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Test mining with raise caving mining method: one-time chance to prove the concept?

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Abstract

Raise caving is a novel mining method, which is based on the raise mining method. Raises play a central role in the method and are utilised for different purposes. In the de-stressing variant, raise caving, the de-stressing slots are created first in a so-called de-stressing phase. The de-stressing slots have a tabular shape, and their objective is to provide stress shadows for mining activities in the subsequent production phase.

To prove the concept and provide input parameters for a feasibility level evaluation, a limited scale trial is required.

Located at the depth of LKAB's Kiruna mine in Sweden (a +25 Mtpa underground, sublevel caving (SLC) iron ore mine), the raise caving test site will be constructed in deeper parts of the mine, in an area partially prepared for SLC but mining not yet initiated. Geotechnical investigations and numerical modelling preceding development work are underway with first de-stressing raise scheduled for early 2023. Mining activities and consequent preliminary method evaluations are due during 2023–2024 with the final, a feasibility level, study to be completed by the end of 2025.

The site selection process focused on locating a site that is, in key aspects, comparable with the future mining environment in the deeper parts of the mine. These are rock stress (direction and magnitude), geology and geotechnical properties. Additional aspects assessed were absence of major weakness zones, minimised negative impact for mine's performance and life-of-mine (LOMP), and relatively rapid execution of the test site construction. Both Malmberget and Kiruna mines were considered as potential sites.

During the extraction of the pillar at the test site, the behaviour and condition of the pillar is continuously monitored. Other aspects to be evaluated are the feasibility to work in high stress environments during de-stressing slot development (tunnelling, raiseboring, longhole drilling), during mucking waste rock dilution entry, ore flow and ore recovery rate from a single-level mucking location.

When proven successful, the raise caving can contribute to a safe and cost-effective alternative mining method in high stress environments.

This paper describes steps taken in selection of a test site and integration with mine production activities.

Keywords: *raise caving, raise mining, trial, de-stressing, yielding pillars*

1 Introduction

Raise caving is a novel mining method, which is based on two applied and proven technologies, namely:

- Modern raise mining method.
- Active stress management.

Depending on the prevailing mining environment, two different variants can be distinguished: a de-stressing variant and a block caving variant. A detailed description of the raise caving method, its variants, its advantages, key issues and conducted research and development is given by Ladinig et al. (2021, 2022a).

Furthermore, a paper submitted for the conference provides additional background information on the raise caving method (Ladinig et al. 2022b). The following section provides a brief description of the de-stressing variant, which concentrates on relevant aspects for the present paper, namely the active stress control approach and the corresponding slot-pillar system.

1.1 De-stressing variant of raise caving

The de-stressing variant addresses deep and high stress situations with an active, foresighted approach. The objective of the de-stressing variant is to tackle potential sources of rock pressure problems by their roots. In practice, this means that high stress areas and seismically active areas are constrained to zones where active mining activities do not take place. Moreover, the stress magnitudes and seismic energy release in and near active mining areas and active infrastructure are limited so that damage is avoided. The mine layout and mining sequence are critical for this active stress management.

LKAB mines have been experiencing rock pressure problems at current mining depths for more than a decade. These rock pressure problems have been causing operational and safety issues. Experienced rock pressure problems are outlined and analysed for example by Dahnér et al. (2012), Krekula (2017), and Dahnér & Dineva (2020). As LKAB plans to advance its mines to even greater depths, the de-stressing variant of raise caving is considered and investigated as a possible method. The main motivation for this is the offered active stress control approach and the highly efficient raise mining technology, which enables to keep mining costs at a low level.

The de-stressing variant can be divided into two phases, namely a de-stressing phase and a subsequent production phase. Figure 1 provides an overview of the raise caving method, showing mining advances from left to right.

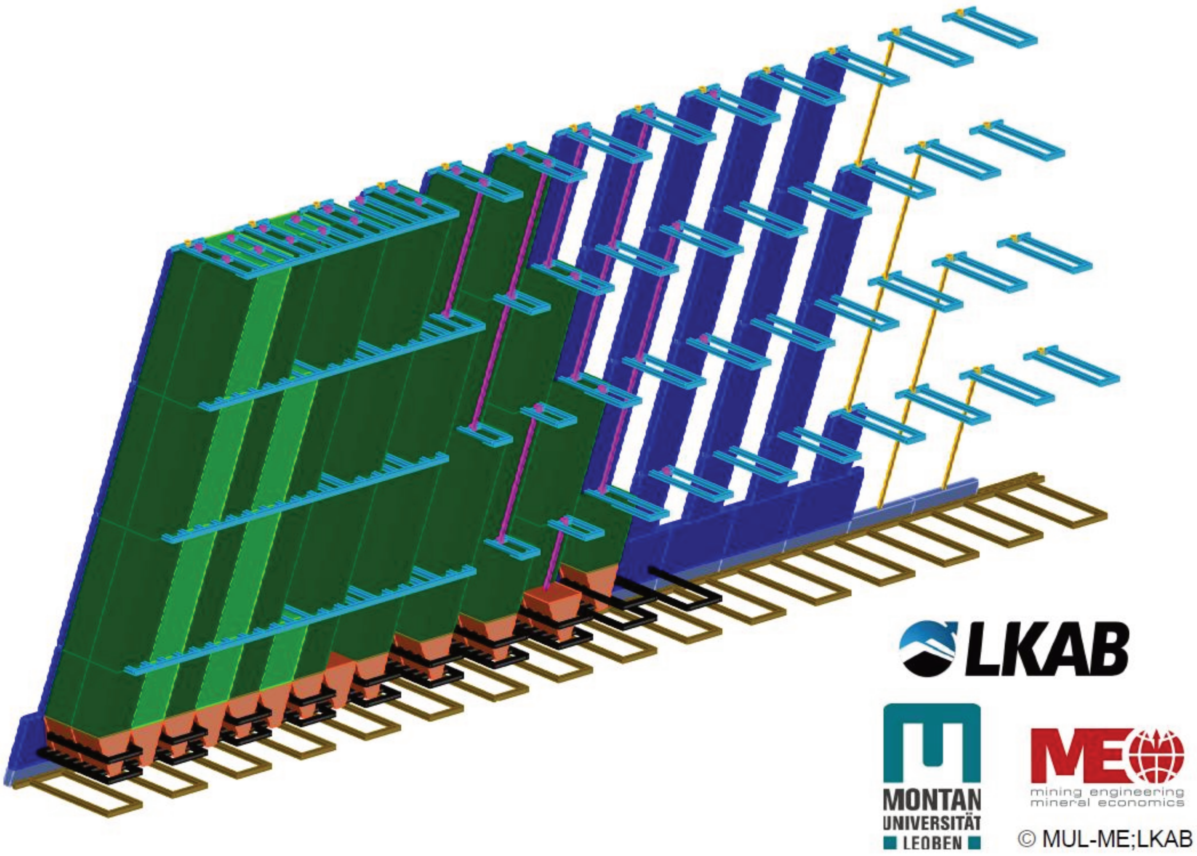

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Figure 1 Schematic layout of the de-stressing variant of raise caving in a steeply dipping, thick tabular deposit (Ladinig et al. 2021)

