Installation of Lattice Girders with TH Yielding Elements in Poor Ground Conditions

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Abstract

In block cave mines, the permanent Life of Mine tunnelling infrastructure require withstanding multiple changes in ground stresses and remain functional for up to +60 year. In block cave mines, in general the changes in ground stresses originate from initial induced stresses during tunnels and chambers excavations. Following this comes 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 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 pillars 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 undercutting phase. Multiple changes in ground stresses are likely to cause large deformations in the tunnels and pose challenges to ground support designers with the choice of ground support/reinforcement types/systems/elements, particularly if permanent infrastructure is sited in poor ground due to the presence of large weak structures.

At Oyu Tolgoi mine, the tunnel stability in the Haulage Level is very important for 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 +60 years mine life in the Haulage Level requiring innovative ground support/reinforcement design involving installation of fibercrete embedded Lattice Girders with yielding elements. The authors believe the design of the Lettice Girders with yielding elements made from sliding sections of TH beams has been implemented first time in the world in either civil tunnelling or the mining industry.

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. At full production rate the mine will be producing 95,000 tons of ore per day. The mine utilises haulage level underneath extraction level for moving ore by 160-ton 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 surface.

Drive stability in the Haulage Level is very important for uninterrupted movement of 160-ton payload trucks from truck chutes to crusher chambers. A large and weak Lower Fault intersects a section of the Haulage level near the Truck Chute 4. During mining of the Haulage Level Drive through the Lower Fault, a large fall-out occurred from the backs of the drive. Mine-wide scale FLAC3D geotechnical stress modelling indicates 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 the Truck Chute 4 and where the fall-out occurred.

There was a requirement to fill out large fall-out in the backs where the fall-out occurred at the Lower Fault intersection with the Haulage Level near the 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-ton 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 combining yielding joints made from sliding elements of TH beams sections was adopted. Innovative footings design for the Lattice Girders arches had to be designed for the Lattice Girders arches. Lettice Girders arches design with yielding elements passed rigorous process of structural capacity modelling, evaluation of bearing capacity of the footings and natural size testing of yielding elements. This innovative design passed external and internal review by geotechnical peers and mining engineers. The OT underground construction team reviewed the installation methodology elaborated by the on-site geotechnical team. The design was adopted by senior Mine Management and successfully implemented by the underground construction and development teams throughout 2021 - 2022.

The below paper will outline the design considerations, technical evaluation and installation of the Lettice Girders 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 54m. The distance from the backs of the Haulage Level to the floor of the Extraction Level is 36mm. The Primary Crusher 1 is located to the South-West of the footprint. The Haulage Level forms a loop whereas the payload trucks travel clockwise from the PC1 to the Truck Chutes #1 - #4 and back to PC1. Figure 1 shows the Haulage Level with respect to the footprint OT Block Cave.

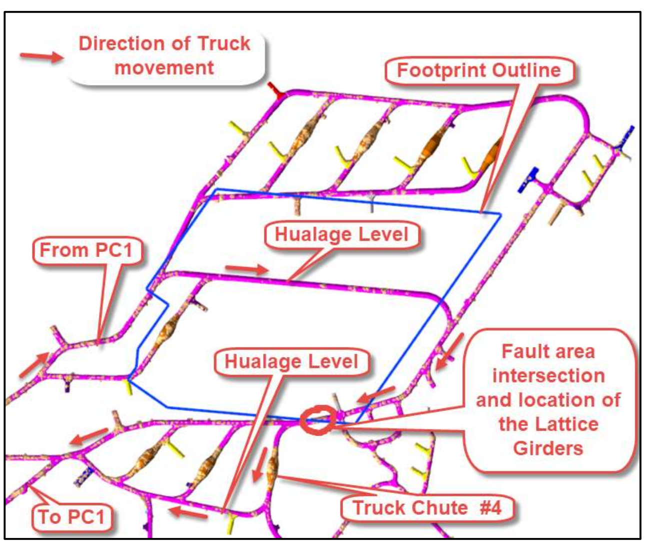
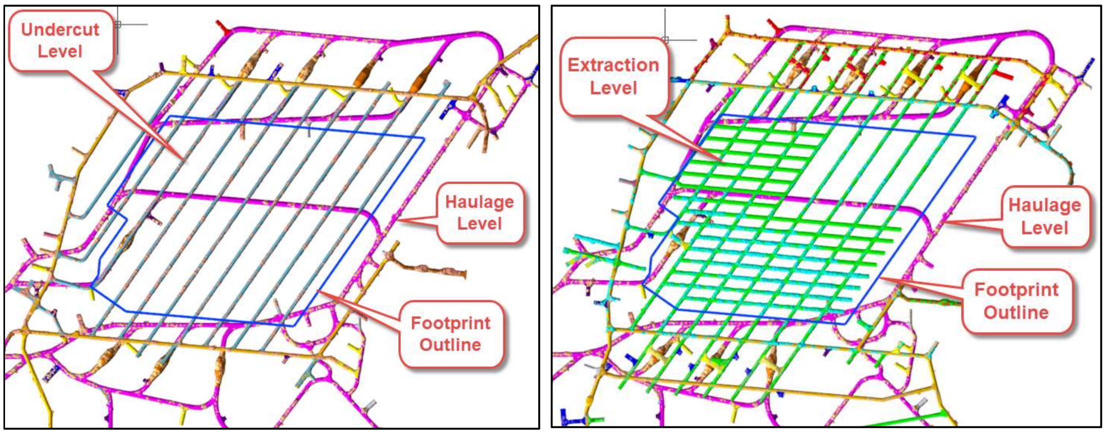


