Crosscut deformation as a function of ring blast location in LKAB's Malmberget mine

Tvärortsdeformation som funktion av produktionsskjutning i LKABs Malmbergsgruva

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Summary

Between 2007 and 2010, 20 SMART cable bolts collected crosscut deformation data on levels 932 and 962 of the Malmberget mine. Using 3D mapping techniques, the coordinates of each instrument were determined, along with the coordinates of every production blast occurring during their lifetimes. These coordinates were used to calculate the relative distance and inclination angle (vertical angle above the horizontal plane) from each instrument to each production blast. The instrument data was analyzed to determine average-weekly deformation magnitude and rate.

Specific deformation trends were identified when the deformation data was compared to the average weekly distance and inclination angle of the blasts. When blasts detonated at the same distance were compared, those blasts occurring on the level above the instrumentation produced greater deformation rates on every recorded occasion. Also, decreased distances produced higher deformation rates. These rates were all highly influenced by the varying RQD present at each bolt location, with higher RQD giving less deformation. While these results are not unexpected, they resulting data produced further interesting connections when the actual position of each blast was considered.

In total, 1026 data points were produced from the eight bolts that recorded significant movement. Of these data points, only 49 instances (5%) occurred where deformation rates higher than 150 μm/day were realized. Given that increased deformation rate is a known indicator of instability or approaching failure, the individual blasts that created these 49 instances were investigated to see if causal patterns could be determined.

Of the 49 elevated-rate readings, specific production blasts could be identified for 45 of them. Six types of blasting events were identified as common triggers. Nearly two-thirds of these events were caused by types of stress redistribution including redistribution onto artificial pillars created during mining, and redistribution caused by the opening blasts in a new crosscut.

Using the causal events and deformation patterns as keys, it may be possible to develop a new method of empirical support design, wherein expected deformation could be anticipated and the necessary support installed in advance. This could prevent entry degradation, improve safety, and potentially lower support costs by tailoring support to suit the particular needs of a location, rather than using a blanket support policy.

Sammanfattning

Mellan åren 2007 och 2010 samlade 20 st instrumenterade kabelbultar (SMART) deformationsdata i tvärorter på nivåerna 932 respektive 962 i Malmbergsgruvan. Med hjälp av kartläggning i 3D bestämdes koordinaterna för varje instrument samt koordinaterna för varje produktionssalva. Koordinater användes för att bestämma det relativa avståndet och lutningsvinkeln (vertikal vinkel ovanför horisontalplanet) mellan varje instrument och varje produktionssalva. Insamlad data analyserades för att bestämma (på vecko-basis) den genomsnittliga storleken och hastigheten på uppmätta deformationer.

Genom att jämföra deformationerna med det relativa avståndet och lutningsvinkeln till produktionssalvor identifierades specifika deformationsbeteenden. När mätningar med samma avstånd till salvorna jämfördes, så visar analysen att salvor som sprängs på en nivå ovanför mätpunkten gav den största deformationen i tvärorterna nedanför. Vad som även kunde observeras var att deformationshastigheten ökade med minskat avstånd mellan salva och mätpunkt, och att deformationshastigheten beror på bergmassans RQD-värde vid varje bult, där ett lägre RQD-värde gav mindre deformation.

Totalt genererades 1026 datapunkter från åtta bultar där betydande deformationer uppmätts. I endast 49 fall (5%) var deformationshasigheten större än 150 µm/dag. Då ökad deformationshastighet är en känd indikator för instabilitet eller förväntat brott utvärderades dessa 49 fall i detalj för att se om det fanns ett orsaksmönster.

Av de 49 observationerna med förhöjd deformationshastighet kunde 45 härledas till specifika produktionssalvor. Sex olika typer av händelser identifierades som utlösande faktorer. Nästan två tredjedelar av händelserna orsakades av spänningsomlagringar, dels till de artificiella pelare som skapas av brytningsmetoden, och dels vid öppningsskjutningar av produktionsnivåer.

Studien visar att det är möjligt att utveckla en metod för att empirisk bedöma förstärkningsbehovet baserat på händelse- och deformationsmönster. Utifrån de förväntade deformationerna kan nödvändig förstärkning installeras i tid. Detta kan förebygga stängning av områden, förbättra säkerheteten samt minska kostnaderna genom att förstärkningsinsatserna är anpassade för de varierande behoven istället för att baseras på en standard.

