Midland Institute of Mining Engineers' 18th Safety Seminar

Title: Enhancing Mining Safety: Challenges and Solutions in the Design of the Woodsmith Project's MTS Station Chamber and Roadways

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Abstract:

Mining safety presents significant challenges, particularly when designing and constructing underground structures. The Mines Regulations 2014 [8] and the General Principles of Prevention outlined in the CDM Regulations 2015 [7] place critical responsibilities on the Mine Operator and the Designer to ensure safe practices throughout the project.

Dr Sauer & Partners (DSP) provided design of the excavation and ground support measures for the MTS Shaft Inset, MTS Station Chamber and associated MTS roadways as well as site representation during construction on the Woodsmith Project.

This paper explores the challenges faced in safely designing and constructing the underground structures, and outlines the solutions implemented to overcome these challenges, based on the technical site support provided over the recent years.

A primary focus in the project was managing and minimizing the risks through the design process. The ground support design itself serves as a solution to mining safety, considering the equipment requirements.

Special emphasis is placed on the application of finite element modelling as a tool to assess and address risks, taking into account constructability, ground support selection, and the specific ground conditions encountered. Specific examples will be provided from the modelling of breakout from the MTS Shaft and roadway junctions, where the analysis informed critical decisions on ground support and the structural integrity of the junctions.

Additionally, the numerical modelling helped to determine the monitoring trigger values. This allowed to optimise the design of support systems, offering a more precise approach to managing risks and ensuring safety. A comparison of the predicted monitoring trigger values against the actual monitoring data from the site played a key role in assessing the accuracy and reliability of these predictions. Coordinated workshops between the client, design and construction teams enabled the implementation of an appropriate safety response and possible counter measures in an event of reaching or exceeding the trigger values.

The finite element models were initially optimised to provide the most conservative and low risk design solutions. As construction progressed, the contractor was able to raise technical queries that allowed for design updates in alignment with practical construction requirements. These updates not only improved the constructability and feasibility of the design but also ensured that the safety standards were maintained throughout the project. This dynamic approach facilitated both the refinement of the design and the continuous management of risks on-site.

1 Introduction

The Woodsmith Mine, developed by Anglo American and located south of Whitby in North Yorkshire, is being developed to extract Polyhalite, a multi-nutrient fertilizer. This innovative mining project includes the development of several key infrastructure components, including the Mineral Transport System (MTS), which is critical to the operation. The MTS will transport material from the mine's deep shafts to a Material Handling Facility (MHF) at Teesside harbour, while minimising environmental impact on the nearby National Park.

To ensure the stability, safety, and long-term performance of the MTS structures, Dr. Sauer & Partners (DSP), the MTS Inset geotechnical designer, employed advanced finite element analysis (FEA) techniques. The aim was to achieve a robust design that would meet the required 50-year design life of the permanent assets. FEA was applied to accurately model the behaviour of key underground structures, including junctions, connections, and headwalls, ensuring that potential geotechnical risks were identified and mitigated in advance.

The FEA process was essential for adequate design of the MTS structures, ensuring that they would not only meet safety standards but also be resilient under varying geological and loading conditions. The 2D FEA analysis, conducted using Rocscience Phase2, was applied for quick initial analysis to assess the stability of the excavation and the effectiveness of ground support systems early in the design process. For more complex and spatially interactive regions, 3D FEA modelling was carried out using Abaqus software from Dassault Systèmes. This was particularly important for key structures such as junctions and connections.

Both 2D and 3D modelling was used throughout the design and construction phases, allowing the design to be adjusted in response to changes in excavation geometry or sequencing, ensuring continued optimisation and stability. By integrating 2D and 3D FEA techniques, DSP ensured that the design of the MTS structures was robust, safe, and capable of achieving the required 50-year design life, setting a new benchmark for mining projects in challenging geological conditions.

2 Team

The design work performed by DSP for the temporary and permanent ground support and the detailed excavation sequences of the MTS Shaft Inset and Station Chambers with associated roadways was carried out for Worley. Worley acted as the Engineering, Procurement, and Construction Manager (EPCM) for the mine owner Anglo American. Specialist contractor Redpath-Deilmann executed the works. A DSP site support and design representative carried out observations of the works to verify the design intent (Figure 1).

Figure 1 - Team organisation chart.