Figure 1 Haulage Level layout with respect to Block Cave footprint at Oyu Tolgoi

Figure 2a and Figure 2b illustrate the Haulage Level with respect to Extraction and Undercut respectively. Note that the undercutting process is designed to be initiated from the South-Western extremity of the footprint, then advance as a narrow strip along the southern boundary of the footprint to the South-Eastern extremity and then full UC front is advanced North with the eastern leading edge.



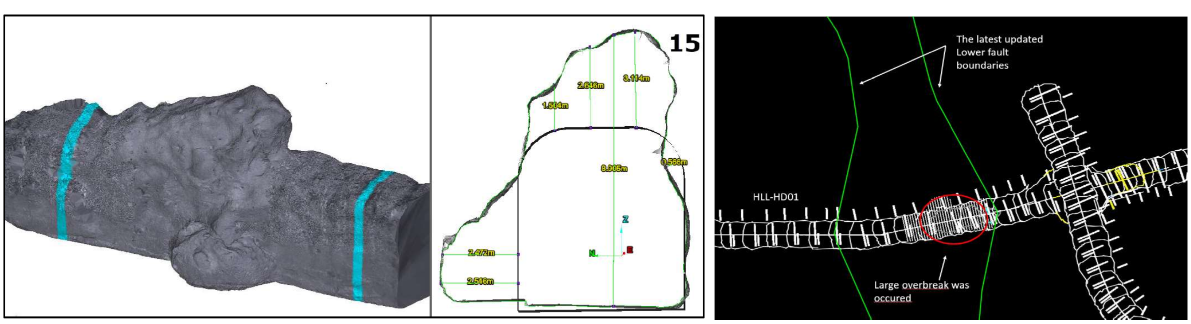
(a) (b)

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 Girders installation

Several papers have been published in the past on Geological and Geotechnical setting at Oyu Tolgoi mine. A recent paper by Ooi et al (2022) published in the proceedings for the Block Caving Conference held in Australia, Adelaide, in 2022 can be referred to. Only a brief description of ground conditions is outline below.

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



(a) (b)

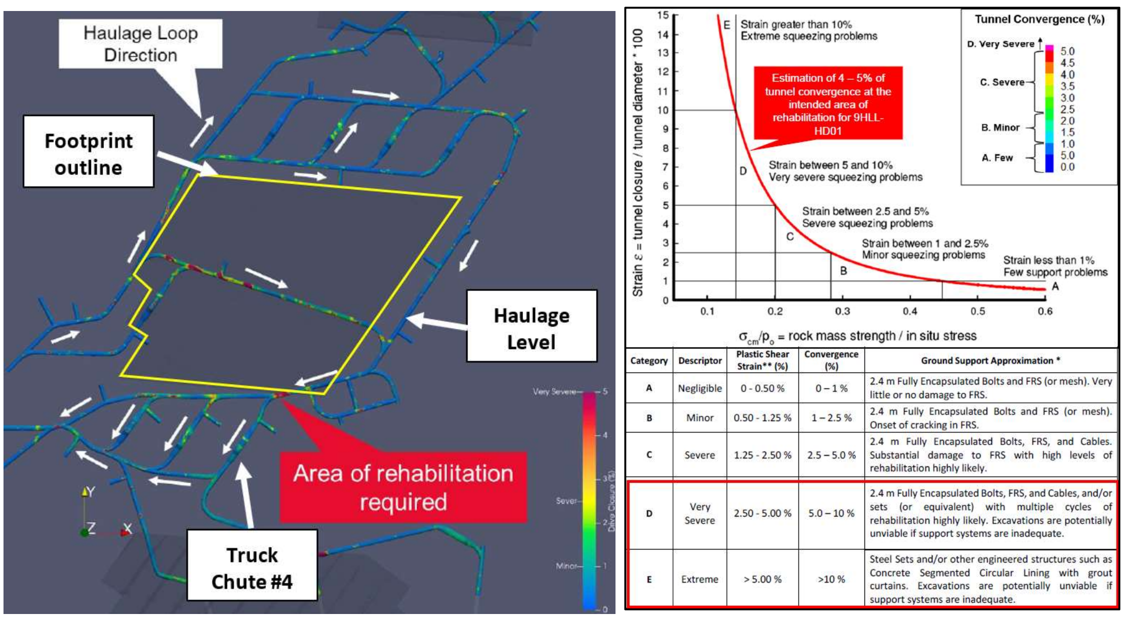
Figure 3 Extent of the fault zone in the haulage Level: a) Laser scan survey and cross section view; b) plan view of the Haulage Level at the location of the backs fall-out

