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Rockburst management at LKAB's Kiirunavaara Mine: what can we learn from COVID-19 management

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Abstract

Managing rockburst has been a challenging task in hard rock mines for many decades, and which still remains difficult especially when mining goes deeper. Since 2007, Kiirunavaara Mine has been identified as a seismically active mine and many severe rockbursts have occurred since then. Management of SARS-CoV-2 (severe acute respiratory syndrome coronavirus 2) infection and treatment is also challenging in our society and we have been suffering from the wide-spreading of the coronavirus. Based on our recent studies, it is found that there are many similarities between triggered rockburst and coronavirus infection. Considering the experiences obtained from coronavirus prevention and treatment, it is worthy of making a decent comparison of these two things and try to learn the lessons from COVID-19 management when thinking about rockburst management at LKAB's Kiirunavaara Mine.

This paper first reviews the chain of infection, pathophysiology of COVID-19, various preventative measures to reduce the chances of infection and current treatments after being infected with SARS-CoV-2. After that, the rockburst management at LKAB's Kiirunavaara Mine is presented and compared with the COVID-19 management in terms of chain of dynamic interaction, damage mechanism, prevention or mitigation measures as well as treatment. Through the comparison, some suggestions are given regarding how to improve the present rockburst management at the Kiirunavaara Mine. Examples from recent studies in the mine are used to illustrate the improved understanding of the rockburst issues and improvement of the rockburst mitigation strategies. Discussion is presented on where further research or improvements would be conducted in the future.

Keywords: *rockburst, damage mechanism, mitigation measures, treatment, COVID-19*

1 Introduction

Managing rockburst has been a challenging task in hard rock mines for many decades, and which still remains difficult especially when mining goes deeper. Since 2007, Kiirunavaara Mine has been identified as a seismically active mine and many severe rockbursts have occurred since then (Dahner et al. 2012). It becomes significant in the mine when it continues to reach deeper deposits. It has posed greater challenges to mine safety and production. The seismic event (moment magnitude 4.2) that occurred on 18 May 2020 at Kiirunavaara Mine caused enormous damage over large areas with an extension of more than 1 km at the production area (Boskovic et al. 2020). Production has still not reached its full capacity.

Management of the coronavirus infection and treatment is also challenging in our society and we have been suffering from the wide-spreading SARS-CoV-2 since 2019. As of 26 April 2022, there were around 510 million global cases of COVID-19 and there had been around 6.2 million deaths (Johns Hopkins University & Medicine 2022), making it one of the deadliest pandemics in history.

Based on our recent studies, it is found that there are many similarities between remotely-triggered rockburst and the coronavirus infection. As Winston Churchill was working to form the United Nations after WWII, he famously said, '*never let a good crisis go to waste*'. In another context, Churchill's insight on human nature can also be applied to the COVID-19 crisis management we face today in our society, particularly as it has some similarities to rockburst management. Considering the experiences obtained from coronavirus prevention and treatment, it is worthy of making a comparison of these two things and to try to learn the lessons from COVID-19 management when thinking about rockburst management at LKAB's Kiirunavaara Mine.

This paper first reviews the chain of infection, pathophysiology of COVID-19, various preventative measures to reduce the chances of infection and current treatments after being infected with SARS-CoV-2. After that, the rockburst management at LKAB's Kiirunavaara Mine is presented and compared with the COVID-19 management in terms of chain of dynamic interaction from remotely-triggered rockburst, damage mechanism, prevention or mitigation measures as well as treatment. Through the comparison, some suggestions are given regarding how to improve the present rockburst management at the Kiirunavaara Mine.

2 COVID-19 and its management

Coronavirus disease 2019, also known as COVID-19, is a contagious disease caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). Since 2019, the disease has spread worldwide, leading to an ongoing pandemic (Wikipedia 2021).

2.1 Chain of infection

A framework that can help us to understand how COVID-19 infections occur is the 'chain of infection' which describes the sequence of events that must occur in order for an infection to occur, see Figure 1. When considering this framework, envision the links of a chain connected in a continuous circle in which the cycle repeats itself unless or until broken. More specifically, transmission occurs when the agent leaves its reservoir or host through a portal of exit, is conveyed by some mode of transmission, and enters through an appropriate portal of entry to infect a susceptible host (CDC 2012).

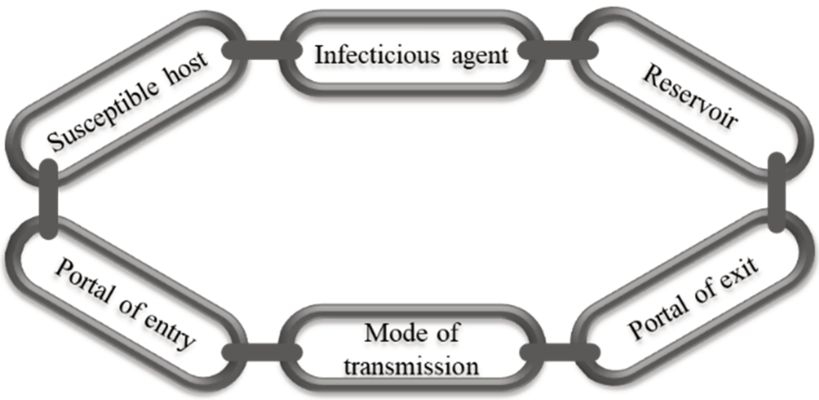


Figure 1 Chain of infection (modified from Robertson et al. (2022))

2.2 Pathophysiology of COVID-19

The severity of the inflammation from COVID-19 can be attributed to the severity of what is known as the cytokine storm. The cytokine storm, also called hypercytokinemia, is a physiological reaction in humans and other animals in which the innate immune system causes an uncontrolled and excessive release of pro-inflammatory signalling molecules called cytokines. Normally, cytokines are part of the body's immune response to infection, but their sudden release in large quantities can cause multisystem organ failure and death (Konstantinos et al. 2020).

