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Evolution of dynamic rock support systems at the El Teniente mine

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Abstract

El Teniente mine is the largest underground copper mine in the world and has been in operation since 1905. As the mine has become deeper, developments and exploitation have faced more complex geomechanical environments. Different strategies have been implemented to manage and control the risk of rockbursts and collapses. These strategies include improvement and optimisation of the rock support systems not only at the footprint areas, but also at main infrastructure tunnels.

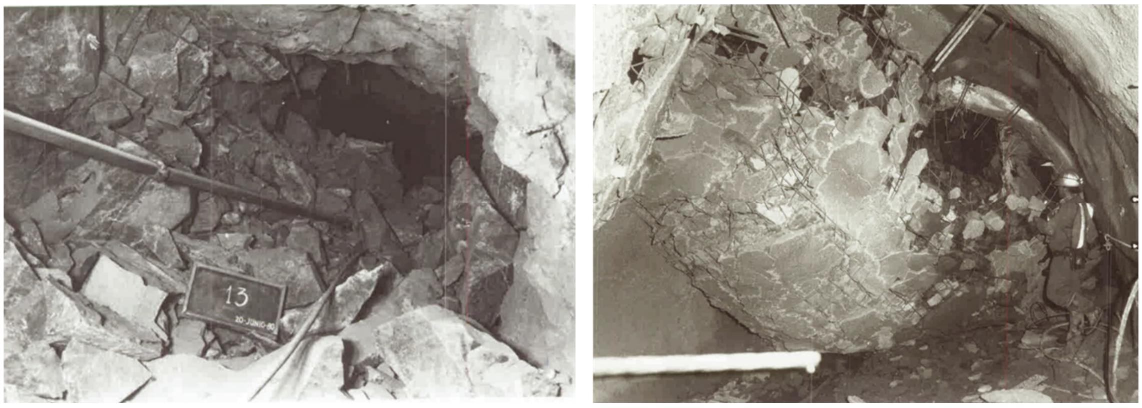
One of the key concepts has been the integral improvement of the rock support system's capacity, based on the understanding of the rock mass failure process and how energy is transferred and dissipated by the support systems. The dynamic rock support designs used at the El Teniente mine have evolved over time, depending on the site conditions and geotechnical vulnerability. The focus has been on addressing the relationship between system capabilities, operational flexibility, mechanisation, and field behaviour.

This paper describes the design principles and evolution of the dynamic rock support systems, providing practical examples that support the design assumptions and understanding of the phenomena involved.

Keywords: *dynamic rock support systems, El Teniente mine, dynamic failure, dynamic support evolution*

1 Introduction

The phenomenon of rockbursts has been present at El Teniente mine since 1976, causing damage to excavations of the mine's exploitation systems (Figure 1). Starting from the early extraction of primary ore in the 1980s and as the mine has deepened, the effects of these seismic events have become more intense, leading to the need for repairs due to the damages caused, as well as the suspension of productive sectors (Córdova & Baeza 1980). Indeed, fatal accidents occurred in the Sub6 sector in 1990 due to this phenomenon, which led to the suspension of operations in that sector.



(a) (b)

Figure 1 Rockburst damage. (a) Early primary rock mass exploitations (1980); (b) Sub6 operation sector (1990)

Before 1990, strategies involved approaches from a local perspective of each sector, considering the influence of regional stresses (Kvapil et al. 1989). Later, the focus changed to describing the concepts of seismicity as a response to the caving process. This was the case with the 'experimental mining stage' that supported different definitions for design considerations, planning, and operations based on the geomechanical response of the rock mass to mining, implemented from 1999 onwards (Rojas et al. 1993, 2000).

The experimental mining stage tested a conceptual framework developed during 1992–1993 which connected the mining parameters to the rock mass response characteristics. This allowed control of the induced seismicity by modifying the mining parameters. The caving methods are initiated by the blasting of the bottom volume of a rock mass column. The broken material is mined out creating cavities that allow gravity to continue the fracture process of the rock mass, producing new broken material. The subsequent production generates the continuity of the breaking process to the upper levels. In general terms, a seismic event corresponds to the radiated energy associated with a rock mass rupture. Then the induced seismicity is always associated with a rupture process affecting a competent rock mass, and its characteristics will be determined by the spatial and temporal distribution of the mining activities and conditioned by the geometrical, geological and structural characteristics of the mined volume. This framework is described in Figure 2.

