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Case study: use of rebars with microalloyed steels in tunnels with induced seismicity

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Abstract

The planned El Teniente mine conveyor tunnel has a length of over 9 km, going from the underground mine to the surface and is currently being developed with four active advance faces: from the surface, from inside the mine, and two faces with access through the construction decline facility called P4600. The conveyor tunnel will be used to extract all the production of El Teniente mine and therefore has a strategic role for the corporation. In early February 2023, a high-magnitude induced seismic event was recorded near the face of the Correa tunnel. Due to its energy and magnitude characteristics, this seismic event is the highest recorded in the El Teniente project's tunnels and developments.

Due to the high induced seismic activity experienced in this tunnel in recent years, the El Teniente division has implemented a ground support design focused on improving the interaction between the support elements that make up the support system. The aim is to enable the system to dissipate energy, deform, and maintain the stability of the tunnel during large seismic events. In particular, the retention capacity has been increased, and reinforcement bars with microalloyed steels have been used to enhance the probability of the bolt achieving the desired behaviour; that is, a ductile behaviour that fully develops its toughness.

Keywords: *ground support, El Teniente mine, dissipate energy, ground control*

1 Introduction

In February 2023, a seismic event with a local magnitude of 2.6 was recorded near the advancing front of the Correa tunnel, which extends from the mine to the surface. The event occurred 59 seconds after firing. This seismic event represents the highest energy and magnitude recorded during the construction of the main tunnels.

Considering the characteristics of energy and magnitude, the ground support system managed to contain the rupture of the rock, preserving the stability and global geometry of the tunnel. Additionally, there are measures prior to support which determine the condition of the tunnel after the induced seismic event, since they have been implemented to reduce the damage and risk to people in the tunnels, such as exposure reduction, mechanised methods and preconditioning of the rock mass. However, the rupture mechanism of the seismic sources does influence the amount of damage that will be experienced by the tunnel.

2 Tunnel and reinforcement characteristics

The Correa tunnel has a length of over 9 km, with a semi-circular shape measuring 8.5 m in width and 6 m in height. It is currently being developed from four working fronts: two at both ends and two central fronts accessed through the tunnel P4600 construction facility. The front affected by the event is known as the Tunnel Correa Interior Mina (TCOIM).

The seismic event data is as follows: date 5 February 2023, time 01:22:59, M_L2.6, and energy 2,500 MJ.

At the beginning of 2016, El Teniente's geomechanics department updated the ground support criteria previously used in the tunnel, incorporating new support elements and systems.

A zoning approach was developed based on available information, considering the tunnel's path through different lithologies, depth below surface of the tunnel, and geotechnical conditions. Initially, five types of ground support systems were designed for use in five different zones. Currently, the zones have undergone minor variations in length, and the ground support designs have been modified only for the systems implemented in areas with greater geomechanical complexity.

2.1 Reinforcement criterion

2.1.1 Development reinforcement

An initial phase of ground support elements is installed immediately after firing (at and in front of the face) to ensure personnel safety and to prevent deterioration of the rock mass. The timely installation of these elements plays a crucial role in achieving the objectives. The installation process for the ground support elements is mechanised to reduce personnel exposure.

2.1.2 Final reinforcement

The final phase of ground support installation is implemented to achieve the scheduled continuous operation in the sector. The final ground support system is generally installed behind the active development front.

For both types of support (development and final), the configuration, arrangement, elements, and safety factors of the components are determined according to the established criteria for each sector. The design of these support systems considers the specific requirements and conditions of the tunnel, ensuring the necessary stability and safety measures are in place to support continuous operations.

2.2 Aspects considered for increasing capacity in higher-risk support categories

The seismic activity observed in recent years has affected the construction of the Correa tunnel, sometimes causing damage and reducing the capacity of the support systems and risk management measures implemented in these work fronts to their limits. The information and lessons learned from each of the seismic events that have affected the tunnel have been studied and have allowed for the incorporation of additions.

Figure 1 shows the conveyor tunnel and the induced seismicity between 2018 and 2021. The magnitude is local magnitude based on Hanks and Kanamori estimation control measures and modifications to the support systems (Rojas et al. 2022).