Introduction

Much research has used empirical relationships to better understand mining hazards and thus improve safety. The worldwide underground coal industry especially, being relatively more hazardous than underground metal, has developed many tools utilizing simple relationships to better understand geotechnical phenomena. Stress and strain measurements have been a significant part of this, but deformations both within and without the rock mass have been measured to better understand the geotechnical challenges. Some very critical advances in coal mine ground control have been simply due to the identification of relationships between the relative position of the mining face and the stresses or deformation measured at a location of interest (Mark, C., 1990; Salomon and Wagner, 1985; Colwell, M.G., 2006; Wagner, H., 1974).

Monitoring of deformation or displacement within the rock mass and at the rock surface is an excellent method of gaining critical information about its behavior. Between 2010 and 2007, Sundström collected deformation and RQD data from the 932 and 962 levels of the Luossavaara-Kiirunavaara AB (LKAB) Malmberget Mine (Sundström, 2010). This study further explores that data and the impact of individual production blasts on the instruments.

Methods

Deformation data was acquired from a suite of 20 SMART cable bolts installed on levels 932 and 962 of the Norra Alliansen orebody. Five pairs of bolts were installed on each level in such a way that comparisons could be made between similar geologies on each level (Figure 1 and Figure 2). Bolts 1-10 operated for five months from July, 2007 until November, 2007 on level 932, and bolts 11-20 for 33 months from July, 2007 until April, 2010 on level 962. Data was acquired manually on an irregular time schedule. This deformation data provided the dependent variables in this study.

The bolts in Figure 1 and Figure 2 are labeled in four groups, A – D. Group A bolts were installed in the magnetite ore which was generally competent and fairly strong. Group B bolts were installed in the weak, low-stiffness biotite schist that formed as intrusions into the orebody. Group C bolts were installed in the strong red leptite found in the footwall, while Group D bolts were installed in biotite schist that formed along the footwall.

Each bolt was installed vertically in the center of the crosscut roof and included anchors spaced at the hole collar (0.00 m), 0.50 m, 1.00 m, 1.50 m, 2.00 m, 3.00 m and 5.00 m. Deformation and deformation-rate values, the dependent variables in this study, were taken from the hole-collar anchor. Overall deformation is greatest at this location as it includes the cumulative effect of the entire hole and also represents the greatest hazard for falling material and instability. Other anchors were used for interpretation purposes.

Detailed mine maps were acquired and combined within AutoCAD to create a single 3D model and were registered within the (global) mine coordinate system. New layers were created and the location of each installed SMART cable bolt was plotted using the head of the bolt as a reference. Blasting records were also acquired and the coordinates of each production blast ring were determined. Production blasts were referenced by a point along the centerline of the crosscut at floor level, vertically aligned with each ring. This was accomplished for all production blasts occurring during the instrument's lifetimes.

Using the developed coordinates, local spherical coordinate systems (Figure 3) were created at the location of each instrument. These allowed determination of the relative distance (r), and inclination angle (φ), the angle in degrees above or below the horizontal plane, between each instrument and production blast. Since each instrument sits at the

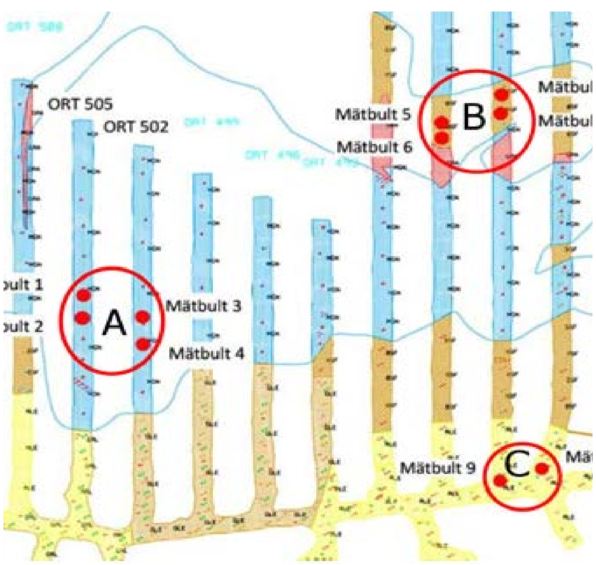

Figure 1: Bolt placement, level 932.

