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Yielding steel sets for high-convergence conditions in block caving: design basis and expected performance at Chuquicamata underground mine

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Abstract

Underground excavations developed under high-stress and poor rock mass quality frequently experience severe convergence, compromising the performance of conventional support systems. This is particularly relevant in block caving operations, where stress redistribution and progressive damage can induce large deformations around infrastructure located in production levels.

At Chuquicamata underground mine (Chile), adverse geomechanical conditions characterised by highly fractured rock masses, low Q-values, and significant stress concentrations led to the implementation of yielding steel sets as a specialised support system. These systems were selected to accommodate large displacements while maintaining load-bearing capacity, unlike conventional rigid support that tends to fail under squeezing conditions.

This paper presents the geological and geotechnical framework that justified the adoption of yielding support, including rock mass characterisation, expected deformation mechanisms, and limitations observed in traditional support schemes. The design approach is described, focusing on the mechanical behaviour of yielding steel sets, which are engineered to allow controlled deformation in both axial and lateral directions through predefined yielding elements. Their structural response is discussed in terms of load–displacement capacity, energy absorption, and interaction with surrounding rock.

Additionally, the technical basis used to estimate their performance is presented, including analytical considerations and numerical analysis of expected convergence scenarios. Although the system has been installed in selected sectors, it has not yet been subjected to operational loading conditions, as the corresponding mining areas are not yet in production. Therefore, this work emphasises the design philosophy and expected performance envelope, establishing a baseline for future field validation.

The study contributes to the understanding of yielding support systems as a viable alternative for managing large deformation demands in deep and high-stress mining environments.

Keywords: *support, rock mechanics, yielding steel arches, dynamic support systems, squeezing, underground mining*

1 Introduction

Chuquicamata is a porphyry copper deposit that was mined as one of the world's largest open pits for decades. As the economically viable reserves accessible by open-pit mining were depleted, the operation transitioned to underground mining using the block caving method.

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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 state undergoes substantial intensification, triggering complex rock mass responses that challenge conventional engineering paradigms. Under these extreme confinement-loss conditions, structural components such as pillars are subjected to severe displacement and localised stress concentrations that frequently manifest as violent spalling, progressive slabbing, or deep-seated plastic failure. Consequently, the mitigation of these unstable conditions demands a shift toward robust, high-energy-absorbing support systems capable of maintaining industrial footprint integrity over extended operational lifespans.

At the Chuquicamata underground mine, ensuring the structural stability of production-level pillars is a critical operational requirement to maximise extraction area availability until drawdown completion. The high-stress environments encountered in active mining blocks have resulted in intense rock mass fracturing, accelerating the deterioration of pillars that are essential for excavation stability. To address this severe degradation, various rehabilitation and ground support strategies have been implemented in the areas experiencing the greatest geomechanical demand. In the southern sector of the mine, specifically within the S04 macroblock, the geomechanical conditions are characterised by poor rock mass quality and high levels of deformation, requiring the installation of yielding steel sets as part of the ground support system to maintain excavation stability and ensure operational continuity. As these geomechanical conditions are expected to persist with the progression of mining, the implementation of this support system is also planned for the development of the S05 macroblock.

1.1 Origin and evolution of the design concept

The concept adopted in this study originated from the experience of Codelco's El Teniente Division following the rockburst of 26 September 2020 in the 'Túnel Correa (conveyor belt tunnel) P4600 Fw'. The event left approximately 30 m of the installed support out of service and showed that, in the most severely damaged zone, the failed rock volume extended beyond the bolt anchorage and dynamically loaded the cable support beyond its installed design capacity. The causal investigation therefore recommended evaluating steel sets in the most vulnerable section of the tunnel to provide containment and retention with less dependence on anchorage in damaged rock, while increasing the energy-dissipation capacity of the complete support system (Balboa et al. 2020).

El Teniente subsequently developed a circular yielding steel set for the 'Túnel Correa', based on 6 friction-sliding joints distributed around the perimeter. Each joint was designed to activate at a predefined load and provide up to 120 mm of controlled sliding. Incremental analyses estimated that the sets could contribute approximately 40–60 kJ/m², depending on the loading geometry, and that their combined action with the bolt–cable–mesh system could provide a total energy-dissipation capacity of approximately 100 kJ/m² (Benavides 2021; Codelco 2021). This experience established the central principle used here: the steel structure should remain stable while designated connections yield in a controlled manner, allowing the overall support system to absorb energy and accommodate deformation.

Chuquicamata underground mine adopted the experience developed in El Teniente as a conceptual starting point and transformed it for the distinct conditions of the Chuquicamata mine by accommodating ground movement instead of resisting it completely. Whereas the Túnel Correa solution was conceived primarily to increase dynamic capacity under rockburst loading, the Chuquicamata underground mine development also addresses sustained, large convergence associated with squeezing and block-caving-induced stress redistribution. Within the support strategy, the yielding sets form part of an integrated solution intended both to accommodate convergence and to increase the deformation capacity of the complete support system. The resulting design is therefore a site-specific evolution rather than a direct transfer: it retains controlled yielding as design principles, but recalibrates the excavation geometry, structural profiles, joint locations, activation loads, displacement capacity, and operational clearance for the S04 production level. In this way, a concept initiated at El Teniente was converted by Chuquicamata underground into a deformable support solution for Chuquicamata's expected ground response.

1.2 Yielding steel sets

A yielding steel set is a structural support used in underground mines and tunnels that is designed to carry heavy loads while also allowing a controlled amount of movement. Unlike a rigid steel frame, which may bend or fail if the surrounding rock exerts excessive pressure, a yielding steel set is built to deform gradually without losing its ability to support the excavation.

