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Time-dependent movements of the hangingwall at the Kiirunavaara mine

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The hangingwall deformation behaviour at the Kiirunavaara mine has been characterised after several years of collecting surveying data from the ground surface. The monitoring system was implemented to track surface subsidence because the city of Kiruna and the railway are situated on the hangingwall. Data time–displacement and time–velocity curves were used and different stages of deformation behaviour were identified – regressive, progressive and steady state. The movement starts with a regressive behaviour for which subsidence is characterised by continuous deformations. At the end of this stage the movement accelerates, marking the beginning of the progressive behaviour where subsidence becomes more discontinuous. A steady state stage is reached when the strength of the failure surface decreases to the residual value. To predict displacement in the vicinity of the railway, accumulated displacements per year were analysed for several stations for which data for the full regressive stage were available. Displacement tendencies were fitted with quadratic polynomial functions. Therefore, the rate of movement follows a linear trend with a constant acceleration. Finally, a critical horizontal strain limit was determined based on the estimated displacement.

Keywords: Kiirunavaara mine; hangingwall; time-dependent movements

1. Introduction

1.1. Mine description

The Kiirunavaara iron ore mine is located to the west of the city of Kiruna in northern Sweden about 150 km north of the Arctic Circle (Figure 1). The mine is owned and operated by Luossavaara-Kiirunavaara AB, LKAB. At the beginning of the last century, the ore was extracted by open pit mining. The transition to underground mining started during the [1950s]. Today, the entire orebody is mined using large-scale transversal sublevel caving, though sometimes longitudinal sublevel caving is also used depending on the orebody geometry. The orebody is more than 4 km long and around 80–160 m wide extending to a depth of at least 2 km. The orebody dips 60° to the east and strikes in a mostly north-south direction. Mining is currently carried out about 700 m below the ground surface and the production plan

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Figure 1. Location of the City of Kiruna, Sweden in Europe.

is 29 Mton of crude ore per year. The iron ore contains mainly fine-graded magnetite with variations in apatite contents. The rock type in the footwall side is a sequence of trachyandesitic lavas, and the hangingwall side comprises pyroclastic rhyodacites.

The orebody is divided into main haulage levels where transportation haulage of the ore takes place. Sublevels are developed between the main levels at a regular vertical spacing of 28.5 m with a footwall drift (parallel to the orebody) and cross-cuts (perpendicular to the orebody). The cross-cuts (production drifts) are made at 25 m horizontal intervals from the footwall to the hangingwall. The drifts are 7 m wide and 5 m high. Fans of production holes are drilled in the ore from the cross-cuts with a burden of 3.0–3.5 per ring. The broken ore, mobilised by the effect of gravity flow, is drawn at the brow of the cross-cut. Load-haul-dump machines carry the run-of-mine ore to the nearest ore pass. Using one of the shuttle trains operating on the current level at the 1045 m mining level, the ore is transported to one of four crushing stations. The ore is then skip hoisted in two stages to the 775 m level and then to surface.

1.2. Mine subsidence

The city of Kiruna and the railway are situated on the hangingwall side of Kiirunavaara mine. Mining using sublevel caving induces large-scale surface subsidence, primarily on the hangingwall side. The subsidence is characterised by discontinuous deformations, close to the orebody and continuous deformations farther out into the hangingwall. Displacement measurements and crack mapping on the hangingwall surface at the Kiirunavaara mine have been used in subsidence studies to locate the failure surface on the ground [1,2]. The first sign of instability on the ground surface is small cracks which are constantly growing and widening. After a certain amount of deformation larger tension cracks or steps form. At this time the cracks define the limit between the continuous and the discontinuous subsidence zones. However, previous studies and back-analysis have not been able to quantify the displacement magnitude and strain when a failure surface is formed. This data is important in order to calibrate numerical models.

Based on field observations at the mine, it has been assumed that the hangingwall behaves as a rock slope where the toe is undercut. Hence, limit equilibrium methods have been used to analyse the hangingwall and footwall failure assuming plane and circular failure surfaces [1–4]. In addition, Villegas [5] stated that the time-dependent behaviour of the hangingwall resembles the behaviour of open-pit slopes classified as transitional type [6]. Finite element analysis showed that the failure surface is well defined when the vertical displacement reaches a critical magnitude which is coincident with the displacement magnitude where the behaviour of the hangingwall changes from regressive to progressive [7]. This finding motivated a literature review of the subject and a more comprehensive surveying data analysis of the hangingwall.

