Deep Mining 2024 – P Andrieux & D Cumming-Potvin (eds)

doi:10.36487/ACG_repo/2465_27

Ground support design for rockburst damage rehabilitation at El Teniente mine, Codelco, Chile

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Abstract

Since the beginning of mining in primary copper ore rock mass at El Teniente mine in the 1980s, seismic events have been recorded due to the brittle behaviour of this type of rock mass in response to these dynamic loads. Some of these seismic events, classified as 'rockbursts with strong damage', have caused severe damage to drifts, sometime resulting in their total closure. These drifts have been rehabilitated with different strategies based on ground conditions (initial rock mass quality and observed damage), excavation size and the type of ground support previously installed. This paper presents historical cases from the Recursos Norte sector of El Teniente mine. It describes the field's geological and geomechanical conditions, the types of support elements used and the design of ground support implemented, while also considering external factors such as operational constraints of the equipment in the mine. Based on this experience, a methodology is proposed that uses a diagram to represent the rehabilitation ground support designs implemented in the field. These designs address vulnerabilities associated with large spans, significant overbreak, pillars of very degraded rock mass or outdated ground support elements. The paper presents relevant field information for rehabilitation designs and explains how this information can be used to modify designs during the progress of the works. Finally, the review concludes with a discussion on the role of geometric and geological singularities in the stability of drifts, highlighting these factors as essential components to be incorporated into mining designs.

Keywords: *rockburst, ground support, rehabilitation, case studies*

1 Introduction

In the El Teniente mine, panel caving since the 1990s has been developed in primary rock that is characterised by brittle behaviour and which has generated rockbursts in response to mining. At El Teniente mine, rockbursts are defined as the instantaneous rupture and ejection of a rock mass associated with a seismic event that results in a loss of continuity of the production process in the mining operation (Figure 1) (Parraguez et al. 2021).

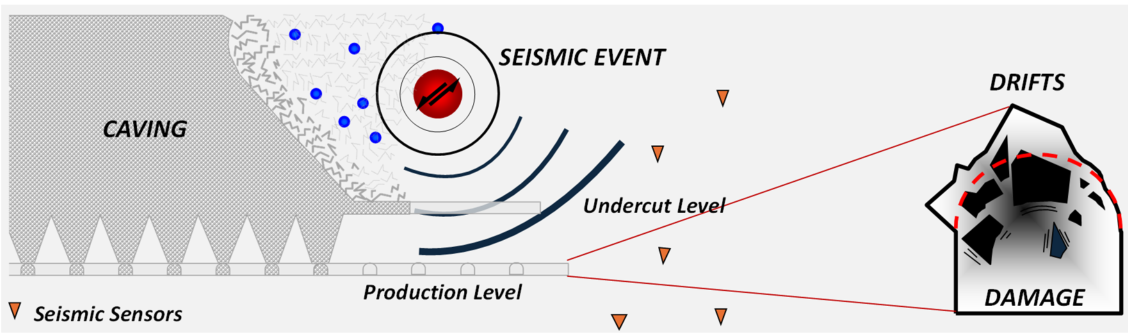

Figure 1 Rockburst source origin

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Based on the previous definition it is evident that implementing strategies to reduce the risk of rockbursts is crucial.

Along these lines, three control measures are identified (Figure 2):

- Source – aim to reduce the magnitude of seismic events by implementing caving rules (for mining control) and hydraulic fracturing.
- Damage – ground support plays a key role as a control barrier to mitigate damage. If damage occurs, rehabilitation is key to the prompt restoration of the productive sectors and to minimise the negative impact of the production process. The rehabilitation designs must consider the presence of deteriorated rock mass conditions as a result of the seismic activity, as well as the access difficulties typically associated with the damage. This present a significant challenge as it requires optimising resources and rehabilitation execution time while the productive sectors involved are halted. Additionally, a high standard of safety is needed to protect workers and equipment, quality standards must be improved during implementation and constant evaluation is necessary since changes in ground conditions may require modifications to the rehabilitation design.
- Exposure of people – to control the exposure of workers to areas prone to seismic events, these areas are isolated before blasting. Transition zones or sectors requiring specific safety procedures are delimited with seismic information and the use of equipment is promoted for the execution of activities without exposing personnel.

