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# Design and field implementation of steel straps reinforcement for pillar stability in high-deformation underground mining: engineering basis and lessons learned

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## Abstract

*The stability of pillars in large-scale underground operations represents a significant geomechanical challenge, particularly in environments characterised by high-stress and pronounced rock mass deformation. This paper presents the engineering, design, and field implementation of a steel straps (hereafter referred to as straps) reinforcement system as a supplementary support element for pillar repair and rehabilitation at the Chuquicamata underground mine.*

*The proposed system integrates high-strength steel straps with conventional support elements, including welded wire mesh, shotcrete, and tensioned cable bolts, with the objective of enhancing confinement and improving load redistribution within the support system. A design framework was developed based on static structural analysis using SAP2000, where the support system was modelled to evaluate its response under representative loading conditions. The results indicate that the inclusion of straps contributes to a reduction in bending demands within the shotcrete lining through improved load transfer mechanisms.*

*The paper describes the design methodology, including the conceptual basis of the reinforcement system, modelling assumptions, and criteria adopted for dimensioning. Emphasis is placed on understanding the role of straps within the overall support system, particularly in terms of structural continuity and interaction between reinforcement elements.*

*Field implementation is discussed in terms of constructability, installation sequence, and integration with operational constraints. While no direct measurements of support loads were available, the study incorporates 3D scanner measurements and qualitative field observations of the early-stage response.*

*Key lessons learned are presented, highlighting both the benefits and limitations of the system, and identifying opportunities for design optimisation in future applications. The findings contribute to the development of more robust and adaptable support strategies for underground mining environments subjected to large deformation demands.*

**Keywords:** *anchorage systems, rock mechanics, pilar reinforcement, underground mining, steel straps*

## 1 Introduction

Chuquicamata is a porphyry copper deposit that has been recognised globally for its large-scale open pit operation. The progressive depletion of economically recoverable surface reserves led to the transition from open pit to underground mining using the block-caving method.

The evolution of modern underground mining has been increasingly defined by the transition toward deep, mass-scale exploitation environments. As operations extend hundreds of metres below the surface, the stress

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state undergoes substantial intensification, triggering complex rock mass responses that challenge conventional engineering paradigms. Under these high-stress and confinement-loss conditions, structural components such as pillars are subjected to severe deformation and localised stress concentrations. Consequently, the mitigation of these unstable conditions demands a shift toward robust, high-energy-absorbing support systems capable of maintaining the integrity of the mining infrastructure over extended operational lifespans.

At the Chuquicamata underground mine, safeguarding the structural stability of pillars within the extraction level constitutes a critical operational requirement to maximise extraction area availability until drawdown completion. The active mining blocks are subjected to high-stress conditions consistent with the in situ stress field summarised in Table 1. The production level evaluated in this study is located approximately 200 m below the surface. These stress conditions, together with the intact-rock geomechanical properties of the Basic Geotechnical Units (Unidades Geotécnicas Básicas, UGTB) summarised in Table 2, have contributed to intense rock mass fracturing, thereby accelerating pillar degradation. To address severe pillar degradation, comprehensive rehabilitation strategies were deployed across the central macroblocks and subsequently extended to the N02–N03 and S02–S03 macroblocks.

**Table 1 Values of the principal stress presented in the central macroblock (Stress magnitude, azimuth (Az), and inclination of the major, intermediate, and minor principal stresses)**

| Macroblock ID | Principal stress | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Stress magnitude | | | Azimut | | | Inclination | | |
| | $\sigma_1$ (MPa) | $\sigma_2$ (MPa) | $\sigma_3$ (MPa) | $Az_1$ (°) | $Az_2$ (°) | $Az_3$ (°) | $Dip_1$ (°) | $Dip_2$ (°) | $Dip_3$ (°) |
| N01-S01 | 28.1 | 26.1 | 6.6 | 90.0 | 179.3 | 307.1 | 2.7 | 2.1 | 86.8 |

**Table 2 Summary of the intact rock properties considered in this study: density (ρ), compressive and tensile strengths ($UCS_{50}$, $\sigma_{ci}$, $\sigma_{tb}$), elastic parameters ($E_i$, ν), and the Hoek–Brown constant ($m_i$).**

| UGTB | Intact rock properties | | | | | | |
|---|---|---|---|---|---|---|---|
| | ρ (g/cm$^3$) | $UCS_{50}$ (MPa) | $E_i$ (GPa) | ν | $\sigma_{tb}$ (MPa) | $\sigma_{ci}$ (MPa) | $m_i$ |
| PEK (Potassic East Porphyry) | 2.61 | 96.5 | 37.12 | 0.21 | −3.84 | 92.4 | 20.77 |
| PES (Potassic East Sericitic) | 2.66 | 69.9 | 29.48 | 0.21 | −3.07 | 65.5 | 16.13 |
| QIS (Quartz Equal Sericite) | 2.70 | 67.2 | 20.06 | 0.21 | −2.38 | 62.2 | 17.36 |
| QMS (Quartz Major Sericite) | 2.70 | 76.5 | 27.01 | 0.22 | −2.29 | 69.3 | 23.64 |
| QMES (Quartz Minor Sericite) | 2.58 | 20.3 | 9.39 | 0.23 | −0.79 | 19.5 | 22.82 |

## 1.1 Straps

In sectors subjected to extreme strain demands, conventional ground support assemblies – typically consisting of shotcrete, welded wire mesh, and tensioned cable bolts – often experience serviceability limits, structural distress, or localised bending failures (Hadjigeorgiou & Potvin 2011). These limitations have driven the industry to evaluate high-performance surface support elements capable of enhancing confinement and

optimising load redistribution. The straps reinforcement system has emerged as a robust supplementary support element designed for high-deformation underground environments.