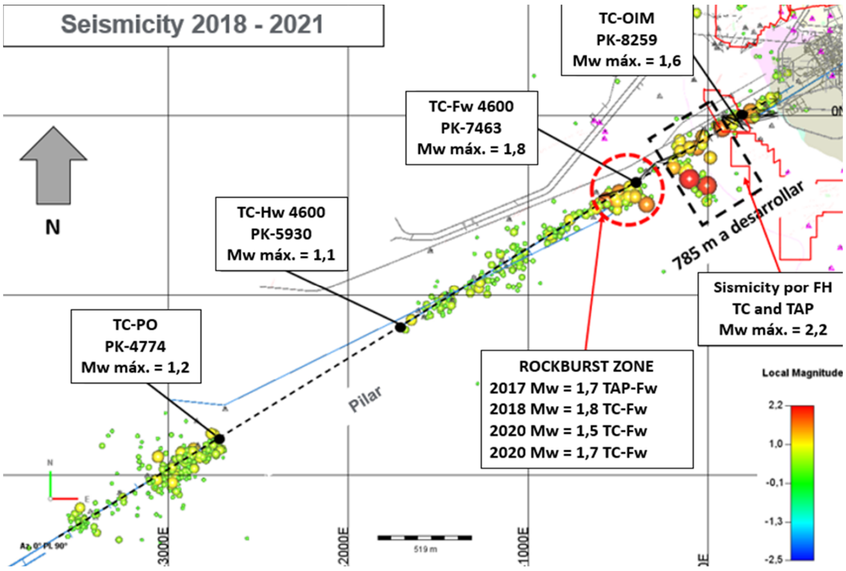

Figure 1 **Recorded seismicity on the Correa tunnel development. High frequency and magnitude of events have affected the tunnel in between 2018 to 2021**

2.3 Characteristics of the ground support system in Tunnel Correa Interior Mina development

Currently, the installation of development ground support is carried out using mechanised equipment immediately after the isolation period following the advancement blasting. This process ensures the stability of the excavation and prevents workers from being exposed to areas without ground support. The process of incorporating ground support elements is regulated by a geomechanical methodology (Muñoz et al. 2016) with defined steps for the implementation of new elements. In particular, the elements used in the support of the Correa tunnel are part of the studies carried out in recent years by El Teniente division. The support elements are the result of dynamic and static testing, as well as corrosion evaluations.

Table 1 shows the ground support installed immediately after blast and the second layer of ground support or final ground support (Muñoz et al. 2014)

Table 1 Principal characteristics of installed reinforcement at Tunnel Correa Interior Mina

Development ground support	Second layer ground support
0.05 m shotcrete grade H-30	Must be installed 3 m behind the advance face
Rebar	0.05 m second layer of shotcrete
Diameter 25 mm	Second mesh type chain-link Ø63
Steel A706 Gr80	Two cables per hole on the back
Grouting at full column (cement grout)	Length 8.0 m
Rebar length 4 m (3.85 m inside the rock)	Space between cable 2 m
Space between bolts 1 m	Space between cables lines 1 m
Burden between bolts lines 1 m	Two cables per hole on the sides
	Length 6.5 m
Mesh type chain-link Ø63	Space between cable 2 m
Wire diameter 4 mm, tensile breaking strength >1,770 N/mm^2	Space between cables lines 1 m
	Cables considering anchors (fully grouted and plate and wedge) and are plain strand

2.3.1 Mesh

At the beginning of the mining in primary rock (hard rock with UCS > 100 MPa), following rockbursts that affected and halted the operation in the Reservas Norte, the division initiated a series of investigations related to mining operations and improvements in support systems. These investigations led to modifications in the types of mesh used and transitioned from welded mesh to woven (chain-link mesh).

The rock failure mechanics, the volumes involved, the interaction with reinforcement elements, and the required capacity to maintain the rock in place, while allowing limited displacements have driven continuous development in woven mesh with greater capacity. These advancements aim to enhance the support system's effectiveness in mitigating rock mass movements and maintaining stability of the mine excavations.

Currently, the meshes used in the TCOIM are installed mechanically – that is, without exposure to people – and they dissipate between 12 and 18 kJ of energy based on laboratory drop tests.