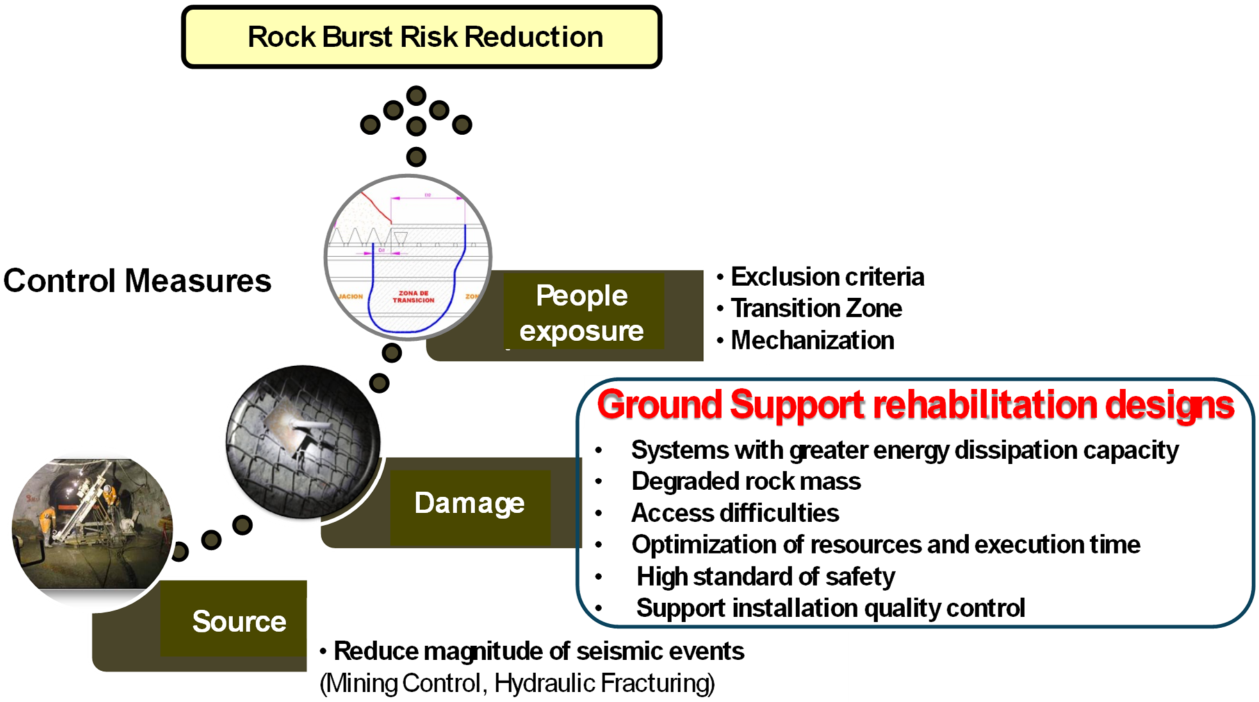


Figure 2 Rockburst risk reduction

The implementation of control measures for source and damage has allowed a reduction in the number of annual rockbursts, which has gone hand in hand with the increase in primary mineral production.

Over time, changes have been made to ground support designs to minimise damage from seismic events by introducing elements with greater load capacity and energy dissipation, thus reducing the extent of rehabilitation needed in terms of linear metres.

This document proposes a methodology that establishes input parameters obtained from the field which can assist in defining the design of post-rockburst rehabilitations.

2 Ground support systems

The primary ground support standard for drifts on all production levels includes reinforcement support with bolts complemented by chain-link mesh and shotcrete (without fibre), which together fulfil the containment function (Celis & Parraguez 2023). This ground support system is systematically installed in all drifts throughout the mine, covering the entire profile from floor to floor, as shown in Figure 3.

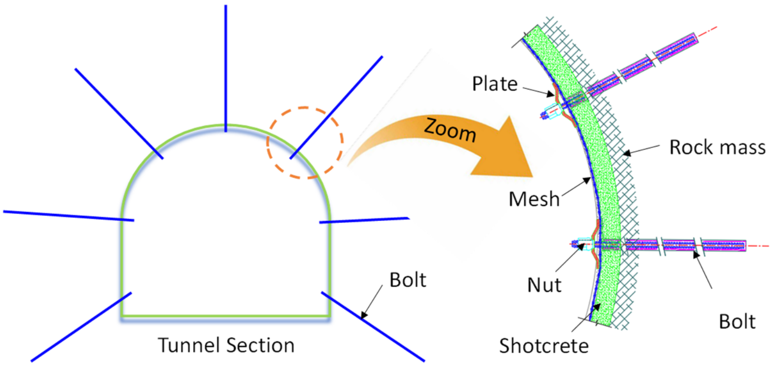


Figure 3 Bolt, mesh and shotcrete design

At the intersection of drift where larger spans are created, the primary ground support is complemented by cable bolts installed in the roof of the intersections, as shown in Figure 4.

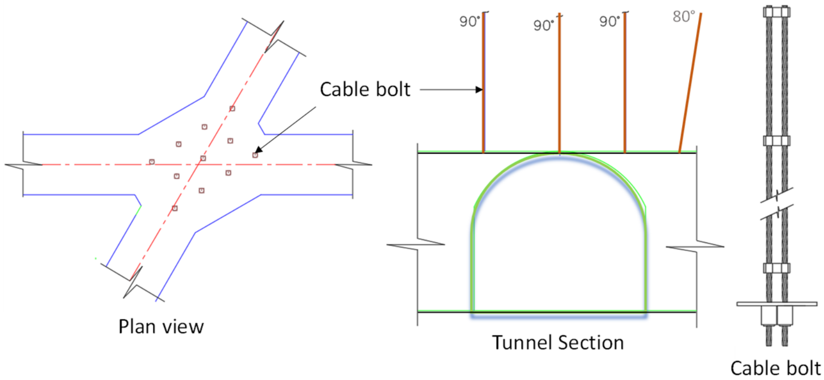


Figure 4 Intersection cable bolt design

In the production levels where rock pillars are created, civil infrastructure or continuous reinforcement walls are added as support elements. These walls form a more rigid structure aimed at better controlling the displacement of the contour of the excavations (Figure 5).