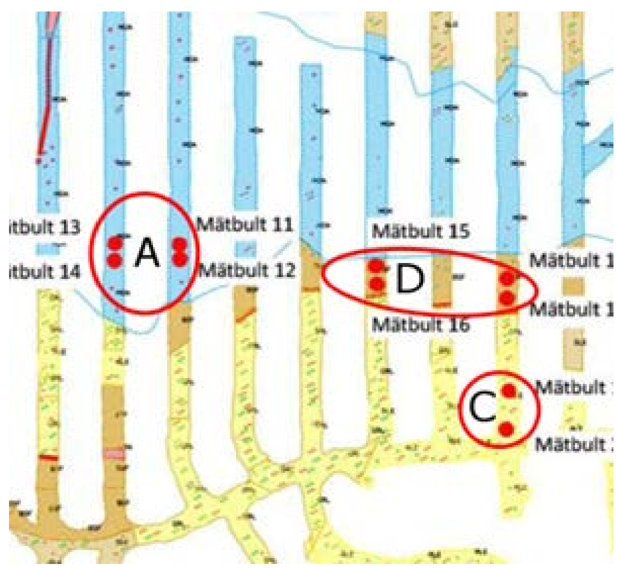

Figure 2: Bolt placement, level 962

origin of its own local coordinate system, analysis can be done individually to identify specific factors contributing to deformation for individual bolts, yet all the results can be collated and analyzed cumulatively to investigate mine-wide trends.

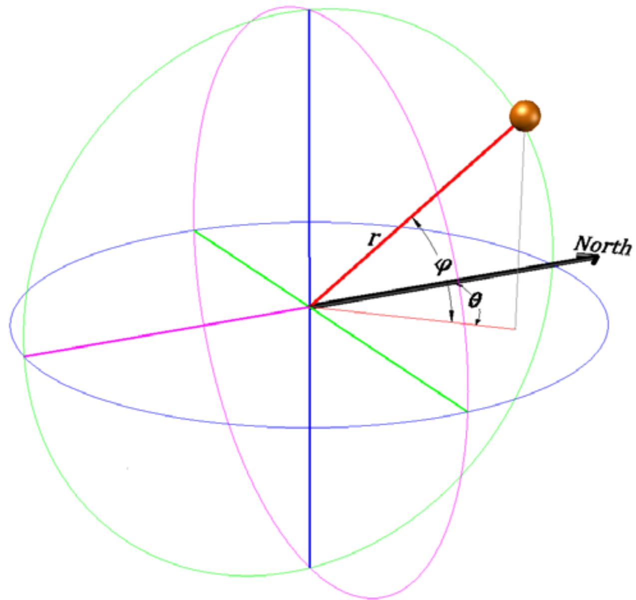

Figure 3: Variables used in the spherical coordinate systems. Bolt located at the origin, blast at the orange ball.

Readings from the SMART bolts were collected approximately once every 4.6 days over the course of the study period. Production blasts averaged once every 2.45 days over the same period. Since there are also times when the gap between blasts and instrument readings was significantly greater than these averages, average-weekly distance and vertical elevation values were compared with average-weekly deformation rates. If three production blasts had occurred during one week at distances of 60, 150, and 87 m, the average-weekly distance would be 99 m and would be compared against the corresponding average-weekly deformation rate. In this way distance and deformation or deformation rate could be compared even though blasting and measurement didn't happen at the same time.

RQD

RQD was calculated from exploratory cores located at each pair of bolts. This data was sourced from Sundström, 2010, and paired with displacement values. The most significant result shown by the RQD is simply the variation between bolt-groups. Bolts 5-8 had an average RQD of 73, and showed an average displacement magnitude of 7 mm. Bolts 15-18 had an average RQD of 57 and recorded an average displacement magnitude of 38. All other bolts had higher averages, 75-100, and showed zero displacement. The bolts with lower RQD had systematically-worse behavior than their counterparts did.

Distance

Only bolts 5-8 and 15-18 showed significant movement. Figure 4 illustrates the impact of blast distance on deformation. The distance between each production blast and the bolts is plotted along with the level on which the blast occurred. Additionally, average weekly distance is plotted. The distance can be compared with the recorded displacement from distance decreases. Bolts 5-8 had similar deformation patters to bolts 15-18. Bolts 7, 8, 17 and 18 had larger magnitudes of deformation due to lower RQD values.