2.3.2 Cables

Cables provide deeper anchoring so that in the event of block activation, due to dynamic loads, the support system can ensure that it has the capacity to support the fractured rock together with the retention elements. Previous dynamic loadings have caused damage to the Correa tunnel, and it has been observed that the depth of the damage can exceed the length of the rebar bolts. If the zone where block formation is possible is not reinforced or if there are installation issues with the cables, nothing will prevent the collapse of the tunnel.

The cables used are 0.6 in diameter and their quality is rated at 261 kN (minimum breaking strength of strand) according to ASTM Standard 416-06.

2.3.3 Rebars

In recent years, El Teniente division has been working to improve the interaction between the elements that make up the support system, with the aim being to dissipate energy, deformation, and maintaining tunnel stability during dynamic loading. One area of focus has been the behaviour of the rebar (bolt) when rapidly loaded. While previous efforts aimed to maximise the energy dissipation capacity of the system, the focus has shifted to increasing the probability that the bolt exhibits the desired behaviour, specifically, fully developing its ductility and toughness.

Studies led by the geomechanical studies department at El Teniente division have shown that the use of 'low-alloy steels' yields the best results in terms of strength and toughness. These steels are a family of alloys based on low carbon steels (<0.30% weight percentage) that exhibit improved mechanical properties. This is achieved through controlled thermomechanical treatments applied to steels with small additions (less than 0.5% by weight) of elements such as niobium, titanium, and vanadium. The role of these microalloying elements, along with appropriate thermomechanical treatments, is to modify the microstructure by refining the grain size and employing other micro-hardening mechanisms that maintain reasonable toughness and ductility. This ensures the development of the load–displacement curve with the area under this curve related to the energy 'consumed' during deformation.

In line with this purpose, international standards related to mechanical behaviour and chemical composition have been reviewed, establishing relationships with the desired properties for adequate toughness and strength. Specifically, ASTM A572 and ASTM A706 standards concerning microalloyed steel bars have been examined. Simultaneously, domestic suppliers capable of producing bars with these characteristics have been sought, identifying that A706 Grade 80 reinforcement bolts offer advantages over the carbon steels typically used until that time.

Currently, all four faces of the Correa tunnel incorporate reinforcement bars made of A706 Gr 80 steel.

2.4 Conceptual interpretation of the functioning of the ground support system

The designed system incorporates reinforcement elements and retention elements arranged sequentially to create different layers of support that collectively form the support system. The system includes a dense pattern of bolts that reinforce the area closest to the excavation and serve as anchor points, supporting and securing the mesh that will retain and limit rock displacement in the areas between the rebars. In a second stage, following a second 5 cm shotcrete application layer (together with the first application shotcrete layer, totalling 10 cm in thickness), cables are installed that anchor to less disturbed areas of the excavation and beyond the reach of the rebars. This reinforces the zone where larger block activations may occur during dynamic events. These cables support a second mesh and the previously installed retention layer (5 cm of shotcrete, mesh, and another 5 cm of shotcrete), resulting in one of the most capable retention support systems used in El Teniente division. Figure 2 shows the scheme of the distribution of the ground support elements and the area of the tunnel where the system is installed. The degree of alteration of the rock as a result of the excavation is mentioned.