1.1.1 De-stressing phase

In the de-stressing phase, a slot-pillar system is established. In Figure 1, the de-stressing phase is situated at the right-hand side. Slots are dark blue, massive pillars between slots are left blank, slot raises are yellow, and levels used for slot development are brown and light blue. The purpose of the slots is to provide stress shadows for later developed infrastructure in the production phase and the purpose of pillars is to control the stress situation and seismic energy release near active infrastructure, mainly raises, which is required for the creation of de-stressing slots. In order to fulfil their purpose, the pillars are highly stressed, and they must be able to withstand these high stresses. Therefore, these pillars have a high effective width-to-height ratio typically exceeding 10. The pillar width is the pillar extension in strike direction, the pillar length is the pillar extension in dip direction and the (effective) pillar height is the pillar extension perpendicular to pillar width and pillar length, which is approximately in transverse direction for the steeply dipping pillars. This terminology is used as the pillar extension in approximate transverse direction has a similar effect on pillar strength and behaviour as the height (vertical extension) for pillars being oriented horizontal. The dimensions, geometry and orientation depend on the prevailing mining environment, especially the deposit geometry, the rock mass conditions and the stress situation. Current investigations on the slot-pillar system yield that cross-sections of slots and pillars will be in the range of 30–70 m (strike extension) × 5–10 m (transverse extension) and the dip extension of slots and pillars can be several hundred metres. At LKAB mines it is planned to create the slot-pillar system at the hangingwall contact and to arrange slots and pillars in strike direction, because this position and orientation provide the best de-stressing effect and still enable to install a high capacity access and transportation system in the orebody and the footwall.

1.1.2 Production phase

In the production phase, large-scale mineral extraction commences. In Figure 1 the production phase is situated at the left-hand side. Production raises are pink, large drawbells are orange, stopes behind slots are dark green, stopes in pillars are light green, production level infrastructure is black and further required infrastructure is light blue. Further main and primary infrastructure, such as ore passes, ramps or hoist tunnels, as well as progressing hangingwall caving are not shown for overview reasons. Large stopes with cross-sections in the range of 35 × 35 m to 50 × 50 m are extracted. Initially, stopes are only mined behind slots, where production raises utilised for stope extraction can be situated in de-stressed ground provided by slots. Stopes are extracted from production raises in upwards direction by blasting the roof slice by slice. After each blast only the swell is mucked from the stope to provide sufficient free volume for the next blast. Hence, the stope is always filled with blasted rock mass, which provides some support to stope walls. Once blasting of a stope finished, it is drawn empty. Hangingwall is allowed to cave and fills up the stope while it is drawn empty. After stopes behind slots were mined, all or a portion of pillars are extracted with stopes in the same steps. Important for pillar extraction is that the extraction of stopes behind slots has a significant effect on pillars, namely the pillar dimensions are changed. Principally, the effective pillar width-to-height ratio is decreased considerably and, depending on the deposit thickness, the effective width-to-height ratio may fall even below 1. Consequently, pillars are overloaded and crush. As a result of pillar crushing, the stresses in the pillar reduced and pillars become de-stressed, regional abutments develop near stoping areas and regional energy changes and the associated release of seismic energy occur. As pillars are de-stressed, they can also be extracted at this point.

2 Proving the concept of raise caving

As highlighted in the beginning, the raise caving method is based on the existing and applied technologies of an active stress management and of modern raise mining. However, the specific combination of these two technologies is novel. Furthermore, the active stress management approach has not been applied on a comparable scale in steeply dipping tabular deposits or in massive deposits where stresses in horizontal direction need to be blocked. Accordingly, in situ experience is not available and the raise caving method must be thoroughly developed, engineered and tested to reduce the risk associated with the introduction of a new method as far as possible and to an acceptable threshold. A comprehensive research and development project has therefore been set up. Within this project, proving the concept of raise caving will be critical for a successful method development and for a potential future application of raise caving. The reason for this is to reduce the risk, which is associated with a new method, and to gain confidence and acceptance for the method at an operational, engineering and management level. Three different approaches for proving the concept are conducted:

- Experience from and site visits to other mines.
- Desktop studies.
- In situ tests.

These three approaches are discussed below respective the active stress management approach and the raise mining technology of raise caving. Regarding the raise mining technology, the emphasis is on the development of a highly automated or remote-controlled machinery, which is central for applying modern raise mining.

2.1 Experience from and site visits at other mines

One of the easiest and cheapest available sources for proving the concept are experiences from and visits to other mines. Specific site visits have been conducted and experience has been shared with rock engineers and mining engineers. Site visits to deep South African gold mines showed that an active stress management is state-of-the-art in these mines and that it offers significant advantages in deep mining. However, the layouts and sequences used in deep South African mines are principally tailored to the prevailing narrow reef mining environment; compare Jager and Ryder (1999). These layouts and sequence and the non-mechanised mining technology are generally not comparable to and applicable in raise caving. An exception is South Deep mine, where a reef package is mined with large-scale stoping methods, which are applied in parts of the deposit that were de-stressed before by horizontal de-stress cuts; compare Watson et al. (2014) and Andrews et al. (2019). The utilised layouts and sequences of South Deep mine come closest to raise caving. However, there are still considerable differences; amongst others, the span of de-stress cuts, the role and function of pillars and the position of infrastructure utilised for developing the de-stressing cuts.