3 Geology

The geology at the MTS Inset and horizontal development is dominated by the Redcar Mudstone Formation, comprising interbedded mudstones, siltstones, and sandstones. Excavations are primarily within the Siliceous and Pyritous Shale Members, which exhibit moderate strength, anisotropy, and laminated bedding, influencing stability and support design. The stratigraphy assumed in the design is shown in Figure 2.

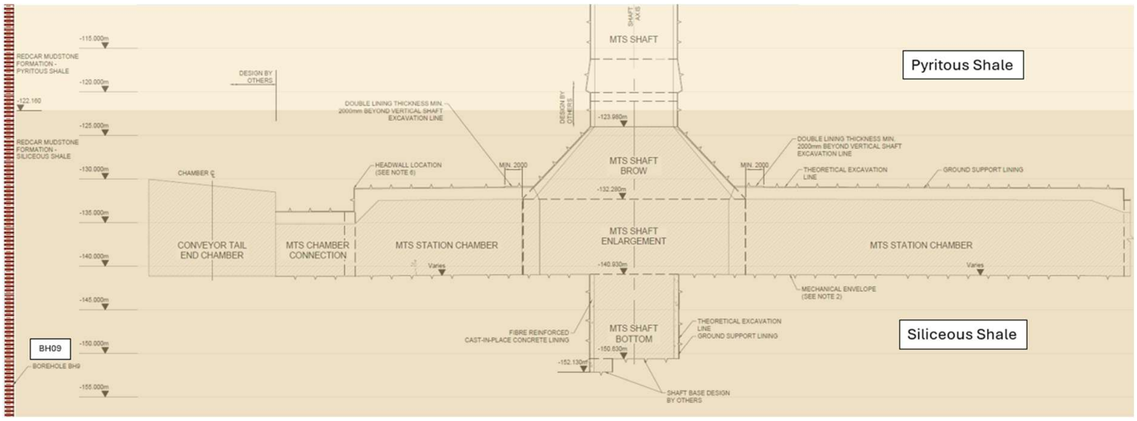


Figure 2 - Stratigraphy assumed in the design.

Site investigation works carried out at the Woodsmith site to confirm the ground properties included six boreholes that were deep enough to reach the required levels. Borehole BH09, the only borehole drilled at the location of the MTS shaft (Figure 3), provided critical geotechnical data, including strength properties, deformation characteristics, and in-situ stress conditions. To ensure accurate numerical modelling, geotechnical input parameters were derived from laboratory tests on BH09 core samples as well as downhole geophysical survey and supplemented by other boreholes on site. The Q-System and Geological Strength Index (GSI) classification based on borehole data confirmed that the rockmass at excavation depth falls within ‘fair to good’ stability conditions, further supporting the parameter choice.

Figure 3: Plan view of the Woodsmith site showing the location of the BH09.

The geological conditions at the MTS shaft dictated the selection of geotechnical parameters for numerical modelling. By applying conservative material properties and utilizing both 2D and 3D FEA for sensitivity analyses, the design team ensured that excavation-induced deformations were accurately predicted and mitigated. This approach provided a robust framework for optimising support design, minimising geotechnical risks, and enhancing overall mining safety.

4 Key Structures

To ensure a safe and robust design for the MTS Shaft Inset and Station Chamber structures, Finite Element Analysis modelling was carried out at critical locations within the proposed excavations. FEA, both in 2D and 3D, offers detailed insights into the behaviour of materials under stress, enabling precise structural design.

The modelling process began with the definition of key study areas for 2D and 3D FEA modelling as listed below.

The 2D FEA modelling has been carried out for the following structures:

- MTS Station Chamber;
- Roadways;
- Temporary headwalls; and
- Sump niche chambers.

The 3D FEA modelling has been carried out for the following structures:

- MTS Shaft brow to Station Chamber connection;
- Roadway junctions;
- MTS Station Chamber and Conveyor Tail End Chamber interface.

Figure 4 summarises key areas for the application of FEA modelling.

These were determined as representative locations due to their complexity and load-bearing demands. The FE analysis results could be applied to all other structures in DSP's scope.

The use of 2D FEA allowed for a quick preliminary assessment, while 3D FEA modelling was employed for a more comprehensive evaluation of the spatial interactions and potential failure points. By applying both modelling techniques, the design team ensured that all areas of the scope would meet safety and performance standards.