The straps are close to a mesh with 5 longitudinal steel bars of 10 mm diameter, interlocked with 6 mm diameter transverse cross-members, the schematic layout of which is illustrated in Figure 1. This design accommodates higher displacement and ensures uniform load distribution across the support system. Furthermore, its initial stiffness provides higher yielding resistance during the early stages of deformation compared to alternative ground support elements.

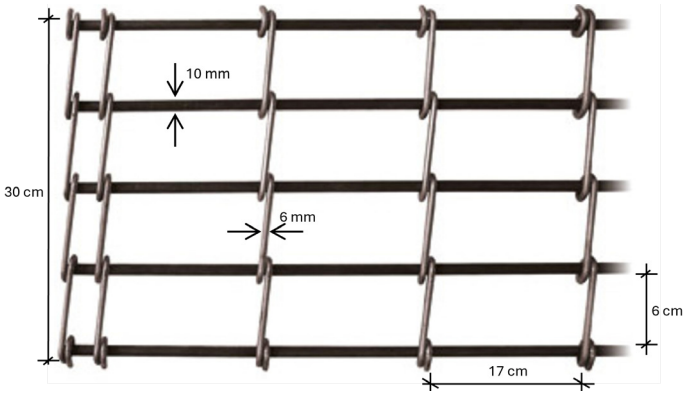



**Figure 1 Scheme of the straps**

## 1.2 Previous implementation experiences in global mining

Globally, steel straps have been successfully implemented to control adverse ground conditions. Notable applications include managing dynamic and seismic loading at Leinster Nickel Operations in Australia (Sandy et al. 2007), the use of integrated yielding-bolt, welded-mesh, and steel-strap systems in Canadian rockburst-prone mines (Simser et al. 2007), controlling high-deformation in drawpoints at the Didipio Gold–Copper Mine in the Philippines (Reola et al. 2023), and providing external pillar wrapping and confinement at the New Afton Mine in Canada (Yanagimura & Hadjigeorgiou 2022). Despite these empirical successes, technical literature has not yet formalised specific, theoretical design criteria for integrating these elements into composite linings. Consequently, current design frameworks rely primarily on laboratory testing, numerical approximations, and operational case studies.

Table 3 summarises previous applications and studies involving steel straps.

**Table 3 Summary of previous experiences**

| Location/operation | Bibliographic reference | Research focus and key technical information |
|---|---|---|
| Australia (Leinster Nickel Operations) | Sandy et al. (2007) | Performance-based seismic design utilising transverse straps in underground drives. |
| South Africa | Watson et al. (2017) | Large-scale punch tests recording higher initial stiffness than welded wire mesh, but lower deformability. |
| Philippines (Didipio Mine) | Reola et al. (2023) | Evaluation of operational versatility through the deployment of multiple ground support configurations. |
| Canada (New Afton Mine) | Yanagimura & Hadjigeorgiou (2022); Yanagimura (2023) | Pillar confinement under high-stress conditions. Analogous case to Chuquicamata, validated via a technical site visit. |
| Switzerland (Walenstadt) | Cuello et al. (2024) | Large-scale dynamic testing for design optimisation under severe impact and seismic loading. |

# 2 Industrial-scale trial proposal

An industrial-scale trial was developed to assess the use of straps for the repair and reinforcement of deteriorated pillars in the central macroblock. These trials aim to validate the structural and operational efficiency of the straps, ensuring their capacity to withstand loads, distribute them, and adapt to high deformations. These trials will include:

- design: development of the proposed support configurations
- implementation: installation of the straps together with conventional support elements
- instrumentation: three-dimensional (3D) scanner monitoring of the reinforced pillars
- evaluation of results: comparison of field observations and measured surface deformation.

## 2.1 Proposed ground support designs

The proposed design was developed based on existing empirical evidence, incorporating straps in combination with conventional pillar support techniques. Two distinct support schemes were developed to address different pillar conditions: one intended for pillars requiring rehabilitation following a scaling process, and another for pillars requiring reinforcement only.

The support configurations were developed for pillars associated with the 16 × 16 m and 16 × 20 m extraction level layouts. These dimensions correspond to the centre-to-centre spacing of the extraction drifts and drawbell drifts, respectively, and do not represent the pillar width and height. The production drifts have a nominal cross-section of 5.0 m in width and 4.75 m in height. Therefore, the effective pillar dimensions depend on the corresponding layout spacing and the geometry of the surrounding excavations, as illustrated in Figure 2.