This controlled deformation is achieved through specially designed joints or friction connections that allow parts of the steel frame to slide or compress when the load becomes too great. As the surrounding rock moves and presses against the support, the steel set yields in a predictable manner, absorbing energy and reducing the concentration of stress within the support. By accommodating ground movement instead of resisting it completely, the support remains effective even in difficult ground conditions.

Yielding steel sets are widely used in underground mining around the world because they provide reliable support in conditions where high ground stresses and rock movement make rigid supports unsuitable. Their use has become increasingly important as mines become deeper and encounter more challenging geotechnical conditions.

Globally, yielding steel sets are most commonly used in deep underground coal mines, where the surrounding rock often undergoes significant deformation after excavation. Countries such as China, India, Poland, and South Africa have extensively adopted yielding steel supports in coal roadways because they can accommodate roof convergence and sidewall squeezing while maintaining the stability of underground openings.

1.3 Previous experiences with yielding support in weak and squeezing ground

The summary of previous applications of yielding support systems is in Table 1.

Table 1 Summary of previous experiences in dynamic support systems

Location/ operation	Bibliographic reference	Research focus and key technical information
Italy (Alps/tunnels)	Barla & Barla (2009)	Innovative tunnelling construction methods in squeezing rock. Application of yielding elements and heavy steel sets to accommodate high-convergence in weak rock masses and manage severe rock squeeze during excavation.
Switzerland/ France/Italy (Alps/tunnels)	Kovári (2009)	Design methods for yielding support in squeezing and swelling rocks. Toussaint–Heintzmann (TH) yielding steel ribs with sliding joints accommodated up to 0.7 m of radial convergence in a full-scale test for the Gotthard Base Tunnel. Use of highly compressible concrete elements in longitudinal shotcrete slots to control severe pressure (Saint Martin La Porte and Lötschberg). Implementation of 'Modular Yielding Support' to mitigate floor heave in swelling anhydrite (Chienberg Tunnel).

2 General design framework

The design methodology adopted in this study was developed for the purpose of designing a ground support system using yielding steel sets capable of maintaining its structural integrity while accommodating the large convergences associated with squeezing conditions (Codelco 2023). Unlike conventional rigid sets, which are designed to resist the progressive increase in rock mass pressure without significant deformation, the

proposed system was conceived to undergo controlled yielding once a previously defined load level is achieved. This design philosophy allows the deformation to dissipate through sliding mechanisms, while simultaneously preserving the load-bearing capacity of the structure and minimising structural damage.

The design methodology was developed in different stages:

- definition of the excavation geometry and design loading conditions.
- initial analysis of alternatives using yielding steel sets
- detail design of double-T profile steel set
- installation location of yielding steel arches.

The primary objective was to develop a support system capable of accommodating an expected convergence of 100 mm without compromising the structural stability of the excavation.

2.1 Excavation geometry

The ground support system was designed for the Production Level MB-S04 of the Chuquicamata underground mine. The excavation corresponds to a D-Shape gallery, widely used in mining infrastructure, composed of a lower rectangular section topped by a semicircular arch (vault).

The dimensions considered in the structural analysis are shown in Table 2 and Figure 1.

Table 2 Dimensions considered in the structural analysis

Parameter	Value
Excavation width	4.60 m
Excavation height	4.30 m
Sidewall height	2.00 m
Arch radius	2.30 m
Expected convergence	100 mm

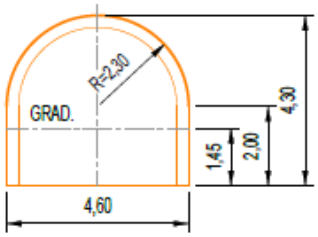


Figure 1 Scheme of dimensions considered in the structural analysis

These dimensions correspond to the design geometry provided for the production level and adequately represent the excavations where the development of squeezing conditions is anticipated. The structural behaviour of the set was evaluated considering both the initial geometry of the excavation and the deformed geometry once the yielding mechanism is activated.

2.2 Design loading conditions

The design loads were established from the geomechanical evaluation conducted for the extraction level (Barindelli et al. 2023) and represent the projected pressures exerted by the rock mass on the excavation boundary under progressive deformation conditions (Table 3). The applied load distribution is illustrated in Figure 2.