In summary, mining experience highlights that active stress management works and that it is advantageous. However, the currently applied layouts and sequences are generally not comparable to the raise caving situation. Hence, experiences from other mines are not suited for proving the full concept of raise caving sufficiently.

2.2 Desktop studies

Desktop studies are central in the raise caving development project. These studies comprise analyses of the local and regional stress distribution and stress changes as mining progresses, investigations related to energy changes and mining-induced seismicity, analyses of infrastructure, stope and slot stability, studies of ore flow and hangingwall caving, and the development of machinery. Utilised methods are manifold and comprise conceptual considerations, empirical and semi-empirical methods, analytical methods, laboratory modelling, numerical modelling and back-analyses. Whilst all of these investigations and methods are useful and required for the overall development of the method which is, more specifically, the design of an implementable layout and sequence of raise caving in LKAB mines, they are generally not suitable to prove the full concept in practice, because all of these studies are either based on mining experience in a different extraction situation, namely a sublevel caving environment, or based on mining experience in mines outside LKAB or based and dependent on assumptions regarding the strength and behaviour of the prevailing rock mass and the prevailing stress state. Of particular relevance are the uncertainties associated with the rock mass strength and behaviour, because the rock mass strength and behaviour of hard rock masses is largely unknown, but its impact on the overall raise caving system is large, especially on the strength and behaviour of pillars. A further disadvantage of desktop studies is that they may not be accepted by mining personnel, mine management and high-level management as a sufficient proof of concept, especially because of a lack of in situ experience with the raise caving method.

2.3 In situ tests

In situ tests are an option to overcome the drawbacks of the other two options for proving the concept of raise caving. The reasons for this are that in situ tests allow to replicate and simulate specific aspects of the raise caving method or the full raise caving system and that in situ tests can be conducted in a mining environment in which the raise caving method is potentially applied in future. Accordingly, data and experience on key issues of the method can be collected during these tests too. However, in situ tests have the disadvantage that they are costly, that they may cause interruption and disturbance to the regular extraction activities and that they are associated with risk, particularly in case of unforeseen and unplanned developments in the test area. Risks comprise for example loss of reserves, disruptions to ongoing production and safety hazards resulting from test activities. Hence, in situ tests shall be utilised only for aspects that are critical and cannot be proven sufficiently with above-outlined options. Furthermore, for the design of an in situ test, the reduction of associated risks is of utmost importance.

2.3.1 Need for in situ tests for the development of raise caving method

The need for in situ tests of the raise caving method was identified early in the development project because experiences from other mines and desktop studies do not allow to prove the full concept of raise caving and they do not allow designing an implementable layout and sequence of raise caving, particularly because of inherent uncertainties in respective rock mass strength and behaviour. In order to overcome these issues, LKAB took the decision to conduct full-scale tests of two aspects of raise caving, which require in situ tests for proving the concept and for generating data and experience. These aspects are:

- The active stress management approach.
- The automated and remote-controlled machinery.

This paper emphasises the in situ test of the active stress management approach, which is within the project referred to as the ‘mining method test site’. The background of the test site, its objectives, the ongoing design work, planning and scheduling of the test site in the operating sublevel cave and risks are highlighted and discussed. The test site for the machinery is not included in this paper because it is completely separated from the mining method test site. The reason for this was to reduce the risk in the mining method test site, which would be introduced by a novel machinery, which is under development.

3 Mining method test site

3.1 Objective

The mining method test site has two main objectives, which are mostly related to rock engineering aspects, namely:

- To demonstrate the applicability and advantages of an active stress management approach (proof of concept).
- To generate and deliver experience and data on key issues of the active stress management approach in raise caving.

Both objectives are important for the development of raise caving. The first objective targets an overall level, namely the successful utilisation of an active stress management approach in a steeply dipping, thick tabular deposit. This proof of concept is not only important for the general evaluation of the potential of the raise caving method, but it is important to reduce risk, to remove doubts and to convince mining personnel, mine management and high-level management of the raise caving method. The second objective is more specific for the ongoing research and development activities around raise caving. The generated data and experience will be required and central for the method development.

Concluding, a successful trial in the test site is considered decisive for the method development. A failure of the test could be a major drawback for the raise caving method. Either the concept of raise caving does not work or acceptance from mining personnel, local mine management or senior management may be lost, and the development of the method stopped. Hence, careful planning and design of the test site and reduction of risks associated with the test site are of paramount importance.

3.2 Required tests related to the active stress management approach

Central for the active stress management approach is the slot-pillar system, which is established in the de-stressing phase and which is altered in the production phase. Slots provide stress shadows for production infrastructure and stopes. Pillars control the stress situation and energy release in the de-stressing phase and in the production phase pillars need to be crushed before they can be extracted. Pillar crushing must be stable to ensure safe working conditions. This role of pillars is special, delicate and central for the success of the de-stressing variant of raise caving. Hence, their role is highlighted and discussed further, before outlining the required tests in the test site.

3.2.1 Importance of pillars in the slot-pillar system

The massive pillars in the slot-pillar system are identified as being decisive for a successful application of the de-stressing variant of raise caving; compare Ladinig et al. (2021, 2022a, 2022b). In the de-stressing phase, these pillars must be able to transfer considerable stresses to enable the safe extraction of de-stressing slots. Hence, pillars are highly stressed and pillars store significant amounts of energy. However, in the production phase at least some of these highly stressed pillars must be extracted to enable a reasonable extraction ratio.

The central question related to pillars is whether massive, highly stressed pillars can be extracted in a safe manner in the production phase. This question is strongly related to the strength and stress–strain behaviour of pillars because the peak strength of pillars needs to be exceeded and pillar crushing must be initiated to de-stress pillars sufficiently for their later extraction. Moreover, the stoping activities have a marked effect on the pillar geometry and thus on pillar strength and pillar behaviour. Hence, pillar overloading and crushing are likely to occur as a result of the extraction of stopes behind slots and the option of leaving the massive pillars, for which it is ensured that their strength is not exceeded, does most likely not exist. Decisive is that the pillars remain in a stable state during this overloading and crushing phase, which implies that a sudden violent failure of the pillar, namely a pillar burst, does not occur.