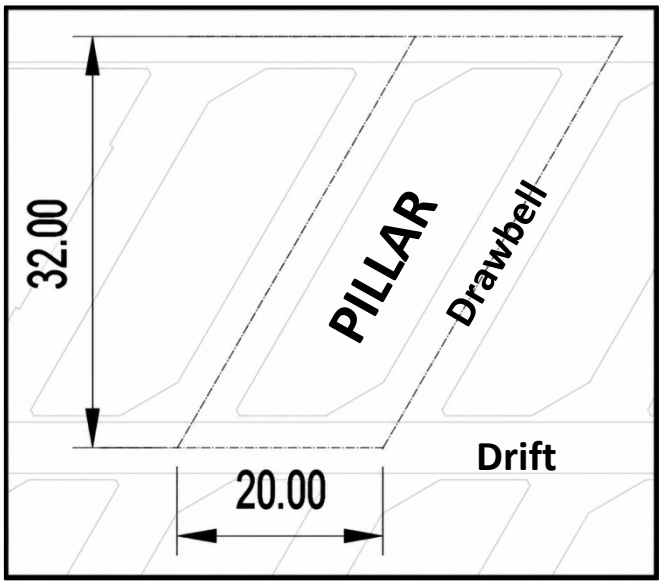



**Figure 2 Dimensions of the pillars and the mesh of the footprint used in the central macroblocks**

Figure 3 presents the support design for a 16 × 20 m pillar after scaling and surface preparation. This design incorporates the standard development support system, consisting of rockbolts, welded wire mesh, and shotcrete. Building upon this primary support system, an additional layer of ACMA C503 mesh layer is installed together with the straps. The straps are anchored to the rock mass using tensioned twin cable bolts and subsequently covered with an additional layer of shotcrete, resulting in a support system fully encapsulated within the shotcrete lining.

The strap arrangement was defined based on previous pillar wrapping applications (Yanagimura & Hadjigeorgiou 2022; Yanagimura 2023), which indicate that a longitudinal orientation along the pillar axis represents the most suitable configuration for this type of application. Nevertheless, this arrangement was complemented with transversely oriented straps to enhance load distribution throughout the entire pillar structure. A critical aspect of this configuration is the overlap length required to ensure the effective performance of the straps. According to Cuello et al. (2024), a minimum overlap of 0.8 m is recommended. However, an overlap of 1.2 m was adopted in the present design to accommodate specific construction and installation requirements.

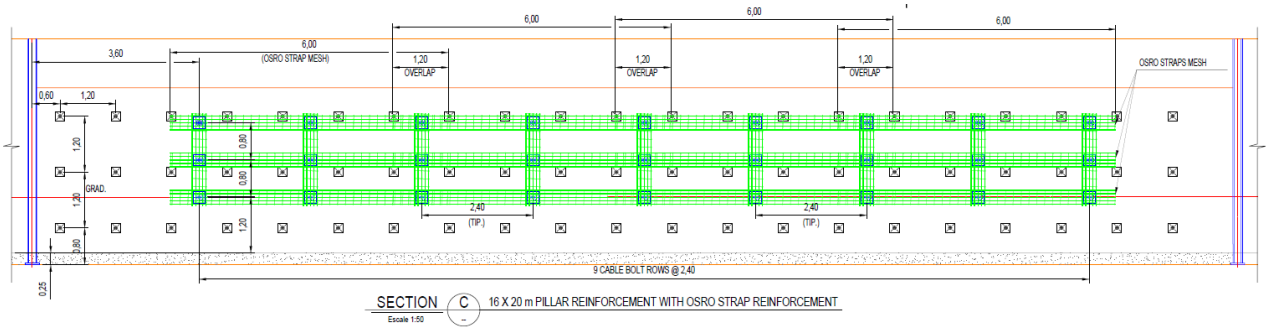
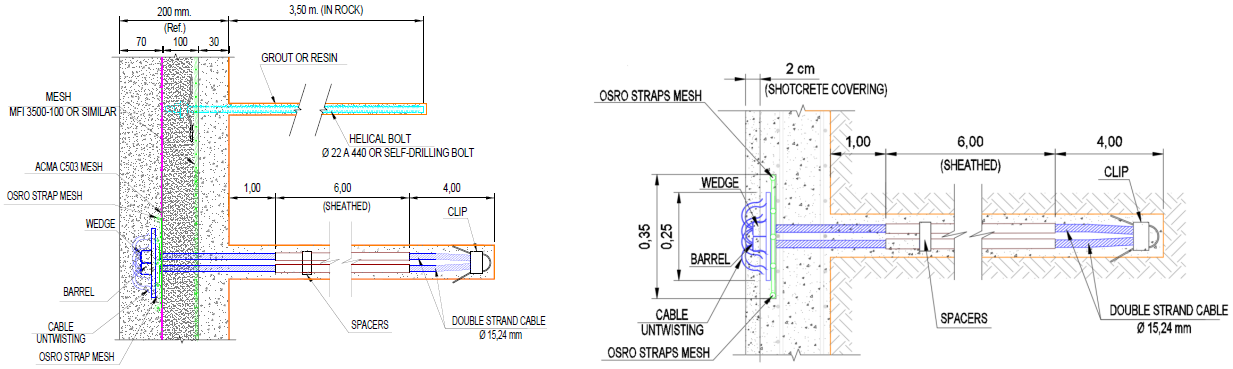



**Figure 3 Proposed ground support design for a 16 × 20 m pillar post-rehabilitation**

For rehabilitated pillars, the support system comprises a total shotcrete thickness of 200 mm, including a 70 mm outer layer that fully embeds the straps (Figure 4a). For pillars not requiring rehabilitation, the straps are covered by a 20 mm sealing layer, and localised recesses are prepared to access the existing mesh and cable bolt anchorage points (Figure 4b).