Inclination Angle

Inclination angle provides useful insight into the patterns of deformation. Angle and distance are linked to one another trigonometrically, such that shorter distances equate to larger inclination angles. For blasts occurring on the level above the instrument, inclination angle was universally higher than when mining on the instrumented level. This same link means that any comparison between deformation rate and inclination angle must eliminate the distance-based element of deformation.

These comparisons were made by only comparing the data occurring within 10-m distance ranges. The average-weekly deformation rate was compared for same-level or level-above mining, using all of the data from instruments 15-18. In every single instance, average-weekly deformation rate was higher when mining occurred on the level above (Figure 5.)

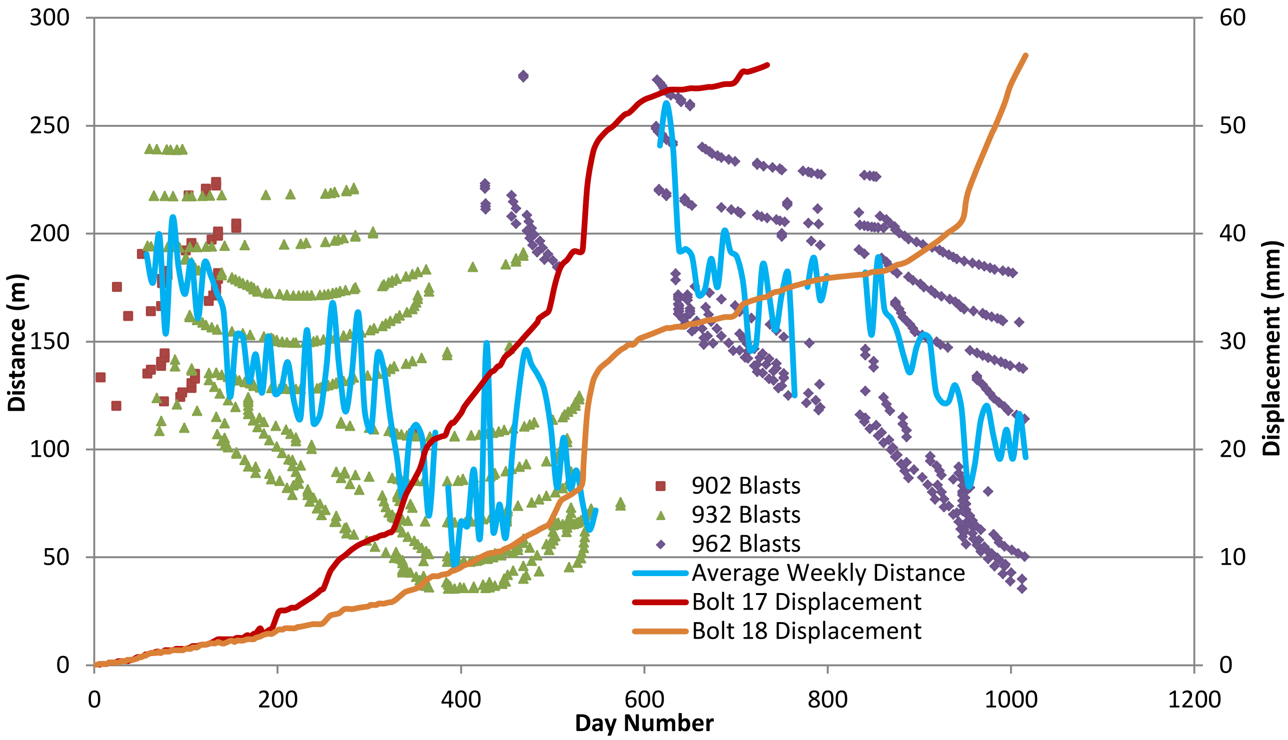

Figure 4: Relationship between blast distance and deformation for bolts 17 & 18.