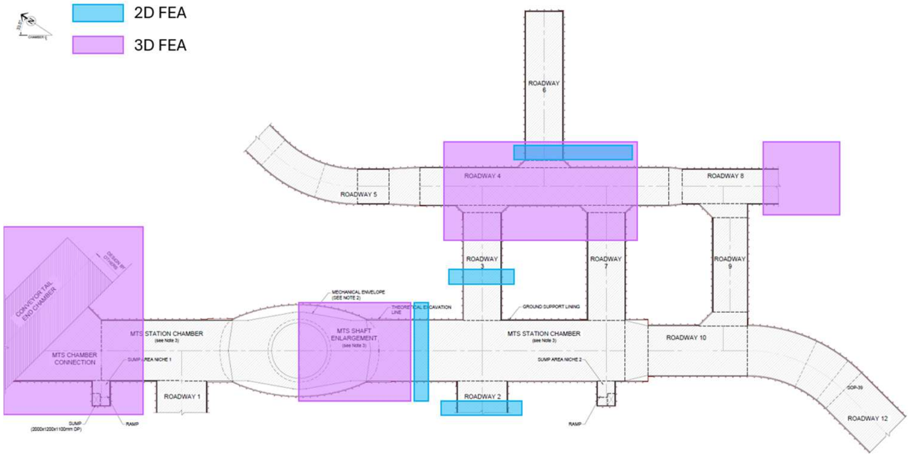


Figure 4: Plan view of MTS Shaft, Station Chamber and Roadways, highlighting key areas selected for FE analysis.

5 Initial Ground Support Selection

The initial design of the structural elements was carried out using the Q-system based on E. Grimstad and N. Barton [3], as shown in Figure 5. The ground support system was designed by DSP as a combined temporary and permanent system.

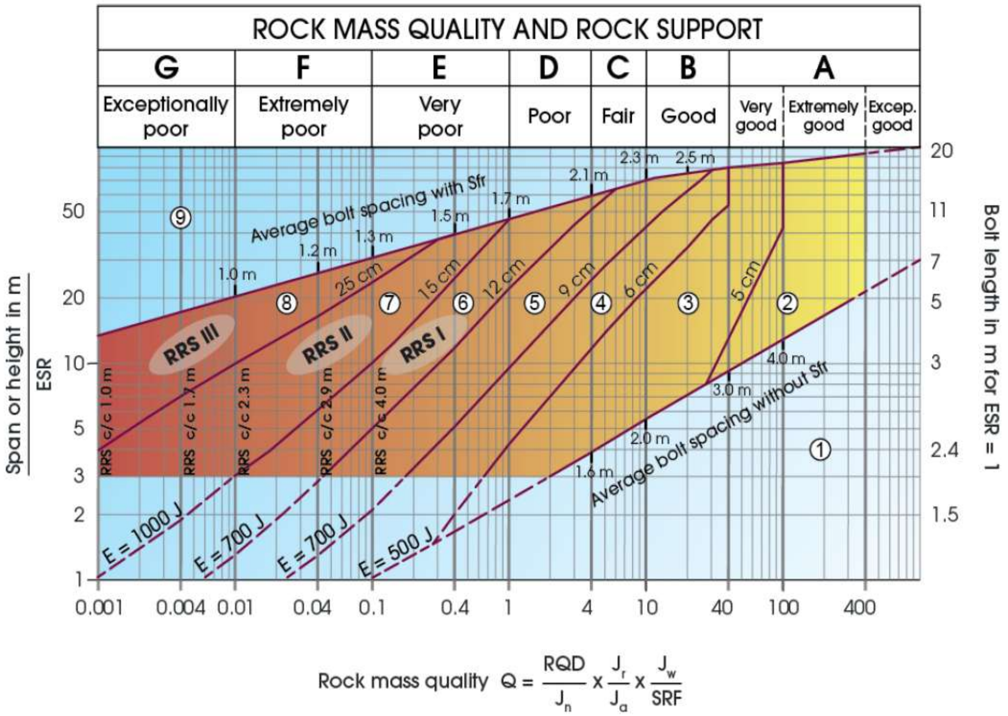


Figure 5: Permanent support recommandations based on Q-values.

For the initial design, Q-values were based on a ground conditions assessment report prepared by Anglo American's site geotechnical team, and were later confirmed through as-built data.

The designed support system consisted of fibre reinforced sprayed concrete (FRSC) lining and CT rock bolts, with non-structural mesh. The Q-system was also used to develop an initial design for the bolt length and spacing.

During construction an additional temporary ground support option was developed. Upon contractor request it consisted of mesh and bolt only, with the permanent support being provided behind initial support at a later date.