(a) (b)

**Figure 4 Detailed pillar ground support cross-section. (a) Post-rehabilitation; (b) Without rehabilitation**

## 2.2 Numerical model

A 3D numerical model was developed in SAP2000 to investigate the structural response of the reinforced shotcrete lining and quantify the internal forces developed within its components. Two configurations, with and without straps, were analysed to assess the contribution of the straps to load redistribution and lining performance.

The reinforced shotcrete lining was modeled using layered shell elements, which accounts for both membrane and bending behaviour. The layered section included G30 shotcrete, an inner MFI 3500 mesh, and an outer ACMA C503 mesh. The location of each reinforcement layer within the lining thickness was explicitly considered to account for its contribution to the flexural stiffness and capacity of the composite section.

Ground support elements, including cable bolts and rockbolts, were represented using frame elements connected to the lining at their corresponding anchorage locations. A representative symmetric section of the support system was analysed to reduce model size while preserving the support spacing and load transfer mechanism.

The main parameters and modeling assumptions are summarised in Table 4.

**Table 4 Main parameters adopted in the SAP2000 numerical model**

| Component | Numerical representation | Main properties and assumptions |
|---|---|---|
| Shotcrete | Layered shell element | G30 concrete; compressive strength of concrete $f_c' = 30$ MPa |
| Inner reinforcement | Steel layer within the layered shell | Commercial MFI 3500 wire mesh installed on the rock mass side |
| Outer reinforcement | Steel layer within the layered shell | Commercial ACMA C503 welded wire mesh positioned toward the exposed surface |
| Cable bolts | Frame elements | Connected to the lining at the corresponding anchorage locations |
| Rockbolts | Frame elements | Included to represent support stiffness and load distribution |
| Straps | Equivalent-area frame elements ($A_{\mathrm{eq}}$) | Five Ø10 mm longitudinal bars represented by one frame element with $A_{\mathrm{eq}} = 392.7$ mm$^2$ |
| Strap transverse bars | Not explicitly modelled | Ø6 mm bars spaced at 150 mm |
| Applied demand | Uniform static pressure ($q_s$) | $q_s = 98.1$ kPa $(10$ tf/m$^2)$ applied to the rear face of the lining |
| Lining safety criterion | Capacity-to-demand ratio | Minimum Factor of Safety of 1.20 against cracking |
| Anchorage safety criterion | Capacity-to-demand ratio | Minimum Factor of Safety of 1.50 |

For modeling purposes, each strap was simplified as a single frame element with a cross-sectional area equivalent to that of its five Ø10 mm longitudinal bars. This representation preserves the axial stiffness, $EA$, of the original strap. The validity of the simplification was assessed through comparison with a detailed model in which each longitudinal bar was represented individually. Although the detailed representation provided a more distributed load transfer mechanism, it required a substantially more complex nodal compatibility scheme between the frame and shell elements. The comparison showed no significant differences in the resulting bending moments and overall load distribution. Therefore, the equivalent-area frame representation was adopted.

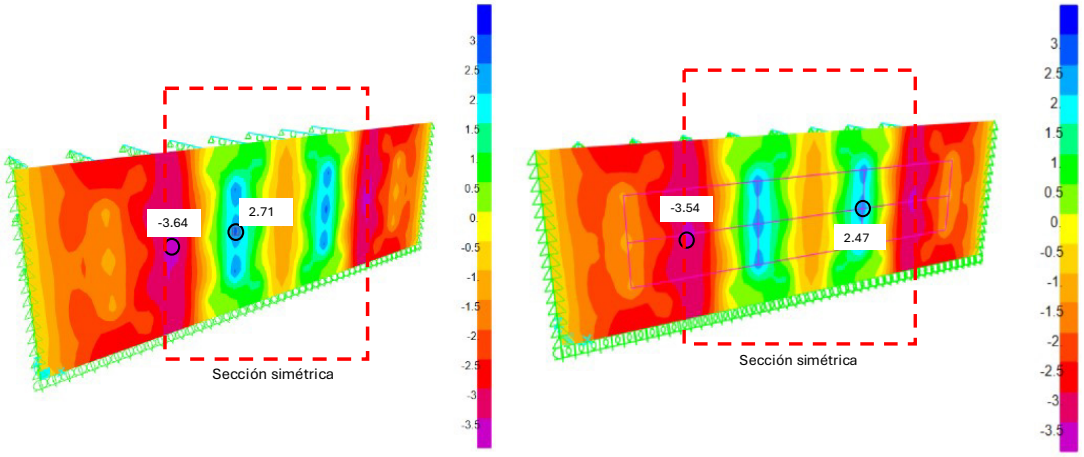
Full displacement compatibility was assumed between the shotcrete, reinforcement layers, and strap connection nodes. A uniform static pressure of $q_s = 98.1$ kPa $(10$ tf/m$^2)$, based on Barindelli et al. (2023), was applied normal to the rear face of the lining. Cable bolts and rockbolts were included to represent support stiffness and load distribution; however, only cable bolts were considered in the anchorage capacity calculation. Dynamic loading, cyclic degradation, and connection failure were outside the scope of the model.