4 Mine-wide modelling results for the Haulage Level at the location of the Lattice Girders installation

Mine-wide scale FLAC3D geotechnical stress modelling was caried out by Sharrock et al (2020) for the mine PFS study. The modelling indicated potential excessive drive deformations (up to 5% tunnel closure) due to cave abutment stresses likely to occur throughout the mine life where the Lower Fault intersects the Haulage Level near the Truck Chute 4 and where the fall-out occurred.

Closure 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. Figure 4 below shows the geotechnical numerical results completed by Sharrock et al (2020). Note that drive closure classification is modelled from empirical relationship of strain and the degree of difficulty to tunnel through squeezing rock by Hoek & Marinos (2000).

Given the numerical modelling result, prevailing ground conditions and large fall-out in the backs where the Lower Fault intersected the Haulage Level it was necessary to reconsider ground support/reinforcement strategy for the long-term stability of the drive at this particular 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 **Geotechnical numerical modelling results a) by Sharrock et al (2020) for Oyu Tolgoi PFS; b) damage classification and associated difficulties of tunnelling, updated and modified by ITASCA based on Hoek and Marinos (2000)**

5 Backfilling fall-out in the backs, stripping for horseshoe profile and installation of long-term ground support/reinforcement for the Haulage Level at the location of the Lower Fault intersection and large fall out in the backs

5.1 Backfilling fall-out in the backs

There was a requirement to fill out large fall-out in the backs where the fall-out occurred at the Lower Fault intersection with the Haulage Level near the Truck Chute 4. Mine site geotechnical engineers designed backfilling strategy involving multiple layers of fibercrete, mesh and staple shape 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 shape steel cage was installed with the base facing upward for ease of spraying fibercrete for proper fibercrete embedment without “shadows/gaps” behind steel bars. After completion of backfilling, cablebolts were installed through the backfilled material to hold it place. Figure 5 below shows general arrangement for the backfilling the fall-out in the backs.

As was mentioned about, the fall-out was laser scanned it was possible to design exact location of all the ground support and reinforcement during backfilling. Installation of resin bolts to hold mesh and staple shape steel cages was assisted and controlled by u/g 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 final laser scan.

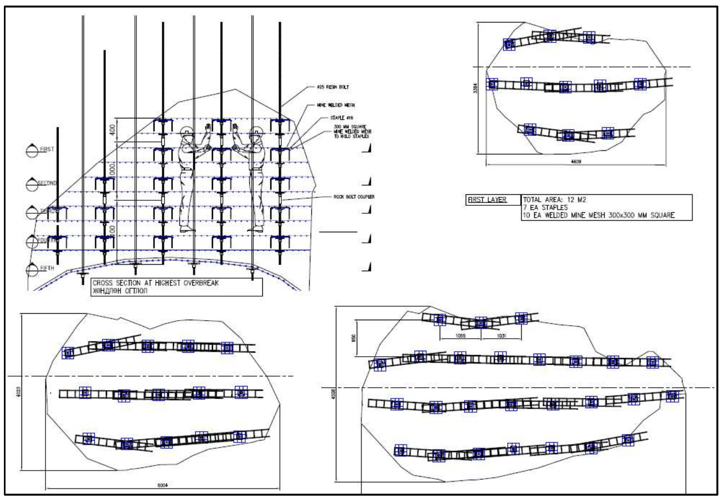


Figure 5 Backfilling fall-out with multiple layers of fibercrete, mesh and staple shape steel cage

5.1 Stripping of walls and backs to fit horseshoe profile Lattice Girders and installation of ground support/reinforcement

Before the fall-out from the backs the shape of the drive had flat backs with rounded shoulders. For the installation of the Lattice Girders the shape of the drive had to be changed to 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, see Figure 6 below.

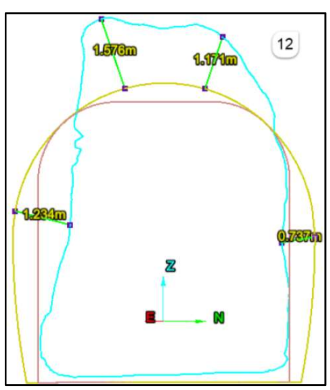


Figure 6 Cross-section of the horseshoe profile vs original Haulage Level profile as-built

The mechanical envelope clearance for the horseshoe profile had to be designed by considering payload trucks operating tolerance (truck moving not on a straight line), Mongolian UG Regulations, ground support/reinforcement thickness following the stripping, construction clearance, height of Lattice Girders with additional fibercrete embedment, 50mm allowable convergence. Figure 7 below shows overall extend of the stripping and installation of steel arch support. Figure 8 below shows the cross section of the horseshoe profile.