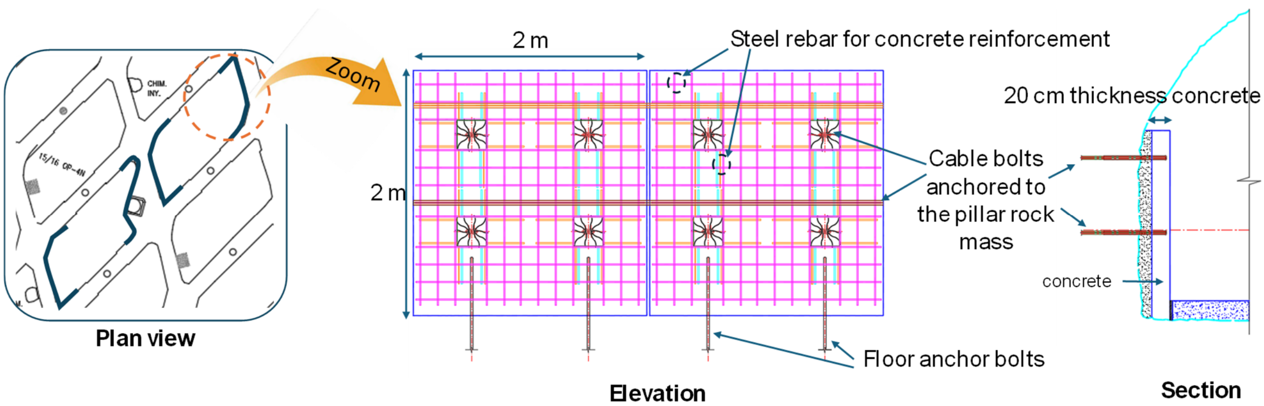


Figure 5 Continuous reinforcement wall design

Finally, in crucial infrastructure for operations such as drawpoints or drawbells, civil infrastructure steel arches or a reinforced concrete arch are incorporated to provide additional surface support (Figure 6).

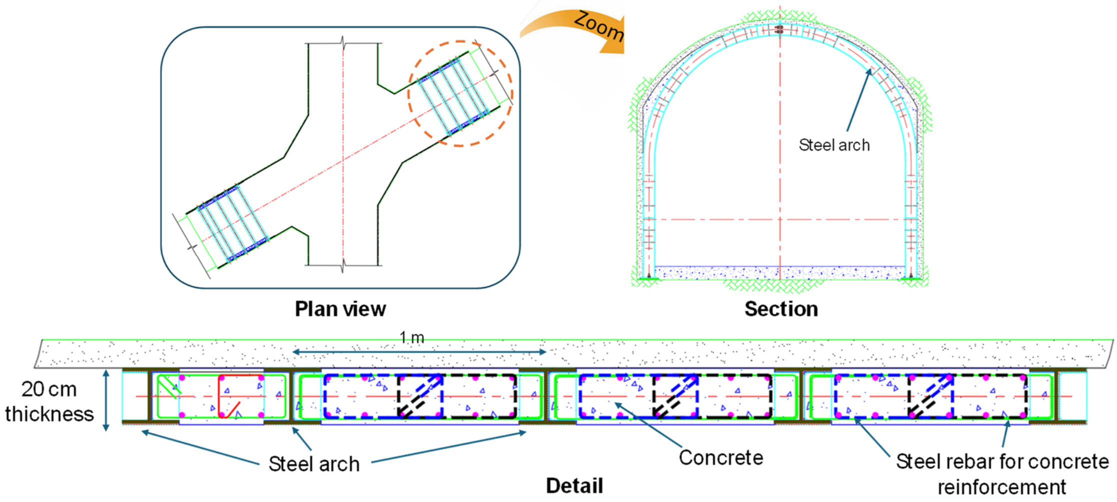


Figure 6 Steel concrete structure design

3 Post-rockburst classification of damage to ground support systems

In general, the excavation of drifts and installation of ground support in caving mines are performed in sectors where the mineral extraction process has not yet begun. Consequently, these areas have a more favourable environment in terms of stress conditions and loads on the support systems. This means that rockbursts affecting the drifts occur several months after their construction, once mining activities commence in the surrounding areas.

The classification 'damage of the drifts' is based on a visual evaluation. This information, collected by geomechanics staff in the field as soon as possible after a rockburst occurs, serves as the starting point for the design and subsequent planning of the rehabilitation.

Ground damage is classified into severe, moderate and minor categories based on its severity. When surveys of post-rockburst damage are completed, a colour-coded nomenclature is used to identify these categories: green for minor damage, blue for moderate damage and red for severe damage.

For example, Figure 7 shows damage observations following the rockburst on 24 July 2023 at the haulage level of Recursos Norte mine. Rehabilitation of some sectors at this level will be discussed in more detail in Section 5.2 of this paper.

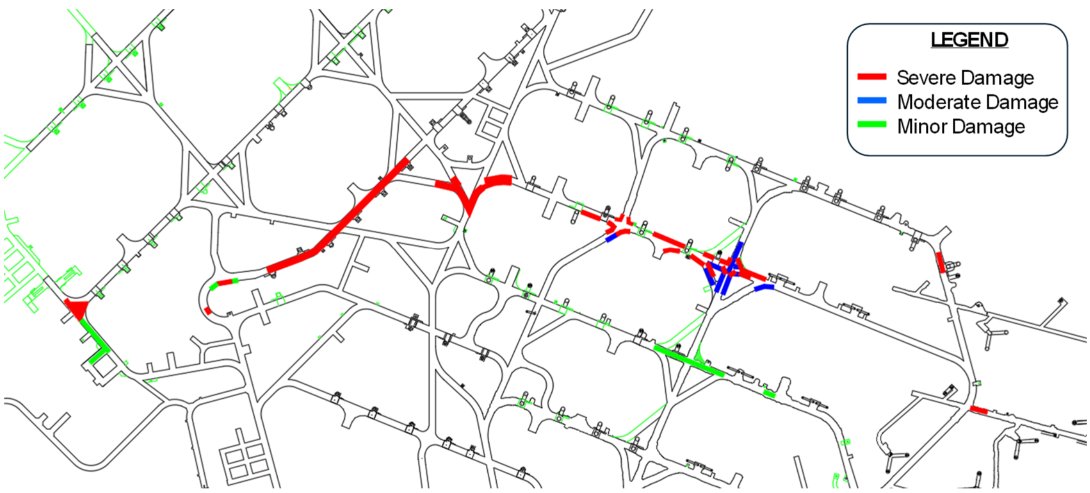


Figure 7 Damage assessment in the Recursos Norte mine haulage level after the 24 July 2023 rockburst

The minor damage category corresponds to minor slabbing or falling of shotcrete, where the primary steel support (bolts and mesh) of the drift was not damaged and maintains its capacity. Moderate damage corresponds to visible bulking in the bolt-mesh-shotcrete system, where it is expected that bolts and/or cables have been cut inside the bulking volume. Severe damage corresponds to complete failure of the ground support system, where the rock mass has been exposed. An example of each of the damage categories is shown in Figure 8.