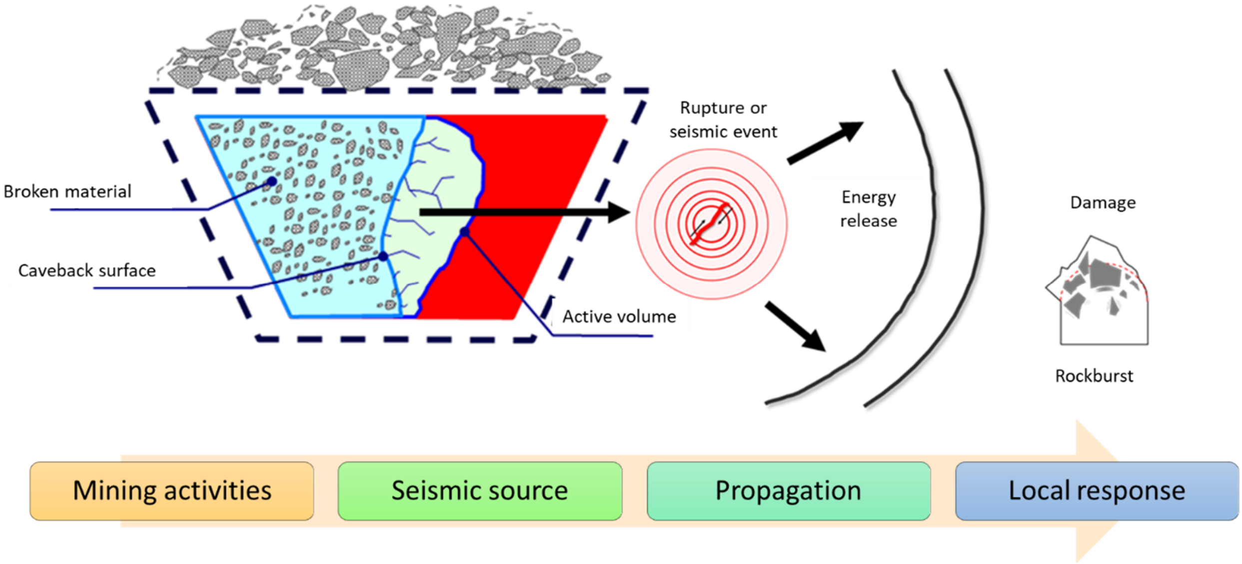


Figure 2 Conceptual framework for the induced seismicity (modified from Rojas et al. 1993)

With this conceptual model described, Tinucci & Rojas (1994) listed several source mechanisms for seismic events around a cavity, classifying types of failure mechanisms and their influence on how energy is released from the source.

Then the management and control of geomechanical risks, specifically the risk of rockbursts, strategically defined several key concepts such as:

- Mitigating seismic hazard by moving events of larger magnitude and energy away from the infrastructure through the inclusion of preconditioning techniques, such as hydraulic fracturing, and limiting certain mining processes that cause greater disturbance (e.g. blasting, extraction, undercutting).
- Controlling the effects of seismicity near the infrastructure, including improvements in rock support systems that minimise observed damage following the occurrence of a seismic event.

In August 2005, a rockburst was registered in the Reservas Norte sector, which caused damage to different zones and levels, impacting the sector's planning and requiring an additional focus on geomechanical management and control at the caving scale and the performance of rock support systems. In Figure 3 shows some of the damage.