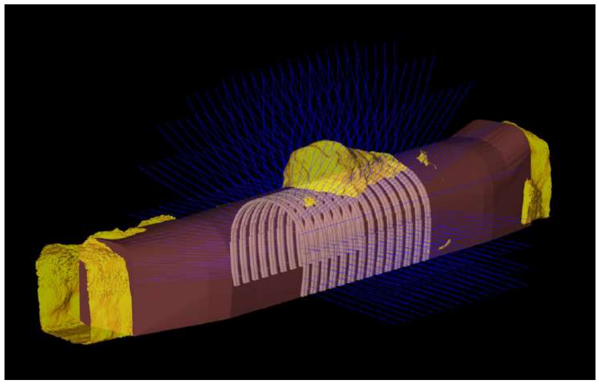


Figure 7 **Extent of fall-out, stripping requirement and steel arch support**

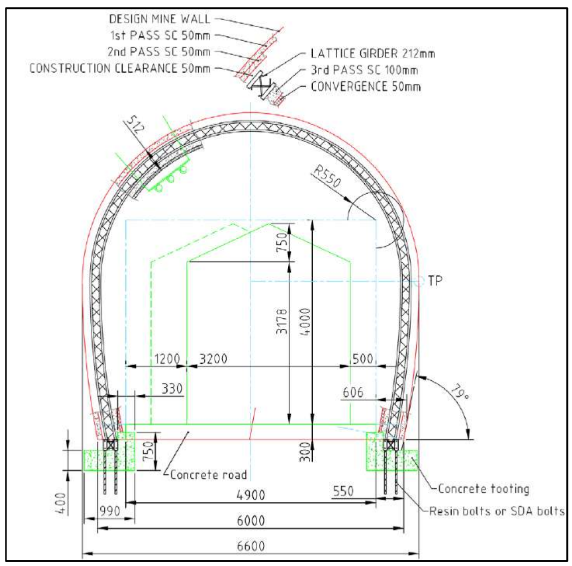


Figure 8 **Cross-section of Horseshoe profile showing tolerances and clearances**

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-ton payload trucks from truck chutes to the crusher chambers. The ground support/reinforcement consisted of two layers of fibercrete, two layers of Woven mesh installed in between the two layers of fibercrete pinned with 3m resin bolts. Cablebolts 8m in length were installed atop of the second layer of Woven mesh on 1m x 1m pattern; the bottom 1.5m of the walls had cablebolts installed on 0.5m x 0.5m patter 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 by Rio Tinto external to the mine site geotechnical team, members of external geotechnical review board and consultants for consideration. OT on-site geotechnical team member in collaboration with Engineering Team of Lattice Girders supplier put forward innovative design of Lattice Girders combining yielding joints made from sliding elements of TH arches. The reasoning for this design was the following:

- the Lattice Girders provide passive support comparable to other heavy steel arch types;
- the Lattice Girders in combination with fibercrete embedment provide immediate confinement across the whole perimeter of the drive without resorting to protracted and laboursome work for steel arches embedment for other types of arches, that 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 fibecrete curing compared to concrete pour, etc;
- ease of installation of the Lattice Girders, which are lighter and do not require special equipment vs other types of steel arches;
- ease of installation of the yielding joints and protecting them from fibercrete embedment, therefore, more chance for the yielding joints to work as intended;
- relative ease of stripping of the Lattice Girders compared to other types of steel arches in case of damage due to drive deformation requiring rehab;
- cost of the Lattice Girders vs 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 production facility for manufacturing the Lattice Girders, engineering expertise for design and structural analysis for the proposed Lattice Girders. The supplier was requested to manufacture the required Lattice Girders in accordance to Oyu Tolgoi mine specifications. Some of the specifications are given below:

1. 4-bar Lattice Girders, DXF shape was provided by the mine.
2. Specifications for 4-bar Steel Girders shall be P140-36, as per supplier's Catalogue Specifications for the Lattice Girders.
3. Lattice girders shall be manufactured in 4-piece Horseshoe shape – 2-piece central arch and two legs, no invert.
4. All steel elements for Lattice Girders had to be galvanized.
5. Yielding joints design had to be made of TH beam sections as sliding mechanism.
6. Sliding on yielding joint made of sliding TH beam sections had to be limited to 300mm.
7. The TH beams sliding joint had to be inserted on both sides, at 2900mm above the excavation floor where the three arch pieces joined together.
8. 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 girder before sliding joint starts sliding.
9. 4-bar lattice girder footings integrated with LG arches, P140-36, see Sketch 1 and 2 below.
10. All steel elements for footings had to be galvanized.
11. Lattice Girders 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 Lattice Girders;
    e. concrete footing design analysis.

