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Installation of lattice girders with Toussaint–Heintzmann yielding elements in poor ground

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Abstract

In block cave mines, the permanent life of mine tunnels are required to withstand multiple changes in ground stresses and remain functional for up to several decades. In block cave mines, in general, the changes in ground stresses originate from initial induced stresses during tunnels and chamber excavations. Following this is an increase in abutment stresses due to undercut front advancement phase. Further increase in abutment stresses occurs due to cave growth and upward propagation. Then, the abutment stress reduction takes place due to the cave breakthrough to the surface. It should be noted that at some mines, the ground stresses may increase due to cave material re-compaction or due to remnant pillar loading if undercutting was not carried out properly.

As a matter of good practice, the key requirement for a block cave mine permanent infrastructure, such as an ore handling system, is to have it excavated and fitted out before the start of the undercutting phase. Multiple changes in ground stresses are likely to cause large deformations in the tunnels and pose challenges to ground support designs with the choice of ground support/reinforcement types/systems/elements, particularly if the permanent infrastructure is situated in the poor ground due to the presence of large weak structures.

At Oyu Tolgoi mine, the tunnel stability of the haulage level is very important for the uninterrupted movement of payload trucks delivering ore from truck chutes to crusher chambers. Affected by changes in abutment stresses and poor ground conditions in certain sections of the tunnels, excessive drive deformations are expected throughout the several decades of mine life in the haulage level requiring innovative ground support/reinforcement design involving installation of fibrecrete embedded lattice girders with yielding elements.

Keywords: *steel arch, lattice girders, yielding elements, poor ground, innovative design, block cave, permanent tunnelling infrastructure*

1 Introduction

Oyu Tolgoi is a newly built large copper/gold block cave mine situated in the South Gobi region of Mongolia. The mine utilises haulage level underneath the extraction level for moving ore by 160 t payload trucks from several truck chutes to primary crusher chambers. From the crusher chambers, the crushed ore is transported by conveyors to the loading station at production shaft SH2 and to conveyor to surface system, then the ore is transported to the surface.

Drive stability in the haulage level is very important for the uninterrupted movement of 160 t payload trucks from truck chutes to crusher chambers. A large and weak lower fault intersects a section of the haulage level near Truck Chute #4. During the mining of the haulage level drive through the lower fault, a large fall-out occurred from the backs of the drive. Mine-scale geotechnical modelling indicates that potential excessive drive deformations due to cave abutment stresses are likely to occur throughout the mine life where the lower fault intersects the haulage level near Truck Chute #4 and where the fall-out occurred.

There was a requirement to fill a large fall-out in the backs at the lower fault intersection with the haulage level near Truck Chute #4. In addition, the section of the haulage level drive at the intersection with the lower fault had to be enlarged by stripping both walls and backs to fit heavy steel arch support. Heavy ground support/reinforcement had to be installed in the stripped section of the haulage drive before the installation of the steel arches. This campaign of heavy ground support/reinforcement installations was necessary to be able to withstand potential large deformations throughout the mine life of the haulage level without resorting to significant ground support/reinforcement rehabilitation campaign to avoid interruption to the movement of 160 t payload trucks from truck chutes to the crusher chambers.

Various steel arch types were put forward for consideration. Eventually, an innovative design of lattice girders (LG) combining yielding joints made from sliding elements of Toussaint–Heintzmann (TH) beam sections was adopted. Innovative footings design for the LG arches had to be designed for the LG arches. LG arch design with yielding elements passed a rigorous process of structural capacity modelling, evaluation of the bearing capacity of the footings, and natural size testing of yielding elements. This innovative design passed external and internal reviews by geotechnical peers and mining engineers. The Oyu Tolgoi underground construction team reviewed the installation methodology elaborated by the onsite geotechnical team. The design was adopted by senior mine management and successfully implemented by the underground construction and development teams throughout 2021–2022.

This paper will outline the design considerations, technical evaluation, and installation of the LG arches with yielding elements. For that matter, several monitoring devices have been installed to measure the ground movement around the LG arches and ground loading to be imposed on the LG arches.

2 Haulage level layout with respect to block cave footprint

At Oyu Tolgoi block cave mine, the haulage level is located below the footprint. The distance from the backs of the haulage level to the floor of the undercut Level is 54 m. The distance from the backs of the haulage level to the floor of the extraction level is 36 m. Primary Crusher 1 (PC1) is located to the southwest of the footprint. The haulage level forms a loop, whereas the payload trucks travel clockwise from PC1 to Truck Chutes #1–4 and back to PC1. Figure 1 shows the haulage level with respect to the footprint of Oyu Tolgoi block cave.

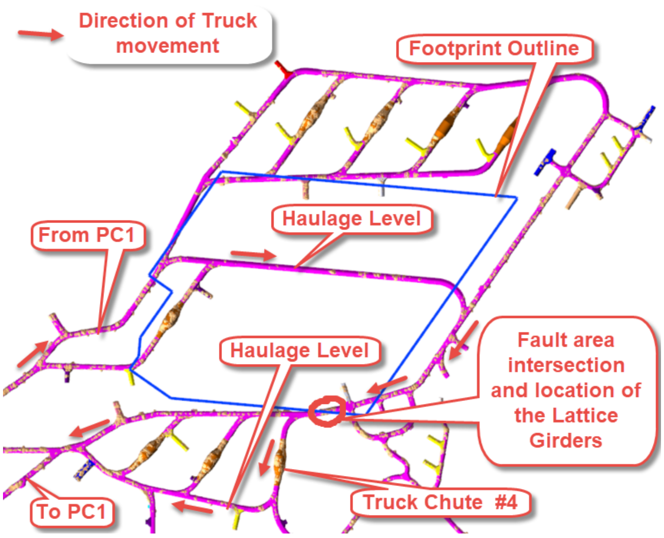
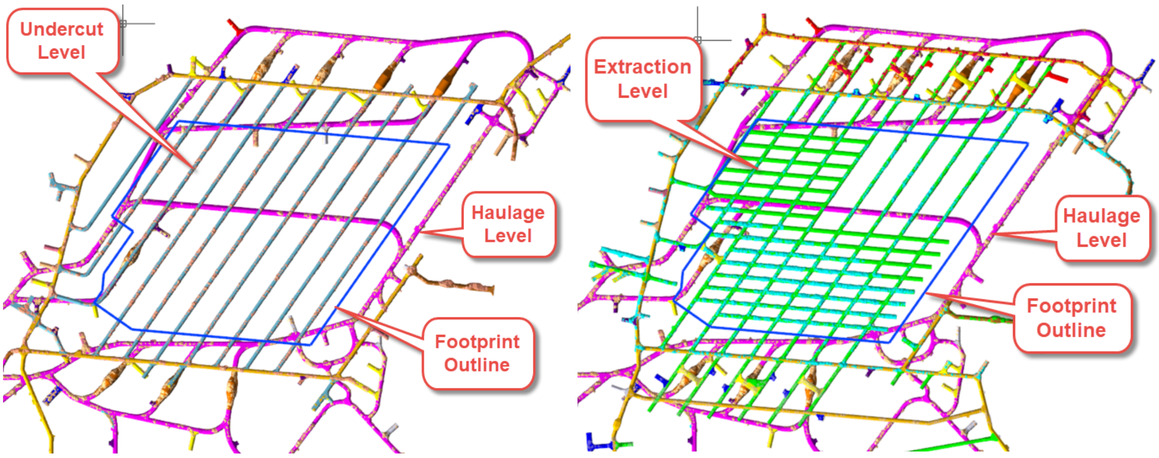