The pillar issue above is aggravated by the instance that there is very limited to no experience available related to it. The reasons for this are a lack of knowledge of the strength and stress–strain behaviour of pillars with dimensions in raise caving and a lack of knowledge of crushing massive, highly stressed pillars (Ladinig 2022). Hence, investigating the strength and stress–strain behaviour of pillars of large dimensions and the crushing behaviour of such pillars is of utmost importance for the de-stressing variant of raise caving. Of equal importance is the integration of pillar crushing and extraction design into the regional mine design.

Concluding, the established research and development project on raise caving must address this demand on pillar strength and pillar stress–strain behaviour. Due to the complex nature of pillars, desktop studies are not able to cover the open points respective to pillars sufficiently. Hence, in situ tests on pillars are necessary. Besides pillars, the de-stressing effect, raise stability, mining-induced seismicity and regional stress changes shall also be tested to meet the test site objectives.

3.2.2 Tests related to pillar strength and stress–strain behaviour

As outlined above, knowledge of the strength and the stress–strain behaviour of pillars is of paramount importance for the implementation of the active stress management approach in the de-stressing phase as well as the continuation of the active stress management approach in the production phase. The knowledge of pillar strength and behaviour of pillars with dimensions, which are required in the raise caving method, is furthermore limited. Thus, it was decided to conduct tests on pillars in the test site. These tests should help to improve the knowledge of the strength and stress–strain behaviour of pillars as well as to improve the knowledge of pillar behaviour and response during pillar crushing in the production phase. Moreover, the fracture patterns, which are created during pillar crushing, are of interest for the production raise stability and thus they are observed. Due to the importance of pillars, the pillar tests are considered to be of highest priority.

3.2.3 Tests related to the de-stressing effect

The active stress management approach aims at providing stress shadows for mining activities. The positive effect of these stress shadows on infrastructure stability (and the therefrom conducted mining activities) is of interest and is investigated in the test site. Furthermore, the stress state in the stress shadow and the spatial extent of the stress shadow are of interest. The stress shadow differs in the de-stressing phase, where stress shadows are situated behind slots and where the stress shadows are of comparatively small extent, and the production phase, after pillars crushed or after pillars were extracted, where the stress shadows can be of rather large spatial extent. Showing the positive effect of stress shadows can further improve the confidence in the active stress management approach.

3.2.4 Tests related to raise stability

Raises are central in the de-stressing and production phase. In order to develop raises and in order to operate machinery inside raises the stability of raises is of interest, namely the fracture zone size and the deformation of raises. Particularly important is the response of raises during boring, because no or only a very limited amount of support can be installed at this stage. The main support system in raises can only be installed once raise boring finished. The raise stability is investigated in high stress conditions, which are expected in the de-stressing phase. The positive effect of de-stressing on raises are pointed out as well by developing a raise in de-stressed ground. As crushed pillars are also planned to be extracted from raises, which are situated in the crushed pillar, the stability of raises in crushed pillars is of interest as well and a raise is developed in the crushed pillar in the test site.

3.2.5 Tests related to mining-induced seismicity and regional stress changes

As a consequence of creating the slot-pillar system in the test site and the subsequent crushing and extraction of the pillar, regional stress and energy changes are induced and seismic energy is released. Knowledge of these regional stress and energy changes are valuable information for the further design of a raise caving operation and they can be observed in the test site, whilst other tests are conducted. An appropriate monitoring program needs to therefore be set up.

3.3 Test site layout and sequence

The test site design has to be governed by the requirements of the tests for the above-mentioned required tests. The layout and sequence must be selected such that these tests can be conducted safely and that these tests deliver the required data and information. Replicating the dimension and geometry of the slot-pillar system is critical to achieve reliable results. Moreover, the layout and sequence must also enable the installation of an appropriate and targeted monitoring and observation program.

An appropriate test site layout and sequence has been derived to meet required points listed above. Figures 2 and Figure 3 show the layout and sequence, as it is currently planned in Kiruna mine. The layout and sequence replicate the individual steps of the raise caving method; compare Ladinig et al. (2021, 2022a, 2022b).

3.3.1 Layout

The layout comprises following excavations; compare also Figures 2 to 5 for location of the test site in comparison to Kiiruna mine tunnel system:

- *Slots:* Two different slot types can be distinguished, namely slots left and right from the pillar and slots above the pillar, between the pillar and the sublevel cave. All slots will be filled with broken rock mass. The purpose of slots left and right of the pillar are: First, slots define the initial pillar dimension and pillar geometry. Second, slots create stress shadows for testing the de-stressing effect. Third, the slot extension in strike direction can be used for the rock engineering design, because it controls the stress magnitudes in the pillar (for a given pillar dimension and geometry). The purpose of slots above the pillar between the pillar and the sublevel cave is mainly to separate the test site from ongoing sublevel caving activities. The extraction of this slot above the pillar is necessary to avoid the formation of a (highly stressed) sill pillar between the sublevel cave and the test site. Moreover, the slot above the pillar enables to proceed with sublevel caving an additional level downwards without interfering with test site activities.
- *Pillar:* The pillar is the central feature of the layout. Its initial dimension and geometry are defined by the surrounding slots. The pillar dimensions are altered during the tests by extracting pillar cuts.
- *Pillar cuts:* The pillar cuts are thin slices, which are blasted successively retreating from slots towards the footwall. The purpose of pillar cuts is to change the pillar dimensions and geometry; namely, to gradually decrease its effective width-to-height ratio. Pillar cuts are also filled with broken rock mass. The pillar cuts must be parallel to the slot walls to create a pillar of defined and constant dimension and geometry.
- *Further excavations:* These excavations comprise (additional) infrastructure for extraction of slots and pillar cuts, raises for the tests addressing raise stability and (additional) monitoring infrastructure. All of these excavations may not be shown for overview reasons.