The general arrangement for the Lattice Girders is show in the Figure 12 below.

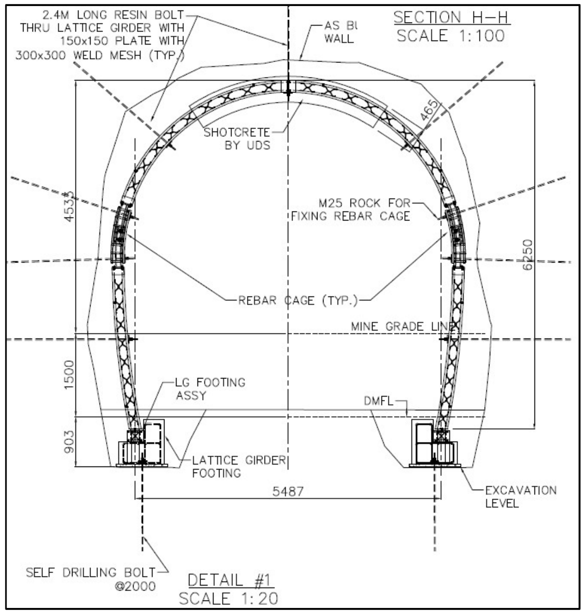


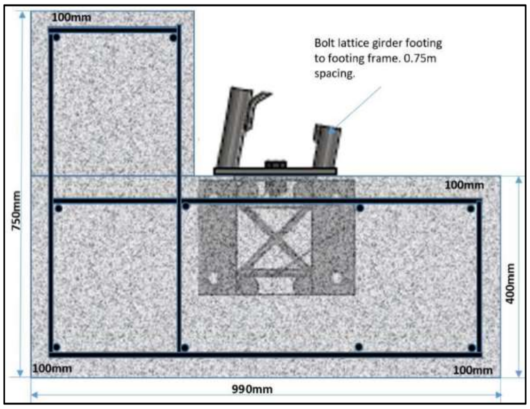
Figure 9 Lattice Girders engineering drawings

6.3 Specifics for the 4-bar footings integrated with Lattice Girders arches

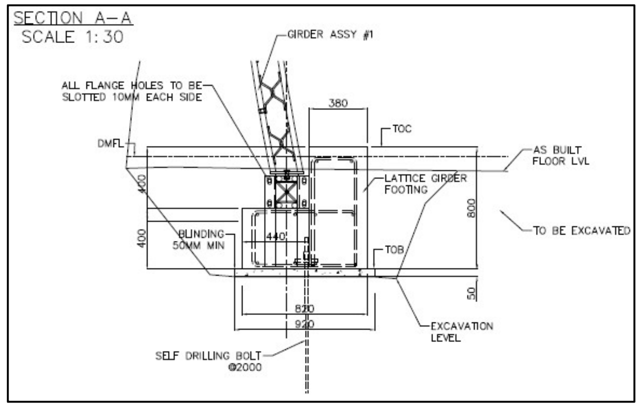
Steel reinforced concrete invert or any other steel reinforcement in the floor were deliberately excluded from the design in case the floor heave force the steel to protrude from the floor requiring rehab involving breaking concrete floor, removing steel, etc. This would stop haulage level trucks running to the crusher causing costly production delays. From the beginning, it was opted for footings only and 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 Lattice Girders supplier was requested to supply all the footings reinforcement as assembled cage of certain length. In addition, the arch legs were designed to be connected to the floor girders by means of bolts and the floor girders would be pinned to the floor with 2m long resin bolts or Self-Drilling Anchors.

The weakness of the joints between the arch members of the Lattice Girders are well known from the published literature. Therefore, footing in front of the Lattice Girders leg had to be extended slightly up to be above the final floor level. This would give the leg extra resistance preventing the heal of the leg to kick out 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 from of the Lattice Girders leg would prevent the arch legs from the road grader damage. Figure 10 below show footings arrangement for the Lattice Girders. It should be noted the concrete footing design was analyzed as per ACI specifications.