Figure 1 Haulage level layout with respect to block cave footprint at Oyu Tolgoi

Figures 2a and 2b illustrate the haulage level with respect to extraction and undercut, respectively. Note that the undercutting process is designed to be initiated from the southwestern extremity of the footprint, then advance as a narrow strip along the southern boundary of the footprint to the southeastern extremity, and then the full undercut front is advanced North with the eastern leading edge.



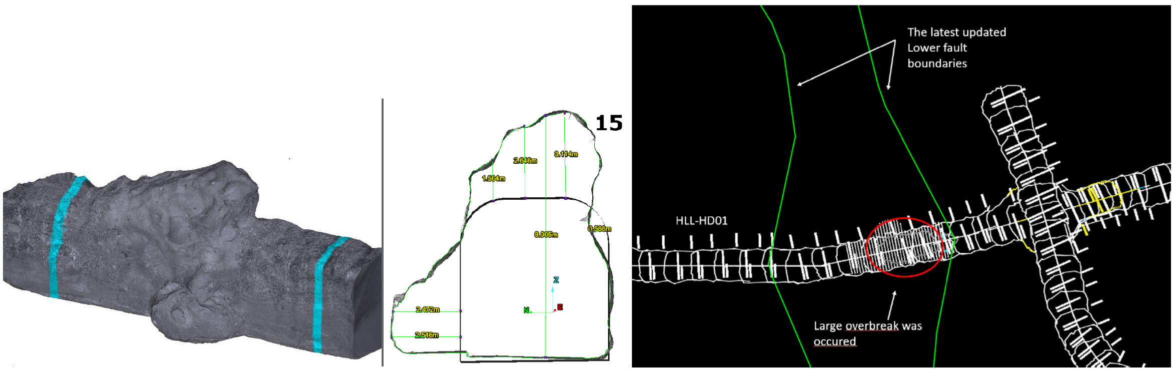
(a) (b)

Figure 2 Haulage level layout with respect to (a) Undercut level; (b) Extraction level

3 Geological and geotechnical settings at the haulage level at the location of the lattice girder installation

Several papers have been published in the past on the geological and geotechnical setting at Oyu Tolgoi mine. A recent paper by Ooi et al. (2022) can be referred to. Only a brief description of ground conditions is outlined in the following paragraph.

A large regional lower fault zone intersects the haulage level just east of Truck Chute #4. The fault itself dips to the east-northeast at approximately 60°. The fault is gouge-filled and of extremely low strength. It can form sharp contrast in strength at the contact with the surrounding rock mass or can affect the ground gradually from very poor to medium strength rock. The fault zone affected an approximately 40 m section of the haulage drive and caused a large overbreak and a relatively large fall-out in the backs of up to 2–3 m during development straight after the blast. The fall-out was supported and reinforced with multiple layers of fibrecrete, mesh, resin bolts, and 8 m cable bolts. Following that, the fall-out area has been scanned to ascertain the exact extent of the back failure as well as the baseline for subsequent drive deformation measurements. Figure 3 shows the extent of the back failure affected by the fault zone.



(a) (b)

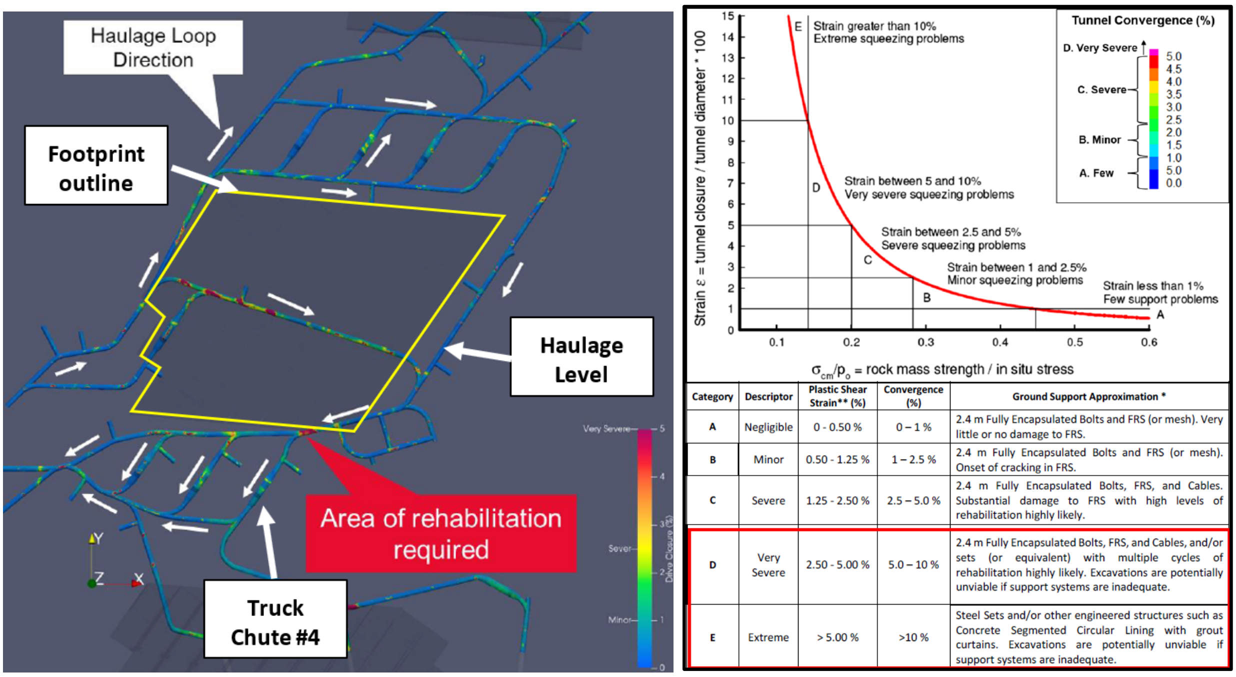
Figure 3 Extent of the fault zone in the haulage Level: (a) Laser scan survey and cross-section view; (b) Plan view of the haulage level at the location of the backs fall-out

4 Mine-wide modelling results for the haulage level at the location of the lattice girder installation

Mine-wide FLAC3D geotechnical modelling was carried out by Sharrock et al. (2020) for the mine pre-feasibility study. The modelling indicated potential excessive drive deformations (up to 5% tunnel closure/convergence) due to cave abutment stresses likely to occur throughout the mine life where the lower fault intersects the haulage level near Truck Chute #4 and where the fall-out occurred.