The DSP design did not require a reinforced secondary cast concrete lining to meet the 50 years design life requirement for the permanent case. This resulted in savings of 100% of concrete and steel bar reinforcement or 100% reduction of carbon emissions for the secondary lining.

Further development in the design allowed to substitute 2.5m Combination CT-bolts with 2.4m Advanced Technology AT bolts. The rockbolt diameter was also reduced from 33mm for CT bolts to 22mm for AT bolts. To accommodate this change, an added row of 4.0m flexi bolts was introduced and bolt spacing reduced from 1.5m to 1.0m. Additionally, GFRP bolts were introduced for stabilisation of temporary walls between the top heading side drifts.

The Q-system was used to determine the FRSC thickness for the lining. The expected FRSC thickness was predicted between 75 – 120mm, depending on excavation size and support class.

6 Application of FEA

Numerical modelling was employed to consider rock/bolt interaction, construction sequence i.e. stepwise excavation and rock bolt installation as well as conditions which cannot be considered using empirical approaches.

6.1 Rocscience Unwedge Models

Rocscience Unwedge is a specialized geotechnical software used for stability analysis of rock wedges in underground excavations. It helps to assess the potential failure of wedges formed by the intersection of discontinuities in rock masses.

The stability of the excavation of the Station Chamber and roadways, as well as the potential of rock wedges were analysed using Unwedge based on the discontinuities and proposed ground support.

As the construction advanced, the Contractor would issue requests to support project requirements. These would typically include increasing maximum advance lengths for drill and blast sequence, changes in the rock bolt type, length and spacing, or developing temporary ground support options.

Dr. Sauer & Partners' team managed and addressed the requests throughout the process and continuously worked on refining the design to support construction activities. Unwedge allowed to facilitate these requests in an effective manner.

Due to the 3D nature of the excavations, the MTS Shaft Brow, Station Chamber and the associated roadways have been analysed considering different orientations (trends and plunges). The wedges have been generated in the model based on the provided discontinuity sets (Figure 6).

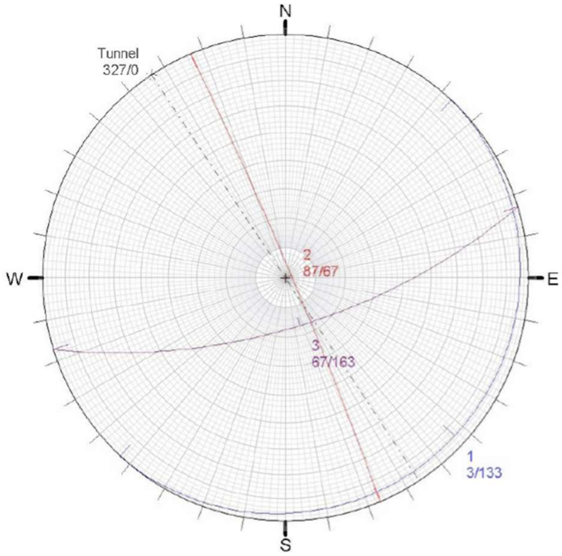


Figure 6: Equal area lower hemisphere plot of great circles representing the dip and dip directions of the discontinuity sets.

Modelled excavations have been examined to ensure all wedges have a factor of safety greater than 1.5 and are considered sufficient (Hoek [4]). The main factors influencing the stability of the wedges would typically include proposed sprayed concrete thickness, rock bolt capacity, length and spacing as well as maximum advance length. The sizes of falling wedges would also be assessed, if applicable, which would then be considered in confirming the capacity and spacing of the mesh proposed by the Contractor.

Figure 7 shows the extract from the Unwedge model, indicating the position and size of the wedges predicted for the MTS Station Chamber Top Heading sections.