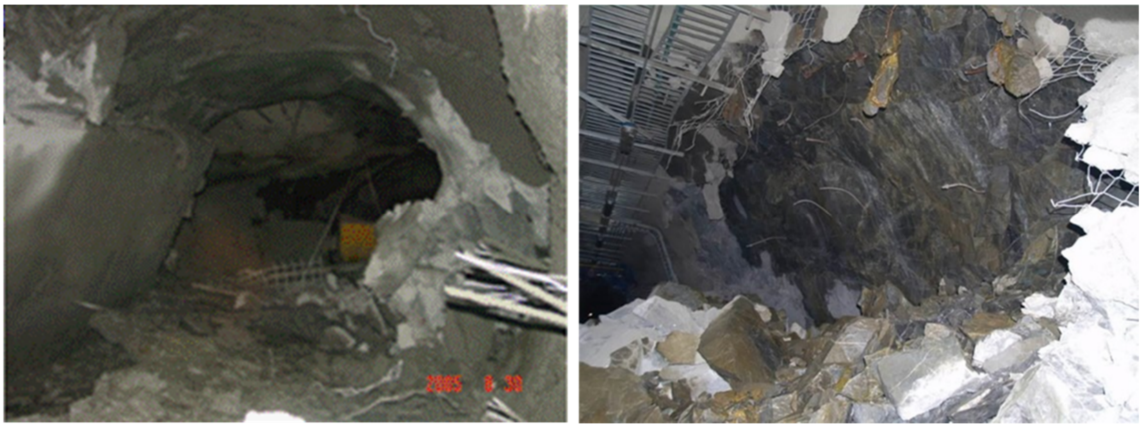


Figure 3 Rockburst damage after a seismic event M_W2.5 in Reservas Norte sector (Gonzalez et al. 2005).

During the period from 2013 to 2015, with the occurrence of rockbursts in the main infrastructure tunnels of the new mine level project (Figure 4), there was a need to understand the phenomena on another scale, which led to a new learning process in deeper and more complex geomechanical environments.

Figure 4 Rockburst damage after a seismic event M_W2.0 in main infrastructure tunnels of the New Mine Level Project (Rojas et al. 2015)

2 Behaviour of the rock support system and damage around the excavation

In this section, recent experiences from the conveyor belt tunnel (TC Tunnel) of the Andes Norte project will be used to explain main concepts with practical examples. TC Tunnel is one of the main infrastructure tunnels and is a fundamental part of the future mineral handling system. Its design dimensions are 8.4 × 6.2 m cross-section and 8.9 km in length, enabling the extraction of minerals from the bottom of the inner crusher chamber in the mine. During its development, several seismic events and rockbursts have been recorded, causing interruptions in the advancement of cycles due to the need for rehabilitation to continue its development (Rojas & Landeros 2017). The rockburst risk management and control strategy at the tunnel scale consists of key aspects such as an integrated geotechnical ground control system, preconditioning techniques, mechanisation for the most critical activities and monitoring of the installed rock support system (Rojas & Landeros 2022).

In this section, two example cases are described. The first one corresponds to the proper functioning of the rock support system where depth of failure is not exceeded and the second is a case where the system's capacity is exceeded. In both cases, it is possible to observe damage to the rock mass around the tunnel due to the dynamic load induced by a seismic event and how this loading may extend deeper than the initial observations as a clear indication of energy dissipation process during the rock mass failure process and the interaction with the installed rock support.

2.1 Rock support elements working as a system

In September 2018, a change in ground conditions was observed in one of the working faces of the conveyor belt tunnel following a seismic event that occurred during the re-entry time after blasting. The changes corresponded to deformation of the excavation boundary, as shown in Figure 5.