The following assumptions were considered in the analysis:

- The lining was treated as a flexible structural element. The shotcrete core between the reinforcement meshes was considered the primary load-bearing component, while the reinforcement layers contributed to the tensile and flexural resistance of the composite section.

- The structural contribution of the MFI 3500 and ACMA C503 mesh was incorporated through its equivalent steel area and its position within the layered shell section.
- The contribution of the straps was represented by their equivalent longitudinal steel area at the exposed side of the lining.
- Minimum Factor of Safety of 1.20 against lining cracking and 1.50 for the anchorage system were adopted.

The numerical results presented in Figure 5 show a non-uniform bending moment distribution governed by differences in stiffness and load transfer between the cable bolts and rockbolts. As the cable bolts attract a larger proportion of the applied load, maximum positive bending moments develop near the cable bolt anchorage locations, whereas maximum negative moments occur approximately midway between adjacent cable bolts. The incorporation of the straps reduced the maximum positive vertical bending moment from) 26.5 to 24.2 (kN m/m) (2.71 to 2.47 tf m/m), corresponding to a reduction of approximately 9%. This reduction is particularly relevant because the inner face represents a critical region of the lining, where the lower reinforcement ratio provided by the MFI 3500 mesh limits the structural capacity. Overall, these results demonstrate the contribution of the straps to reducing local moment concentrations and improving the structural response of the reinforced shotcrete lining.




(a) (b)

**Figure 5 Vertical Moments. (a) Wall without strap; (b) Wall with strap**

## 2.3 System capacity analysis

The capacity of the system was verified through the individual and combined assessment of its structural components, following the methodology reported by Castro et al. (2025). Assuming adequate borehole bonding, the anchorage capacity was governed by the steel cross-sectional area and grade. Double-strand cables were considered the primary support elements, while helical bolts provided a secondary contribution, with equivalent capacities of 192.2 and 113.7 kPa (19.6 and 11.6 tf/m²), respectively. By incorporating the equivalent steel area of the straps into the external face of the lining, an equivalent reinforced-lining capacity of $C_{\text{lining}} = 121.6\ \text{kPa}\ (12.4\ \text{tf/m}^2)$ was obtained.

## 2.4 Demanding load and safety factors

For a static design load of $q_s = 98.1\ \text{kPa}\ (10\ \text{tf/m}^2)$, the system satisfied the adopted acceptance criteria. The factors of safety, calculated as the capacity-to-demand ratio following Castro et al. (2025), reached 1.77 for the cable anchorage system and 1.24 against shotcrete lining cracking, exceeding the required values of 1.50 and 1.20, respectively. Dynamic loading conditions were outside the scope of this assessment.

# 3 Pilot trial on the use of straps

The pilot trial was implemented on 2 pillars located between drawbell drifts 11–12 South and 3–4 North along Production Drift 04 North in Macroblock N01/S01, as shown in Figure 6.

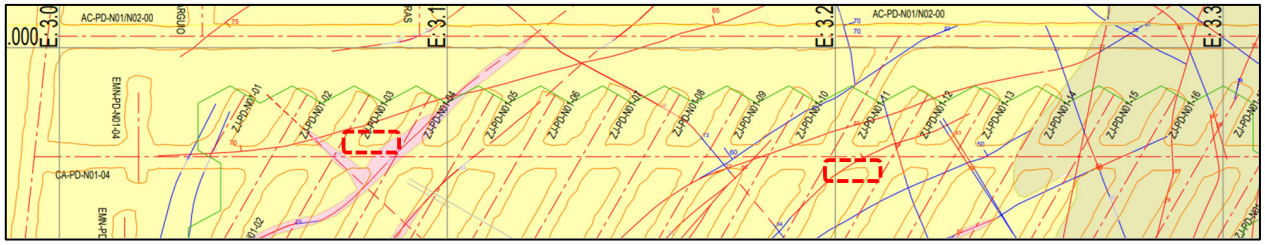



**Figure 6 Plan view of Macroblock N01/S01 showing the 2 pillars reinforced with straps along Production Drift 04 North**

The pilot design consisted of straps installed as supplementary surface reinforcement over the conventional bolt–mesh–shotcrete system. The straps act as confinement and load distribution elements connecting adjacent anchorage points around the pillar. The design defines the arrangement (orientation/location), sequence, and overlaps of the straps, as well as their integration with the mesh configuration and shotcrete seals, as shown in Figure 7.