Closure/convergence of such magnitude will result in disruptions in the haulage loop requiring periodic prolonged and costly rehabilitations, which, in turn, would significantly affect the production from the mine, (Baasanjav 2020). Figure 4 shows the geotechnical numerical results completed by Sharrock et al. (2020). Note that drive closure/convergence classification was modelled using the empirical relationship of plastic shear strain and the tunnel closure/convergence for tunnelling through squeezing rock by Hoek & Marinos (2000).

Given the numerical modelling result, prevailing ground conditions, and the large fall-out in the backs where the lower fault intersected the haulage level, it was necessary to reconsider the ground support/reinforcement strategy for the long-term stability of the drive at this location.



Category	Descriptor	Plastic Shear Strain** (%)	Convergence (%)	Ground Support Approximation *
A	Negligible	0 - 0.50 %	0 – 1 %	2.4 m Fully Encapsulated Bolts and FRS (or mesh). Very little or no damage to FRS.
B	Minor	0.50 - 1.25 %	1 – 2.5 %	2.4 m Fully Encapsulated Bolts and FRS (or mesh). Onset of cracking in FRS.
C	Severe	1.25 - 2.50 %	2.5 – 5.0 %	2.4 m Fully Encapsulated Bolts, FRS, and Cables. Substantial damage to FRS with high levels of rehabilitation highly likely.
D	Very Severe	2.50 - 5.00 %	5.0 – 10 %	2.4 m Fully Encapsulated Bolts, FRS, and Cables, and/or sets (or equivalent) with multiple cycles of rehabilitation highly likely. Excavations are potentially unviable if support systems are inadequate.
E	Extreme	> 5.00 %	>10 %	Steel Sets and/or other engineered structures such as Concrete Segmented Circular Lining with grout curtains. Excavations are potentially unviable if support systems are inadequate.

(a) (b)

Figure 4 (a) Geotechnical numerical modelling results by Sharrock et al. (2020) for Oyu Tolgoi pre-feasibility study; (b) Damage classification and associated difficulties of tunnelling, updated and modified by Itasca based on Hoek & Marinos (2000)

5 Rehabilitation work for the haulage level at the location of the lower fault intersection and the large fall-out in the backs

5.1 Backfilling fall-out in the backs

There was a requirement to fill the large fall-out in the backs at the lower fault intersection with the haulage level near Truck Chute #4. Mine site geotechnical engineers designed backfilling strategy involving multiple layers of fibrecrete, mesh, and staple-shaped steel cage. Mesh and steel staples were to be installed manually and fixed in place each time with plates on long resin bolt tails pre-installed in pre-defined locations.

Staple-shaped steel cage was installed with the base facing upward for ease of spraying fibrecrete for proper fibrecrete embedment without 'shadows/gaps' behind steel bars. After the completion of backfilling, cable bolts were installed through the backfilled material to hold the backfill in place. Figure 5 shows the general arrangement for the backfilling of the fall-out in the backs.

As mentioned at the start of Section 3, the fall-out was laser scanned. It was possible to design the exact location of all the ground support and reinforcement during backfilling. Installation of resin bolts to hold mesh and staple-shaped steel cages was assisted and controlled by the underground survey team. The extent of the backfill was pre-determined by the shape of the steel arches and was controlled by survey pick-ups and the final laser scan.

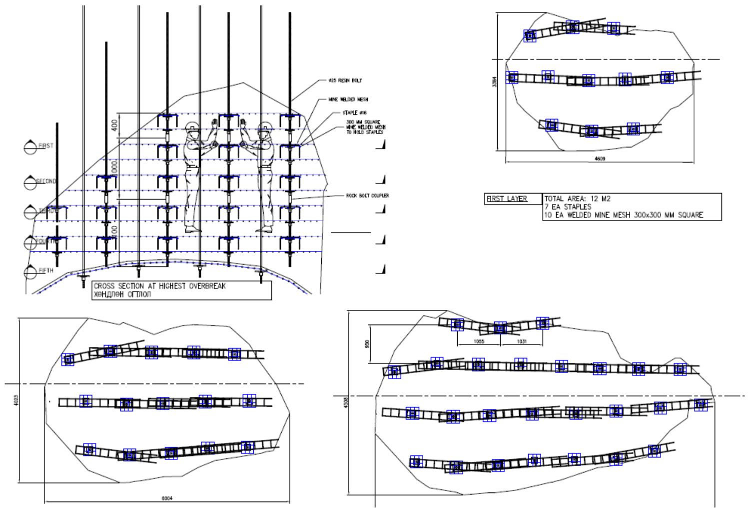


Figure 5 Backfilling fall-out in the backs with multiple layers of fibrecrete, mesh, and staple-shaped steel cage

5.2 Stripping of walls and backs to fit horseshoe profile lattice girders and installation of ground support/reinforcement

Before the back fall-out, the shape of the drive had flat backs with rounded shoulders. For the installation of the lattice girder arch sets, the shape of the drive had to be changed to a horseshoe profile. Therefore, the section of the haulage level drive at the intersection with the lower fault had to be enlarged by stripping both walls and backs to fit heavy steel arch support (Figure 6).

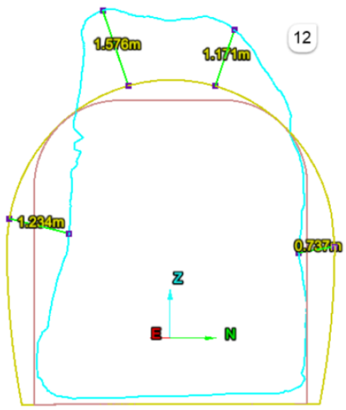


Figure 6 Cross-section of the horseshoe profile versus original haulage level profile as built

The mechanical envelope clearance for the horseshoe profile had to be designed by considering truck operating tolerance (truck not moving in a straight line), Mongolian underground regulations, ground support/reinforcement thickness following the stripping, construction clearance, height of LG with additional fibrecrete embedment, and 50 mm allowable convergence. Figure 7 shows the overall extent of the stripping and installation of steel arch support. Figure 8 shows the cross-section of the horseshoe profile.