(a)



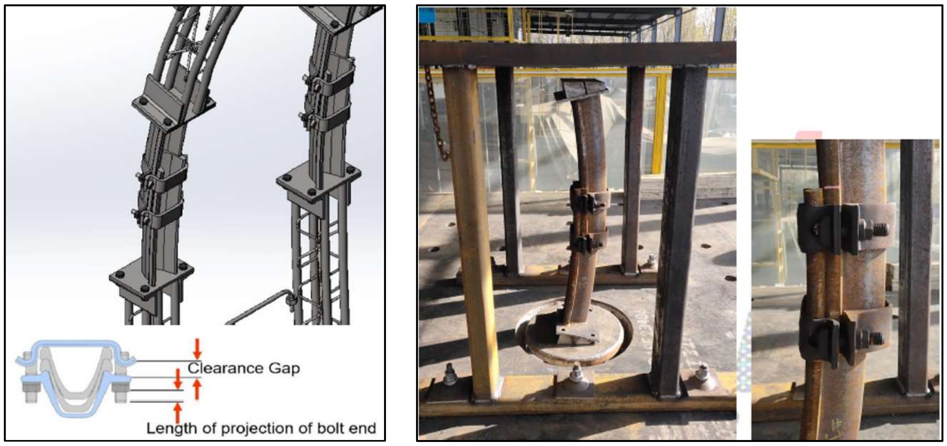
(b)

Figure 10 Lattice Girders footings arrangement: a) as adopted for structural design analysis; b) showing floor girders to be pinned with floor SDA

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 Lattice Girders will be gradual, developing over a few years and ever increasing with block cave propagation. The Lattice Girders had to be installed before the start of the undercutting due to requirement to have Mine Ore Handling System operational before the start of the undercut or at the least before reaching 50% of the Hydraulic Radius. To avoid potential premature failure of the Lattice Girders arches and protracted and costly rehab due to delay in production the yielding joint was designed made from TH29 beam sections. Note that originally, five yielding joints were designed for the Lattice Girders, that is in the center of the arch, two just above/at the shoulders and two in the walls. However, this design was ruled out two to technical and constructability issues. Other types of yielding joints were considered, including the Lining Stress Controllers commonly used in civil tunneling, particularly in Europe. However, TH29 beam sections were preferred due to simplicity of manufacturing and construction.

The movement/sliding within the yielding joint was designed to be limited to 200mm. The bolts/nuts on the clamps clamping TH29 beams were specified to be torqued at specific value to allow sliding at 80% of the Lattice Girders arch support capacity. Supplier of the Lattice Girders was requested to perform natural size testing to establish the required torque value, see Figure 11 below. It is known 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 Girders 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 fibercrete. The Lattice Girders will become stiff support. To enhance stiffness of the fibercrete 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 Lattice Girders were embedded into the fibercrete.

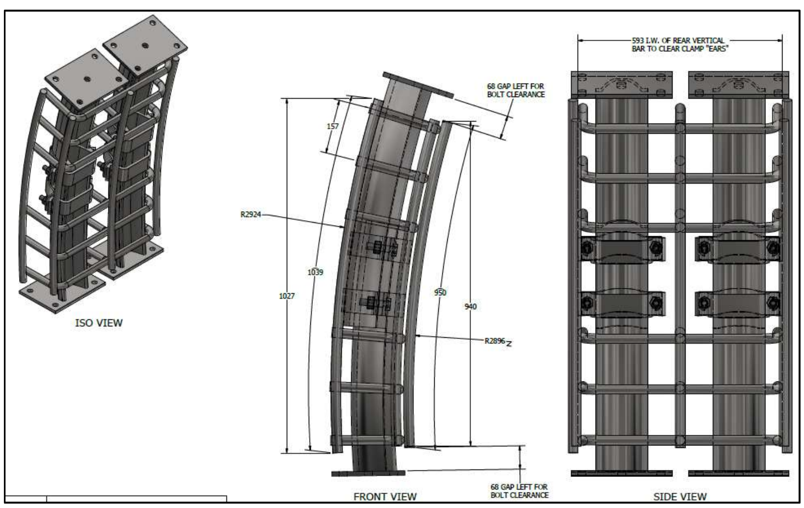
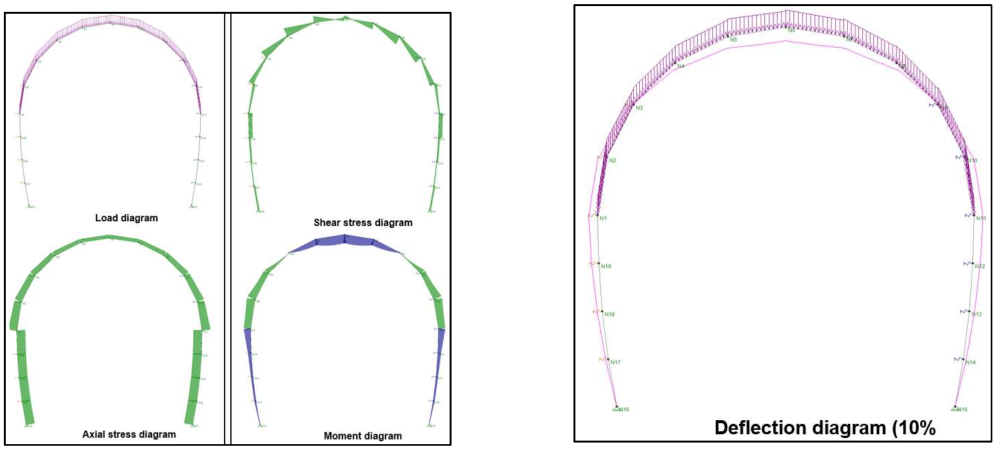


Figure 12 Steel reinforcement cage installed over TH29 beam sections for yielding joint backfilling after joint slides 100mm – 200mm as to be determined by the on-site geotechnical engineers

6.5 Lattice Girders structural analysis

Structural analysis was performed on the arch following the ACI318 specifications. Figure 13 below shows the load, axial, shear, moment, deflection diagrams.