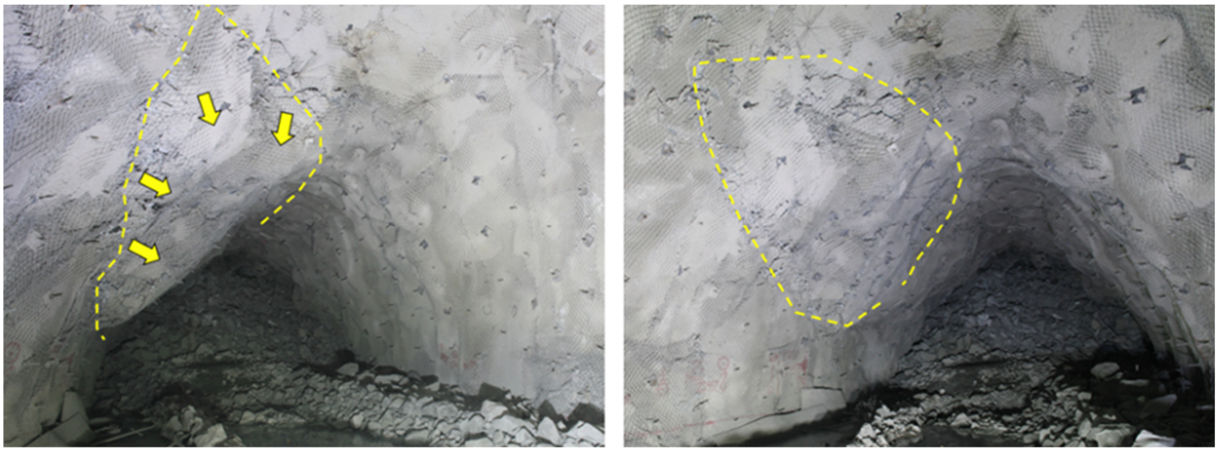


Figure 5 Loaded rock support system after a seismic event (geotech ground control)

At that time, the operational action consisted of completely restoring the capacity of the rock support system by discharging the loaded systems, implementing mechanised scaling processes, and subsequently installing new elements of rock support design. Additionally, during the rehabilitation process, it was seen that the degree of rock deterioration behind the surface exceeded the depth of fracturing estimated from the geotechnical and stress conditions, as shown in Figure 6.

Figure 6 Rehabilitation process exposing rock fracturing behind retained volume by rock support system (operational ground control records)

In this case, the damage behind the deformed volume was larger in comparison to the initial observation from the ground control inspection (see Figure 7), which raised the question of how energy is actually dissipated during dynamic loading. Rock support systems design must consider both structurally defined volumes and stress induced fracturing potential situations.

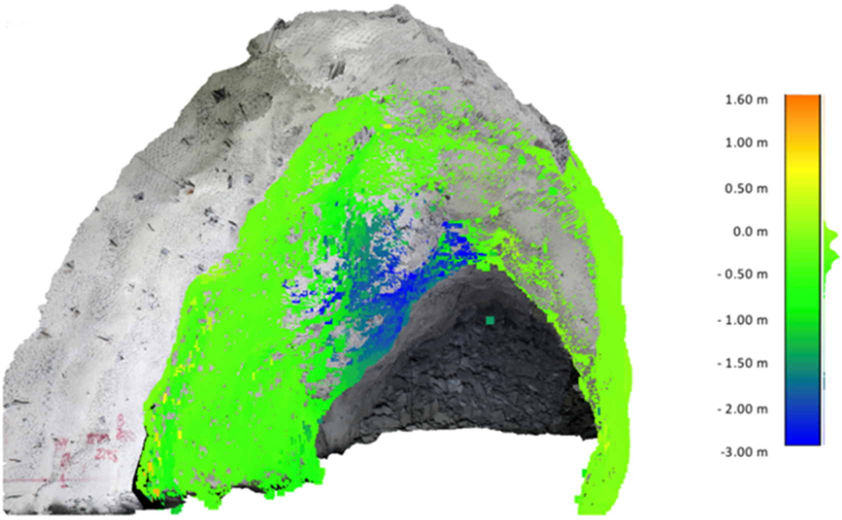
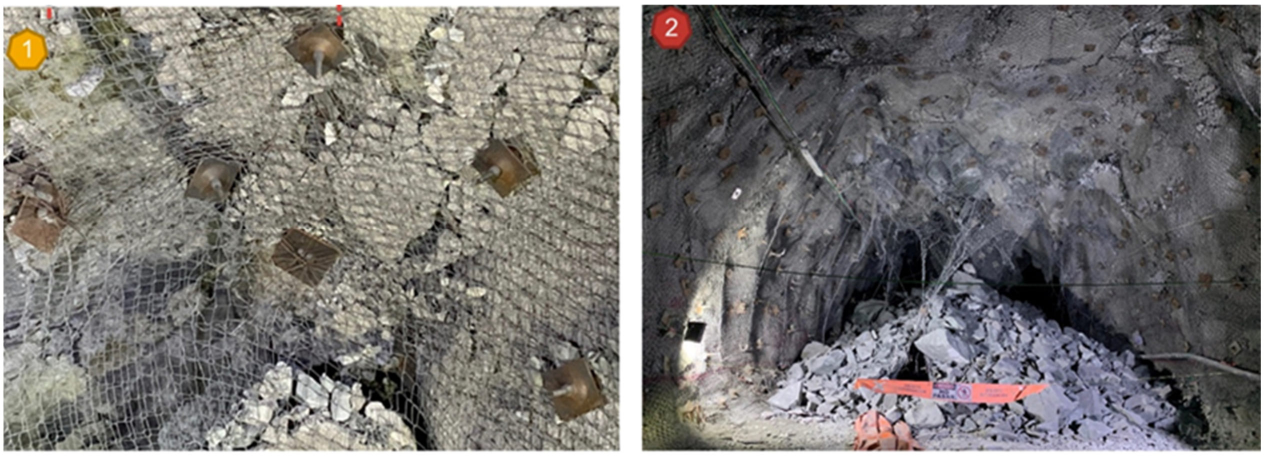