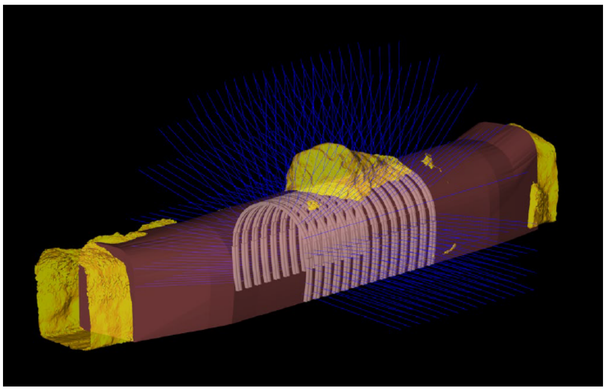


Figure 7 Extent of fall-out, stripping requirement and steel arch support

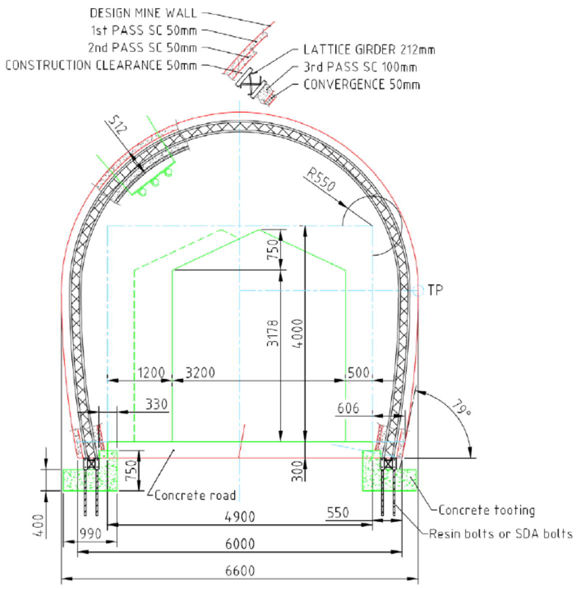


Figure 8 Cross-section of horseshoe profile showing tolerances and clearances

Heavy ground support/reinforcement had to be installed in the stripped section of the haulage drive before the installation of the steel arches. This campaign of heavy ground support/reinforcement installations was necessary to be able to withstand potential large deformations throughout the mine life of the haulage level without resorting to significant ground support/reinforcement rehabilitation campaign to avoid interruption to the movement of 160 t payload trucks from truck chutes to the crusher chambers. The ground support/reinforcement consisted of two layers of fibrecrete, and two layers of woven mesh installed in between the two layers of fibrecrete pinned with 3 m resin bolts. Cable bolts (8 m in length) were installed atop the second layer of woven mesh on a 1 × 1 m pattern. The bottom 1.5 m of the walls had cable bolts installed on a 0.5 × 0.5 m pattern to counter potential lower wall movement due to potential floor heave.

6 Design of lattice girders

6.1 Reasons for the lattice girders

Various steel arch types were put forward for consideration by Rio Tinto external to the mine site geotechnical team, members of the external geotechnical review board, and consultants. Oyu Tolgoi onsite geotechnical team member, in collaboration with the engineering team of the LG supplier, put forward an innovative design of LG combining yielding joints made from sliding elements of TH arches. The reasoning for this design was the following:

- The LG provide passive support comparable to other heavy steel arch types.
- The LG, in combination with fibrecrete embedment, provides immediate confinement across the whole perimeter of the drive without resorting to protracted and labour-intensive work. For steel arch embedment or other types of arches, there is no need to design and manufacture special formwork/shutters, no need for additional equipment for formwork/shutters erection, no need for continuous concrete poring behind formwork/shutters, less time for sprayed fibrecrete to cure compared with the concrete pour etc.
- Ease of installation of the LG which are lighter and do not require special equipment versus other types of steel arches.
- Ease of installation of the yielding joints and protecting them from fibrecrete embedment, therefore, more chance for the yielding joints to work as intended.
- The relative ease of stripping the LG compared to other types of steel arches in case of damage due to drive deformation requiring rehabilitation work.
- Cost of the LG versus other types of steel arches.
- Previous experience of installation by the mine site workforce.

6.2 Specifics for the lattice girders

The supplier of the ground support/reinforcement for Oyu Tolgoi mine had a production facility for manufacturing the LG, engineering expertise for design, and structural analysis for the proposed LG. The supplier was requested to manufacture the required LG per Oyu Tolgoi mine specifications. Some of the specifications are given below:

1. Four-bar LG shape in electronic format was provided by the mine.
2. Specifications for four-bar steel girders shall be P140-36, as per the supplier’s catalogue specifications for the LG.
3. LG shall be manufactured in a four-piece Horseshoe shape: two-piece central arch and two legs, no invert.
4. All steel elements for LG had to be galvanised.
5. The yielding joints design had to be made of TH beam sections as a sliding mechanism.
6. Sliding on yielding joint made of sliding TH beam sections had to be limited to 300 mm.
7. The TH beams sliding joint had to be inserted on both sides, at 2,900 mm above the excavation floor where the three arch pieces joined together.
8. The supplier had to specify torque on bolts for the clamps for TH29 sliding beams to give 80% of the ultimate loading capacity of the LG before the sliding joint starts sliding.
9. Four-bar lattice girder footings integrated with LG arches, P140-36.
10. All steel elements for footings had to be galvanised.
11. LG supplier had to provide:
    a. Engineering drawings and specifications for steel grade.
    b. Welding seams quality requirements.
    c. Sliding joints surface treatment to prevent corrosion.

d. Numerical structural analysis for the LG.

e. Concrete footing design analysis.

The general arrangement for the LG is shown in Figure 9.