Table 3 Loads considered in the excavation analysis

Load	Magnitude
Vertical pressure	15.6 tf/m^2
Horizontal pressure	18.3 tf/m^2

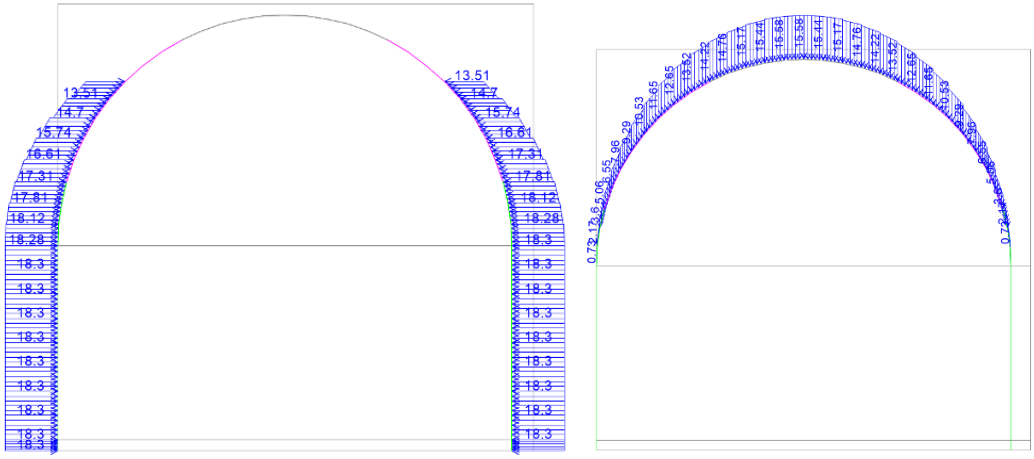


Figure 2 Distribution of the loads around the geometry of the excavation

The horizontal component is higher than the vertical one, reflecting the stress redistribution induced by mining and the high in situ stresses present at the production level. An expected radial convergence of 100 mm was adopted as the design deformation. Instead of completely restricting this deformation, the support system was conceived to accommodate it through controlled yielding mechanisms.

3 Initial analysis of alternatives using yielding steel sets

For each alternative studied, a static analysis of the set is performed using the loads indicated above. In both cases, hinged supports are assumed at the base of the columns, along with springs that simulate the load generated by the rock mass. These springs work exclusively in compression, with a ballast modulus of k=100 kgf/cm^3. The results for each alternative are shown below.

3.1 Steel sets with double-T profiles (I-beams)

The first alternative considered double-T profiles manufactured using welded plates of variable thickness, allowing for the simultaneous optimisation of load capacity and the total weight of the structure. The height of the profile was selected considering 2 fundamental criteria:

1. provide sufficient stiffness against the design loads
2. ensure that, once the anticipated convergence occurred, the remaining clear width of the excavation met operational requirements.

The selected double-T profiles are shown in Figure 3. The height of the largest profile is chosen so that the set fits with some clearance inside the excavation, and so that, when the maximum yielding occurs, the clear width is at least 4.0 m.

The internal height between flanges, which corresponds to 110 mm, must be the same for all sections to facilitate the design of the yielding joint. The variation of thicknesses in the set section is chosen in order to optimise the weight of the structure. A spacing between sets of 70 cm and a buckling length of 1.5 m in the columns and roof have been considered, consistent with the bracing indicated in the drawing (threadbar and rock-bolts).

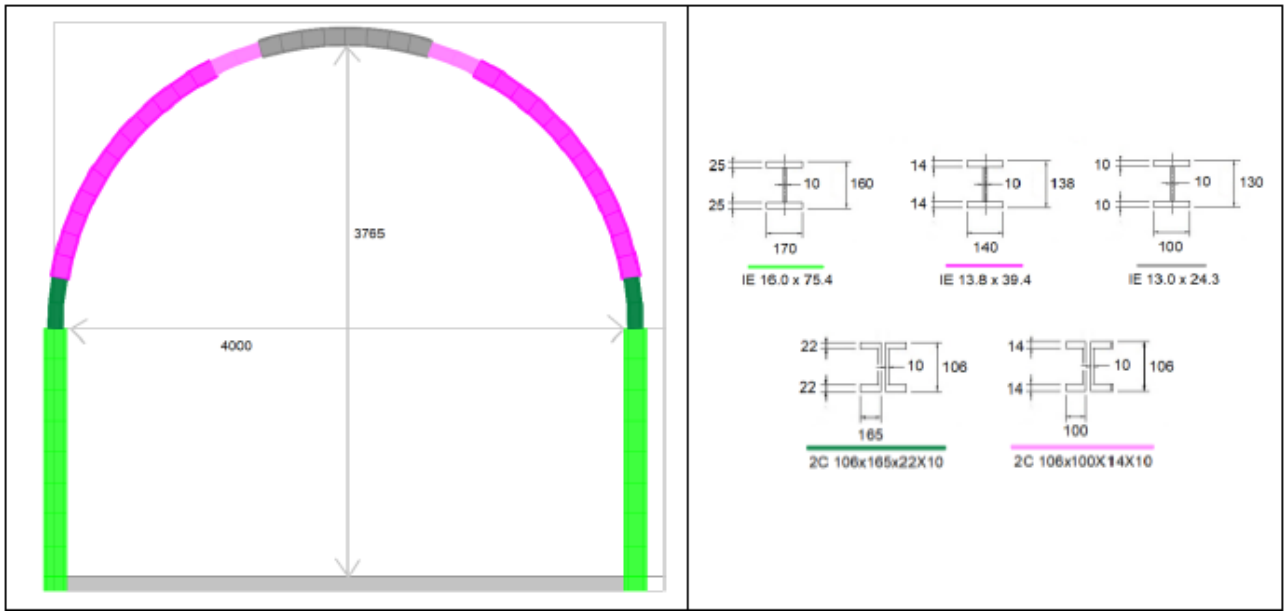
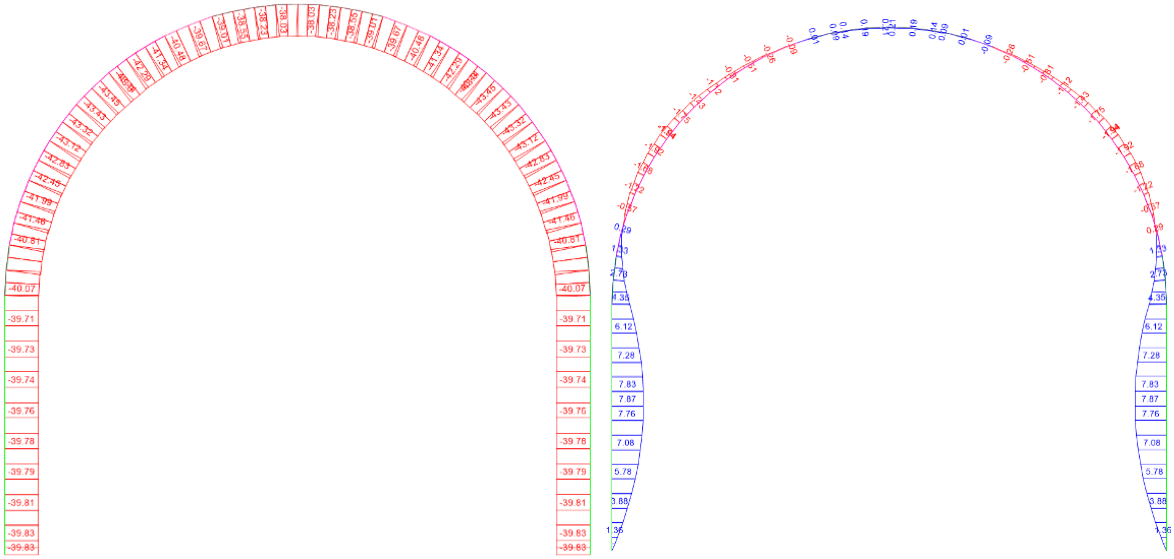