1.3. Review of time-dependent deformation behaviour of rock slopes

Martin [8] documented three different cases of rock slope failures each with different rock mass quality. During excavation the initial response of the rock mass was different for each case with the higher quality rock mass experiencing lower initial and ongoing movement rates and lower total movement.

By plotting time versus displacement or velocity, Broadbent and Zavodni [6] described two general behaviours of large-scale open pit failures – regressive and progressive. A regressive behaviour is one that shows short-term decelerating displacement cycles if disturbing events external to the rock are removed from the slope environment. The ratio of driving forces to resisting stress decreases with displacement and become more stable with time. A progressive behaviour, on the other hand, is one that will displace at an accelerating rate, usually an algebraically predictable rate until collapse. During this time the rock mass experiences large-scale deformation and strain softening [9]. A transitional condition is observed when the curve shows regressive behaviour in an initial stage and then changes to progressive behaviour in a second stage until collapse. The point where the curve changes the behaviour was named onset of failure (OOF). Different failure modes were associated with these general behaviours by Savely [10]. Regressive failure behaviour is typical for deep-seated rotational failures, complex failure geometries such as active-passive blocks, and failures that show toe heave, such as non-daylighted failures with horizontal or upward movement at the toe. Progressive failure behaviour typically results from daylighting structures causing plane shear and wedge failures. It was pointed out that the regressive failure behaviour can become progressive when:

- mining daylights a previously non-daylighted failure surface or new failure surface,
- the rock mass at the toe breaks up and a shear surface or shear zone is developed,
- water pressures increases and/or
- mining is continued without letting the slope regain equilibrium, and the slope accelerates beyond recovery.

When a rock slope creeps at a constant velocity with a gradual increase in displacement with time it is regarded to be in a steady state [10]. This behaviour occurs when a well-defined failure surface has a dip approximately equal to the

sliding friction angle, and when the shear strength shows no peak strength. This has been observed in slope failures where failure surfaces have become well defined and the strength of the surface reaches its residual value after experiencing large displacements.

Savely [10] stated that velocity is a better measure of slope performance than displacement with respect to tendencies over a long period of time. After a comprehensive graph analysis, Mercer [11] claimed that the pre-collapse deformation rate behaviour is largely independent of the slope failure mechanism and mode, concluding 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. His model is characterised, both in terms of horizontal and vertical displacement rates, by five distinct stages of deformation behaviour. Only the first three stages are applicable to the hangingwall case and are described below. The last two describe slope deformation after total collapse under unconfined conditions.

Stage 1: Primary rock mass creep mode

Stage 2: Secondary rock mass creep mode

Stage 3: Post-onset-of-failure to collapse behaviour mode

During Stages 1 and 2, the overall behaviour is regressive but in Stage 2 the rock mass becomes more stressed and the average deformation rate increases.

Stage 1 was subdivided into three phases of deformation as follows:

- Phase 1 is an initial response as a result of change in the stress field provoked by a trigger event. The movement shows rapid acceleration.
- Phase 2 is a transient creep that follows Phase 1 and is characterised by a rapidly reducing velocity.
- Phase 3 is a steady state creep characterised by a slow and relatively constant deformation of the rock mass over a long period of time, gradually reducing to a zero velocity over a very long period of time.

Stage 2 only shows Phases 1 and 2. In this stage, cracks may appear at the crest of the slope and the rock mass behind the crack may start to exhibit deceleration and elastic rebound. Stage 3 has a progressive overall behaviour until the point of collapse. The rock mass behind the failure mass like the rock mass behind the crack in Stage 2 exhibits elastic rebound and deceleration.

An optional plot commonly used to examine movement patterns in landslides and rock slopes in open pits is the inverse of velocity against time [12]. Petley et al. [13] demonstrated that the plot shows a linear trend with a negative gradient during periods of acceleration toward failure. The linear form occurs when crack growth is the major mechanism in determining movement. An asymptotic trend is seen when the movement is generated through a ductile deformation process such as that of sliding on existing planes of weakness.

Although the hangingwall movement is restricted by the presence of caved rock which could affect the rate of movement, it is expected to follow a similar pathway as rock slopes in open pit mines as was shown by Villegas [5]. Time-displacement and time-velocity plots are used in Section 3 to analyse the time-dependent deformation behaviour of the hangingwall at the Kiirunavaara mine.