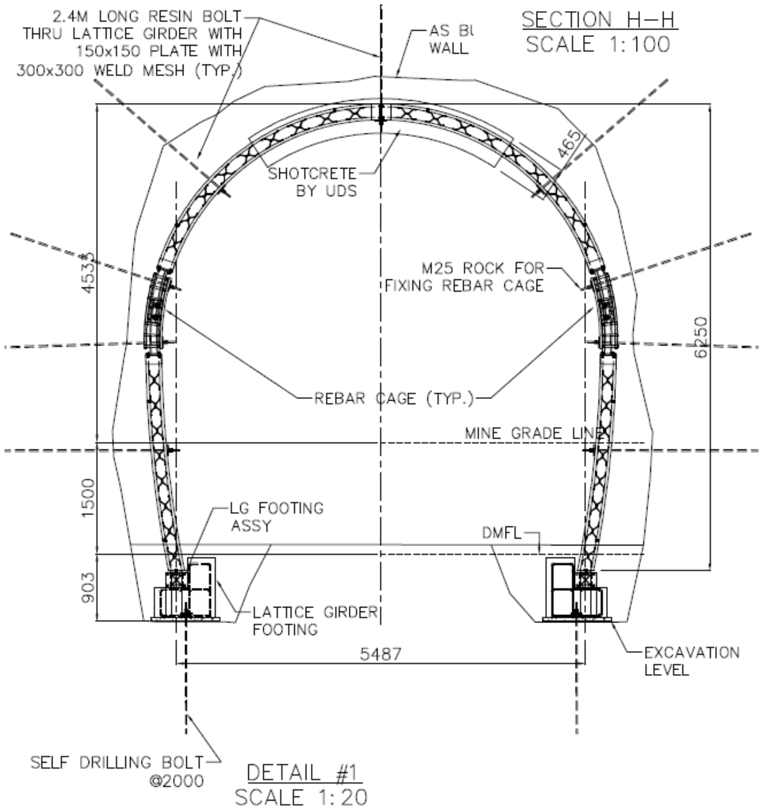


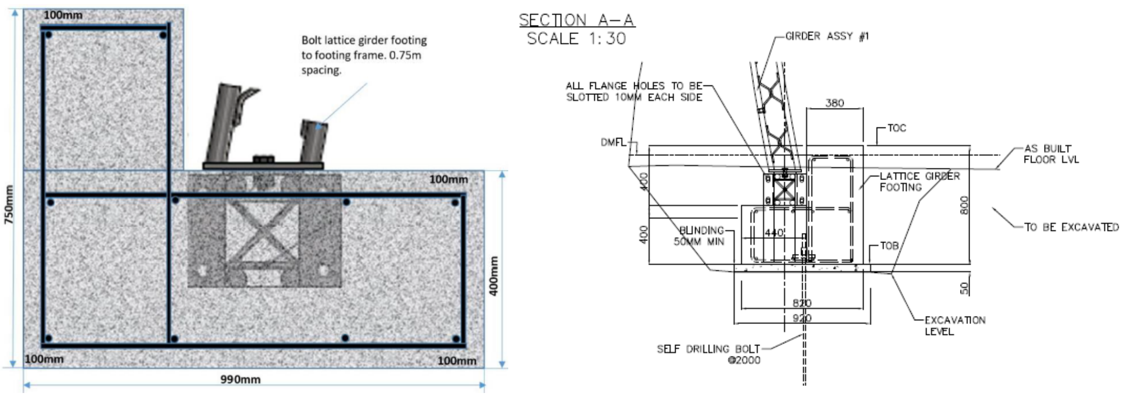
Figure 9 Lattice girder engineering drawings

6.3 Specifics for the four-bar footings integrated with lattice girder arches

Steel-reinforced concrete invert or any other steel reinforcement in the floor was deliberately excluded from the design in case the floor heave forces the steel to protrude from the floor requiring rehab to break the concrete floor, remove steel etc. This would stop haulage level trucks running into the crusher, resulting in costly production delays. From the beginning, footings only were opted for, with engineered fill-in between the footings for ease of re-grading quickly if the floor heave occurs.

To speed/ease up footing construction and installation of arch legs, the LG supplier was requested to supply all the footing reinforcement as an assembled cage with a certain length. In addition, the arch legs were designed to be connected to the floor girders utilising bolts and the floor girders would be pinned to the floor with 2 m long resin bolts or self-drilling anchors.

The weakness of the joints between the arch members of the LG is well-known. Therefore, the footing in front of the LG's leg had to be extended slightly up to be above the final floor level. This would give the leg extra resistance preventing the heel of the leg from moving into the drive during the floor heave or movement of the bottom of the walls of the drive. In addition, this extension should force the leg to transmit the movement up through the TH29 yielding joint. Also, this extension of the footing in front of the LG leg would prevent the arch legs from being accidentally damage by the road grader. Figure 10 shows the footing arrangement for the LG. It should be noted that the concrete footing design was analysed per the specifications and standards of American Concrete Institute 318 *Building Code Requirements for Structural Concrete and Commentary* (American Concrete Institute [ACI] ca. 2019).



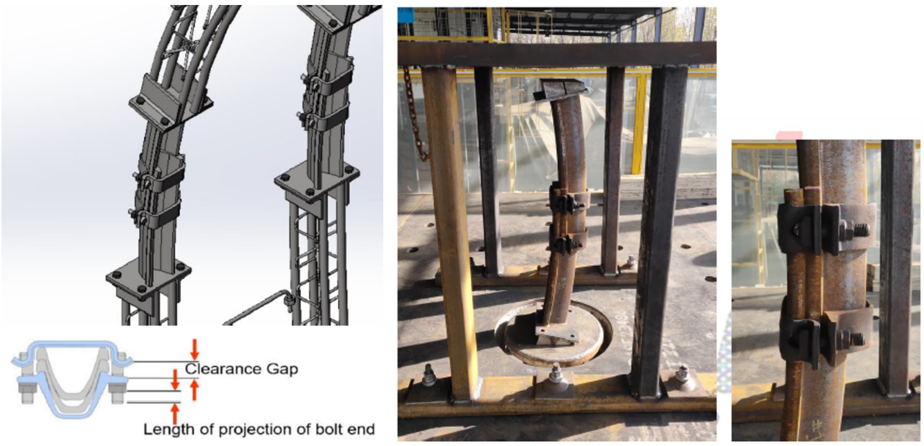
(a) (b)

Figure 10 Lattice girder footings arrangement. (a) As adopted for structural design analysis; (b) Showing floor girders to be pinned with self-drilling anchors

6.4 Specifics of the TH29 beams acting as yielding joint

The abutment stress loading onto the section of the haulage level at the proposed locations of the LG will be gradual, developing over a few years and ever-increasing with block cave propagation. The LG had to be installed before the start of the undercutting due to the requirement to have mine ore handling system operational before the start of the undercut or at least before reaching 50% of the hydraulic radius. To avoid potential premature failure of the lattice girder arches and protracted and costly rehabilitation due to delay in production, the yielding joint was designed to be made from TH29 beam sections. Note that originally five yielding joints were designed for the LG that are in the centre of the arch, two just above/at the shoulders and two in the walls. However, this design was ruled out due to technical and construction issues. Other types of yielding joints were considered, including the lining stress controllers commonly used in civil tunnelling, particularly in Europe. However, TH29 beam sections were preferred due to the simplicity of manufacturing and construction.