Figure 3 Dimensions and structure of the double-T profile

The stresses on the steel set are shown in Figure 4. The utilisation factors (UFs) of the steel set are shown in Figure 5, yielding a maximum UF equal to 1.05. The weight of the steel set profiles equals 550 kg, considering only the profile itself, excluding connection plates, tie rods, bolts, and bases.



(a) (b)

Figure 4 Axial force and bending moment for double-T steel set (the blue area is compression, and the red area is tension) (a) Axial force (tf): maximum value (column): −39.8 tf, minimum value (roof): −43.5 tf. (b) Bending moment (tf·m): maximum value at roof: 0.2 tf·m, minimum value at roof: −1.9 tf·m, Maximum value at column: 7.9 tf·m

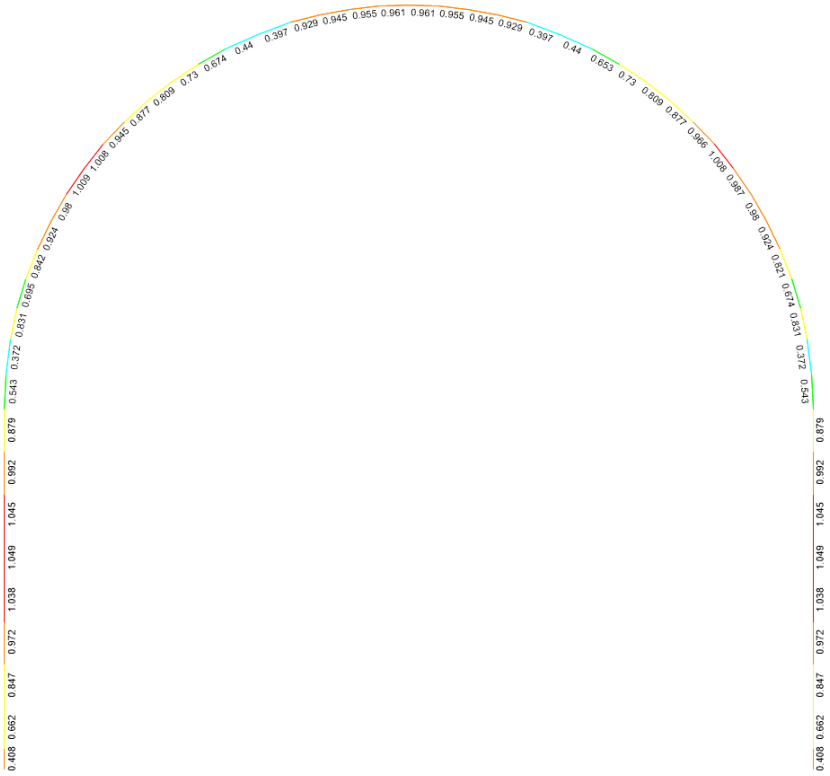


Figure 5 Utilisation factors (UFs) for double-T-set. Max UF = 1.049

The structural analysis showed maximum axial forces between 40 and 44 tf, while bending moments remained relatively low in the arch, concentrating mainly in the sidewalls. The maximum UF obtained was close to 1.05 (see Figure 5), indicating that only minor adjustments were required to fully satisfy the design criteria.

3.2 Set with TH profiles

As a second alternative, commercial TH profiles, widely used in underground works with deformable support, were evaluated. However, structural analyses demonstrated that the available sections were not capable of safely resisting the design loads established for the project. The required structural capacity exceeded the strength properties of the TH profiles available on the market, so this alternative was discarded. Consequently, subsequent design development focused exclusively on the solution based on manufactured double-T profiles.

4 Detail design of double-T profile steel set

A new analysis of the steel set is performed, considering the geometry of the newly installed set. To protect the set prior to yielding, it is defined that yielding occurs at a fraction of the design load such that the most demanded element has a UF of 0.9 or less. This load corresponds to 83% of the design load (see Figure 6).

The position of the yielding joints is defined, attempting to locate them in zones where the developing bending moment is minimal. At those points, the axial force that will serve as the design load for the yielding joints is obtained, resulting in a value of 35 tf. the yielding load at the base corresponds to a basal shear force of 12 tf on each column (see Figure 7).

