaviour. It seems that a mine pillar which failed 1985 (Lupo, 1996) has constrained the deformation in this area.

Figure 6 shows the accumulated displacement at two stations on the ground surface of the hangingwall. The curves indicate the general deformation pathway of the two stations; one is far from the mine and the other is close to the mine. Although both curves start in the year 0 which is the year when the total displacement reaches 2 cm, each station starts to move at different date. The displacement magnitude of 2 cm is used in the mine to define the limit of subsidence.

Figure 6 Typical displacement-time curves of two stations on the hangingwall surface at different positions

It can be seen in Figure 6 that the farthest station from the mine moves at a lower rate of movement and will take a longer period of time to reach the same displacement magnitude as the nearest station.

Finally, the data of those stations close to the railway that shows the whole regressive stage were used to fit the curves. The equations to calculate horizontal displacement in X direction, shown in Table 2, are functions of time measured in years starting from the year 0. Similar equations for vertical displacement were obtained. By using these equations, it was possible to make a subsidence prediction for the railway for at least 10 years. These are conservative predictions because the new stations under the influence of subsidence will experience longer periods of time in the regressive stage than those stations used to acquire the predictive functions. However, because geological structures affect the deformation behaviour, it is likely that future corrections will be made.

Table 2 Fitted functions of the regressive stage

Line	Direction	Polynomial Function	R-Squared
B	X	$-0.005 + 0.0762 * t - 0.01994 * t^2 + 0.00182 * t^3$	0.978
	Z	$0.03 + 0.0741 * t - 0.01831 * t^2 + 0.002023 * t^3$	0.967
D	X	$0.034 - 0.0093 * t + 0.00441 * t^2$	0.984
	Z	$0.001 + 0.0145 * t$	0.960
F	X	$0.026 + 0.0217 * t - 0.00824 * t^2 + 0.00091 * t^3$	0.995
	Z	$0.006 + 0.0114 * t - 0.00425 * t^2 + 0.000695 * t^3$	0.995
L	X	$0.041 - 0.0103 * t + 0.00484 * t^2$	0.991
	Z	$0.022 + 0.0022 * t + 0.00334 * t^2$	0.991
M	X	$0.022 + 0.0076 * t + 0.00226 * t^2$	0.994
	Z	$0.012 + 0.0132 * t$	0.982
N	X	$0.018 + 0.013 * t + 0.00675 * t^2$	0.984
	Z	$0.025 + 0.0007 * t + 0.00522 * t^2$	0.985
S	X	$0.045 + 0.003 * t + 0.00421 * t^2$	0.983
	Z	$0.019 - 0.0004 * t + 0.0025 * t^2$	0.986
T	X	$0.037 - 0.0138 * t + 0.00611 * t^2$	0.987
	Z	$0.018 + 0.0327 * t$	0.982

5 Conclusions

Using displacement and rate of movement curves plotted from surveying data the overall time-dependent deformation behaviour of the hangingwall at the Kiirunavaara Mine has been defined. Three stages were identified in the curves. The regressive stage is characterised by a decay type movement where acceleration is initiated by the exploitation of a new sublevel. The behaviour changes to a progressive stage when the displacement reaches the onset of failure. In this second stage the movement accelerates until the point of failure which defines the start of the steady state stage where the rate of movement is constant. Finally, a second progressive stage starts with the proximity of the caving zone where the movement accelerates until collapse. This last stage has been inferred from visual observations because surveying is not possible for safety reasons.

Predictive displacement functions were obtained from the displacement curves and applied to predict the movement along the railway in X (east–west) and Z (vertical) directions for a period of 10 years.

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