The movement/sliding within the yielding joint was designed to be limited to 200 mm. The bolts/nuts on the clamps clamping TH29 beams were specified to be torqued at a specific level to allow sliding at 80% of the LG arch support capacity. The supplier of the LG was requested to perform natural size testing to establish the required torque value (Figure 11). It is known that the sliding TH beams lock up due to severe corrosion on the surface of the beams, preventing required sliding/yielding. Corrosion protection for TH29 beam sections was considered but ruled out for the final specifications due to technical constraints.



(a) (b)

Figure 11 Lattice girder TH29 yielding joint details. (a) Clamp details; (b) Details of testing to establish torque on nuts/bolts

After reaching the sliding capacity, the 'gap' where the TH29 yielding joint is installed will be filled with sprayed fibrecrete. The LG will become stiff support. To enhance the stiffness of the fibrecrete in the 'gap', a special cage was designed to be installed inside the 'gap' formed by the yielding joint. Figure 12 details the design of this steel cage. The steel cage inside the 'gap' was installed after all the LG were embedded into the fibrecrete.

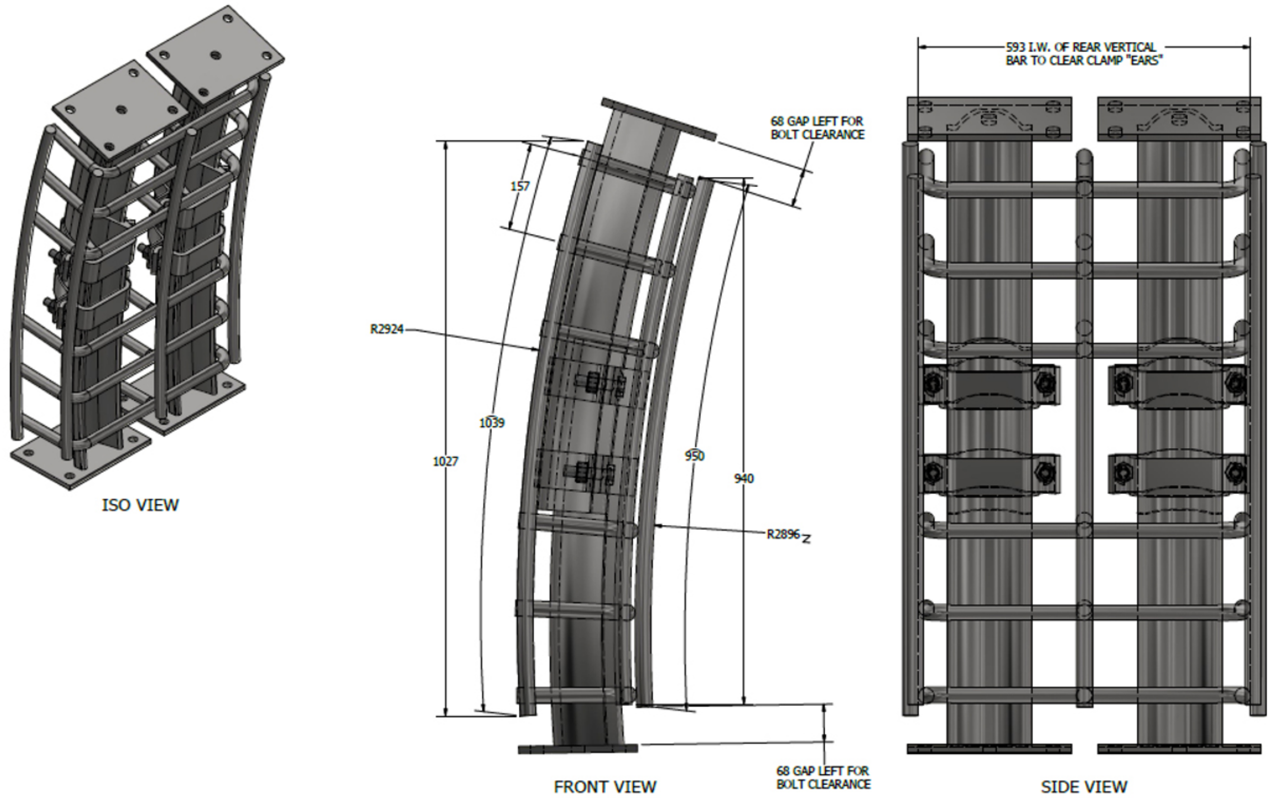


Figure 12 Steel reinforcement cage installed over TH29 beam sections for yielding joint backfilling after joint slides 100–200 mm, as determined by the onsite geotechnical engineers

6.5 Lattice girder structural analysis

Structural analysis was performed on the lattice girder arch set following the American Concrete Institute 318 (ACI ca. 2019) specifications. Figure 13 shows the load, axial, shear, moment, and deflection diagrams.

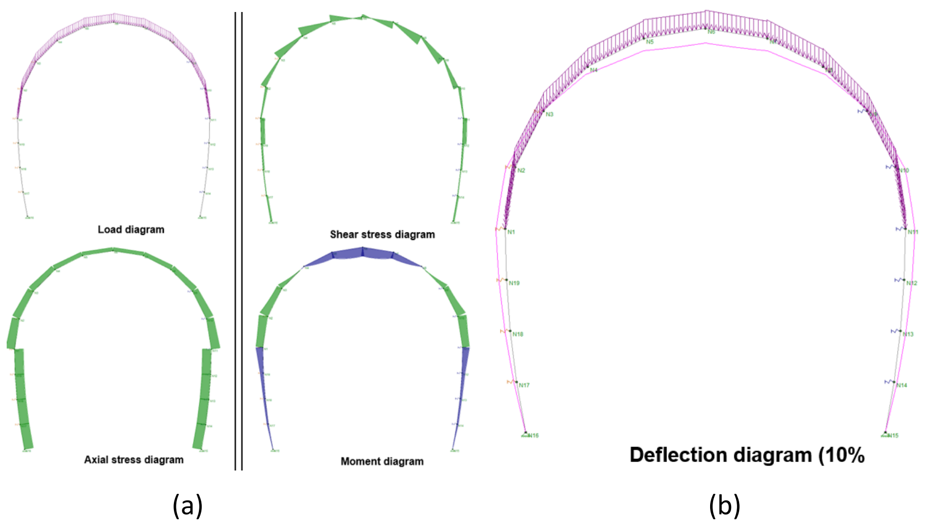


Figure 13 Results of the lattice girder structural analysis as per American Concrete Institute 318 (ACI ca. 2019) showing: (a) Load, axial, shear, moment diagrams; (b) Deflection diagram