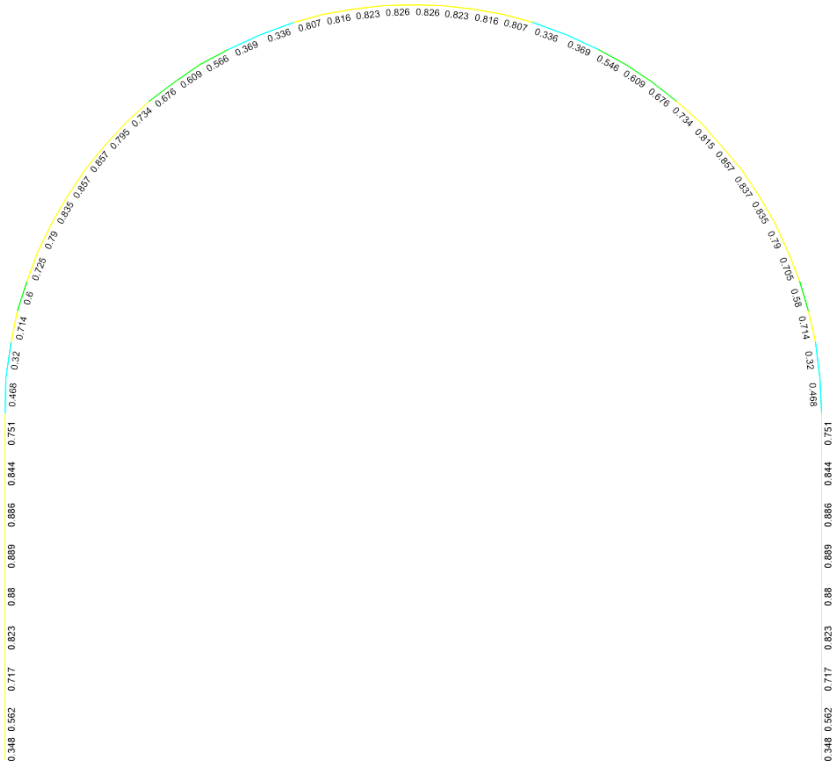


Figure 6 Set utilisation factors without yielding at 83% of the design load

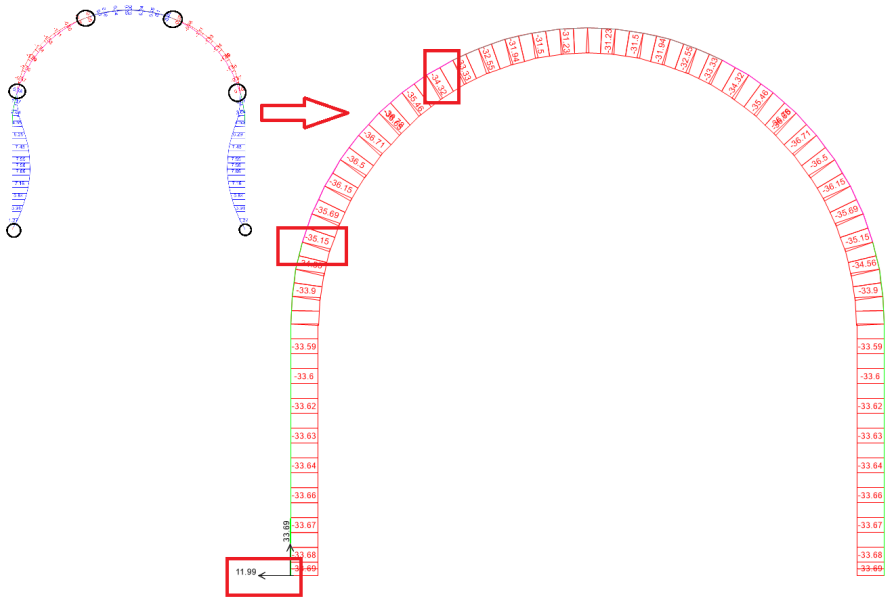


Figure 7 Set axial force (35 tf) and shear force (12 tf) at yielding joint positions at 83% of the design load

Considering the information presented in the Figures 6 and 7, the yielding joints are designed just as shown in Figure 8.

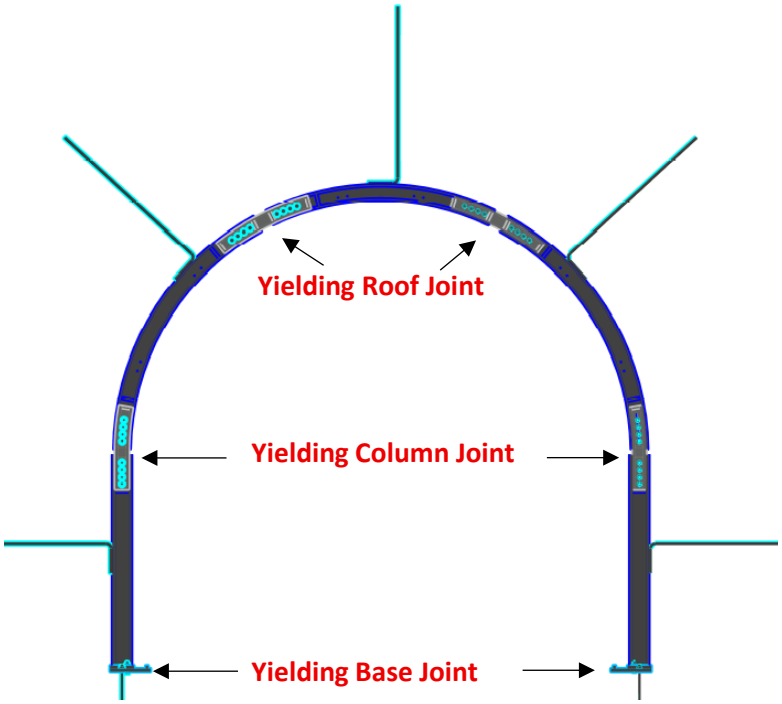


Figure 8 Yielding joint designations

4.1 Yielding roof joint

The yielding roof joint is located at an angle of 27° with respect to the vertical. It must be capable of moving 100 mm horizontally; therefore, its inclined travel must be 112 mm.