:seismic event damage

(a) (b) (c)

Figure 8 Damage classification: (a) Minor damage; (b) Moderate damage; (c) Severe damage

In the case of civil infrastructure such as continuous reinforcement walls, damage includes obvious toppling of the walls that indicate cutting of the anchor cables in the rock mass or the total loss of their capacity. Regarding civil infrastructure that includes steel frames, it has been shown that as they are more rigid structures they present local failures such as buckling or deformations in the areas of load concentration. Examples of damage to civil infrastructure are shown in Figure 9.

(a) (b)

Figure 9 Damage in civil structures: (a) Continuous reinforcement wall; (b) Steel and concrete arches

4 Diagram for rehabilitation ground support design

For the design of post-rockburst rehabilitation it is important to consider the following input data associated with the post-rockburst ground conditions:

- excavation geometry – current drift width and height to identify levels of overbreak when comparing with the design geometry
- recording of the depth of damage
- presence of geological structures limiting the depth of the damage
- lithology of the sector with damage
- water seepage or moisture condition
- presence of oxidation in the rock mass and in the failure planes of support elements
- type of ground support installed before the rockburst – identify diameter of reinforcing elements, type of mesh or containment system, shotcrete thickness
- identification of the failure mode of the support elements in response to the acting loads – the failures can be due to tensile stress, shear stress or a combination of both (Figure 10) (Celis & Parraguez 2023).

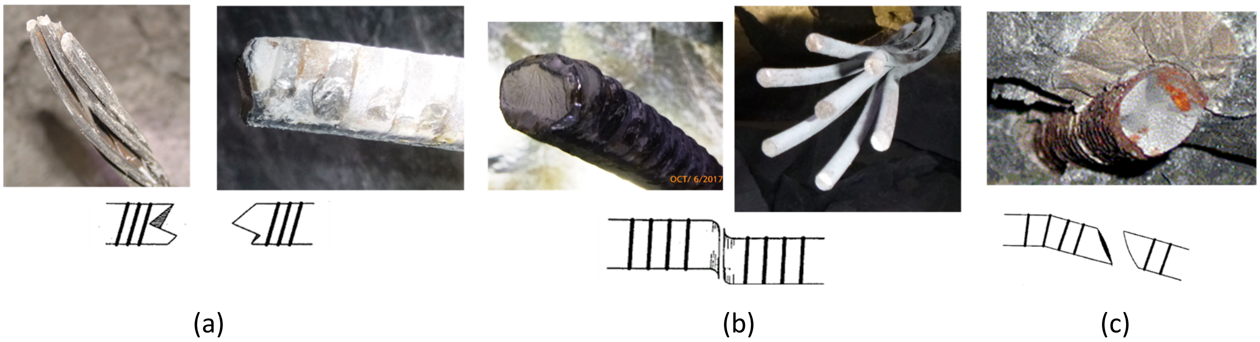


Figure 10 Bolt and cable bolt failure modes: (a) Tensile stress; (b) Shear stress; (c) Tensile and shear stresses

- response of the internal anchorage or grout of the reinforcing elements (such as bolt or cables) – identify possible failures due to debonding at the rock, e.g. internal anchor or internal anchor-reinforcing element interfaces
- deficiencies identified in the quality of the ground support installation in the damaged sector – technical design specifications of the support system must be reviewed (diameters of bolts and cables, mesh configuration, technical specifications of external anchors such as plates, nuts and barrel-wedge and shotcrete thicknesses, among others). In addition, the spacing configurations between these elements and deficiencies in the installation of the grout must be reviewed.

The final geometry of the post-rockburst excavation must be compatible with the operational restrictions of the drilling equipment for rehabilitation. It may be necessary to build ramps to allow equipment access to the areas with the largest overbreak in the roof or to explore alternatives such as completely filling drifts and re-excavating with explosives if reinforcing the excavation contour is not feasible due to operational constraints.

When it is feasible to install reinforcement elements (when there are no operational constraints associated with the equipment), the depth of damage must be considered in the design of the anchor length of elements such as bolts or cables. Once the ejected material has been removed and the area with damage to the support system (severe and moderate damage) cleaned up, a lidar scanner must be used to also identify the possible formation of wedges and make a reinforcement design with cables appropriate to the conditions. This lidar scanner will also provide information (accurate dimensions) regarding the requirement for reinforcement or the tie-down of pillars or crown pillars.

The history of water seepage or the presence of moisture help to give an idea of how degraded the rock mass is. Water leaks in large areas can be associated with rock masses with open fractures, which could create operational difficulties during drilling activity for the installation of reinforcement elements such as bolts and cables, or during the installation of grouting. When the installation of these reinforcing elements is not feasible, a decision should be made to include heavier surface support such as steel frames or reinforced concrete structures with anchoring, where possible (e.g. only to the floor or roof).

Observations associated with the failure mode identified in support elements should be considered in order to improve them. For example, in the face of a systematic failure of any element, modify the geometry of that element, choose support systems with greater energy dissipation capacity in the repairs or emphasise quality controls in case a vulnerability regarding this point is identified in the field.