Figure 7 Depth of failure after the rehabilitation process calculated from stereo photogrammetry measurements

2.2 Lessons learnt from a rockburst rehabilitation

In September 2020, a severe rockburst affected the conveyor belt tunnel, inducing damage with a large depth of failure but also another zone around it with induced boundary deformation, as shown in Figure 8.



(a) (b)

Figure 8 (a) Damage on the roof with evidence of loading; (b) Deformation around the rockburst

This example is interesting to analyse because as the rehabilitation of deformed areas and the rockburst zone was carried out, it was observed that the degree of boundary fracturing was similar, with a clear difference in the depth of failure, as shown in Figure 9.

Figure 9 **Rockburst rehabilitation process, including zones with deformed rock support system (Castro & Bahamondes 2020)**

Furthermore, in areas where the anchors did not fail, the mechanical interlocking of blocks was observed together with the intact rock support system elements, supporting the concept that the rock mass and grouting fracture during the dynamic loading caused dissipation of energy during this process, while the rock support system also did not totally fail (see Figure 10). The balance of how much energy each component of the support system dissipates is still not accurately quantifiable, but good progress has been made with dynamic loading cells to monitor rockbolts, which, together with boundary deformation monitoring, have allowed for the determination of the energy dissipated by the system and the consumption of the system capacity at the end of the process from each particular seismic event, improving operational decisions for rehabilitation.

(a) (b)

Figure 10 **(a) Rock fracturing observed around the excavation contour; (b) It is possible to see mechanical interlocking of blocks with fully grouted rebars inside (Muñoz 2021)**

3 Conceptual behaviour of rock support system

The support system, shown in Figure 11, considers reinforcing elements and retaining elements arranged sequentially to achieve different layers of support that, when working together, configure the reinforcement system. The system takes into account a pattern of bolts that reinforce the area closest to the excavation and, at the same time, provide the points of support, holding and securing the mesh that will retain and limit the displacements of the rock between bolts.

Depending on the design, there may be a second layer where cables are installed, anchored to areas less disturbed by the excavation and deeper than the bolts. These cables support a second layer of mesh and the previously installed initial retention layer.