During the COVID-19 pandemic, some doctors attributed many deaths to cytokine storms (Mehta et al. 2020; Ruan et al. 2020). A cytokine storm can cause the severe symptoms of acute respiratory distress syndrome (ARDS), which has a high mortality rate in COVID-19 patients (Hojyo et al. 2020). SARS-CoV-2 activates the immune system resulting in a release of a large number of cytokines, including IL-6, which can increase vascular permeability and cause a migration of fluid and blood cells into the alveoli leading to such consequent symptoms as dyspnea and respiratory failure (Konstantinos et al. 2020).

2.3 Preventative measures

The chain of infection is made up of six links. It seems quite complex to investigate and understand the interaction between the links and corresponding influential factors. However, as each link must align in order for an infection to occur, we can stop infections from occurring by breaking just one link in the chain. Preventative measures to reduce the chances of infection include getting vaccinated, staying at home, wearing a mask in public, avoiding crowded places, keeping distance from others, ventilating indoor spaces, managing potential exposure durations, washing hands with soap and water often and for at least 20 seconds, practicing good respiratory hygiene, and avoiding touching the eyes, nose, or mouth with unwashed hands (Wikipedia 2021).

Social distancing (also known as physical distancing) includes infection control actions intended to slow the spread of the disease by minimising close contact between individuals. Methods include quarantines, travel restrictions, and the closing of schools, workplaces, stadiums, theatres, or shopping centres. Individuals may apply social distancing methods by staying at home, limiting travel, avoiding crowded areas, using no-contact greetings, and physically distancing themselves from others. Some governments are now mandating or recommending social distancing in regions affected by the outbreak (Wikipedia 2021).

A COVID-19 vaccine is a vaccine intended to provide acquired immunity against SARS-CoV-2. The vaccine is a biological product that can be used to safely induce an immune response that confers protection against infection and/or disease on subsequent exposure to a pathogen. The COVID-19 vaccines are widely credited for their role in reducing the spread, severity, and death caused by COVID-19 (Wikipedia 2021).

2.4 Current treatments

There is no specific, effective treatment or cure for COVID-19. Thus, the lack of progress developing effective treatments means that the cornerstone of management of COVID-19 has been supportive care, which includes treatment to relieve symptoms, fluid therapy, oxygen support and prone positioning as needed, and medications or devices to support other affected vital organs (Wikipedia 2021). Treatment has been proposed to combat the cytokine storm as it remains to be one of the leading causes of morbidity and mortality in COVID-19 disease.

3 Kiirunavaara Mine

The Kiirunavaara underground mine is located in the city of Kiruna, approximately 150 km north of the Arctic Circle in northern Sweden. The mine, owned and operated by LKAB, has been in operation since 1898 and produces iron ore. The mining method used in the mine is sublevel caving (LKAB 2021). The sublevel height of 29 m is applied at the current mining depth (Level 1108 m).

The orebody of the Kiirunavaara Mine is tabular and more than 4,000 m long, striking almost north–south and dipping 50°–70° towards the east. The width of the orebody varies from a few metres up to over 150 m, but averages around 80 m (Vatcher et al. 2016). The mine is divided into 10 production blocks, named after the Y coordinate in the mine coordinate system, which can be seen in Figure 2. The current main haulage level is at the Level 1365 m.

The main host rock type in the footwall drift is Precambrian trachyandesite (Björnell et al. 2015), which is internally designated as syenite porphyry and subdivided into five categories with average uniaxial compressive strength varying between 140 to 455 MPa (Vatcher et al. 2016). The dynamic support system used in burst-prone areas consists of 100 mm fibre-reinforced shotcrete (40 kg/m^3 steel fibre), 5.5 mm wire diameter welded steel mesh spaced on a grid (or aperture) of 75 × 75 mm, as well as 3.05 m long, 20 mm diameter yielding bolt on a grid of 1 × 1 m.

Since 2007, Kiirunavaara Mine has been identified as a seismically active mine and lots of seismic events occur. It is found that most of the damaging seismic events occurred in the footwall side are near the footwall–ore contact or close to the ore passes (Ylmefors et al. 2022).