Figure 11 summarises in a diagram the points discussed in this section for the most complex cases.

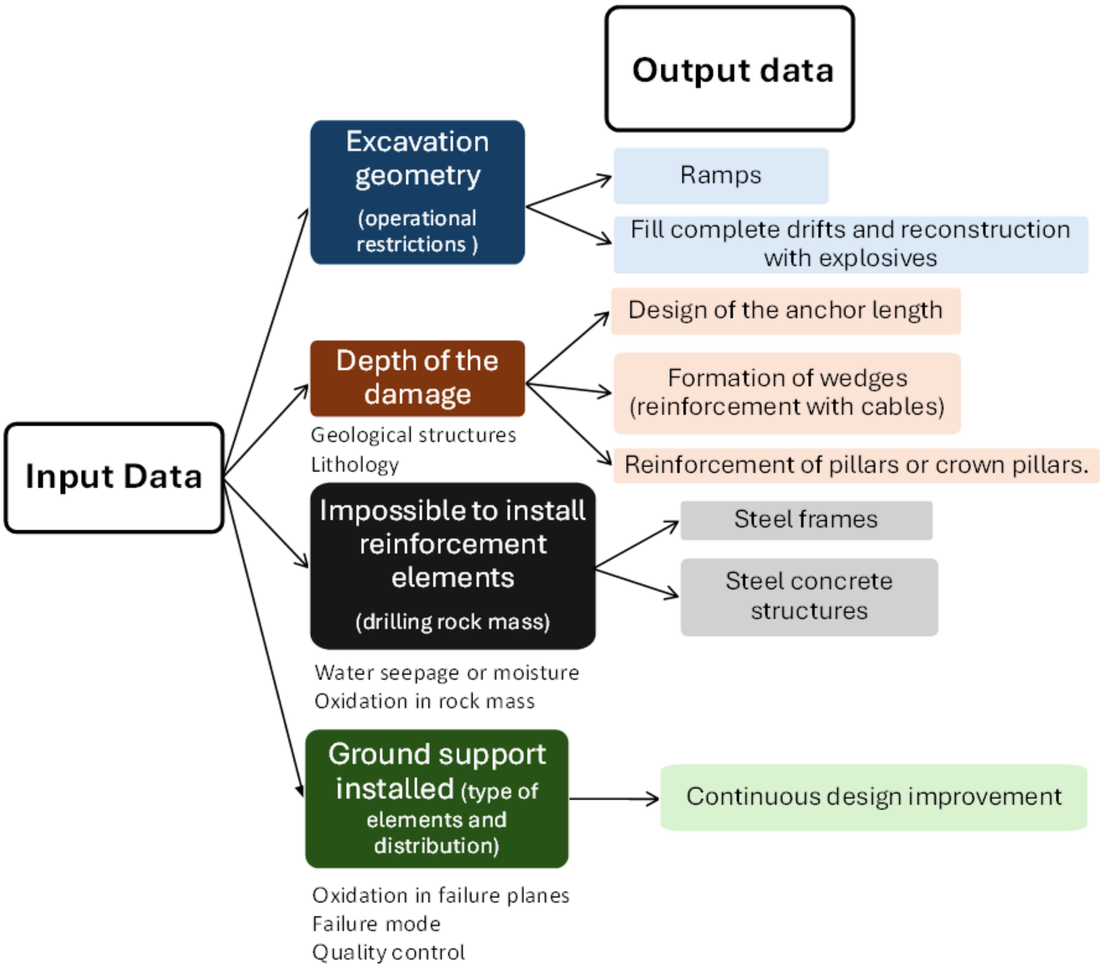


Figure 11 Ground support rehabilitation diagram

Throughout the rehabilitation process, the input data in Figure 11 should be continually evaluated, as any changes could necessitate modifications to the design being implemented in the field. Some examples of application of this diagram are described in the following section.

5 Case studies

Below are some case studies involving application of the methodology described in this paper for defining rehabilitation design for sectors affected by rockbursts.

5.1 Recursos Norte mine rockburst: 18 September 2021

On 18 September 2021 a seismic event of magnitude MW1.9 and energy of MJ5.7 was recorded at the Recursos Norte mine haulage level. The epicentre of the event was recorded in the transition zone at the haulage level elevation, close to the alignment of the N3 geological fault (Constanzo et al. 2021).

The damage, classified as severe (Figure 12), was located at the intersection of two drives (Socavón Hw with Socavón Intermedio) and extended 70 m along the Socavón Hw drift (Celis 2021).

The initial ground support of the damaged sector included bolts, mesh and shotcrete as described in Figure 3, and cables in the roof of the intersection as described in Figure 4.