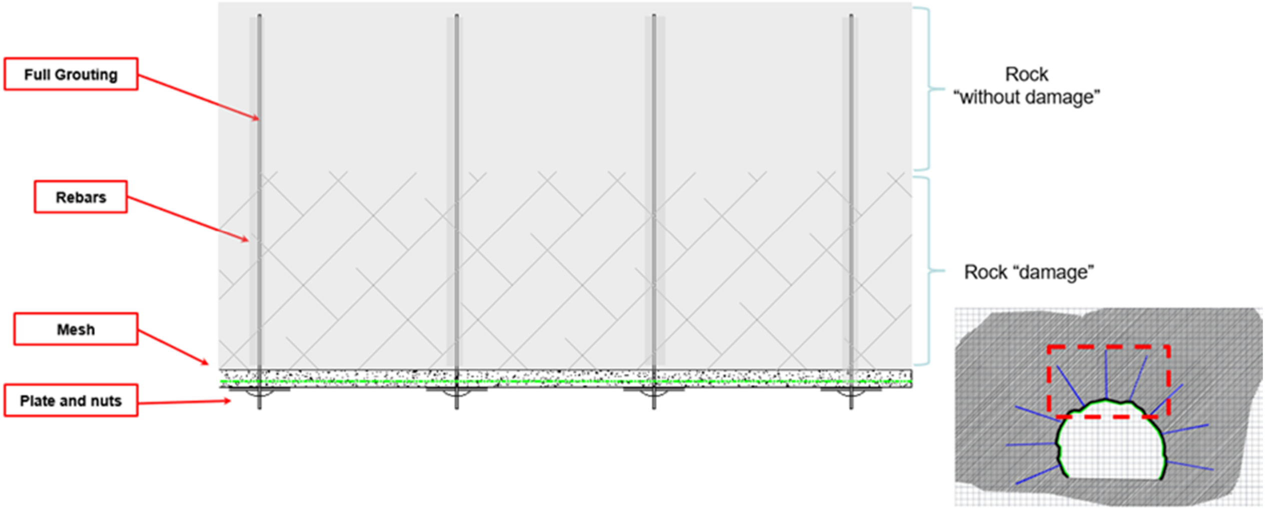


Figure 11 Diagram of rock support elements and stress distribution scheme in the surrounding area

The use of stronger mesh, which allows for the implementation of stronger retention systems, plays a fundamental role in the functioning of the support system. This is because, given the rock's failure mechanics under dynamic loads, rock displacements will occur in all directions, generating stresses in different directions, particularly shear stresses. These stresses can lead to early failure of some reinforcement elements, leaving that volume of rock without reinforcement or support from the mesh. Therefore, the retention system must have sufficient capacity to absorb that load and distribute it to the surrounding elements that have not failed.

By distributing the excess loads to the reinforcement elements in the vicinity, larger displacements are prevented, limiting and stabilising the fractured rock. This creates an arching effect that improves stability and prevents the collapse of specific areas that could trigger further instability (Muñoz 2019). This behaviour is illustrated in Figure 12.

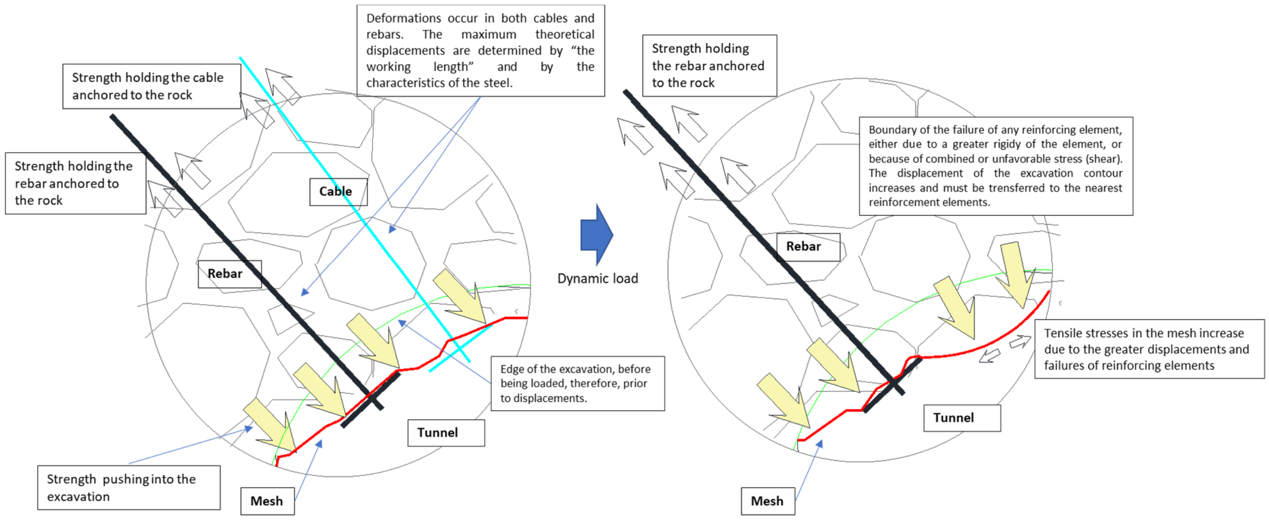


Figure 12 Schematic representation of rebars and cable, before and after being loaded