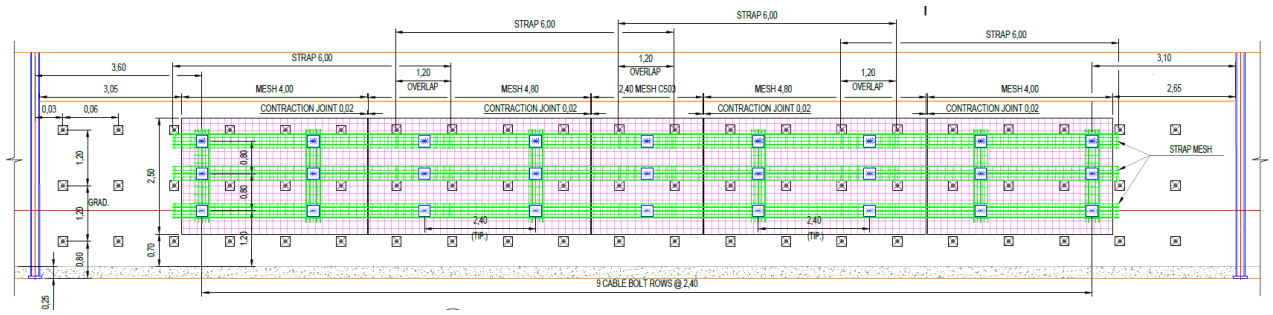
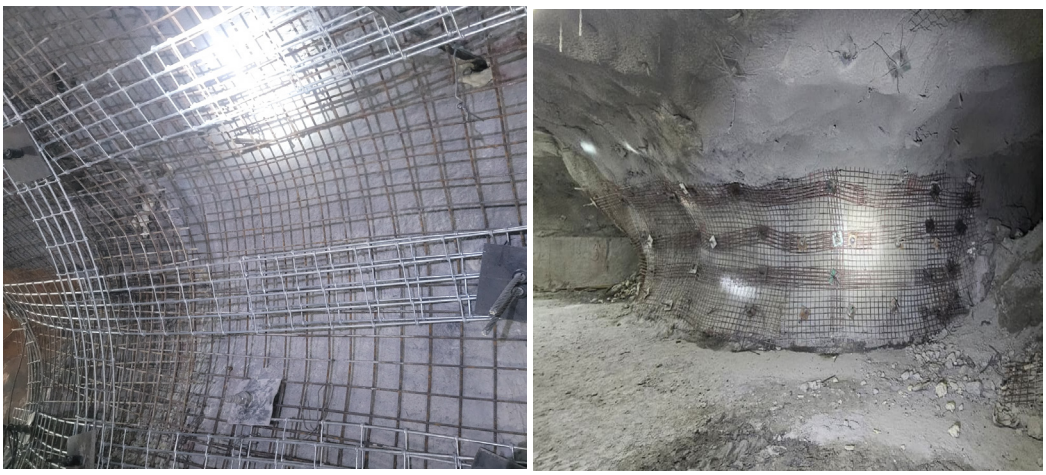



**Figure 7 Elevation view of the strap arrangement adopted for the pilot trial**

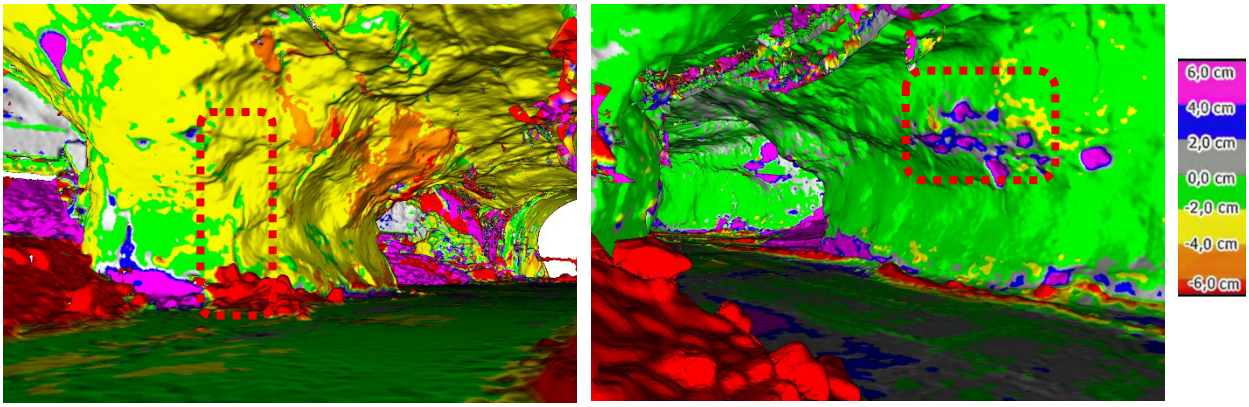
The installation process considered the preparation of the pillar perimeter, the installation of the surface support according to specification, and the assembly and securing of the straps in the arrangement and continuity established in the design, ensuring full contact and continuity of the system around the pillar. Figure 8 presents the photographic record of the construction.