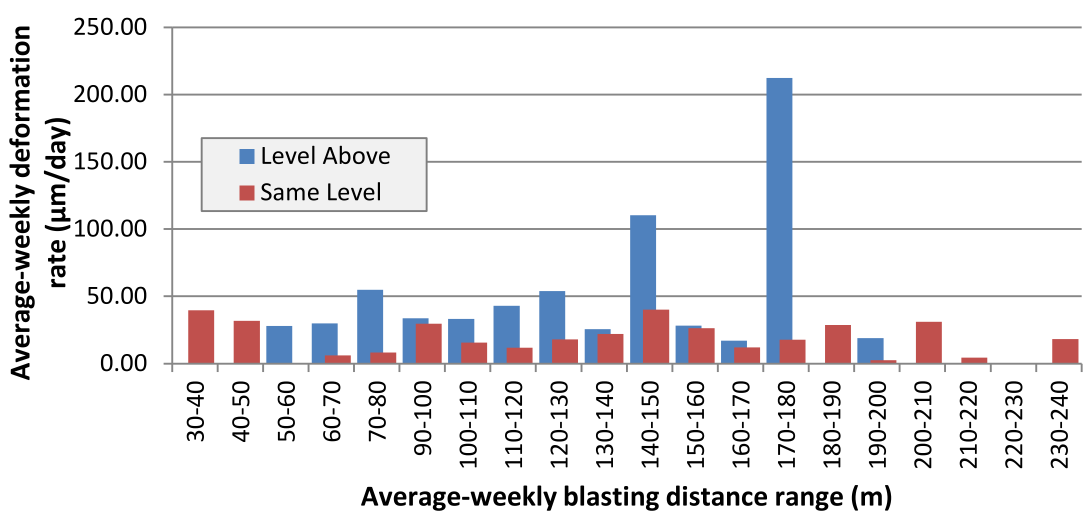

Figure 5: Deformation rate comparison- mining on the level above compared to same-level mining

Deformation Rate

Deformation rate has long been of greater interest than deformation magnitude from the point of view of stability and impending failure (Kennedy, B.A. et al., 1971). The data from the eight bolts was analyzed and average-weekly deformation rates were calculated. Of the 1026 data readings, only the top 5% (49 readings) gave deformation rates higher than 150 μm/day (Figure 6).

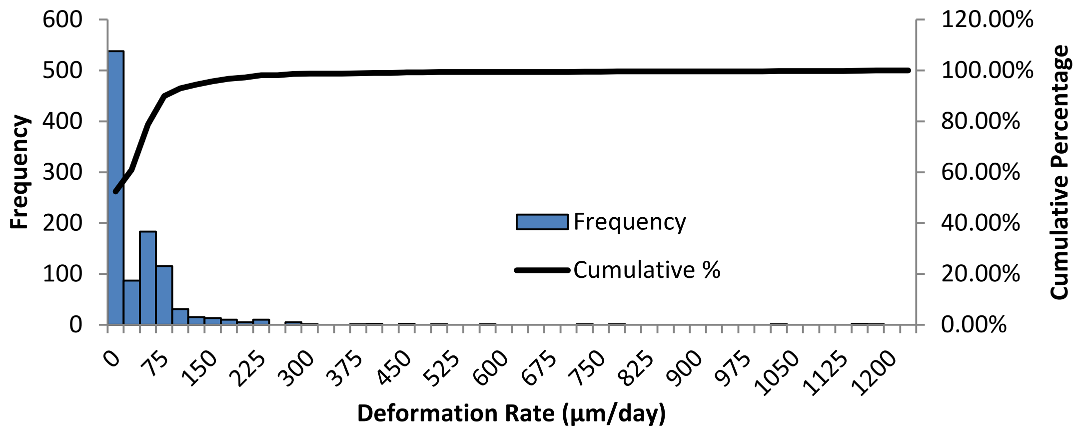

Figure 6: Frequency of deformation rate combined with cumulative percentage.

Consider that each instance of elevated deformation rate corresponds with a physical cause, and that unusually-high deformation rates can be considered a warning sign for increasing instability or likelihood of failure. Back-analysis of the identified points above the 150 μm/day limit lead to the identification of exactly which blasting events contributed to these high rates. Seven categories emerged as shown in Table 1. Only four of the instances of deformation rate higher than 150 μm/day could not be immediately explained.

Event #	Causal Event	Count	%
1	Opening blasts of new crosscut	8	16%
2	Blasting approaches contacts the footwall	15	32%
3	Blasting approaches and contacts an ore/biotite schist contact	8	16%
4	Blasting approaches an instrument in the same crosscut	9	12%
5	Blasting in neighboring crosscuts passes an instrument	3	6%
6	Time-dependent deformation	2	4%
7	Unknown	4	8%

Table 1: Causes of high deformation rates.