(a) (b)

Figure 13 Results of the Lattice Girders structural analysis as per ACI318 showing: a) load, axial, shear, moment diagrams; b) deflection diagram

Structural analysis indicated the Lattice Girders of Type P 140-36, installed at 1m centre-to-centre and encased in 40MPa UCS fibercrete with 100mm embedment can support up to 8.3m of dead weight of the rock, rock density 2563.2kg/m3. This design was considered adequate. Nevertheless, the decision was made to increase the number of steel arches to two at 1m centre-to-centre, Figure 14 shows Long-Section view with general arrangement of the final design for the Lattice Girders. The double Lattice Girders were designed to be installed in between the installed cablebolts to prevent interaction with tails of the cablebolts during construction.

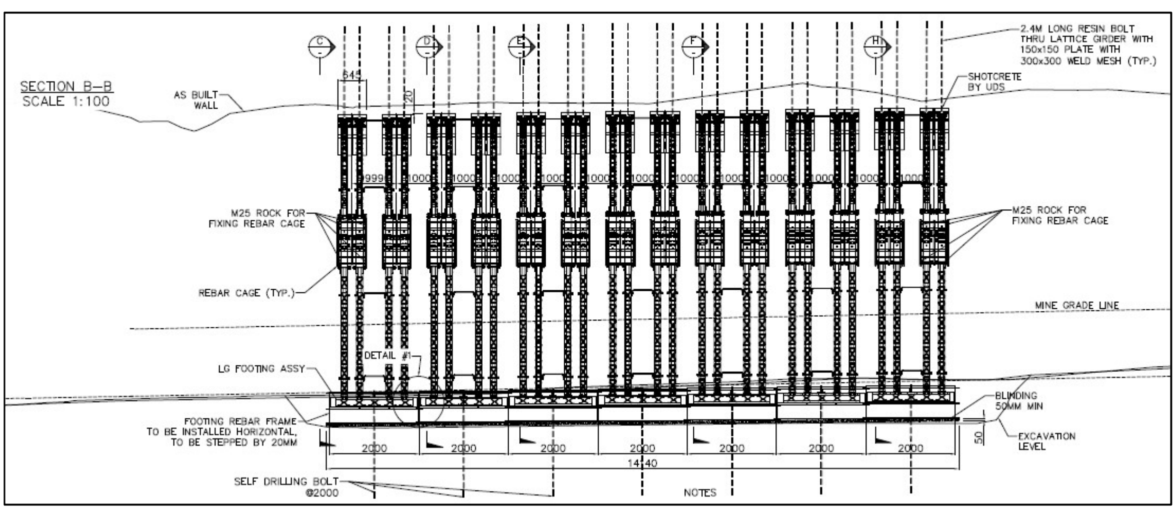


Figure 14 Plan view of the double Lattice Girders

7 Installation of the Lattice Girders

A Standard Work Procedure was developed for the installation of the Lattice Girders. Standard equipment available on site at the time of the installation was utilized. The underground mine development and construction crews installed the Lattice Girders.

There were twenty-eight Lattice Girders (14 twin Lattice Girders) require to be installed. The construction schedule allocated 10 days for installation of the Lattice Girders and four days for embedment of the Lattice Girders with fibercrete. However, the installation of the Lattice Girders happened to be carried out during COVID-19 period, which affected manpower at the mine and the real duration of the installation proved to be longer; exact duration was not established and extended over a long period of time with multiple changes in schedule. It should be noted the installation itself went smooth and would have been completed within or close to the originally scheduled 14days.

Figure 15 through to Figure 19 depict some of the key stages in the Lattice Girders installations and the final product.