2. Surveying system

In 1975, a more formal surface surveying system which covers some sections of the hangingwall was implemented tracking the movement through several stations lined up perpendicular to the cave. Measurements were taken using transit, theodolite and cloth measuring tape. As the surface subsidence has advanced new survey stations have been added. Moreover, a switch from using total station technique, to monitoring ground deformation using Global Positioning System (GPS), was made in 2003. Currently, a total of 300 stations grouped into 12 surveying lines are monitored using GPS. All stations are measured at least annually, with stations located near the limits of measurable deformations and in critical areas being measured quarterly. The first stations were unmarked rebar pounded into soil or waste rock. The construction quality was improved by using a marked bar mounted in a cylindrical concrete base buried 0.5 m below ground surface. Currently, survey stations comprise a 6" steel tube drilled to rock, or to frost-free depth, filled with concrete (see Figure 2). The estimated surface subsidence measurement precision varies from 1 to 2 cm [14] and the theoretical accuracy is 5 mm in a horizontal direction and 20 mm in a vertical direction. Figure 3 shows the surveying lines and the mine coordinate system. In the horizontal plane, the X coordinate increases to the East and the Y coordinate increase to the South. The Z coordinate increases with depth where the reference point is the former top of the Kiirunavaara mountain.

3. Graph analysis

This article covers analyses of movements of surveying lines B, F, L, M, H, N, S, T and D in the X (East-West) direction perpendicular to the cave and the Z (vertical) direction starting from the year 1996 and ending in the year 2009. Movements in the Y direction do not show a clear tendency with the exception of lines B and F that show significant horizontal movement in the Y direction to the south because these lines are located near the northern end of the surface crater where the movement is constrained to the North (see Figure 3). However, this movement was not considered. Surveying lines C, G and U were installed recently; hence, there is not enough data to analyse these.

Figure 2. Surveying stations.

The graph in Figure 4 displays two curves showing velocity (dashed line) and displacement (continuous line) in the X-direction for station T5. This station is located on a waste dump in one of the highest locations of the hangingwall ground surface. It shows almost 8 m of accumulated horizontal displacement. Because section T5 is at about 150 m horizontal distance from the caving area, it was possible

Figure 3. Station map with the mine coordinate system.

Figure 4. Time versus accumulated displacement in East-West direction for station T5.

to measure it during a long consecutive time period without any risk to the surveying crew. For safety reasons, if a station is close to the caving area, it is not surveyed any more. Two changes in the deformation rate pattern (velocity curve) can be seen in the graph. The first one is a sharp change in the year 2002 where the movement accelerates until the year 2004. The year 2002 is thus an inflexion point in the time–velocity curve and the point representing OOF. A regressive behaviour is observed in the first part of the curve until the OOF point where the behaviour becomes progressive. The second change occurs at the point of failure (POF) which marks the limit between the progressive and the steady state stage. Finite element analysis has indicated that a shear failure surface is fully developed at OOF [7].

The plot of the inverse of velocity versus time (Figure 5) shows an asymptotic behaviour. Based on the description by Petley et al. [13], this behaviour indicates that a ductile deformation process is occurring. The movement of the hangingwall is constrained by the failed rock in the cave. Therefore, the hangingwall failure cannot be catastrophic. After the OOF point the shear zone undergoes large deformation until the POF, where the strength of the failure surface is close to the residual value and the failure behaviour will be ductile.

During the regressive behaviour the movement is accelerated by the opening of new sublevels as shown in the following example. Ground surface movements above the mine block 25 are measured in the station S1. Figure 6 shows the plot of rate of movement in the horizontal direction versus time for this station. In the plot three acceleration points can be seen. During the year 2000, there is a small acceleration of the movement which is coincident with the opening of the mine level 820 m. The second acceleration stage during 2003 is also coincident with the opening of the mine level 849 m, and the third acceleration stage during the year 2005 is coincident with the opening of the mine level 878 m.

The deformation rate pattern is affected by the proximity of a tension crack as was observed in almost all the surveying lines. For instance, Figure 7 shows acceleration after year 2004 for stations L6 and L5. However, in 2005 although

Figure 5. Time versus inverse of velocity in East-West direction for station T5.

Figure 6. Time versus velocity in X direction for Station S1.