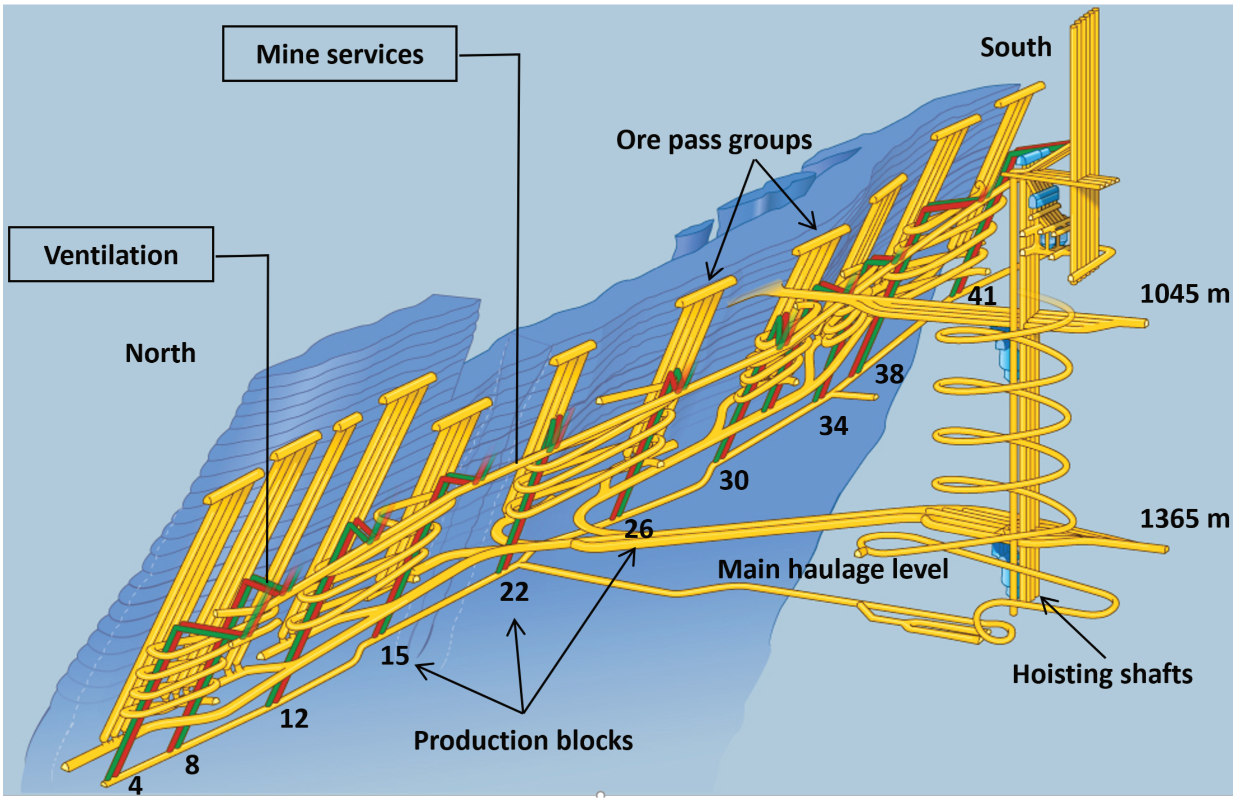


Figure 2 **Sketch of the Kiirunavaara Mine's current main haulage level (Level 1365 m) and associated infrastructures (modified from LKAB)**

4 Rockburst management at Kiirunavaara Mine

A rockburst is defined as damage to an excavation that occurs in a sudden and violent manner and is associated with a seismic event (Kaiser et al. 1996). Rockbursts can be broadly classified according to their genesis as either self-initiated or remotely-triggered (Kaiser and Maloney 1997). Rockbursts triggered by remote, relatively large magnitude seismic events (e.g. fault slip) are a common occurrence in the Kiirunavaara Mine. Therefore, the focus in this paper is placed on the remotely-triggered rockburst.

4.1 Chain of dynamic interaction

For a remotely-triggered rockburst, the damage to excavations normally occurs at some distance from the source, i.e. at a remote target. To manage this type of rockburst, a proper understanding of the seismic source, the wave transmission, and finally the response of the target (the underground excavation and its support) is crucial, which forms a chain of dynamic interaction and is schematically illustrated in Figure 3.

It is known that it is extremely complex to consider the whole chain of dynamic interaction in rockburst management, e.g. the source mechanism of the seismic event, the wave radiation pattern, the refraction and reflection of the seismic waves along the transmission path, the interaction between the seismic waves and excavations, the fractured status of rock mass on wave propagation, as well as the loading mechanism on rock support. Therefore, simplified theoretical equations or empirical charts are used in current rock support design or selection (e.g. Kaiser et al. 1996). Generalised ground motion relationships or scaling laws were developed to capture the effect of attenuation in the ground motion with distance from the source. The scaling laws presented by Kaiser and Maloney (1997) are widely used in determining the peak particle velocity (PPV) and further the kinetic energy of ejected rock blocks or dynamic demand on rock support.

For the sake of simplicity, the site effect due to the interaction between seismic waves and fractured rock mass around the excavation boundary is not considered in the scaling law. The data from field monitoring at Kiirunavaara Mine has indicated that the PPVs near the excavation surface will be amplified due to multiple reflections between fractures during a seismic event (Zhang et al. 2019a). These results are also supported by other researchers (e.g. Durrheim et al. 1996). A chart was proposed with normalised parameters to account for the wave amplification and further calculation of the dynamic demand on rock support (Zhang et al. 2019b).

In short, a rockburst is commonly considered as a failure phenomenon of sudden destruction of the rock mass. Therefore, static analysis by using stress, deformation or energy parameters is usually conducted, where the dynamic interaction between the seismic waves, fractured rock mass, rock excavation and rock support is not considered. In fact, a rockburst, especially a remotely-triggered rockburst, is a dynamic failure process. Therefore, it should be investigated as a process including the chain of dynamic interaction rather than a phenomenon.

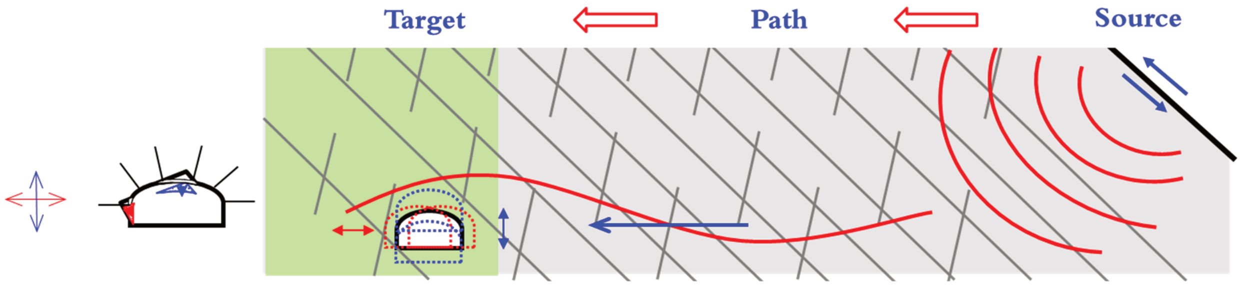


Figure 3 Chain of dynamic interaction illustrated by a remotely-triggered rockburst

4.2 Rockburst damage mechanism

Seismic waves, radiating away from the event (i.e. source), impose dynamic stress changes on already highly stressed rock near an excavation. Seismic energy, released from the seismic source, can transform into kinetic energy for movable blocks. These can lead to local overstressing and fracturing, ejection of rock blocks, as well as rockfall of marginally stable rock. According to Kaiser et al. (1996), the damage mechanisms of rockbursts can be classified into rock bulking due to fracturing; rock ejection due to seismic energy transfer and rockfalls induced by seismic shaking.