(a) (b)

**Figure 8 Installation of the straps reinforcement in the extraction Drift 04 N. (a) Installation in Pilllar-11-12 South; (b) Installation in Pillar 3-4 North**

During the inspections, it was observed that Pillar 3-4N exhibits localised damage in the inner and outer loader-turning zones, areas where damage consistently manifests regardless of the ground support system. It is highlighted that the sector is under a high level of convergence, with historical precedents where even intensified solutions have been compromised (e.g. failure associated with a false tunnel/canopy and triple-mesh ground support in pillars along the same section). Despite these conditions, the strap system showed no evidence of generalised loss of confinement during the inspection period. Scanner measurements backup the deformation condition of the sector and establish baselines for temporal monitoring, as shown in the Figure 9.




(a) (b)

**Figure 9 Installation of the straps reinforcement in the extraction Drift 04 N. (a) Installation in Pilllar-11-12 South; (b) Installation in Pillar 3-4 North**

Pillar 11-12 S exhibits predominantly operational damage caused by loader passage and equipment interaction (impact/scuffing). Conversely, its incipient cracking reflects the geomechanical demand of the surrounding environment, proving that the strap performance successfully accommodates these conditions while maintaining confinement continuity. Additionally, 3D scanner data effectively isolates global pillar deformation from localised operational damage.

# 4 Lessons learned

Based on the analyses previously shown for the Central Macroblock (MB Central), field observations indicate that the straps fulfill the function of surface reinforcement and maintain the structural integrity of the confinement, even under demanding conditions, without showing progressive degradation or systemic failures that affect global stability.

The 3D scanner monitoring indicated that deformation was predominantly localised along the horizontal direction, with measured surface changes of approximately 4.0–6.0 cm in specific areas and no evidence of generalised deformation across the overall pillar surface. These observations supported prioritising horizontal straps in the optimised design. Vertical straps were removed because no relevant vertical surface deformation was identified during the monitoring period and because their intersections affected bolt plate seating and installation efficiency.

Consequently, the observed performance demonstrates an improvement in structural continuity and stress redistribution. Therefore, there is a technical baseline to advance toward its adoption as a recommended practice in similar sectors, incorporating design adjustments to optimise its performance, as shown in Figures 10 and 11.