A value of 115 mm is used, so when fully displaced, it will travel:

- horizontally: 102 mm
- vertically: 52 mm.

The yielding load corresponds to 35 tf, so four 19.05 mm A325 bolts are required

In Figure 9 the details of the yielding roof joint are shown.

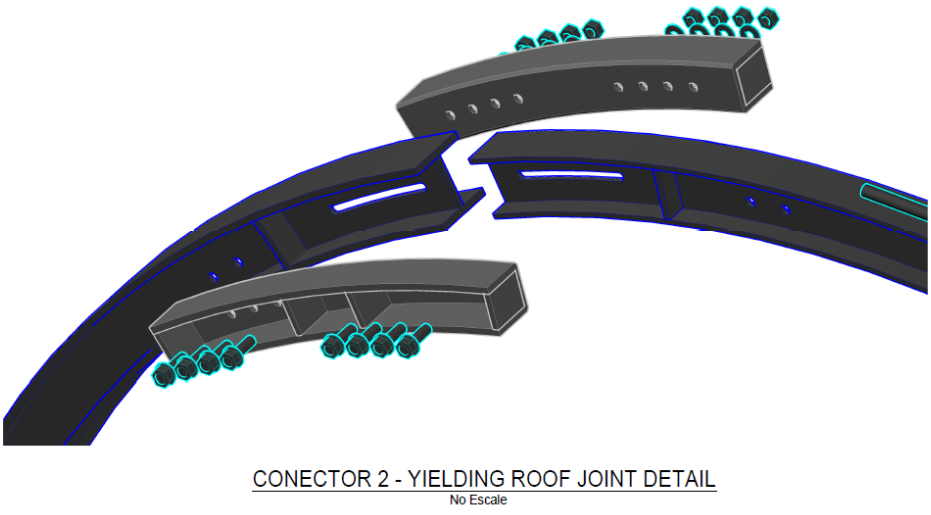


Figure 9 Details of yielding roof joint

4.2 Yielding column joint

The yielding column joint is located at an angle of 0° with respect to the horizontal. The arch must be capable of moving 100 mm vertically in total; therefore, since the roof joint already displaces 52 mm vertically, this joint only needs to complete the remaining 100 mm – meaning it must be capable of moving 48 mm. A value of 50 mm is used.

The yielding load also corresponds to 35 tf, so four 19.05 mm A325 bolts are required, and the calculation is similar to the previous one.

In Figure 10 the details of the yielding column joint are shown.

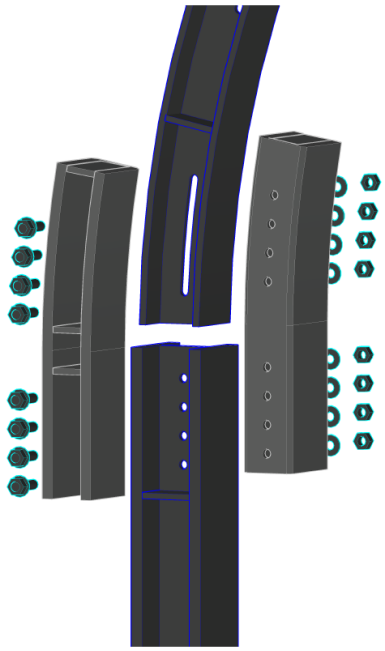


Figure 10 Details of yielding column joint

4.3 Yielding base joint

The bast joint is located at the base of the column and must be capable of moving 100 mm horizontally, just like the upper joint, to prevent the column from rotating. It is constructed as a plate that slides over another plate that is anchored to the rock by means of anchor bolts. Yielding begins once the shear stress at the base of the column exceeds the friction force generated between the upper mobile plate and the lower fixed plate, due to the normal force which is the axial compressive load of the column. The design sliding distance is limited by a stop welded to the fixed plate. The yielding load corresponds to the shear developed at the base of the column at 83% of the design loads, which is 12 tf.

Since the 19.05 mm connection bolts that couple the upper mobile plate and the lower fixed plate do not participate in the calibration of the yielding mechanism, they do not need to be torqued to a specific level. A tightening torque of 5 kgf·m is specified, which is lower than the standard tightening torque, as this is required only to maintain the plates in their initial position during assembly and initial use of the arch, prior to the development of the design loads.

In Figure 11 the details of the yielding base joint are shown.