Forensic investigations have been conducted onsite at Kiirunavaara Mine after large seismic events (Nordlund et al. 2019). It was found from these investigations that it is extremely difficult to separate the damage mechanisms as defined by Kaiser et al. (1996) for a single damage or rockfall (Krekula 2017). It is quite often that several mechanisms are involved and account for a rockfall. When mining goes deeper at the Kiirunavaara Mine, it seems that the major damage mechanism is also changing (detailed analysis on the damage data is ongoing).

When mining above a certain depth, around Level 1022 m, large rockfalls seem to be caused mainly by seismic shaking, as in many cases the rockfalls are close to the seismic events and controlled by geological structures near the production area where the confinement is low (Nordlund et al. 2019). However, when mining goes deeper, the damage could occur at a certain distance to the seismic source even though the seismic event has similar magnitude as that at shallower levels. The rockfall contains lots of small fragments with thin slabbing geometry and large ejection velocity indicated by the significant long ejection path seems to occur.

Numerical analysis further supports this observation (Zhang & Swan 2020). A fault slip event was simulated by applying a slip velocity of 0.8 m/s on a fault plane. Before the seismic waves reached an excavation, the stresses were concentrated around the excavation boundary and kept the wedges in the roof in place, as can be seen in Figures 4a and 4b. However, after the seismic waves passed the excavation for a certain time (at t = 21 ms in this case) as can be seen in Figure 4c and 4d, the particle velocity near the excavation boundary became higher than 10 m/s. The stress concentration zone moved into a deeper location, which creates a large stress relaxation zone with loose rock mass around the excavation boundary. The movement of rock blocks near the excavation surface became enhanced due to strain energy release in the stress concentration zone near the excavation surface.

Even though the rockfall was still controlled by the geological structures, the released elastic energy stored in the rock near the excavation started to play a vital role on the rockfall, ejection as well as the damage to the rock support. These are called either dynamic-loaded or seismically-triggered strainburst by Kaiser and Cai (2013). In this case, the seismic event is not a driving force instead it becomes a triggering factor.