A brief description of each causal event-type is offered:

Type 1: When production is started in a new crosscut there is a sudden shift in the stress fields in the area. This shift can impact deformation rate a great distance away; it was 77 m between bolt 17 on level 962 and the opening blasts of crosscut 4781 on level 932. This type of event has a much greater impact on local stresses than any of the other event types, i.e. it has impact from the greatest distance.

Type 2: This is the narrowing of the magnetite ore as blasting nears and contacts the footwall. In Malmberget, this scenario is analogous to the creation of a fender pillar in a longwall coal mine with a pre-driven recovery room (Gearhart, D.F., Jones, T.H., Compton, C.S., Minoski, T.A., Ochsner, R.E., 2015; Listak, J.M., Bauer, E.R., 1989; Oyler, D., Frith, R., Dolinar, D., Mark, C., 1998). While still far from the footwall, the redirected stresses, which tend to travel through the more competent and stiff ore rather than the weaker schist running along the footwall, have a “pillar” of ore with a nearly infinite cross section to travel through. As the production blasting gets closer to the footwall, stresses are funneled through an ever-narrowing cross-sectional pillar area. More and more stress is forced into the weak biotite schist, causing increased deformation rates and rock degradation.

Type 3: This is similar to Type 2, except that instead of approaching the footwall, the blasting approaches a weak biotite schist intrusion. The “pillar” of remaining ore gets thinner, increasing the levels of stress redistributed to the schist. While the magnitude of stress redistribution is likely much lower than in Type 2, the schist still experiences a higher deformation rate due to its weakness and low quality.

Type 4: As blasting approaches an instrument site on the same level, deformation rate increases. This is partly due to blasting damage, but mostly due to decreased blast distance. Distances in this type of scenario can reach as little as 1 m, but can be up to 35 m. Naturally, closer blasts produce higher deformation.

Type 5: When blasting in a nearby crosscut approaches and then passes an instrument, the instrument experiences increased deformation. In this instance, the ore is removed on either side of the instrument, leaving the instrument on an pillar of competent rock, surrounded by blasted rock. Greater amounts of stress are funneled on this remaining pillar, leading to increased deformation.

Type 6: In two instances, high deformation rates were experienced during time periods immediately following another major event type, even though no other blasting had occurred. In these cases, time-dependent deformation continued as the rockmass attempted to equalize itself. The root cause of increased deformation rate in these cases belongs to other type categories.

Of these event types, Types 2, 3, and 5 are very similar to one another in that they all occur due to the same mechanism of stress redistribution. Together they make account for over one-half of all high deformation-rate events. As such, greater care should be paid to them in difficult areas of the mine. One way to minimize their impact may be to distribute their blasting out over a longer time period, though if time-dependent deformation is critical, accelerating production through difficult areas would likely produce better results.

Discussion

The distance and deformation data indicates that bolts 5-8 on level 932 experienced much lower magnitudes of deformation than did bolts 15-18 on level 962. This was because bolts 5-8 and 15-18 were all installed were installed part-way through the mining of level 932. Thus, bolts 5-8 experienced only the mining of part of 932, while bolts 15-18 experienced much of level 932 mining and most of level 962 mining. Since bolts 5-8 missed all of the level-above mining from level 902 they recorded much less deformation. In reality, it is likely that the crosscut experienced similar deformation to that recorded on bolts 15-18.

There is also a difference notable between bolts within each set. Bolts 5 and 6 are best compared with bolts 15 and 16, while 7 and 8 should be compared with 17 and 18. The performance differences between them are significant. Since the bolts were exposed to very similar stresses, these performance differences must be caused by variation in RQD; higher RQD, lower deformation. This is a reasonable assumption and is supported by the data.

Based on the deformation-rate analysis it is clear that a relatively small number of production blasts cause the majority of high deformation-rate instances. Given that high deformation rates are more detrimental to the rock mass and lead to higher rates of failure, these types of events should be considered in the future. It may be possible to mitigate the formation of high deformation rates by adjusting mining sequences. Further knowledge of these events may also improve the ability to predict them and to allow the installation of preventative support measures before they are necessary. This would not only improve the safety of the mine, but would reduce support cost and worker time by enabling the mine to more-precisely target those areas requiring support.