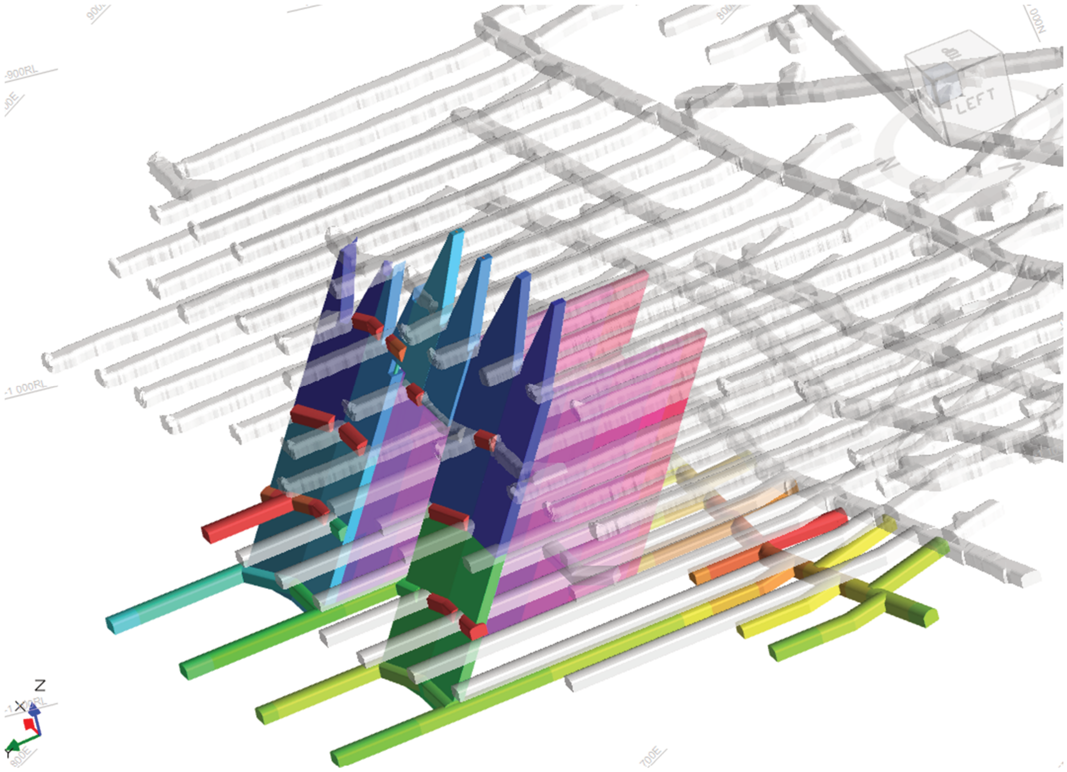

Figure 2 **Kiruna mine test site – isometric view. Grey tunnels are existing workings, bright coloured to be developed as part of the test**