Structural analysis indicated the LG of Type P 140-36, installed at 1 m centre-to-centre and encased in 40 MPa uniaxial compressive strength fibrecrete with 100 mm embedment, can support up to 8.3 m of dead rock weight (rock density 2,563.2 kg/m^3). The design was considered adequate. However, to be conservative, a decision was made to increase the number of steel arches to two at 1 m centre-to-centre. Figure 14 shows a profile view with a general arrangement of the final design for the LG. The double LG were designed to be installed in between the installed cable bolts to prevent interaction with the tails of the cable bolts during construction.

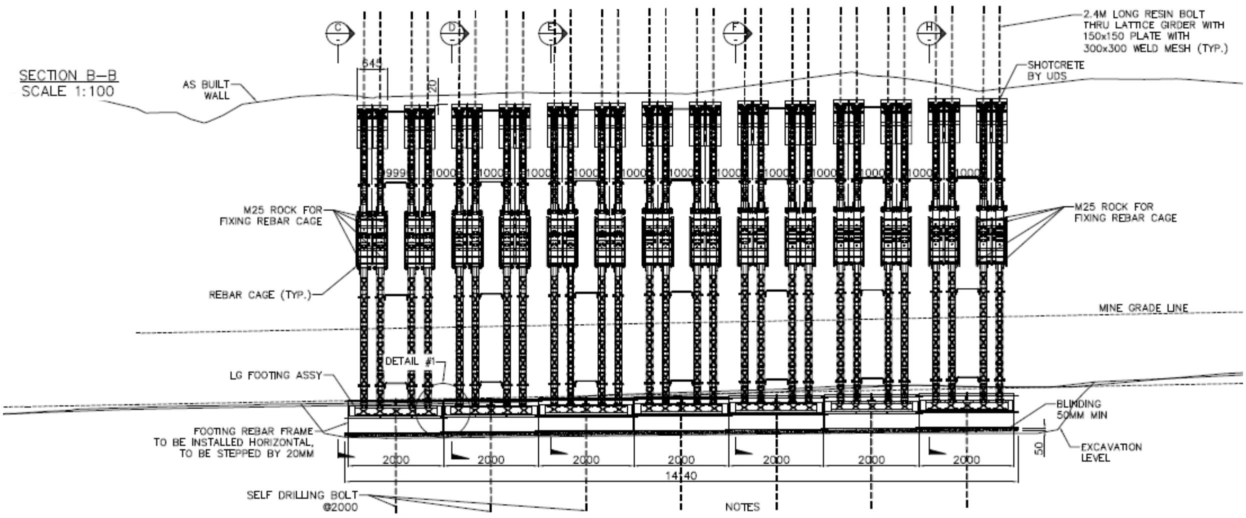


Figure 14 Profile view of the double lattice girders

7 Installation of the lattice girders

A standard work procedure was developed for the installation of the LG. Standard equipment available on site at the time of the installation was utilised. The underground mine development and construction crews installed the LG.

There were 28 LGs (14 twin LG) required to be installed. The construction schedule allocated 10 days for the installation of the LG and four days for the embedment of the LG with fibrecrete. However, the installation of the LG happened to be carried out during the COVID-19 period, which affected manpower at the mine and the actual duration of the installation turned out to be longer. Thus, the exact duration was not established but was extended over a long period with multiple schedule changes. It should be noted that the installation itself went smoothly and would have been completed within or close to the originally scheduled 14 days.

Figures 15 to 21 depict some of the key stages in the lattice girder installations and the final product. The fibrecrete spraying over the LG was carried out in the following sequence: a) Left-hand-side bottom sections below yielding joints were sprayed first; b) Right-hand-side bottom sections below yielding joints were sprayed second; and c) The top section (arch) was sprayed third.

It should be noted that to mitigate potential fibrecrete scats/slabs fall-outs from the backs during tunnel deformation, weld mesh was installed in the arched section of the LG.