As the study is now, the cutoff rate of 150 μm/day was arbitrarily chosen. Ideally the instrument data would be coupled with field observations. By recording rates of entry degradation (shotcrete cracks, bolt-head pops, rock falls, etc.) and coupling them with the recorded deformation rate data, it can be determined what deformation-rate levels are acceptable to the mine, enabling even further precision with the analysis.

Conclusions

When considering support plans in the future, one of the most important aspects to consider is the rock quality, or RQD. This work shows that variation in RQD can have a significant impact on the outcome or success of a support plan. Bolts 15 and 16 survived until they were mined out by blasting, while bolts 17 and 18 failed up to a year before, simply due to the relative RQD of the rock.

Deformation is most-consistently impacted by blasting distance and by the inclination angle. Particular blasting events have been shown to trigger larger-than-normal deformation. These events fall into six categories, plus a few unexplained events. Of these six categories, there are four main mechanisms at work:

- Opening blasts on a new crosscut cause a sudden change in stresses in the mine.
- Pillars of stiff rock can be formed as blasting proceeds. One way is by blasting through the relatively-stiff ore towards a weak zone of biotite where a pillar of stiff rock is formed between the blasted rock and the biotite. This pillar reduced in size with each subsequent blast, causing additional stress to travel through the weak zone rather than bridging across it. Another way is by blasting around an instrument, leaving it on an island of competent rock.
- Decreased blast distances in the instrument's crosscut elevate the deformation rate. Blasting damage can also play a part in reducing rock strength.
- After an exceptionally-large event, time-dependent deformation continues even though no further blasting may occur.

The redistribution of mine stresses onto "pillars" formed by mining around an instrument, or when mining approaches weak zones of rock or the footwall combined to create over half of all high-rate events. Awareness of this problem in the future will help to better define the problem, as well as to begin the process of prevention. As understanding evolves, support strategies can be fine-tuned to allow advance installation of necessary support, improvement in mining sequences, or other options that can improve the stability, safety, and mining speed of high-deformation areas.

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References

Colwell, M.G., 2006. A study of the mechanics of coal mine rib deformation and rib support as a basis for engineering design. University of Queensland, Australia. Dissertation, 164pp.

Gearhart, D.F., Jones, T.H., Compton, C.S., Minoski, T.A., Ochsner, R.E., 2015. Ground Response as a Longwall Advances into a Backfilled Recovery Room under Low Cover. Proc. of the 33rd. Int. Conf. on Ground control in Mining. Jul. 2015, Morgantown, West Virginia, USA. pp. 44-53.

Kennedy, B.A., et al., 1971. A case study of slope stability at the Chuiquicamata Mine, Chile. Trans. of the Amer. Inst. of Mining, Metallurgical and Petroleum Eng. Vol. 250, No. 1. pp. 55-61.

Listak, J.M., Bauer, E.R., 1989. Front Abutment Effects on Supplemental Support in Predriven Longwall Equipment Recovery Rooms. 30th U.S. Symp. on Rock Mech. Vol. 30, No. 1. Jun. 19-22, Morgantown, West Virginia, USA.

Mark, C., 1987. Analysis of Longwall Pillar Stability. West Virginia University, Morgantown, WV, USA. Dissertation, 414pp.

Oyler, D., Frith, R., Dolinar, D., Mark, C., 1998. International Experience with Longwall Mining into Pre-Driven Rooms. Proc. of the 17th Int. Conf. on Ground Control in Mining. August, 1998, Morgantown, West Virginia, USA. pp. 44-53.

Salamon, M.D.G., and Wagner, H., 1985. Practical Experiences in the Design of Coal Pillars. Proc. of the 21st Int. Conf. of the Safety in Mines Research Inst. 21-25 Oct, 1985, Sydney Australia. pp. 3-10.

Sundström, R., 2010. Utvärdering av Smart Cable för att se belastning på bergbultar. Luleå Tekniska Universitet, Luleå, Sweden. LTU-EX-10053. Thesis, 60 pp.

Wagner, H., 1974. Determination of the Complete Load-Deformation Characteristics of Coal Pillars. Proc. of the 3rd Int. Soc. of Rock Mech. Cong. Vol. 2, Iss. B. pp. 1076-1081.