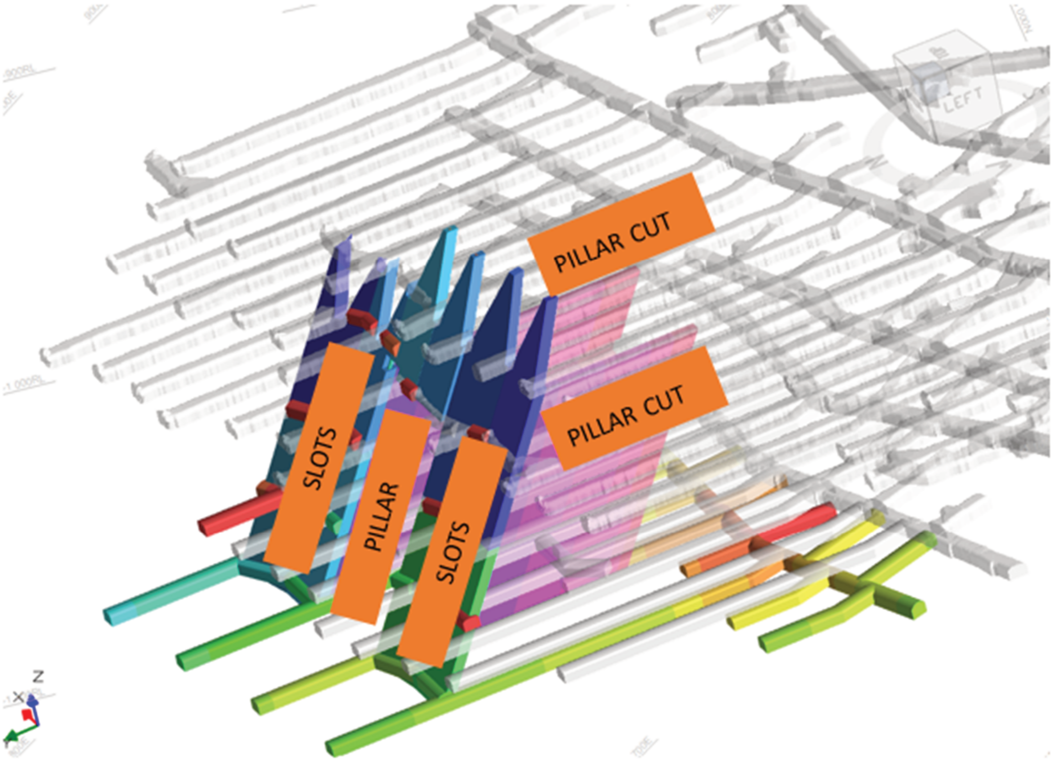

Figure 3 Kiruna mine test site – main parts

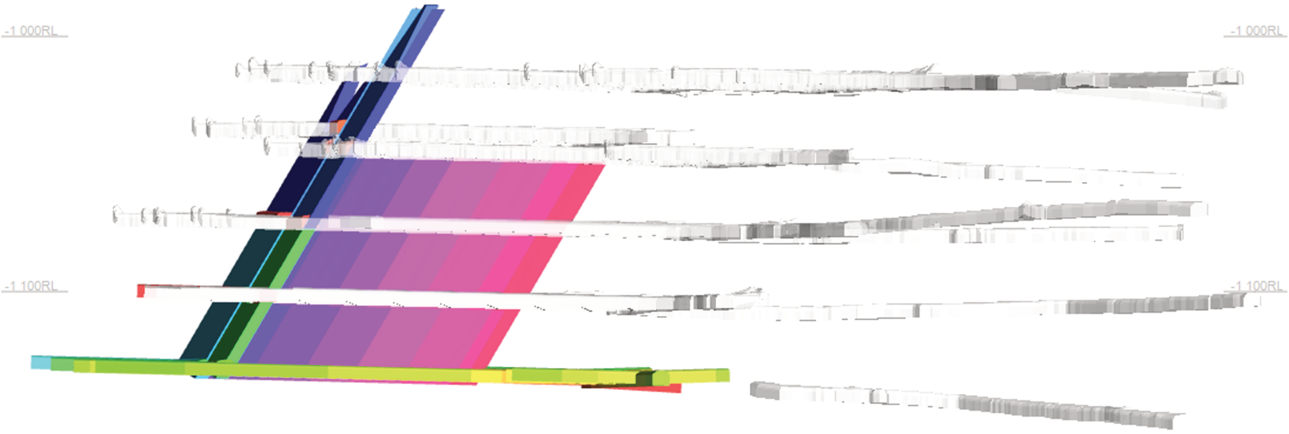

Figure 4 Kiruna mine test site – vertical view

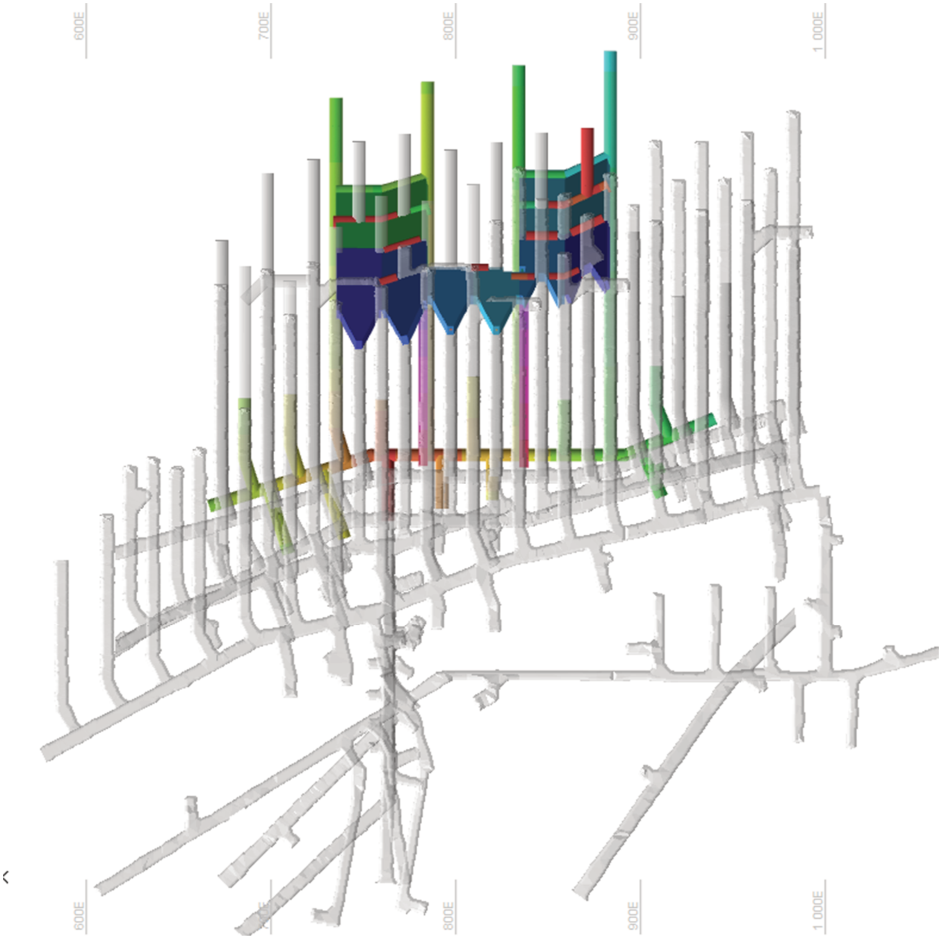

Figure 5 Kiruna mine test site – horizontal view

3.3.2 Sequence

The sequence within the test site should replicate the sequence of raise caving as good as possible. Therefore, a sequence being relatively close to raise caving is considered. Individual steps are:

- *Infrastructure development:* Development of required infrastructure for extraction of excavations (slots, pillar cuts) and for installation of monitoring devices.
- *Installation of monitoring devices:* The installation must be completed before the extraction of slots commences to capture all changes starting from 'state zero'. Most of the monitoring, particularly in and close to the pillar, is done from remote so that personnel does not need to enter infrastructure in the pillar during the test.
- *Extraction of slots:* First the slot above the pillar is extracted followed by the left and right slots. The left and right slots are created successively and away from the pillar. Developing the slot away from the pillar is chosen so that personnel does not need to be in or close to the pillar. Moreover, this development direction has the advantage that the pillar stress is increased slowly and that the pillar strength is not changed, because the pillar has its initial dimensions (before pillar cuts are extracted) immediately after the development of the second slot commenced.
- *Extraction of pillar cuts:* Pillar cuts are extracted after slot extraction finished. The pillar cuts behind the left and right slot are retreated in parallel. Thereby a defined and regular pillar geometry and dimension can be realised. Regarding pillar cuts it is noted that the burden of individual cuts is kept as small as possible. In the current design the burden is around 2 m. The reason for this is to reduce the effective pillar width-to-height ratio as slowly as possible. Introducing slow changes to the pillar is considered best suited for the test site, because it allows to capture the response and behaviour

of the pillar better and because slow gradual changes reduce the risk of sudden, violent pillar failure. However, appropriate monitoring needs to be set up and remedial measures and procedures must be prepared and readily implementable, if behaviour of the pillar departs from the expected range of behaviour or if a hazardous situation develops. Critical is that unplanned deviations are detected at an early stage. Pillar cuts are extracted until the pillar is completely crushed, which means that also the core of the pillar was overloaded.

- *Extraction of ore in test site:* After the pillar cut extraction stopped the test of the pillar in the test site ended and the ore in the test site can be recovered. Besides recovering the ore, additional infrastructure may be developed in de-stressed ground or in the crushed, fractured pillar to see the impact of the stress shadow or to analyse the impact of the crushed pillar on infrastructure stability.