Figure 7. Crack effect on the time-velocity curve of station L5.

station L6 continues to show a high rate of movement, station L5 decelerates for a period of 2 years. During this time a well-defined crack appeared between these stations. Frictional shear traction may develop along the failure surface that connects the crack. Apparently, during the time that the movement of station L6 goes from the OOF to the POF the frictional shear traction decreases because the strength along the failure surface goes from peak to the residual value. Mercer [11] pointed out the possibility that cracks may occur at the crest of a rock slope before the OOF and the rock mass behind the crack may show deceleration and elastic rebound.

The values in Table 1 were estimated from horizontal displacement measurements in the X direction (East-West). Table 1 shows that the regressive stage covers a period of 10–12 years ending with a horizontal displacement magnitude in the range of 0.64–1.92 m which is the onset-of-failure point (OOF). The regressive stage takes only 2 years ending in the POF with displacement magnitudes in the range of 2.17–3.65 m.

There are two surveying lines, H and N, with larger horizontal displacement than vertical displacement that only show regressive behaviour. For instance, Station N29 has an accumulated horizontal displacement of 2.80 m and a vertical displacement of 1.64 m in a time period of 11 years. The movement in surveying line H is lower than that in surveying line N showing 0.92 m in the horizontal displacement and 0.67 in the vertical direction accumulated in 14 years. Apparently deformation has been influenced by the thickness of the orebody. Below this area some section of the orebody can be very thin or even disappear.

It has been observed that the ground surface deformation during the regressive stage is continuous. Only small cracks can be seen during this stage in places where the horizontal strain is higher than 2.3 mm/m and the layer of soil is a few meters thick.

As a consequence of the mining-induced ground deformations, the existing railway will have to be relocated in the near future. A new railway is being constructed on the western side of the mine. Current plans are that this will be ready for traffic in October of 2012. However, some sections of the current railway are close to the limit of the subsidence area, and the existing railway needs to be operational at least until the new line is ready for traffic. Planning maintenance adjustment on the railway requires an assessment of future movements. The horizontal and vertical displacements of stations F47, L10, A17, M10, St2, St3, S10, and S12 located along the railway (see Figure 8) were reviewed. These stations are experiencing small movements which are typical for the regressive behaviour. Stations F38, L4, M3, M26, H22, N34, S4, T9, and D9 are close to the limit of the discontinuous subsidence zones as was mentioned before and they are approaching the OOF point. Thus, the deformation data from these stations was used to predict the regressive stage of the stations along the railway. The resulting deformation

Table 1. Observed accumulated horizontal displacement at the OOF and POF points and period of time for the regressive and progressive stages.

Station	Horizontal displacement at the OOF (m)	Horizontal displacement at the POF (m)	Period of time for the regressive stage	Period of time for the progressive stage
B4	0.65		10	
D9	1.05		12	
F2	0.87		10	
L6 ^a	1.08	3.65	11	2
L5	1.92		11	
M4	1.33		12	
S3	1.14	2.17	11	2
T5 ^a	0.64	2.59	11	2
T7	1.28		11	

Note: ^aSmall movements occurred before surveying started.

tendencies are summarised in Figures 9 and 10. It can be concluded that the horizontal displacement is larger than the vertical displacement in the continuous deformation zone or during the regressive stage. The accumulated displacement per year was fitted with a polynomial quadratic function. Hence, acceleration is constant and the rate of movement increases linearly with respect to time.

4. Strain predictions

Recently, a new criterion for ground deformations outside the industrial area of the mine was imposed on LKAB by the environmental court. This criterion states that deformations cannot exceed 3 mm/m horizontal strain and 2 mm/m tilt. These values

Figure 8. Location of stations along the railway and along the limit of the discontinuous subsidence.

Figure 9. Fitted curve on the horizontal displacement data of Station L4.

represent the state of deformation when damage to existing infrastructure starts. Assuming that the ground surface is horizontal without any significant topographic change and using the polynomial functions, horizontal and vertical displacements were calculated for fictitious stations located every 10 m along each surface profile starting from the outer limit of the discontinuous deformation zone to the continuous deformation zone limit. Thereafter, horizontal strain and tilt between the stations were computed. Figure 11 shows the equations used to calculate tilt and horizontal strain. In Table 2, the limits are given as a distance measured from the failure surface to the East direction as is shown in Figure 12. The failure surface appears as a tension crack on the ground and the rock mass movement around the

Figure 10. Fitted curve on the vertical displacement data of Station L4.

Figure 11. Horizontal strain and tilt calculations.

crack shows a movement magnitude equal to, or higher, than the OOF. From the components of the ground movement only horizontal strain and tilt have been calculated. Based on the horizontal strain calculations, it can be concluded that only extension or tensile strain takes place on the ground surface.