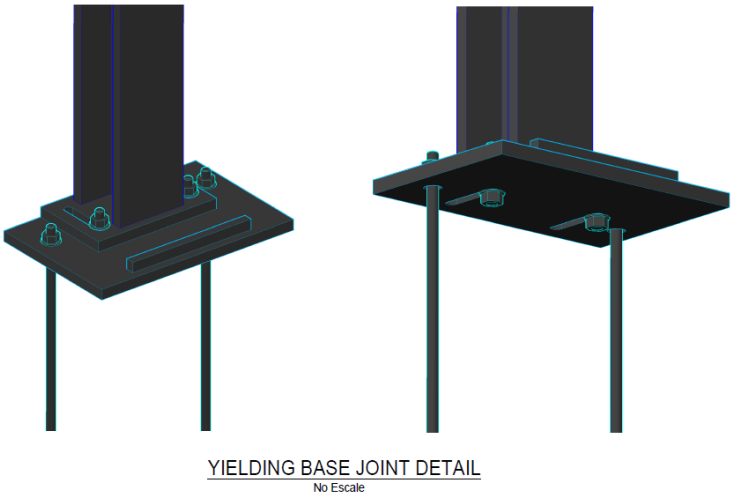


Figure 11 Details of yielding base joint

5 Installation process of the yielding steel sets

The installation process of the yielding steel sets involves several essential stages to ensure their proper performance. Initially, adequate pillar rehabilitation must be executed prior to set placement (Castro et al. 2025). Following this initial repair, the installation procedure must adhere strictly to the sequence detailed Section 5.1–5.5.

5.1 Site preparation and primary support

The construction sequence begins with the topographic clearance of the excavated drift section, followed by the marking of floor anchors and horizontal drill holes. Drilling and grout injections are executed to anchor both the floor and PH bolts. Subsequently, the primary support system is installed, comprising 665 welded wire mesh, bearing plates on the bolts, and 257 wire mesh covering the full excavation profile.

5.2 Base plate leveling

To support the vertical legs (posts), topographic layout of the base plates is performed. Following the installation of anchor bolts, perimeter formwork is assembled and leveling grout (*grouting* or G50 high-fluidity mortar) is poured. Before positioning the vertical steel members, the required clearances are cut into the 257-wire mesh.

5.3 Steel structure assembly

The installation of the legs is carried out by topographically aligning only one side of the drift, facilitating the fitting and geometric adjustment of the upper arches (crowns). The legs are secured to the rock wall and temporarily interconnected using alignment guides to maintain spacing.

At ground level, the crown segments are pre-assembled, verifying their dimensions and applying the specified bolt torque at the connections. The crowns are then hoisted and joined to the legs using the primary connectors. Once the connection torque is verified, longitudinal steel tie rods are installed to interconnect the sets.

5.4 Rebar reinforcement, yielding joints, and geomechanical inspection

Prior to pouring the confinement concrete, the wall rebar reinforcement is placed. To ensure controlled yielding under rock mass deformations, compressible elements are installed: high-density foam at the base

of the legs and 25 mm expanded polystyrene joints (EPS). This stage concludes with formal inspection and approval by the Geomechanics department.

5.5 Three-stage confinement concrete pouring

The confinement wall is cast in 3 consecutive stages:

1. First stage: shear connectors (shear studs) are welded, temporary alignment guides are removed, and a 20 mm EPS joint is placed against the rock face before pouring the first concrete lift.
2. Second stage: a 70 mm EPS joint is extended to the rock contact, and the 257 mesh is secured to the steel sets. Following inspection of the compressible joints, formwork is installed and the second wall segment is poured.
3. Third stage (Final Closure): the upper 140 mm EPS joint is placed extending to the rock mass, ensuring structural decoupling from direct loads. The remaining 257 mesh is adjusted, upper formwork is installed, and the final concrete pour is executed to complete the structural confinement.

Following the installation procedure detailed above, Figure 12 illustrates the final configuration of the installed yielding steel sets.

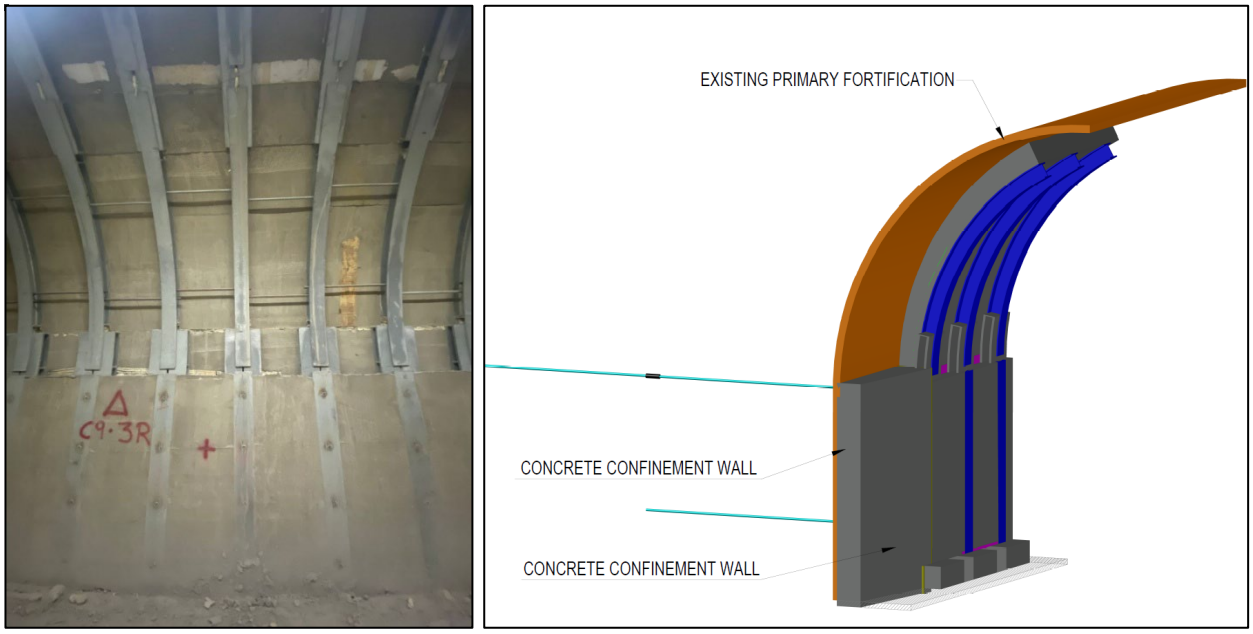


Figure 12 Yielding steel set installed

6 Installation location of yielding arches

The installation of the yielding arches will be carried out in macroblock S04 (Figure 13). This is primarily because, given the rock mass quality conditions, significant deformations are projected; therefore, this support system aims to absorb these displacements and prevent operational failures in the facilities when caving is induced.