3.4 Design basis test site selection

The design of the test site is comprehensive and complex, it comprises many different aspects, including the dimensions of slots, pillars, the extraction sequence, production scheduling, the monitoring program and the impact on the ongoing sublevel caving operation. It is central that the design minimises the risks associated with the test site. It is beyond the scope of this paper to go into the design details. However, two aspects are highlighted briefly, because they are considered critical for the safety in, the approval and the success of the test site. These two aspects are the design of the pillar and the impact on the sublevel caving operation. Site selection processes focused on locating a site that is, in key aspects, comparable with future mining environment in the deeper parts of the mine. These are rock stress (direction and magnitude), geology and geotechnical properties. Additional aspects assessed were absence of major weakness zones, minimised negative impact for mine's performance and LOMP, and relatively rapid execution of the trial. Both Malmberget and Kiruna mines were considered as possible site for the test. Based on comparisons between suitable locations at both Malmberget mine and Kiruna mine respectively, the Kiruna site is currently the primary proposal for the test. In Figure 6, the proposed test site is shown in relation to the current SLC mining front.

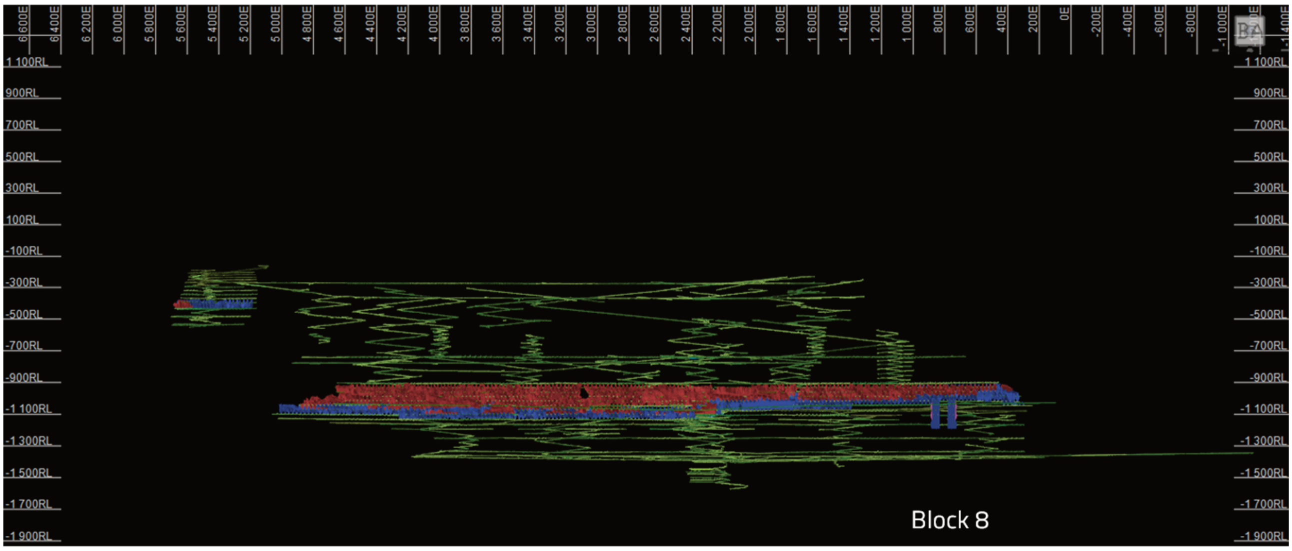

Figure 6 Raise caving test site at Kiruna mine. Current SLC advancement shown in red and planned production front shown in blue

The design of the pillar in the site is delicate. It must ensure two points, namely that the pillar can be completely crushed and that the pillar does not fail violently. The main design parameters are the pillar width and the slot width. The pillar width has an impact on the initial pillar properties and on the rate of change, as the pillar cuts are of constant dimensions. If the pillar is too wide, it cannot be crushed completely. If the pillar width is too small, the risk of a violent pillar failure increases and the desired slow and gradual change of the pillar cannot be fully utilised. A balance must be found. The slot width can be used to control the stress state in the pillar, which is especially important for ensuring that the pillar crushes completely.

The test site consists of construction of two de-stressing slots running over multiple SLC level heights, primary stopes (behind the slots), secondary stopes/pillar and an ore extraction level. Phase 1 is the creation of de-stressing slots, in Phase 2 a gradual change in the width-to-height ratio of the pillar is introduced, Phase 3 is the extraction of the primary stopes and Phase 4 the extraction of the pillar.

The impact of the test site on the sublevel caving operation is of considerable interest for mine management and critical for the approval of the test site. Points of interest comprise the impact on stability of medium- and long-term infrastructure, potential ore losses and required adaptions to the standard layout and sequence. These points are investigated on the short run during the test as well as on the medium to long run, after the test finished. Furthermore, scenarios where unplanned situations and developments occur on the test site, for example that the pillar does not crush completely, are also considered. The analyses of the impact on sublevel caving also help to choose the final position of the test site within the mine.

In the design it is critical to consider remedial measures and to have them ready and easily implementable, if the observed conditions and behaviour of the pillar vary from the expected range. For example, remedial measures for the pillar comprise the increase of slot width to increase the stresses in the pillar, to increase the size of pillar cuts to reduce the pillar width or the application of pre-conditioning, such as hydraulic fracturing or de-stress blasting, inside the pillar from remote places to alter the pillar properties.

During the test the behaviour and condition of the pillar is continuously monitored. A comprehensive monitoring is under development. Considered monitoring measures comprise deformation and stress measurement, observation of fracture zones, observation of infrastructure conditions and microseismic monitoring. Other aspects to be evaluated are feasibility to work in high stress environments during de-stressing slot development (tunnelling, raiseboring, longhole drilling), during mucking waste rock dilution entry, ore flow and ore recovery rate from a single-level mucking location.

3.5 Resources for construction of the test site

The raise caving mining method test site is planned to be constructed by using existing and available resources. The raise caving machine development and consequent test will be conducted separately from the mining method test. By doing this, the mining method can be evaluated entirely independently from the machine tests. Also, availability of resources is unlikely to cause any unexpected delays in test execution.

A dedicated pillar behaviour monitoring system will be planned by the personnel at the mine. The purpose of the monitoring is to detect, quantify and report the changes in the pillar. Means of monitoring can be extensometers, inclinometers, vibration measurements and/or a seismic system installed such a way that changes in pillar condition can be detected. Geotechnical drilling is providing input data for the modelling. Planned drilling depth is more than 3,000 m and the work is ongoing.

Currently, all raiseboring capacity is done by contractors. For the test site, 250 metres is required during the next 12–18 months. Capacity addition will come from existing suppliers.