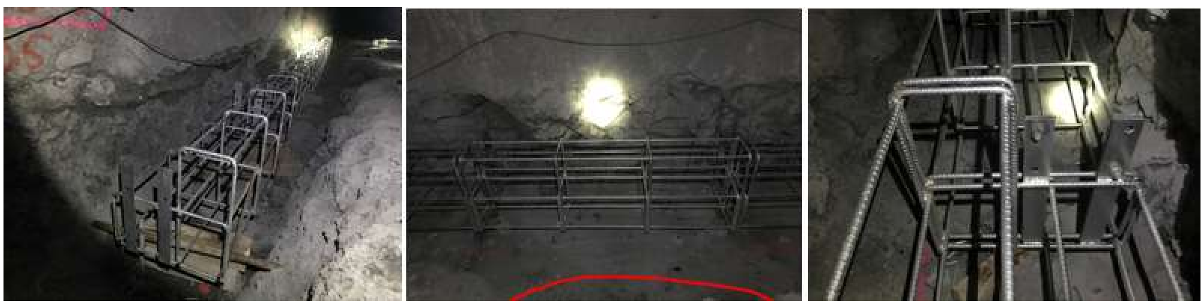


Figure 15 Construction of footings for the Lattice Girders

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 poor for the footings for the Lattice Girders

Figure 19 The Lattice Girders are fully installed, yielding joints are covered, the Lattice Girders are ready to be embedded into fibercrete

(a) (b)

Figure 20 Bottom sections (below the yielding joints) of the Lattice Girders are embedded with fibercrete: a) Left Hand Side first; b) Right Hand Side second

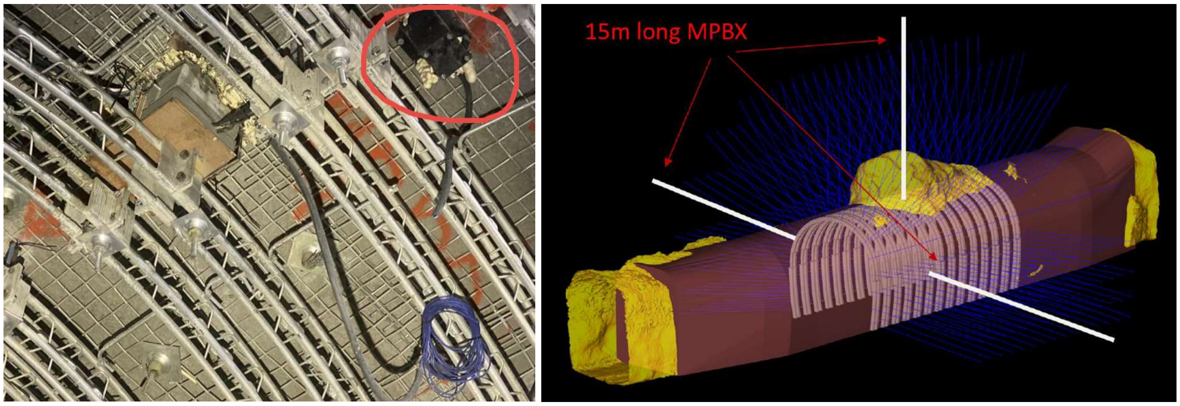
Figure 21 The Lattice Girders fully embedded into fibercrete, weld mesh is installed in the arch section

8 Installation of monitoring instrumentation for the Lattice Girders

Before the embedment of the Lattice Girders with fibercrete, a several types of geotechnical monitoring instruments were installed, such as:

- Two pressure cells, one to measure radial stress and one to measure tangential stress, shown in Figure 22 below;
- 15m MPBXs, one in each wall and one in the backs, show in Figure 23 below;
- Convergence pins will be installed when required;
- Paint marks and other permanent visible marks are placed on the TH29 beams to ascertain relative sliding of the yielding joint;
- Periodic Laser Scanning will be 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 MPBXs: a) in the backs; b) overall view of installed MPBXs

At the time of writing the paper, the monitoring instruments do not show any significant movement in the rock mass or the Lettice Girders.

3 Conclusion

An innovating design of Lattice Girders 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 Lattice Girders was deemed to be necessary to accommodate gradually developing high abutment stresses from upward cave propagation.

The design of Lattice Girders combining yielding joints made from sliding elements of TH29 beam sections appears to be first of its kind in the mining industry and possibly in civil industry. Design, structural analysis and manufacturing of the Lattice Girders with TH29 beams sections was straightforward. Underground assembly and installation proved to be very simple. Majority of the installation work was mechanised meeting the requirement of the mine standards for removing manual work as much as possible to prevent injuries. Time will tell the viability of the Lattice Girders with TH29 beams sections, which can be a replacement for the Lining Stress Controllers commonly used in the civil tunnelling projects. At the time of writing this paper, the monitoring instruments do not show any significant movement in the rock mass or the Lettice Girders. Oyu Tolgoi Geotech Engineers will update the geotechnical community on performance of the Lattice Girders with TH29 beams sections.

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

Acknowledgement

The authors would like to thank underground Development and Construction Teams at Oyu Tolgoi mine for their outstanding technical expertise, work ethics and safety performance during construction of the Lattice Girders at the Haulage Level.

References

Listed references should be cited within the paper, and alternatively all citations must have references listed, Authors will be notified if citations or references are missing, please follow the Author's Guidelines on how to format your references correctly.

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