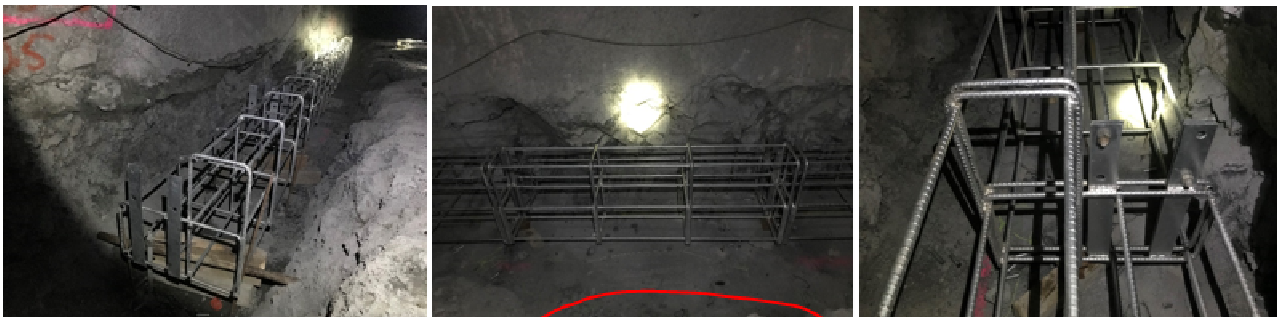


Figure 15 Construction of footings for the lattice girders

Figure 16 Installation of legs for the lattice girders

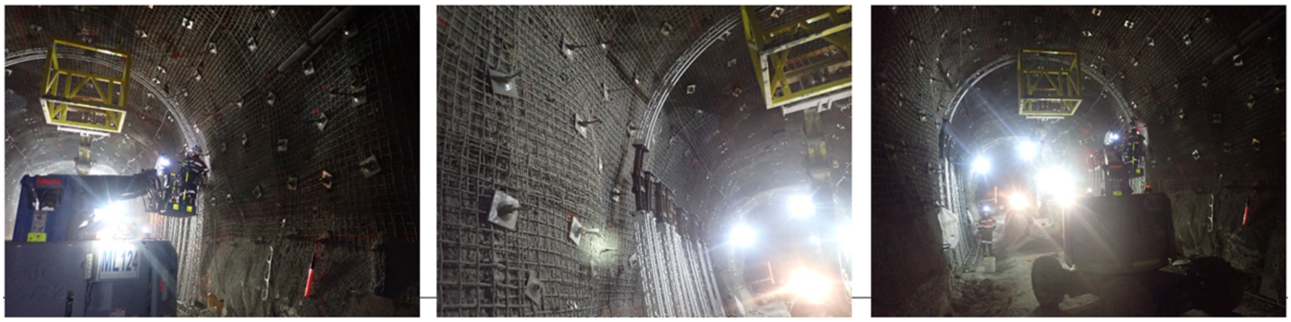


Figure 17 Installation of top arch members for the lattice girders

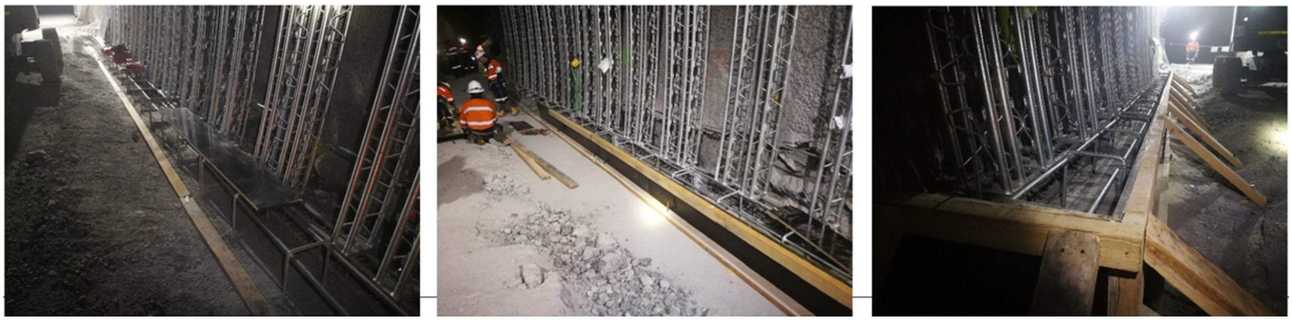


Figure 18 Formwork and concrete pour for the footings for the lattice girders

Figure 19 The lattice girders are fully installed, yielding joints are covered, and the lattice girders are ready to be embedded into fibrecrete

(a) (b)

Figure 20 Bottom sections (below the yielding joints) of the lattice girders are embedded with fibecrete: (a) Left-hand-side first; (b) Right-hand-side second

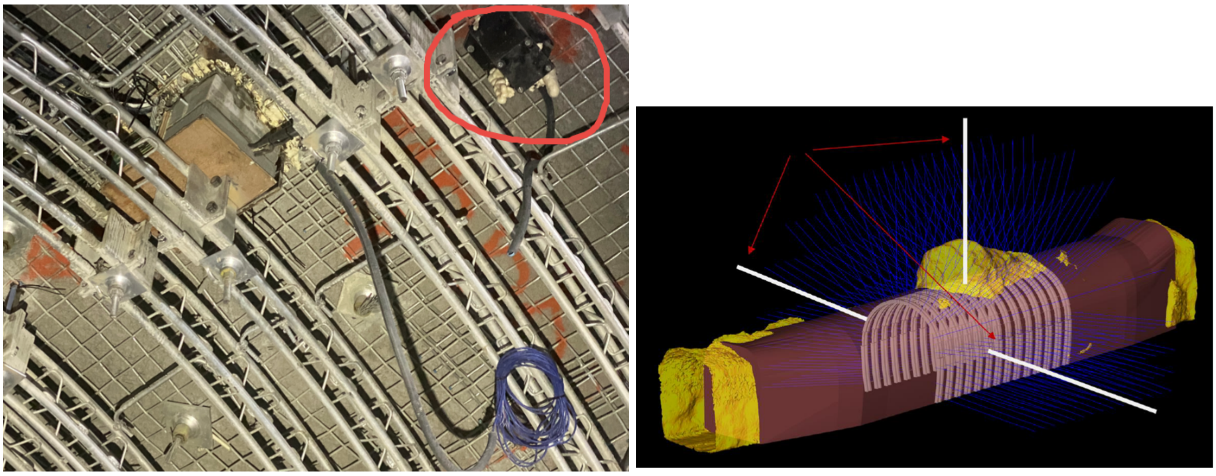
Figure 21 The lattice girders fully embedded into fibrecrete and weld mesh is installed in the arch section

8 Installation of monitoring instrumentation for the lattice girders

Before the embedment of the LG with fibrecrete, several types of geotechnical monitoring instruments were installed:

- Two pressure cells, one to measure radial stress and one to measure tangential stress, as shown in Figure 22.
- 15 m multi-point borehole extensometers (MPBXs), one in each wall and one in the back, as shown in Figure 23.
- Convergence pins were installed when required.
- Defunct tape extensometer tape was cut up in sections of 10 cm long and four pieces were affixed onto the four TH29 beams at four locations to ascertain the relative sliding of the yielding joints.
- Periodic laser scanning was carried out when required.

Figure 22 Example of radial pressure cell installed above the arch of the lattice girders



(a) (b)

Figure 23 Example of installed multiple point borehole extensometers (MPBX). (a) In the backs; (b) Overall view of installed MPBXs

At the time of writing this paper, the monitoring instruments did not show any significant movement in the rock mass or the LG.

9 Conclusion

An innovative design of a lattice girder arch set combining yielding joints made from sliding elements of TH29 beam sections was implemented at Oyu Tolgoi mine in the haulage level. The yielding element inside the LG was deemed to be necessary to accommodate gradually developing, high abutment stresses from upward cave propagation.

The design, structural analyses, and manufacturing of LG combining yielding joints made from sliding elements of TH29 beam sections prove to be technically feasible. Underground assembly and installation of the support system turned out to be simple and practical. The majority of the installation work was mechanised, meeting the requirements of the mine standards in terms of minimising manual work as much as possible and preventing personnel injuries. It is concluded that the lattice girder arch set with TH29 beam yielding section is a viable ground support solution in difficult ground conditions, such as this project.

At the time of writing this paper, the monitoring instruments did not show any significant movement in the rock mass or the LG. Oyu Tolgoi geotechnical engineers will update the geotechnical community on the performance of the yieldable lattice girder arch set in the future.

Ease of constructability and viability could be an attractive option for other Rio Tinto mines in very poor ground conditions, with the potential to trial five TH29 beam sections as yielding joints.

Acknowledgement

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