Figure 13 shows how the fractured rock has been retained, resulting in displacements in the direction normal to the tunnel walls of more than 100 cm. These displacements have caused the central bolts in the bulging area to break. However, the load has been redistributed to the surroundings and is being supported by the peripheral reinforcement elements, preventing uncontrolled disassembly. The basal area of the 'bulged' zone is greater than 16 m^2 and the 'curve height' is over 1 m.

Figure 13 Photographic records with evidence of displacement of the rock mass contained by the support elements

When the boundary of the tunnel is subjected to loads, the rock fractures and displacements occur towards the excavation (free face), generating stresses in the retaining elements (mesh and shotcrete) and forces in bolts and cables. These forces can be direct, transferred from the rock, or indirect, passed on from the retaining elements.

It is worth noting that just like the rock's strength can be exceeded leading to its failure, a similar situation occurs with the grout of the reinforcement elements, allowing for elongation and the functioning of the bars and cables. At this stage, these elements play a crucial role in limiting the displacements of rock fragments.

Furthermore, in the failure zone, there will be displacements in directions that are not necessarily axial to the bars, which could cause them to fail prematurely. The mesh plays a fundamental role in compensating for and transmitting tensions to the reinforcement elements that have not yet failed, thus emphasising the collaborative role of the ‘support system’.

4 Evolution of the main changes in rock support systems

Figure 14 shows the main changes that have been made in rock support systems in relation to primary rock extraction rates at El Teniente mine and the number of rock bursts per year. The chart highlights:

- In the 1980s, the inclusion of better external elements (plates and nuts) along with the application of shotcrete to improve system performance. The bolt, mesh, and shotcrete system became a standard in productive levels.
- In the 1990s, the use of chainlink mesh as a replacement for welded mesh, enhancing the retention capacity of the system and increasing load transfer to external elements and subsequently to rockbolts (Rojas 1993).
- In the 2000s, the use of friction bolts at the working face for block stabilisation, as well as improvements in confinement wall anchoring in the walls of productive levels. Operational guidelines for QA/QC during installation was a key aspect during this period (Celis et al. 2006).
- In the early 2010s, the implementation of layered systems to increase retention capacities (using two meshes) and dedicated anchors for each layer, allowing for progressive transfer of dynamic loads as needed. Dynamic testing of the systems and the appearance of better steels were also considered during this stage to modify the geometries of plates, nuts, and bars, including changes in their diameters (Muñoz et al. 2014).
- In the mid-2010s, the use of meshes with greater energy dissipation capacity became relevant for comprehensive system improvement. Additionally, a strong process of mechanised installation of rock support began as part of the risk management and control strategy for rockbursts. For developments with this risk, mesh application at the working face was also included to ensure worker safety during explosive loading stages (Rojas & Landeros 2022; Landeros Córdova 2022).
- In recent years, one of the most significant improvements has been the use of micro-alloyed steels in bars, maintaining their geometry while increasing the system's capacity without modifying operational practices for rock support installation.