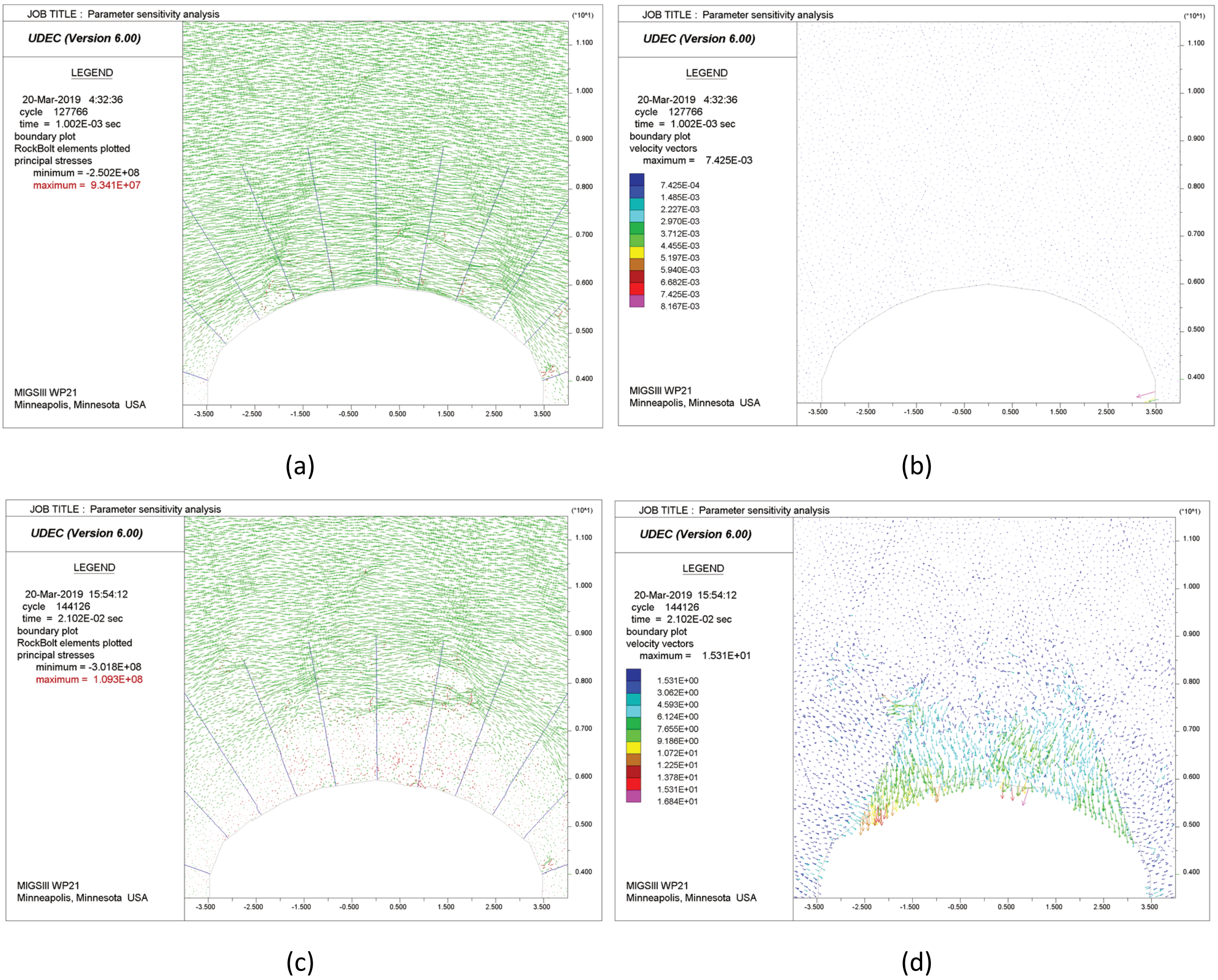


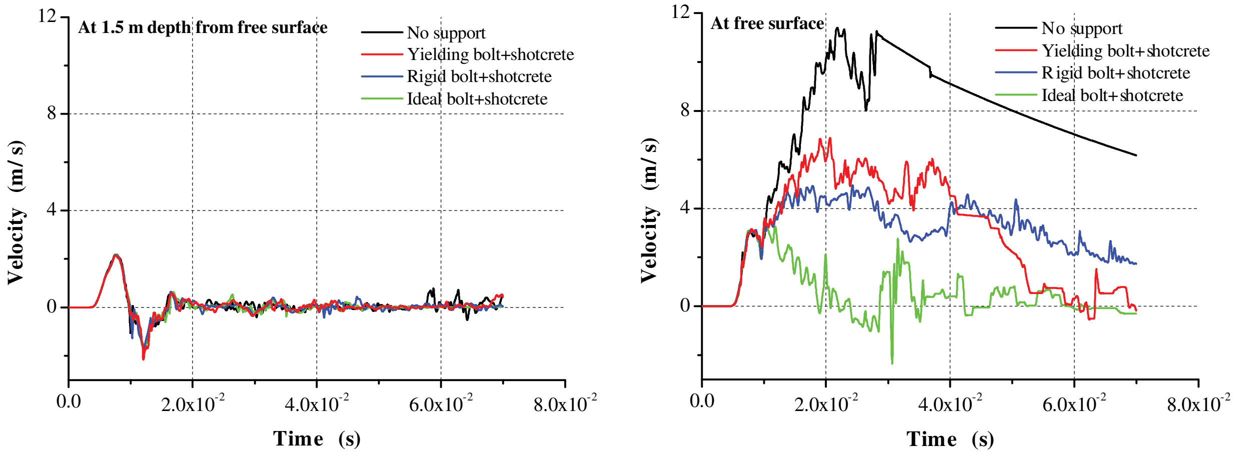
Figure 4 Dynamic response of an excavation roof at *t* = 1 ms and 21 ms after a remote fault slip event. (a) Stress redistribution at *t* = 1 ms; (b) Particle velocity at *t* = 1 ms; (c) Stress redistribution at *t* = 21 ms; (d) Particle velocity at *t* = 21 ms

4.3 Prevention or mitigation measures

Since Kiirunavaara Mine was identified as a seismically active mine, lots of research work has been conducted in order to understand the seismic source mechanism and rockburst damage mechanism. The most practical measure during the early stages at the mine was to find a common line of defence in the mine, i.e. to select a dynamic resistant ground support system.

The effectiveness of different support systems was investigated by using two-dimensional discontinuum models, which can simulate the fracturing, large deformation and ejection of rock (Zhang and Swan 2019). In the numerical models, different rock support systems were tested under dynamic loading conditions. The dynamic response of supported excavations indicated by velocity-time curves at different depths from the free surface in the sidewall are presented in Figure 5.

The numerical simulation indicates that: (i) particle velocity is amplified near the excavation surface due to the interaction of waves with fractures; (ii) particle velocity of rock could be largely reduced by applying ground support near the excavation surface; (iii) rigid bolts could restrain the velocity and displacement during the early stages but could not hold the rock blocks and surface support in place after it is broken; (iv) yielding support could survive from large deformations and keep the broken rock in place; (v) the ideal bolt is functional and behaves the best in terms of limiting the ground motion and movement.



(a) (b)

Figure 5 Dynamic response of a supported excavation indicated by velocity-time curves at different depths from the free surface in the sidewall. (a) At 1.5 m depth from the free surface; (b) At the excavation surface

Even though the dynamic (yielding) support system has been used in the mine, rockburst damage continues to occur as the mining advances deeper. With the occurrence of several large seismic events (e.g. the 18 May 2020 event with moment magnitude of 4.2), it was realised that it is impossible to rely on only the dynamic support system to combat large magnitude seismic events, and measures from all mining-related aspects needed to be investigated in order to mitigate the rockburst risk.

A number of measures have been initiated, some of them are still under investigation including reducing exposure of personnel by establishing a closing and reopening criterion (Dineva et al. 2021), changing the mining method (e.g. raise caving (Wimmer 2021)), improving the mine layout (Quinteiro 2018), optimising the extraction sequences (e.g. Zhang et al. 2021), as well as de-stressing the rock mass under highly stressed conditions by using both hydraulic fracturing (Kristina & Patricia 2018) and de-stress blasting techniques (Zhang 2021) at both large and small-scales. Due to limited space, these studies are not presented in this paper, but interested readers can find the details in the referred publications.

4.4 Treatment

If an underground excavation has to be placed under 'seismically active areas', the probability of rockburst occurrence could be high. Rockburst damage can be classified as minor, moderate and major according to its severity (Kaiser et al. 1996). When an area has experienced a large magnitude seismic event (e.g. local magnitude 1.5), the most common engineering treatment is to inspect the site and then conduct rehabilitation if damage has occurred. Most damage inspection is conducted through visual investigation, e.g. fracturing in shotcrete or rock, damage at the bolt thread, mesh wires and connections, rock ejection, rockfall etc. When damage has occurred, the site needs to be temporarily closed and then rehabilitation needs to be conducted. Scaling of dangerous rock and the application of extra ground support including bolt-shotcrete arches is usually conducted during the rehabilitation at Kiirunavaara Mine. The purpose of applying the ground support is not to carry the load from the rock but to help the rock to mobilise its own loading capacity, e.g. by creating a pressure arch.