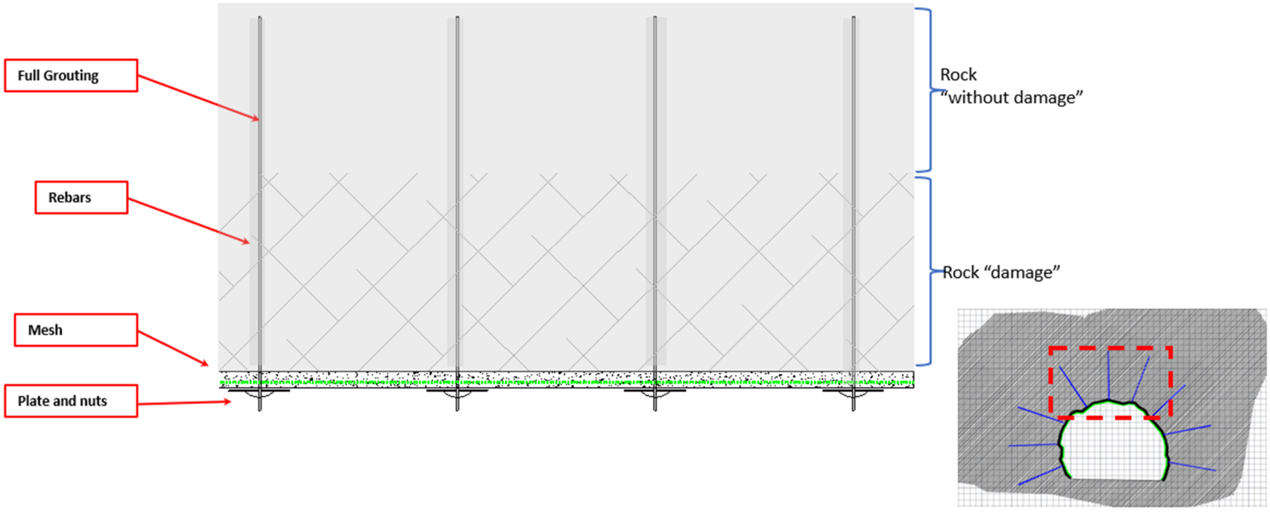

Figure 2 Interaction scheme of reinforcement system

The increase and development of higher capacity meshes in recent years play a crucial role in the functioning of the support system. Given the rock's rupture mechanics under high-magnitude dynamic loads, there will be rock displacements in all directions, generating stresses in different directions, particularly shear stresses. This will lead to early failure of some reinforcement elements, leaving that volume of rock without reinforcement or support for the mesh. Therefore, the retention system must have sufficient capacity to take on that load and distribute it to the surrounding elements that have not failed. By distributing the additional loads to the reinforcement elements in the vicinity, further displacements are prevented, limiting, and stabilising the fractured rock. This creates an arching effect that facilitates stability and prevents the collapse of specific areas that could trigger larger instabilities. Figure 3 shows the scheme of the distribution of the ground support elements once the tunnel has been loaded. The rebars work – some fail and the loads are transferred to the neighbouring reinforcements through the mesh.

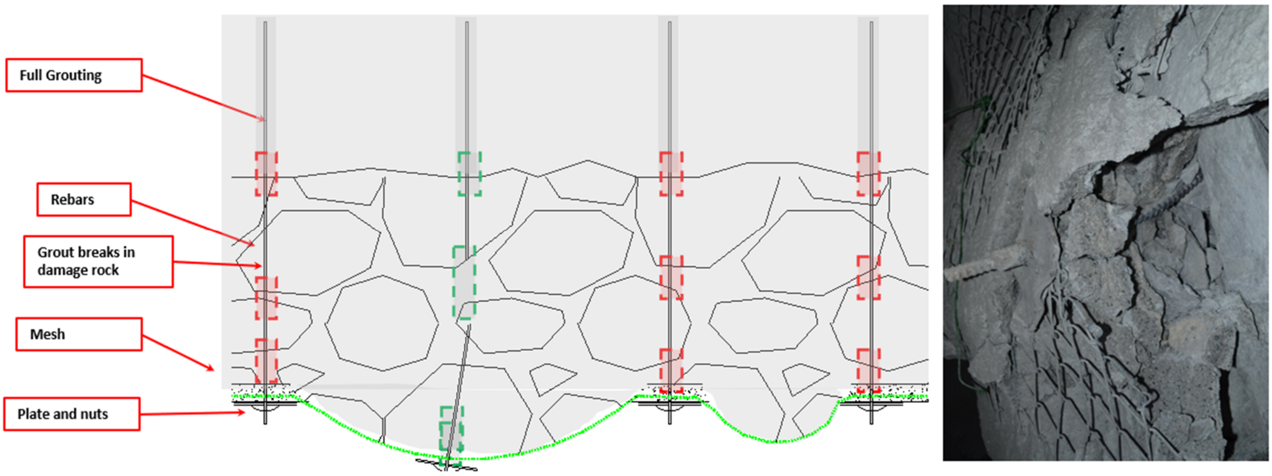

Figure 3 Working scheme of the interaction of the reinforcement, when the rock failure occurs in the tunnel

Considering the different types of meshes and bolts that can be used, it is possible to combine them to create different systems which are currently employed in the division and have varying static and dynamic capacities, as well as variability in costs and installation times.