The fitted functions are continuous, which is not the case in the field where breaking points may occur at geological structures in places where the rock mass quality in general is very good. This effect can be observed by comparing Figures 13 and 14. Figure 13 shows the calculated extension strain between stations along the surveying line L. In this area the rock mass has lower quality and good cavability. The strain is higher close to the cave and decreases in the East direction (increasing coordinate number in X direction) when approaching the outer limit of the continuous deformation zone. More accurate predictions can be obtained under

Table 2. Horizontal distance of the allowed strain limit and the subsidence limit measured from the failure surface.

Surveying line	Horizontal distance between allowed strain limit and the failure surface	Horizontal distance between subsidence limit and the failure surface
B	460	110
F	420	130
L	400	90
M	450	160
H	700	50
N	600	110
S	600	150
T	650	130
D	860	85

Figure 12. Surface profile of the surveying line S.

these conditions because the points in the plot show a clear tendency. On the other hand, Figure 14 shows the calculated extension strain between stations along the surveying line D. In this area the rock mass has better quality and subsidence is characterised by large tension cracks and bad cavability. In the plot, the points do not show a clear tendency because strain does not always decrease when moving in the East direction. This is an irregular behaviour in the continuous deformation zone where the rock mass is stronger.

Figure 13. Calculated extension strain between stations of the surveying line L.

Figure 14. Calculated extension strain between stations of the surveying line D.

5. Discussions

The time–velocity curves showed acceleration points coincident with the opening of deeper sublevels. The new excavation caused stress redistribution that was manifested in the hangingwall as an increase of the rate of movement.

The asymptotic form of the curve in a time versus inverse of velocity plot can be associated with a ductile deformation process, formation of shear band, and sliding on a preexisting shear surface rather than through crack growth [13]. This statement is valid for rock slope failures. However, the hangingwall at the Kiirunavaara mine is confined by the caved rock, which avoids any sudden failure. Under these circumstances the curve will show an asymptotic trend independently of the deformation process.

As mining advances to greater depth, larger volumes of the rock mass in the hangingwall will be affected, although the volume of extracted ore (per level) is constant. Therefore the subsidence magnitude will decrease and it will take longer periods of time to reach the OOF point. In addition, the increasing volume of caved rock in the pit constrains the hangingwall movement.

The secondary creep mode named Stage 2 in Mercer's model [11] associated with the formation of the tension crack can also be seen in the time–velocity curves for the Kiirunavaara hangingwall as is shown in Figure 7. Deceleration of the rock mass behind the crack and the negative horizontal and vertical deformation rates have also been observed. When the secondary creep mode is evident, the accumulated displacement to reach the OOF is usually higher. Therefore, the magnitude of the vertical or horizontal displacement of the OOF varies making the prediction complicated.

Strain prediction along the continuous deformation zone has been done assuming continuous behaviour of the rock mass. However, a strong rock mass emphasises its discontinuous nature when strain is concentrated along geological structures [15,16] distorting the tendency of the strain profiles as was shown in Section 4. Therefore, the prediction must be used with caution in those areas with good quality rock mass and the presence of deformation zones and lithological contacts.

6. Conclusions

The hangingwall deformation behaviour has been analysed for the horizontal direction perpendicular to the orebody strike (X direction) and for the vertical direction (Z direction) using time–displacement and time–velocity curves. The overall behaviour is characterised by the regressive, progressive and steady state stages. The continuous deformation zone experiences only the regressive stage with small displacements and velocities where larger horizontal displacement than vertical is observed. Cracks often develop close to the OOF. During the progressive stage the movement accelerates until the POF, where the velocity reaches the steady state. At this point of deformation a large step is visible in the field. The limit between the continuous deformation zone and the discontinuous deformation zone is marked by this step.

Future horizontal and vertical displacements and rate of movement along the railway in the city of Kiruna were estimated. Predictive functions were determined for each survey station line by fitting polynomial functions to the time–displacement

data of those stations for which there were measurement data for the whole regressive stage.

The components of the ground surface movement of the hangingwall do not show compressive strain. Strain predictions depend on the quality of the rock mass. When rock mass quality is fair to poor, deformations are more predictable. However geological structures may result in concentrations of strain for cases of good rock mass quality. This would require a different type of analysis compared to that used for continuous subsidence.

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