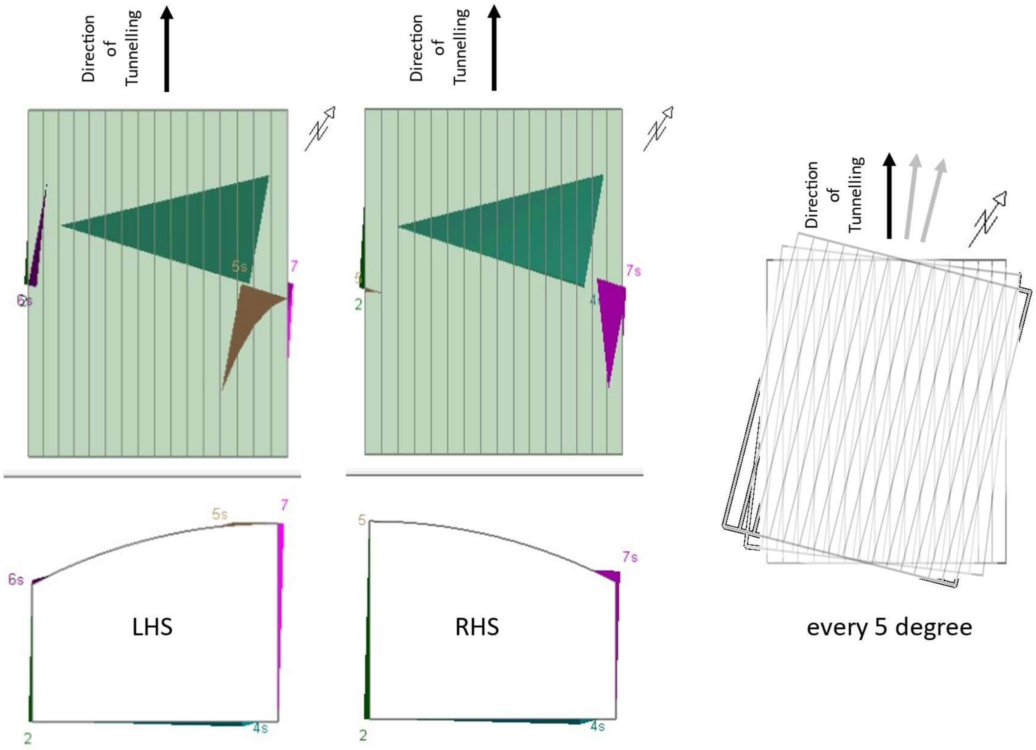


Figure 7: MTS Station Chamber Top Heading Left Hand Side and Right Hand Side, as well as the same cross-sections checked against every 5 degree trend.

6.2 Rocscience Phase2 2D Models

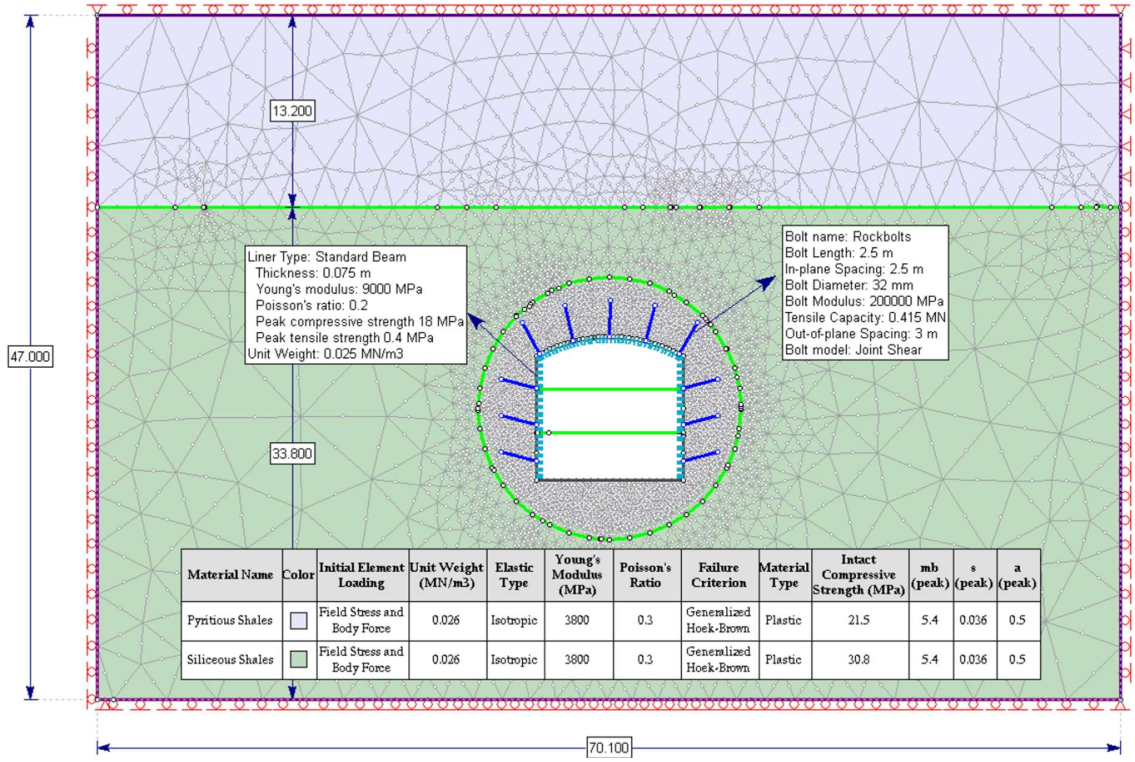
Phase2 by Rocscience is a two-dimensional finite element analysis (2D FEA) software used for stability analysis of underground excavations such as tunnels, caverns, and mine openings. The software allows to create 2D models of underground excavations, defining excavation boundaries, support systems, and surrounding rock mass.