Depending on the conditions of each tunnel or productive sector to be reinforcement, one of the 10 typically used systems will be selected. These systems combine one or two layers of reinforcement and retention, composed of cables and/or bolts of different diameters, steel quality, and patterns. They support one or two layers of mesh, which may or may not be protected by layers of shotcrete, and their combined action determines the overall capacity of the system.

In general, considering the seismic conditions present in El Teniente mine, the focus is on determining the required energy dissipation capacity of the support system and the expected depth of damage. Based on this, the appropriate system is selected.

The TCOIM uses the highest capacity system used in tunnels since it not only has high energy dissipation capacity but also provides reinforcement and anchoring of larger apex blocks; a condition not achievable with rebars alone. Additionally, modifications have been made to the types of steel used in rebars, replacing the traditionally used A630-420H steel with A706 Gr80 steel. This change in steel characteristics reduces the possibility of early failures associated with grain singularity, thereby increasing the working potential of the bars and energy dissipation capabilities.

3 Damage in tunnel by the seismic events of M_L2.6 magnitude

Once the seismic event occurred and after the isolation period, a visual inspection of the tunnel was conducted, revealing a large area affected by displacements and bulking in multiple areas. Evidence of damaged cables and rebars was identified, but there were no areas where the support system had failed.

Figure 4 shows the overall stability of the tunnel and how the support system, despite being damaged over a length of 100 m, prevented rock projection or block falls into the tunnel. The small rock fragments observed on the floor correspond to material from the advancing blasting face.

Figure 4 Photo showing the damage at the Tunnel Correa Interior Mina after a large seismic event

Given the identification of bulking areas, heavily stressed rebars, cables, and plates, and other evidence of capacity consumption in the support system, a request was made for laser scanning and drilling holes for inspection to assess the demand on the ground support and the depth of the damaged zones.

3.1 Tunnel surface displacement

Using previous baseline scans, the geomechanics team of the project performed a point differential analysis and obtained the following results. The evaluated section corresponds to a 100 m linear stretch and has been divided into three zones for easier analysis: Zone 1 consists of the 40 furthest linear metres from the face, Zone 2 consists of the next 20 linear metres, and Zone 3 consists of the 40 linear metres closest to the face.

- In Zone 1, deformations are mostly detected between 0 and 0.05 m.
- In Zone 2, higher deformations are detected, with deformations exceeding 0.1 m in the 10 m closest to Zone 3.
- In Zone 3, displacements greater than 0.2 m were detected in many areas.

Figure 5 shows a schematic comparison between the shape of the tunnel after development and after an induced seismic event. This zone is considered Zone 1.

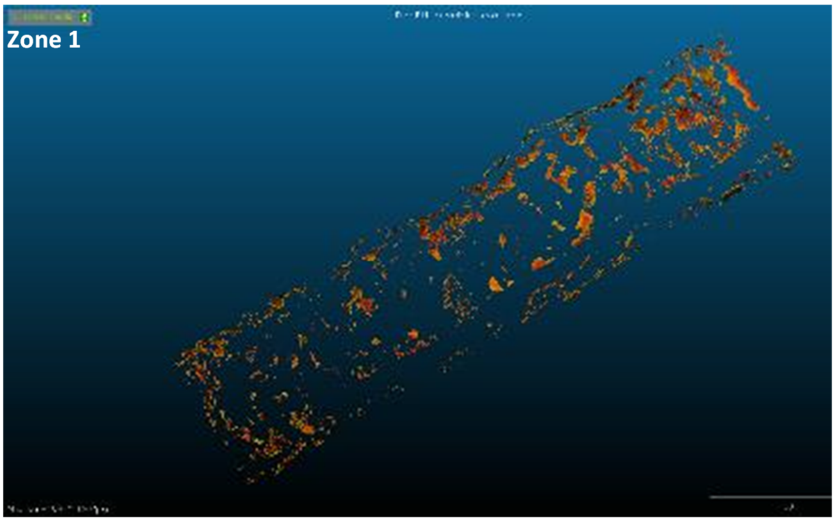

Figure 5 Comparation of the shape measured by LiDAR before and after a induced seismic event

3.2 Reinforcement consumption

Determining the force or energy with which the support elements are subjected to during a seismic event remains a challenge. However, in recent years, the incorporation of new techniques and practices has allowed for improvements in these estimations.