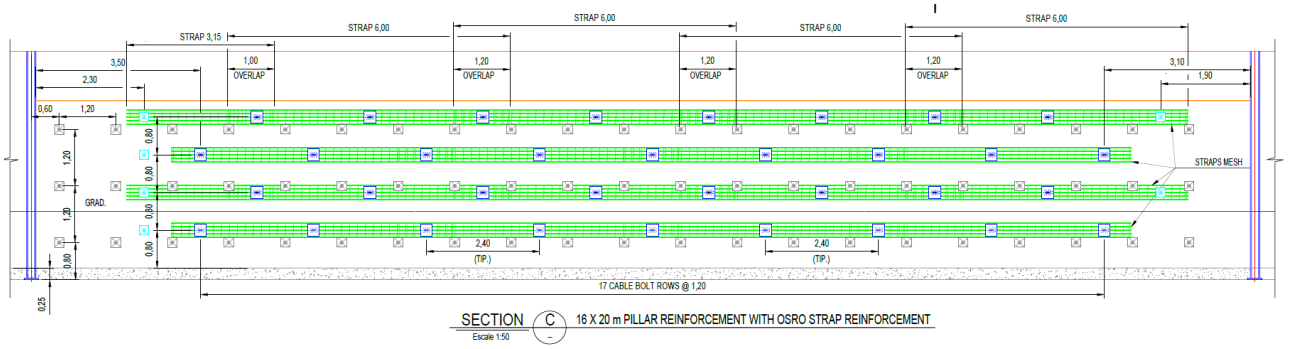



**Figure 10 New plane design based on the lessons learned from the pilot trial**

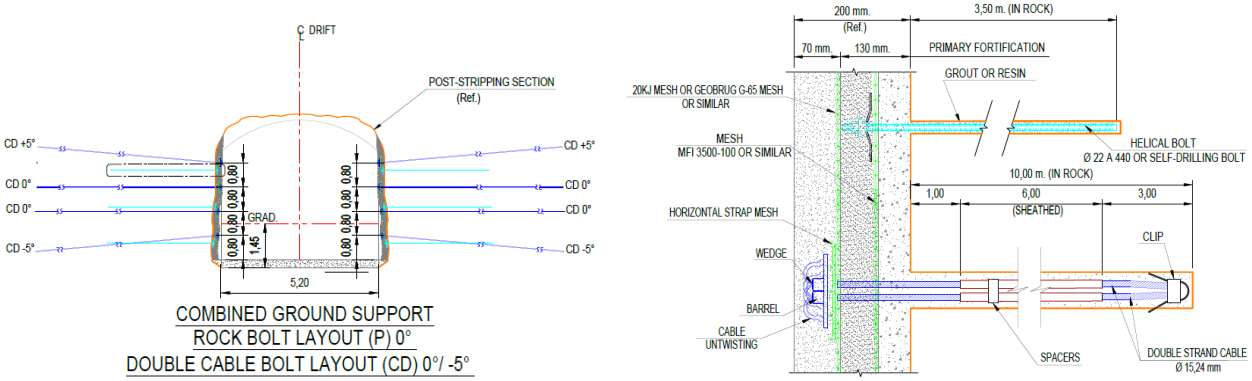
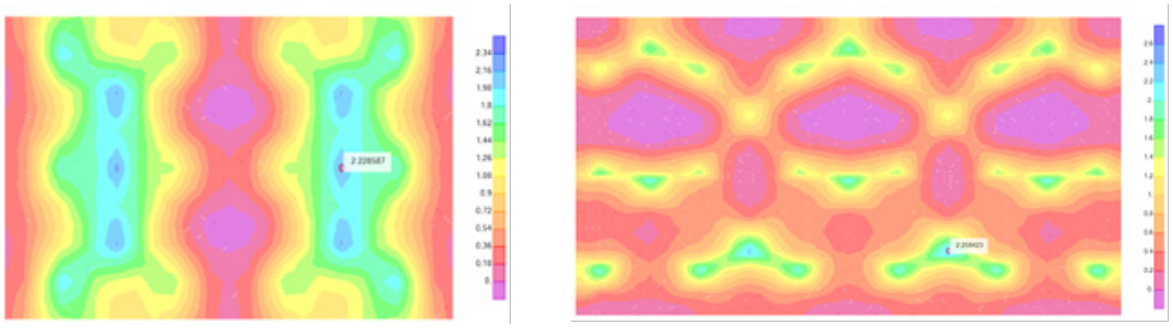



**Figure 11 Installation layout of bolts, cables, and mesh**

Based on Figures 10 and 11, it was decided to develop these new designs from the following considerations:

- Pattern change: due to the search for a better distribution of stress along the pillar, a new pattern of cables is proposed, which optimises the utilisation of the tributary area associated with each reinforcement element and reduces the occurrence of localised stress concentrations, the resulting reduction in moment concentrations is shown in Figure 12.



(a) (b)

**Figure 12 Maximum bending momentum comparison. (a) Base design; (b) New pattern of cablebolts**

- High-strength mesh: a high-strength mesh was proposed for evaluation into the optimised design to improve surface support capacity and deformation tolerance.
- Elimination of vertical straps: the 3D scanner monitoring demonstrated that geomechanical forces within the pillar act horizontally. Therefore, the vertical straps installed in the initial design provided no relevant structural support. Due to this redundancy, they were removed from the new configuration to optimise field installation times and prevent steel accumulation at the intersections.

- Increase of horizontal straps: since the initial design showed that pillar deformation is concentrated along horizontal vectors – resulting in highly localised compression damage to the straps in that plane – the density of horizontal straps was increased. This modification aims to improve load distribution within the support system, control localised rock mass displacement, and reduce concentrated damage in individual straps.
- Cables bolts: cable bolts were inclined at ±5° to reduce alignment with dominant subvertical discontinuities and promote intersection with potentially unstable rock blocks, while maintaining predominantly tensile loading.

The trial provided an initial assessment of the proposed methodology. Its performance will be further evaluated through the recovery of future pillars under varying loading conditions, local rock mass characteristics, and as-built pillar geometries, including detailed variations in the excavated profile. These observations will provide further evidence to assess the effectiveness and applicability of the proposed support system under a broader range of conditions

# Conclusion

The investigation and field implementation detailed in this paper establishes the engineering basis and operational performance of the straps reinforcement system as an alternative supplementary ground support strategy at the Chuquicamata underground mine. Structural analysis conducted during the design phase served as an analytical baseline to evaluate load transfer mechanisms, suggesting that the integration of these high-strength steel straps could optimise stress distribution and mitigate localised bending demands within the shotcrete lining. This proposed mechanism was subsequently evaluated through industrial-scale pilot trials in Macroblock MB N01/S01, where the composite support system showed no generalised loss of confinement the global structural integrity and confinement of the pillars under severe geomechanical demands and high convergence rates. Field data and 3D scanner monitoring provided preliminary field evidence, demonstrating that rock mass deformation was effectively restricted to highly localised, millimetre-scale ranges with no generalised loss of confinement across the global pillar architecture.

A pivotal outcome of this trial involves the operational and structural optimisation derived from the field lessons learned. Because spatial monitoring revealed that the driving geomechanical measured deformation was predominantly oriented along horizontal vectors, the initial vertical straps were identified as of limited benefit under the monitored conditions and subsequently eliminated to prevent steel accumulation, improve bolt plate seating, and accelerate installation times. The optimised design configuration effectively reallocates resources by increasing the density of horizontal straps to more effectively distribute localised compression demands and by inclining the anchor cables at ±5° to align them perpendicularly to subvertical fracturing, ensuring they operate primarily under tensile loading. In conclusion, the straps system represents a robust, high-capacity alternative for pillar rehabilitation in high-deformation underground environments. Although the long-term performance of the optimised configuration requires further monitoring, the numerical assessment and pilot trial provide an initial engineering basis for the use of straps in pillar rehabilitation under high-deformation conditions.

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