Phase2 allows staged excavation modelling to simulate step-by-step excavation sequences. Different ground support systems like bolts and sprayed concrete can be added to assess their effectiveness. The software helps to predict failure zones and assess rock mass stability under different loading conditions. It provides an insight into stress distribution, potential failure modes such as shear failure, wedge failure, squeezing ground conditions, and required support systems.

Rock mass was modelled by non-linear continuum elements using an elastic-plastic material model which adopts the Generalised Hoek-Brown failure criterion. Rock joints were not considered in this model. Instead, the effect of the joints was accounted for by the GSI for jointed rocks. The model assumed following construction stages:

- Establishment of the in-situ stress conditions.
- Stepwise excavation.
- Relaxation of the Top Heading, Bench and Invert;
- followed by stepwise ground support installation.

Figure 8 illustrates the Phase 2 ground model for the MTS Station Chamber at the final stage after the full-face excavation and the application of the support.



Liner Type: Standard Beam
Thickness: 0.075 m
Young's modulus: 9000 MPa
Poisson's ratio: 0.2
Peak compressive strength 18 MPa
Peak tensile strength 0.4 MPa
Unit Weight: 0.025 MN/m3

Bolt name: Rockbolts
Bolt Length: 2.5 m
In-plane Spacing: 2.5 m
Bolt Diameter: 32 mm
Bolt Modulus: 200000 MPa
Tensile Capacity: 0.415 MN
Out-of-plane Spacing: 3 m
Bolt model: Joint Shear

Material Name	Color	Initial Element Loading	Unit Weight (MN/m3)	Elastic Type	Young's Modulus (MPa)	Poisson's Ratio	Failure Criterion	Material Type	Intact Compressive Strength (MPa)	mb (peak)	s (peak)	a (peak)
Pyritious Shales	🟪	Field Stress and Body Force	0.026	Isotropic	3800	0.3	Generalized Hoek-Brown	Plastic	21.5	5.4	0.036	0.5
Siliceous Shales	🟩	Field Stress and Body Force	0.026	Isotropic	3800	0.3	Generalized Hoek-Brown	Plastic	30.8	5.4	0.036	0.5

Figure 8: Ground model in the 2D FEA for the MTS Station Chamber at the final stage.

Phase2 software was utilised to assess the Contractor's design change requests. These included:

- Providing a temporary ground support design for the roadways;
- Replacing rock bolt type, size and spacing;
- Increasing the maximum excavation opening;
- Increasing the maximum advance length to allow for a more efficient drill and blast sequence;
- Excavating additional sump niche chambers.

Phase2 was also used to assess the impact of the interface with structures designed by others, e.g. impact of an upper MTS level on the temporary headwalls of the lower MTS level designed by DSP.

The 2D FE analyses were used to efficiently assess the tensile forces and yield stresses in the rock bolts, as well as to predict expected deformations. At the locations of the bolts with yielded elements, it was ensured that the maximum elongations were limited to below 5% as specified in the supplier's technical data sheet.

Figure 9 shows the summary of the tensile force in rock bolts extracted from the Phase2 model with all elements shown below yield stresses.