The implementation of dynamic load cells in this tunnel has enabled the measurement of loads exerted on the specific bolt where the load cell was installed over time. Depending on their location in the gallery, the load cells are affected differently by the seismic event's associated loads. In the area of interest, four dynamic load cells recorded data during the seismic event.

By evaluating the force measured by the load cell and considering the displacement along the tunnel contour, the work or energy required to displace the tunnel contour can be determined using the equation.

$$Energy = Load\ x\ displacement \tag{1}$$

One of the load cells recorded a maximum amplitude of 272.1 kN. Other load cells recorded lower amplitudes and will not be used for these analyses, and the ultimate capacity of the rebars based on laboratory tests is approximately 372 kN.

The mechanical characteristics of the rebar bolt and cable steel, the elongation of these elements, can be determined based on their working length. It is assumed that the working zone is equal to the rock fracturing zone at the tunnel edge, determined from drillhole inspections. For working lengths of approximately 1.6 m, the elongations of the bolts range from 0.18 to 0.23 m, while for cables, it is only between 0.07 and 0.09 m.

To estimate the energy consumption and consequently the use of ground support, it is possible to determine the displacements obtained from the laser point differences and multiply them by the force recorded by the load cell. This calculates the energy based on the variation in displacement measured by the scanner. It is identified that for a displacement of 0.05 m, the energy is 13.6 kJ, and for 0.23 m, it is 61.2 kJ. These energy ranges are critical for the support elements used, whether cables or rebars, and these values were similar to results obtained from laboratory results in drop-test-type dynamic tests (Villaescusa 2014).

4 Results

With the conducted analyses and determining an average damage length, it is determined that, depending on the tunnel's surface deformation, an estimation of the consumption of the energy dissipation capacity of the support system can be made. Based on this, recommendations are provided to determine the system's design capacity. Table 2 presents the recommendations for reinforcement or rehabilitation according to the tunnel's surface deformation.

Table 2 Actions based on displacements

Displacement (m)	Add rebars Pattern 2 × 1	Add rebars Pattern 1 × 1	Add cables Pattern 2 × 1
< 0.05	–	–	–
0.05–0.15	Yes	–	Yes
0.15–0.23	–	Yes	Yes
> 0.23	–	Rehabilitation	Rehabilitation

5 Conclusion

The historical seismicity of the division indicates that the seismic event that occurred in February 2023, due to its energy and magnitude characteristics, corresponds to the highest recorded event detected during the construction process of the Correa tunnel.

Following the seismic event, onsite inspections revealed areas with bulking and support elements damaged in specific sectors. Despite bulking zones, the support in those areas managed to contain rock fragments, preventing their projection into the tunnel. The evidence of damage extends to approximately 90 m from the active face.

The TCOIM incorporates the highest capacity support system currently available in El Teniente division, with an energy dissipation capacity of over 75 kJ/m^2 using microalloyed rebars to reduce the possibility of early steel failures. Additionally, two layers of mesh, chosen from those with the highest capacity within the available El Teniente division catalogue, are used. The stability results following the seismic event validate the design strategy and highlight the crucial role played by the retention elements in the ground support systems.

From the analysis of rupture and displacements of the support system, it is evident that measuring more areas of the tunnel is necessary to increase the data on force distribution or surface velocities. This will allow for better distribution of the support system and identification of system deficiencies, as well as providing more information to understand the rock rupture mechanism.

A methodology is proposed for sectorising rehabilitation based on tunnel deformation that accounts for consumption of support capacity. It is essential to have baseline scan data to facilitate subsequent comparisons.

The scan of the tunnel using laser technology, estimation of the depth of damage through drilling, and rehabilitation allowed for an assessment of how much of the support systems capacity had been consumed.

This helped identify sectors that required additional rebars and cables to the existing ones, as well as sectors that need complete rehabilitation due to the observed damage.

Acknowledgement

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