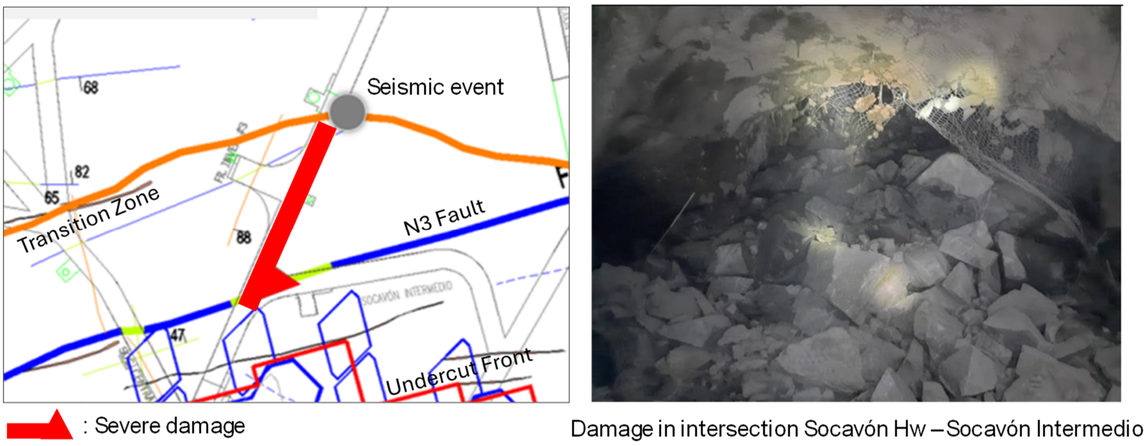


Figure 12 Location of damage

As input data for the rehabilitation design, a maximum overbreak of 12 m was considered (lidar scan measurement). The presence of water suggested degradation of the rock mass and poor grouting was identified in some cables from the roof of the intersection, given that the grout injection hoses were found empty during the investigation (Figure 13).

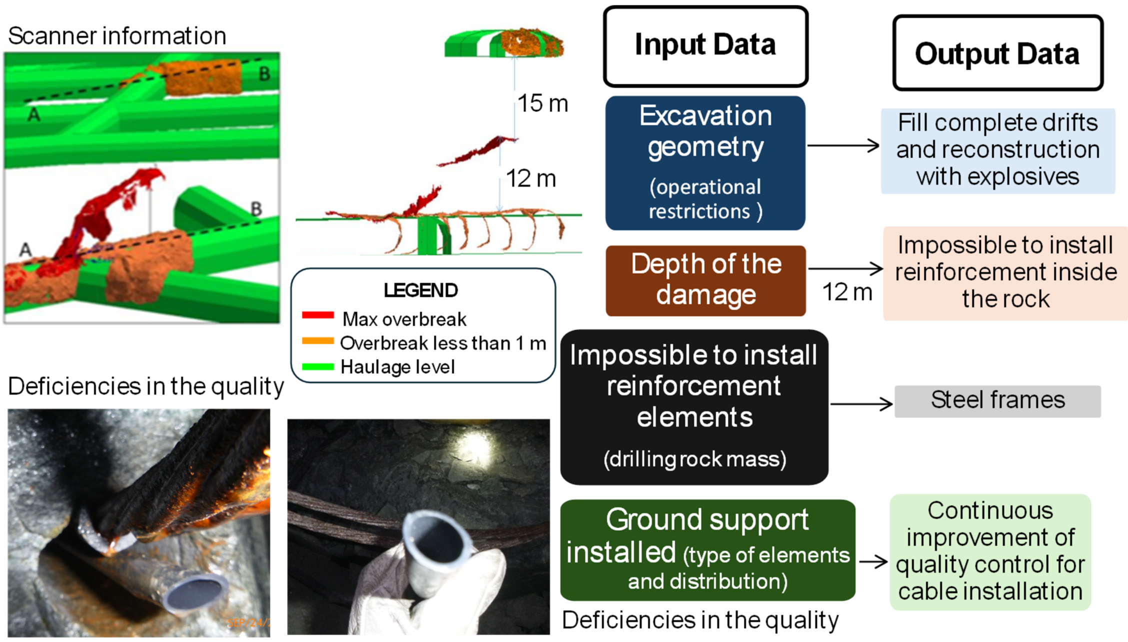
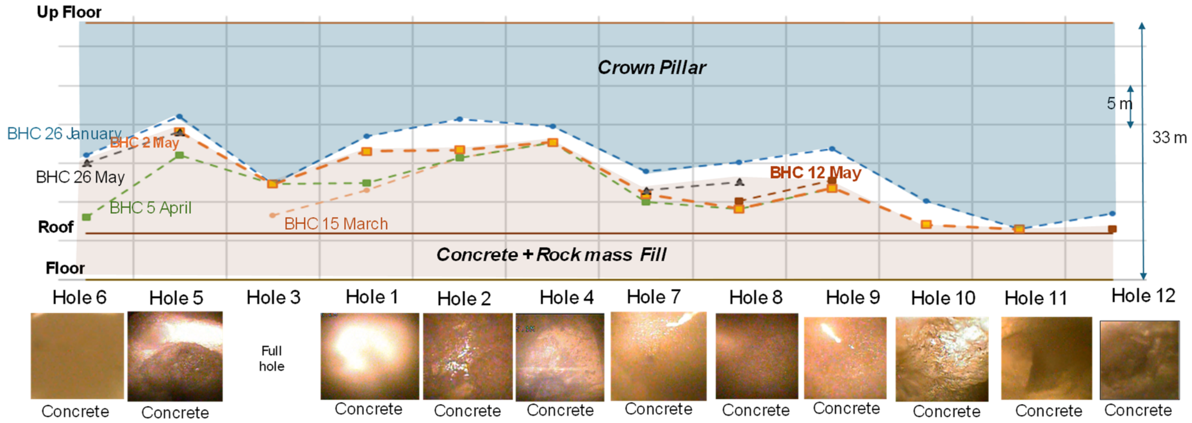


Figure 13 Field observations and input to the ground support rehabilitation diagram

With this information a decision was made to backfill the damaged area with concrete, re-excavate a new drift with explosives and install steel arches joined in sets of five arches each.

Due to the extent of the damage, 12 holes were drilled from the upper level for backfilling. This activity was carried out continuously for three months (4,000 m^3 of concrete). The fill level was controlled by introducing borehole cameras through the same holes until concrete was seen in all of them, at which point the process was stopped (Figure 14).