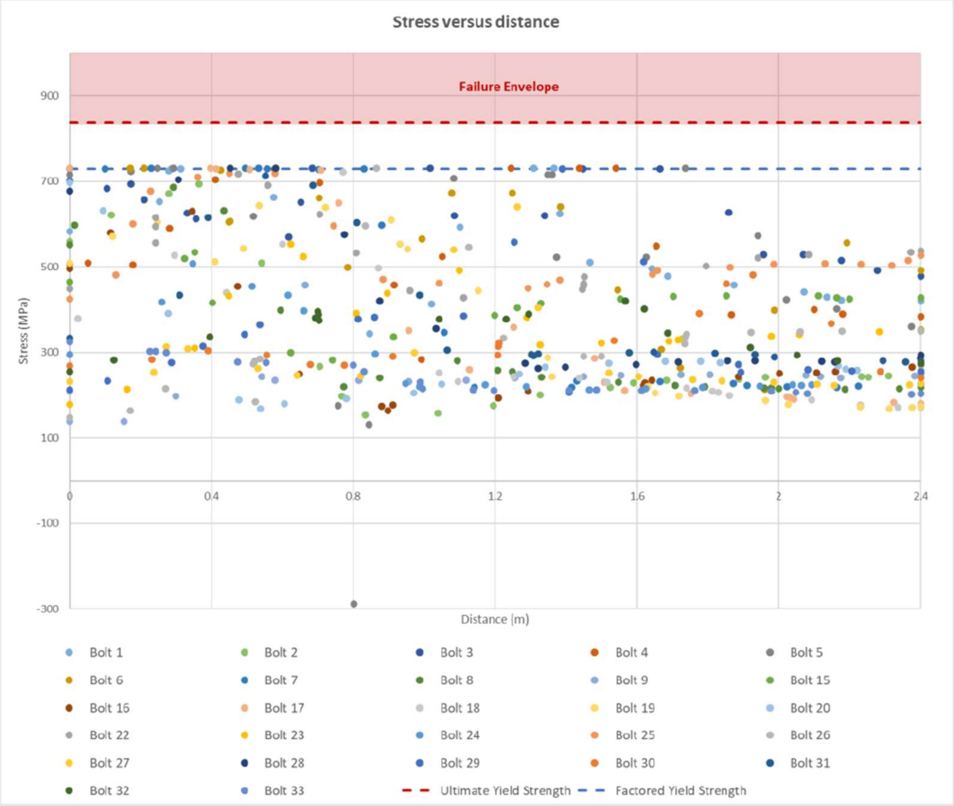


Figure 9: Axial stress calculated along the length of the AT bolts.

Figure 10 shows predicted deformations around the MTS Station Chamber.

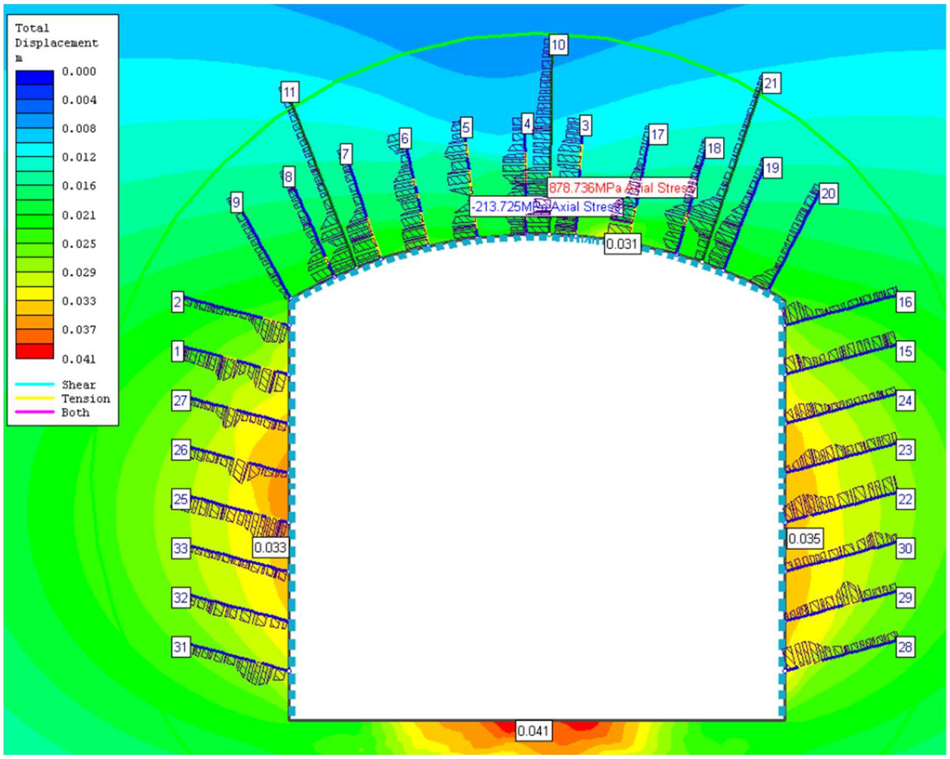


Figure 10: Displacement and axial stress generated for the full face excavation of the MTS Station Chamber.