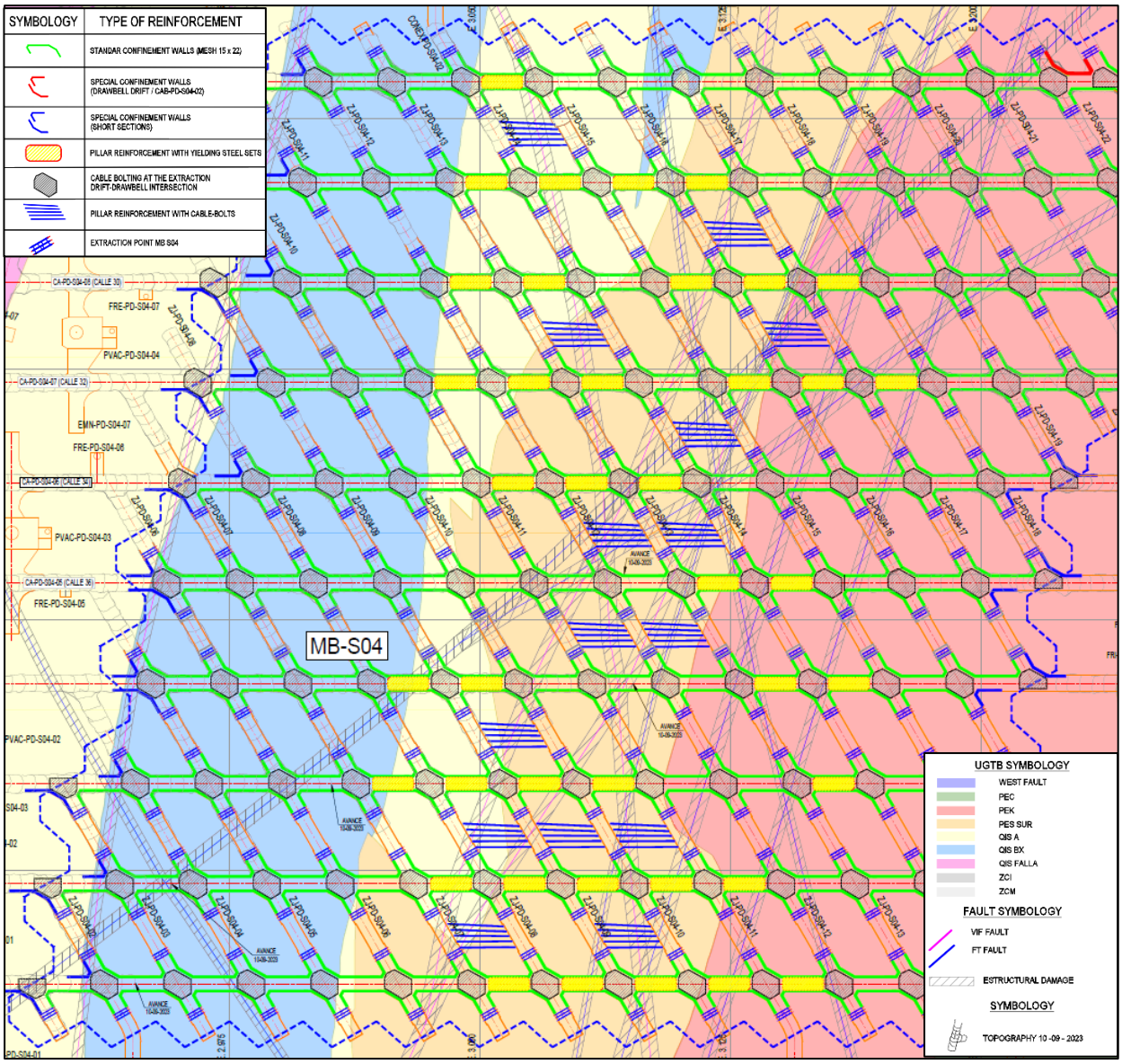


Figure 13 Installation location of yielding arches in macroblock S04

7 Conclusion

The primary objective of this work was to present the design and field implementation of the yielding steel set support system deployed at the Chuquicamata underground mine. High deep-seated stresses and poor rock mass quality created severe squeezing conditions, requiring a specialised ground support strategy capable of accommodating large deformations. Standard commercial profiles were discarded due to structural limitations under the design pressure field, making the installation of engineered, built-up double-T profiles essential to balance high structural rigidity with controlled deformability.

The main strength of this system lies in its ability to absorb severe ground convergence without sacrificing excavation stability. By integrating calibrated friction-sliding joints, the sets yield predictably prior to reaching structural capacity limits, dissipating rock mass energy while maintaining critical load-bearing capacity. Furthermore, establishing precise bolt tightening torques and standardised installation procedures guarantees reliable friction response and constructability in demanding underground environments.

While the yielding steel sets are fully installed in the target production levels, the S04 macroblock has not yet entered active mining. This implementation provides a robust baseline for upcoming instrumented field monitoring, which will be key to evaluating long-term joint behaviour under active block caving conditions.

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