5 Discussion

5.1 Similarity

As can be seen from the text above, the chain of infection from COVID-19 and the chain of dynamic interaction from remotely-triggered rockburst is similar. They both include three critical components: source, path and target and interaction between the components is also similar. In addition, the pathophysiology of COVID-19 and the rockburst damage mechanism for hard rock at great depth (i.e. triggered or dynamically loaded strainburst) is also similar between COVID-19 and remotely-triggered rockburst.

For COVID-19, because of the overreaction of our immune system, it makes the symptom more severe and difficult to control. For triggered or dynamically-loaded strainburst, the seismic event becomes a triggering factor. It is the strain energy stored in the rock around excavations which makes the damage more severe and violent.

5.2 Improvement of the rockburst mitigation strategies

One of the important measures regarding COVID-19 prevention is to break the chain of infection. Thinking about the similarities between COVID-19 and remotely-triggered rockburst, in terms of the chain of infection from COVID-19 versus the chain of dynamic interaction from remotely-triggered rockburst, the borrowed idea is to check if it is possible to break the chain of dynamic interaction in order to prevent the rockburst or reduce the potential rockburst damage.

5.2.1 Creating the excavation as late as possible

According to other mine's experience, when mining at great depth, it is suggested to delay the development of the excavations to avoid sudden and violent failure. Due to the mining method used at Kiirunavaara Mine, the main haulage level (Level 1365 m), media levels (e.g. Level 1165 m, 1252 m) as well as orepass groups have to be developed before mining starts below 1,045 m. However, the sublevels are developed before the production reaches the corresponding depth in order to get everything prepared. Usually, the footwall drifts at sublevels are developed three to even four levels below the production.

As we know, staying at home during COVID-19 is very helpful to avoid the spreading of the virus and further infection on healthy people. Using the similar concept, if the sublevels could be developed later, the seismicity will have negligible effect on the rock mass as the rock blocks are under confined conditions and have no free space to move or be ejected. Additionally, by developing the sublevels later, the mining-induced stress changes could cause the yielding of rock mass one to two levels below the production. Mining in yielded ground is a proven method to reduce rockburst risk (Simser 2019).

5.2.2 Safe distance for infrastructure

Because of the unseen impact of social distancing and isolation on our mental health and emotional wellbeing, as well as the economic effect on society, people are allowed to be out of home unless the outbreak of COVID-19 occurs. However, governments and their respective health agencies also recommend people should stay at least six feet away from other people. The physical distancing seems to be functional to help people avoid getting sick and to 'flatten the curve' in the spread of COVID-19.

At Kiirunavaara Mine, the footwall drifts are located close to the footwall-ore boundary. The typical distance is about 10–30 metres. As the average orebody thickness is around 80 m, the stresses at the footwall drift are highly affected by mining activities. The reason why the footwall drifts and ore passes are placed so close to the footwall-ore boundary, is because by the time the main haulage level was designed the mine had not experienced large seismic events.

A dynamic numerical study was conducted to find an optimum distance for placing the infrastructure. Six cases were investigated by placing a drift at two different sublevels (1108 m and 1365 m) with different stress conditions and three different distances to the footwall-ore contact (20 m, 90 m and 200 m). The seismic source was assumed to occur at the footwall-ore contact and had the same magnitude for all cases.

The stresses applied on the drift were obtained from a 2D mine-scale global model considering the effect of the production front. The interaction between the seismic event and supported excavation was investigated by using a discontinuum model. It was found that the maximum roof displacement and number of broken bolts decreases with increasing distance, i.e. from Case 1 to Case 3 with an intermediate stress condition, and Case 4 to Case 6 with high stress conditions as can be seen in Figure 6. This trend becomes significant when material damping was considered in the models.

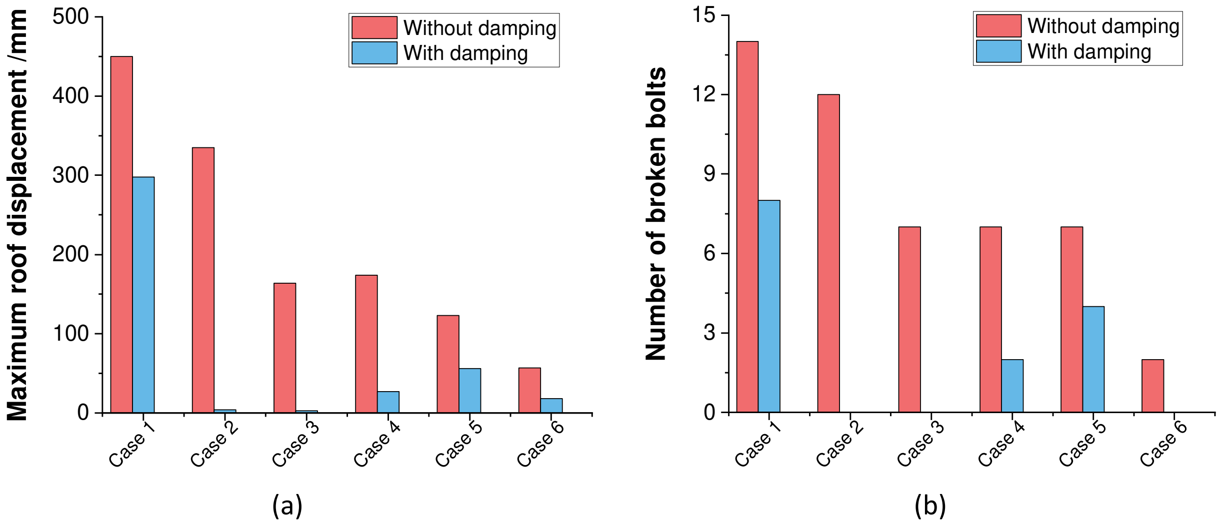


Figure 6 Drift response at different distances to footwall-ore boundary. Drifts are located at 20 m, 90 m and 200 m away from the footwall-ore boundary at Level 1108 m in Cases 1, 2 and 3, and at Level 1365 m in Cases 4, 5 and 6. (a) Maximum roof displacement; (b) Number of broken bolts