	Hole 6	Hole 5	Hole 3	Hole 1	Hole 2	Hole 4	Hole 7	Hole 8	Hole 9	Hole 10	Hole 11	Hole 12
Crown pillar (m)	18	12	21	15	12	13	19	18	16	23	26	24
Over exc. (m)	9	15	6	12	15	14	8	9	11	4	1	3
Unfilled height (m)	1	2	0	2	4	2	3	3	4	3	0	2

Figure 14 Section showing the elevation of concrete at the end of the backfill process

Once backfilling was completed the drift was redeveloped using explosives. A set of steel arches was assembled at the start (under the zone without damage) and mounted on steel profiles, then pushed forward as the excavation advanced. Heavy equipment was used to push the set of arches.

Figure 15 shows different stages of this rehabilitation process.

Figure 15 Stages of the rehabilitation process

As a final stage, once all the arches had been assembled, the gap between the steel arches and the excavation was filled with concrete.

5.2 Recursos Norte mine rockburst: 24 July 2023

On 24 July 2023 a seismic event of magnitude MW3.0 and energy of MJ1,900 was recorded, creating the damage represented in Figure 7 at the haulage level of Recursos Norte mine (Parraguez et al. 2023).

The initial ground support of the damaged sector included bolts, mesh and shotcrete as described in Figure 3, and cables in the roof of the intersection as described in Figure 4.

The rehabilitation process outlined in the diagram in Figure 11 was applied to two sectors with damage to the haulage level of Recursos Norte mine (Figure 16).

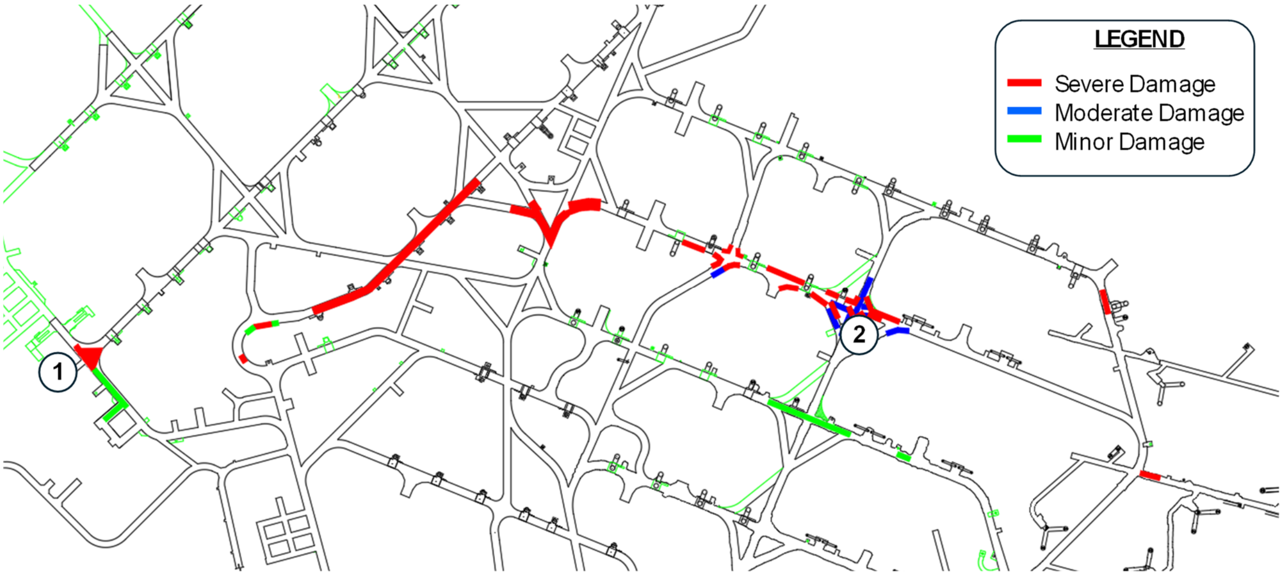


Figure 16 Sectors to review

In sector 1 (Figure 17), the maximum overbreak in the roof was measured at 8 m with the lidar scan. There was no water infiltration and the rock mass was competent, making the installation of reinforcement elements such as bolts and cables on the roof of the excavation feasible. Due to the height, the support of an access ramp to the sector was required. No deviations were identified in the installed ground support and there were no quality issues.

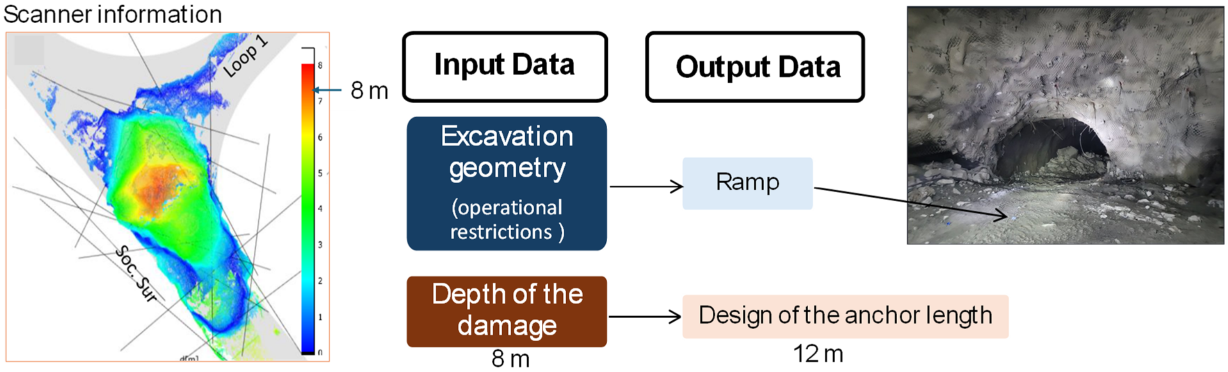


Figure 17 Field background information for sector 1

At the end of the rehabilitation, 71 cables were installed in the roof (Figure 18).