Tunnel development is done by internal resources. For the trial the requirement is up to 2,600 m over the next 12–18 months. Over a long period of time, the development at Kiruna mine has been over 20,000 m annually. This is more than the SLC needs in the long-term, thus in future years the capacity will be decreased by approximately 50%. As a consequence, there is available, installed development capacity that can be allocated for the trial area.

The excavations in the test site will be created with conventional tunnelling and stoping methods, such as longhole drilling and blasting. The raise mining method will not be used. The main reason therefore is risk reduction in the test site because the machinery, which will be used in raises, is currently under development.

Longhole production drilling for ore extraction is planned in such a way that current SLC rigs can be utilised. The amount of drilling is 7,900 m for initial pillar cutting. The total longhole drilling requirement is estimated to approx. 350,000 m. Also, charging and blasting are using same principles as in SLC mining. For the test site construction, the resources are to be taken from SLC operation. Currently, production drilling has good advance (several years) before mucking takes place and re-allocating of resources is not seen as an issue.

For project management and supervision a dedicated team is nominated. The team consists of LKAB R&D personnel, external specialists and an advisory board. The latter is a purpose-compiled team of experts on raise mining, rock mechanics and mine production, providing a sounding board for the project team. Project is led by LKAB R&D personnel.

Currently planned and estimated physicals for the test site are listed in Table 1.

Table 1 Raise caving test site, physicals measures (estimated)

Item	Approximate value
Geotechnical drilling	3,500 m
Tunnelling	2,600 m
Raiseboring	250 m
Longhole drilling	7,900 m
Ore production (from de-stressing slots and pillar cutting only)	330,000 tonnes

3.6 Integration with mine plan

LKAB's Kiruna mine is operating a single-front SLC cave at 27–28 Mtpa. No other mining methods are currently applied. A major seismic event May 2020 in part of the mine caused disturbance to SLC sequence, thus limiting available production alternatives and general flexibility in sequencing. This means that the SLC mining has less options to divert from planned extraction sequence if anything should come and cause areas of the mine becoming unavailable. From this background and setting the raise caving test area is a major risk as it reserves a large area for the duration of the test, in essence making the area unavailable for SLC mining. To mitigate the risk, the site is planned to be in deeper parts of developed infrastructure, on levels that are due for SLC mining after approximately 4–5 years. Also, the execution of the test site, from tunnel development to pillar cutting, to evaluation and extraction of secondary pillars, is due to be completed at the same time as the SLC mining front is approaching the area.

Challenges implementing a large test site separate from ordinary production are evident. In order to de-risk the production impact, careful planning and advance impact modelling are key tools to achieving approval from all stakeholders. To create a change-positive atmosphere, exhaustive information share is important. This can be information or presentations to mine personnel, production shift crews and supervisor as well as for other stakeholder groups.

Undertaking an impact assessment of the test site construction to SLC production is a vital part of project acceptance criteria. Key part of the impact assessment is comprehensive geotechnical modelling. This work is ongoing at the time of writing this paper and results will be presented at a later date.

The construction plan for the test site consists of raiseboring, development of tunnels and ore extraction behind the de-stressing slots. For raiseboring, sufficient additional capacity can be purchased and does not interfere with SLC raiseboring requirements. Impact of additional tunnelling is not considered an issue currently, mainly because the rest of the mine is decreasing the annual requirement for development heavily. The capacity released is therefore available for the test site construction and does not cause delays for SLC development requirements.

Having said the above, the main concern is overall mine production reliability and de-risking. The test site will produce ore just as SLC, but due to the nature of mining, i.e. proof of concept process, the extraction rate and overall recovery are generally lower and less verified than from ongoing SLC operation. If anything changes in SLC sequence, if the ore close to or at the test site is needed for production earlier than currently estimated, it means the test must be aborted. Risking the ore delivery reliability from the mine is not an option. A way of mitigating is locating the test site as far as possible and to deeper levels in relation to the SLC mining front. This, in turn, is not practically possible in the time frame given for the project. Location of the current test site is a compromise between the most optimal location from a geotechnical and mining method test perspective versus maintaining SLC production reliability.

4 Risks and opportunities

In comparison to laboratory- or pilot-scale testing, a production-scale test has potential for higher gains in form of more detailed data produced, but also possesses higher risk for failure. Raise caving test site construction consists of many unknowns that may turn into risks or opportunities. The reasoning behind selection of production-scale test is the nature of the mechanism that will be tested (the pillar relaxation) and, more specifically, the test of mineability of primary and secondary pillars. The latter is not possible to test if the scale is not near or at the intended use of the method.

As a test site is a one-time event, the planning and consequent monitoring of work progress is important. If parts of the test fail for any given reason, it is difficult to complete the test and receive any meaningful results.

4.1 Risks

Following risks are identified with mitigation measures to be assigned for each one:

- Pillar does not crush, remnant high-stressed pillar leads to ore loss.
- Pillar crushes violently, leading to ore loss, risk for personnel/material.
- SLC mining sequence is changed and ‘catches up’ with test site before the test is completed, resulting in the test having to be aborted.
- Creation of de-stressing slot or pillar cutting is not successful; cave-ins occur, blocked holes, unsatisfactory blasting result resulting in smaller void than planned, leading to pillar cutting not being achieved.

4.2 Opportunities

The following opportunities are identified, with corresponding business cases to be evaluated:

- Method allows for flexibility in forming of production areas and can thereby be applied for varying conditions within LKAB’s underground mines; stress field/direction, depth, ore geometry/footprint/ dip et al.
- Based on a successful test, a first draft of production parameters is produced: pillar size, extraction sequence, production rate.
- Provides a safe, de-stressed operating environment for large-scale caving mining.

5 Conclusion

Due to the nature of the mining method, lack of relevant references and inability to produce required data from desktop studies, there is no alternative way to prove the concept of raise caving, thus making the test a necessity. Planning of the test site indicates that the test site can be constructed with existing resources and in time for the selection of future mining methods at LKAB.

In order to de-risk the production impact, careful planning and advance modelling are key tools to achieving approval from stakeholders. Prior to advanced test site planning, an information share is recommended to provided deeper understanding of the method and specifications of the test site for all stakeholders.

Planning and execution of a large-scale test site within an operating mine is a challenge. The production reliability as a whole must be honoured, and test site construction aligned to requirements from mine production.

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