5.2.3 De-stressing

Vaccines are proved to be powerful for preventing COVID-19. One of the reasons why a vaccine is working is because it could reduce the cytokine storm or abrupt the response of our immune system to the virus attack.

The hazard associated with mine seismicity generally increases with stress, which in turn increases with depth. When going deeper, the in situ stresses together with the mining-induced stress changes will become high. Hard rock becomes burst-prone due to high stresses around the excavations and high strain energy stored in the surrounding rock. If the rock could be made softer, the strain energy might not be so high and hence failure will not be so sudden and violent.

Numerical simulation indicates by creating a loose zone around the excavation boundary, it is possible to reduce the maximum roof displacement and number of broken bolts after a seismic event. This can be seen in Figure 6 from the results in Cases 4–6 for high stress conditions, where the large loose zone was created around the excavation boundary, in comparison with Cases 1–3 where stresses were concentrated around the excavation boundary. The reason for this difference is because the loose zone with broken rock around the excavation boundary could attenuate the seismic waves and provide confinement for inner solid rock and hence to avoid sudden failure and strain energy release.

Based on the studies, it is thought by using de-stressing techniques to create a loose zone around the excavation boundary might be a solution to reduce the burst potential of rock and further avoid a rockburst incident from occurring. How to create a loose and soft zone around excavation boundary with appropriate dimension is still under investigation.

5.2.4 Rehabilitation

Rehabilitation is an important measure to avoid further damage from future seismicity nearby. In general, stressed rock around an excavation boundary, after experienced large seismic event, usually becomes less burst-prone due to strain energy release and stress redistribution around the excavation. This is quite similar as infected people by SARS-CoV-2 virus. Most probably, they are immune to the second infection. Therefore, when rehabilitation is conducted, it is important to identify the status of the rock mass and the loading conditions.

If the rock mass is less fractured and still under a high stress loading condition, a yielding support system should be adopted to manage large and sudden deformation. Otherwise, if the rock mass is already fractured and loose, a rigid support system should perhaps be used instead to help the rock mobilise its own loading capacity, e.g. by creating a pressure arch.

6 Conclusion

In summary, by reviewing the chain of infection and pathophysiology of COVID-19, as well as the chain of dynamic interaction and rockburst damage mechanism of remotely-triggered rockbursts, the similarity between coronavirus infection and remotely-triggered rockburst is identified.

The various preventative measures to reduce the chances of infection and current treatments after being infected with SARS-CoV-2 are gone through. After that, the rockburst management at LKAB's Kiirunavaara Mine is presented and compared with the COVID-19 management in terms of damage mechanism, prevention or mitigation measures as well as treatment.

Through the comparison, some suggestions are given regarding how to improve the present rockburst management at the Kiirunavaara Mine. It is suggested that the chain of dynamic interaction (disturbance) could be broken by: (i) creating the excavation as late as possible in the mine, (ii) locating the infrastructure at least 90 m away from the footwall-ore contact considering the highest local magnitude event (i.e. 1.9 in these studied cases) as well as (iii) using de-stressing technique to create a loose zone around the excavation boundary and push the stressed area further away. A yielding support system should be used to accommodate large deformation of fractured rock and keep the loose rock in place. The purpose of applying the ground support is not to carry the load from the rock but to help the rock mobilise its own loading capacity, e.g. by creating a pressure arch.

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References

Björnell, T, Andersson, UB, Eriksson, P, Faber, M & Larsson, CF 2015, 'Structural mapping and 3-D photographing, in and around block 34, levels 1079–1137, in the Kiirunavaara Mine', *LKAB investigation 15–820*, 89 p.

Boskovic, M, Swedberg, E, Aarnio, C, Andersson, U, Töyrä, J, Mäkitaavola, K, Stöckel, BM, Dahner-Lindkvist, C, Dineva, S & Mozaffari, S 2020, 'Seismic event 2020–05–18 – Analysis report', *Internal report*, 52 p.

CDC (Center for Disease Control and Prevention) 2012, *Principles of epidemiology in public health practice*, 3rd edition, https://www.cdc.gov/csels/dsepd/ss1978/SS1978.pdf

Dahner, C, Malmgren, L & Boskovic, M 2012, 'Transition from non-seismic mine to a seismically active mine: Kiirunavaara Mine', *Proceedings of Eurock 2012*, 11 p.

Dineva, S, Erguncu Guclu, I, Mihaylov, D, Dahner-Lindkvist, C, Törnmann, W, Boskovic, M, Wimmer, M, Nyström, A & Mozaffari, S 2021, 'Development of criteria for closing/reopening of mine areas due to seismic risk', *Internal report*, 93 p.

Durrheim, RJ, Kullmann, DH, Stewart, RD & Cichowicz, A 1996, 'Seismic excitation of the rock mass surrounding an excavation in highly stressed ground', in M Aubertin, F Hassani & H Mitri (eds), *Proceedings of the 2nd North American Rock mechanics symposium*, Balkema, Rotterdam, pp. 389–394.