(a) (b)

Figure 18 Rehabilitation in sector 1: (a) Post-rockburst condition; (b) Rehabilitation completed

In sector 2 (Figure 19), a damage depth of 1 to 2 m and rock mass blocks with abundant oxide coatings were identified in the field, which is consistent with the age of this drift compared to sector 1 of the same level. Additionally, the rock mass degradation prevented the anchoring of reinforcement elements so a reinforcing concrete wall anchored to the roof and floor was constructed. This wall was anchored to a more competent rock mass compared to the degraded rock mass of the pillar (wall rocks).

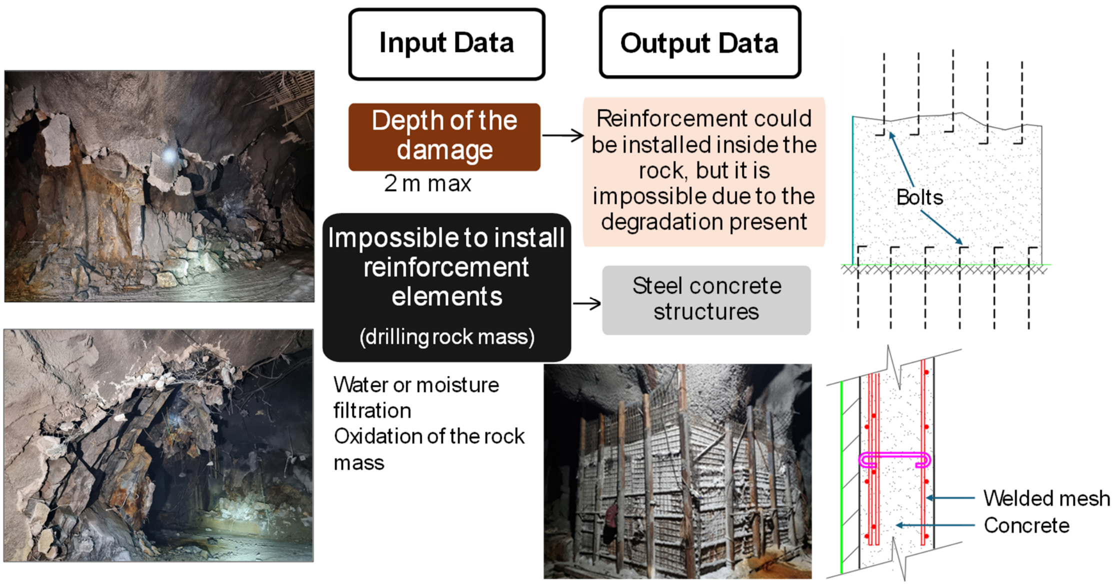


Figure 19 Rehabilitation in sector 2

Figure 20 shows the final completed rehabilitation.

Figure 20 Repairs to sector 2: (a) Post-rockburst condition; (b) Repair work completed

6 Learnings

The key lessons learned are as follows:

- Geometric singularities – avoid irregularly shaped or smaller pillars in engineering designs as they are more vulnerable to damage. Sections with 90° breaks in their geometry, such as brows of civil-type structures, also constitute a vulnerability. These sections should include special reinforcement or cable tying.
- Geological faults – given some damage is caused by the position of the main geological faults, the installation of complementary ground support must be incorporated as a subsequent action to better control damage from new dynamic loads. In practice, in the cases at Recursos Norte mine presented here, drifts at various production levels were reinforced within a 20 m halo on each side of these faults using additional cables and mesh. This measure also applies in other sectors.

- Support system failures – observing the type of failure of the support systems installed in the field, especially in older sectors, and the importance of implementing a system to identify the failure mode of the support elements, were highlighted in this paper. This information should be linked to a maintenance program that considers the installation of complementary support where the supporting elements have already lost their capacity and the service life of the drifts needs to be extended.
- Lidar scanners – performing a lidar survey in the field after the removal of the ejected rock mass aids in defining the support design for the rehabilitation. It helps to estimate the length of reinforcement elements that will be anchored to the rock mass and obtain information regarding the possible formation of wedges that must be stabilised.
- Scaling process – during the scaling processes required to begin the rehabilitation, good control of scaling equipment is required. If not adjusted to the rock mass conditions as scaling progresses, scaling can be very inefficient or cause unnecessary damage.
- Ground conditions – it is important to constantly review the ground conditions during the rehabilitation process. Difficulties during drilling to install cables or bolts (hole closure, excessive grout injection), changes such as audible noise, water leaks or other signs may necessitate re-evaluation of the rehabilitation design.

7 Conclusion

Although the response of the ground support to rockbursts depends on several factors, including the parameters of the seismic event, characteristics of the installed support system and specific ground conditions, it is possible to create a diagram like the one presented in this paper that identifies the relevant field information needed for the design of the rehabilitation.

Having a methodology that clearly identifies the input data for rehabilitation design in sectors affected by rockbursts allows for better adaptation to the ground conditions, thereby optimising resource use during its execution.

Over time the experience gained during the execution of rehabilitations, along with records of how the designs are modified as work progresses and ground conditions change, provides invaluable information that is not always documented. With this documentation we aim to record some of the most complex rehabilitations that we have faced at the El Teniente mine.

Acknowledgement

We thank the Mining Resources and Development management of El Teniente Division for the authorisation and publication of this document.

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