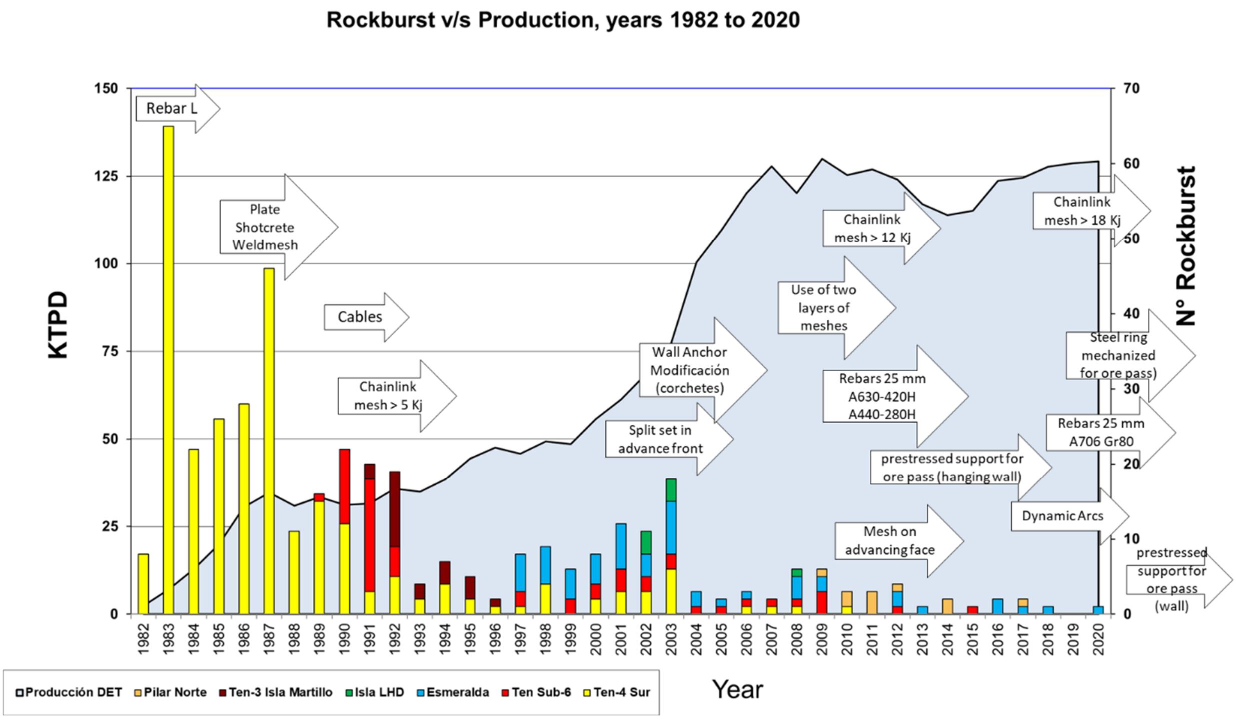


Figure 14 **The graph indicates the number of rockbursts versus ore production in hard rock mining where uniaxial compressive strength is greater than 100 MPa. In addition, the year of the inclusion of any design or modification in relation to support in the mining preparation is indicated (modified and updated from Muñoz et al. 2016)**

5 Conclusions

There are a series of measures aimed at protecting and maintaining tunnel stability, and these are part of the strategy to prevent the consequences of rockbursting. The last link is the support system and if it is loaded, it implies that the previous mitigation stages were not sufficient or were not effective.

A seismic event causes an increase in stresses, suddenly displacing the tunnel boundary. When surpassing the rock's resistance, it fractures and is ejected into the excavation. Therefore, the support system must reduce rock rupture, limit displacements, and keep the tunnel functional.

The elements that make up a support system must be able to sequentially transfer the induced stresses from one element to another. In other words, the mesh, when loaded, must transmit the stresses to the plate; the plate will transfer the stresses to the nut, and the nut to the rebar. These elements must not fail before the rebar. On the other hand, since the process of rock rupture and displacements can generate unfavourable stresses on the bar (shearing), there must be some redundancy in the arrangement of this element.

Dynamic rock support is a fortification system designed in such a way that, when loaded due to a seismic event, it deforms by consuming energy. It must be designed to allow for displacements while limiting them. Retention systems play a fundamental role in this, justifying the sustained development of stronger meshes. The rebars must be made of resistant steels that maximise their toughness. Additionally, the depths of potential failure must be well estimated in order to evaluate the anchorage length and complementing the rebars with cables if necessary. Thus, the support system must not only dissipate the energy from the seismic event but also control rock fractures, limit their displacements, and allow the mechanical interlocking of fractured rock, aided by the arch effect generated, to dissipate the energy and maintain the functionality of the tunnel.

The reviewed cases support the concept that the energy dissipated in the tunnel boundary is the sum of the energy dissipated by the support plus the energy consumed in rock rupture.

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