Hojyo, S, Uchida, M, Tanaka, K, Hasebe, R, Tanaka, Y, Murakami, M & Hirano, T 2020, 'How covid-19 induces cytokine storm with high mortality', *Inflammation and Regeneration*, vol. 40, no. 37, p. 37.

Johns Hopkins University & Medicine, 2022, 'Johns Hopkins University's COVID-19 map', https://coronavirus.jhu.edu/.

Kaiser, PK & Cai, M 2013, 'Critical review of design principles for rock support in burst-prone ground – time to rethink', in Y Potvin & B Brady (eds), *Ground Support 2013*, Australian Centre for Geomechanics, Perth, pp. 3–37.

Kaiser, PK & Maloney, SM 1997, 'Scaling laws for the design of rock support', *Pure and Applied Geophysics*, vol. 150, pp. 415–434.

Kaiser, PK, McCreath, DR & Tannant, DD 1996, *Canadian rockburst support handbook*, Geomechanics Research Centre, Sudbury, 300 p.

Konstantinos, F, Anastasia, B & Raymond, N 2020, 'Systematic review of the prevalence of current smoking among hospitalized COVID-19 patients in China: Could nicotine be a therapeutic option?', *Internal and Emergency Medicine*, vol. 15, no. 5, pp. 845–852.

Krekula, S 2017, 'Evaluation of the rock support system subjected to dynamic loads in Kiirunavaara', *M.Sc thesis*, Luleå University of Technology, Sweden, 146 p.

Kristina, J & Patricia, BG 2018, 'Hydraulic fracturing trials in LKABs mines in Kiruna and Malmberget', *Bergmekanikdagen*, Stockholm, March 20, 115–124.

LKAB 2021, https://www.lkab.com/en/

Mehta, P, McAuley, DF, Brown, M, Sanchez, E, Tattersall, RS & Manson, JJ 2020, 'COVID-19: consider cytokine storm syndromes and immunosuppression', *Lancet*, vol. 395, no. 10229, pp. 1033–1034.

Nordlund, E, Zhang, P, Dineva, S, Nordström, E, Mihaylov, D, Botelho, A, Hansen-Haug, J, Woldemedhin, B, Boskovic, M, Töyrä, J, Andersson, U, Nyström, A, Mozaffari, S & Petersson, A 2019, 'Development of a new methodology for evaluating rock support performance in seismically active mines (ERSP)', *Internal Report*, Luleå University of Technology, Sweden, 178 p.

Quinteiro, C 2018, 'Design of a new layout for sublevel caving at depth', in Y Potvin & J Jakubec (eds), *Caving 2018: Proceedings of the Fourth International Symposium on Block and Sublevel Caving*, Australian Centre for Geomechanics, Perth, pp. 433–442, https://doi.org/10.36487/ACG_rep/1815_33_Quinteiro

Ruan, Q, Yang, K, Wang, W, Jiang, L & Song, J 2020, 'Clinical predictors of mortality due to COVID-19 based on an analysis of data of 150 patients from Wuhan, China', *Intensive Care Medicine*, vol. 46, no. 5, pp. 846–848.

Robertson, L, O'Toole, JA & Evans, N 2022, 'COVID-19 pandemic: A world in turmoil', https://www.atrainceu.com/content/281-covid-19-how-what-when-where-course-intro.

Simser, BP 2019, 'Rockburst management in Canadian hard rock mines', *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 11, pp. 1036–1043.

Vatcher, J, McKinnon, SD & Sjöberg, J 2016, 'Developing 3-Dmine-scale geomechanical models in complex geological environments, as applied to the Kiirunavaara Mine', *Engineering Geology*, vol. 203, pp. 140–150.

Wikipedia, 2021, 'COVID-19 pandemic', https://en.wikipedia.org/wiki/COVID-19_pandemic.

Wimmer, M 2021, 'Heading towards great depths', *Presentation at Euro Mine Connect Conference*, June 1–3, 2021.

Ylmefors, A, Zhang, P & Mozaffari, S 2022, 'Classification of mining induced seismicity at the Kiirunavaara Mine', *RaSiM10: Proceedings of the Rockbursts and Seismicity in Mines Conference*, Society for Mining, Metallurgy, and Exploration, Englewood, 14 p.

Zhang, P 2021, 'Destressing strategies for mining under highly stressed conditions in the deep mines of Sweden', *Project presentation at Swedish Mining Innovation Program Day*, Digital event, Oct 5.

Zhang, P, Botelho, A, Dineva, S & Woldemedhin, B 2019a, 'Field monitoring seismic response of underground excavations and rock bolts at Kiirunavaara underground mine', in SAB da Fontoura, RJ Rocca & JP Mendoza (eds), *Proceedings of the 14th International Congress on Rock Mechanics and Rock Engineering (ISRM 2019)*, CRC Press, pp. 1372–1379.

Zhang, P, Nordlund, E, Swan, G & Yi, CP 2019b, 'Velocity amplification of seismic waves through parallel fractures near a free surface in fractured rock: A theoretical study', *Rock Mechanics and Rock Engineering*, vol. 52, no. 1, pp. 199–213.

Zhang, P, Ma, X, Dahnér-Lindkvist, C, Boskovic, M & Töyrä, J 2021, 'Developing a numerical tool to optimise mining sequences and minimize seismic hazard using mine stiffness concept', *Internal report*, Vinnova project (OPMS, 2018–04616).

Zhang, P & Swan, G 2019, 'Evaluation of rock support response/effectiveness in deep mines under seismic conditions (Stages I – II)', *Final Report, MIGS II (WP13)*, 54 p.

Zhang, P & Swan, G 2020, 'Evaluation of rock support response/effectiveness in deep mines under seismic conditions (Stages III – IV)', *Final Report, MIGS III (WP21)*, 62 p.