6.3 Abaqus 3D Models

In order to consider the three-dimensional (3D) effects, 3D FEA were carried out using Abaqus software from Dassault Systèmes. Ground material was simulated using solid elements with the Mohr Coulomb model in a total stress analysis, and lining was simulated using shell elements with Concrete Damaged Plasticity model. 3D FEA modelling would be initially implemented during the design development and later on utilised to facilitate amendments to the excavation geometry or sequence of the works.

6.3.1 MTS Shaft Brow Connection

Analysis was carried out to assess the stability of the MTS Chamber connection, including MTS Shaft, MTS Shaft Brow & Enlargement and MTS Station Chamber. The excavation of the MTS Shaft & Station Chamber was supported by the 4.0m rock bolts on a 1.5m spacing for the MTS Shaft and 2.4m rocks bolts on a 1.0m spacing for the MTS Station Chamber.

The construction sequence applied in the FEA model included a larger side drift in the top heading of the MTS Station Chamber. Stepwise excavation and support sequences were utilised to ensure the stability of the excavation.

Stratigraphy and ground parameters were extracted from the relevant reports and sensitivity analyses carried out to consider effects in variation in these parameters. The purpose of the sensitivity studies was to assess how the variability of input data can affect the model predictions, and to achieve a robust design based on the FE analyses. Discontinuities were not directly simulated, but the effect of discontinuities has been considered when deriving equivalent Mohr Coulomb parameters using empirical correlations.

The main aim of the bolts is to assist the formation of a structurally active ring and improve the strength of the rock mass at the tunnel walls by application of confining pressures via the bolts; thereby increasing the shear strength properties of the rock mass. As presented by Bischoff and Smart (1977), a support system of rock bolts will increase the thrust capacity to the rock arch as shown in Figure 11 [6].

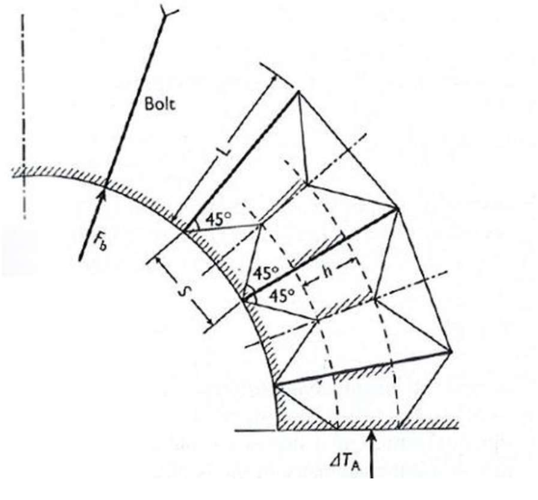


Figure 11: Geometry of tunnel bolting and rock arch thickness.

Drained parameters were determined for the increased confined rock arch [1]. The yield strength of the rock bolts was used to define the increase in rock mass confinement. Using the Hoek Brown failure criterion, the rock mass shear strength envelope could be established, which then provided the effective increase in allowable rock stress.

While assessing the values for the drained parameters, the working stress acting on the tunnel was taken into consideration as a slight reduction in the drained angle of friction of the confined rock continuum. The increase in radial and tangential stresses were calculated using the analytical solution by Feder and Arwanitakis [5].

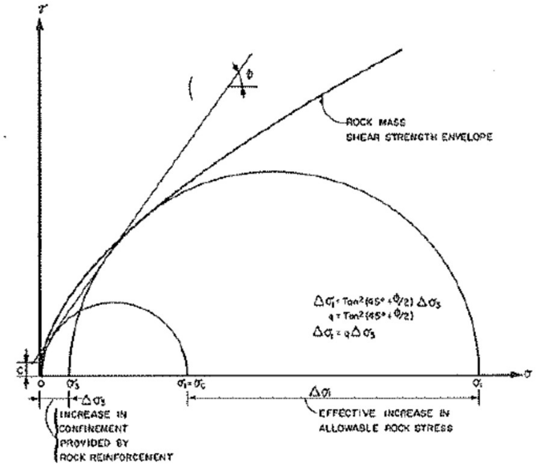


Figure 12: Effective increase in allowable rock stress with increase in confinement.

In order to simulate the bolt support around the MTS Shaft and Station Chamber, a rock arch was applied in the model around the excavations. Flexi bolts and temporary GFRP bolts have not been included to decide the geometry and properties of the rock arch. The model activated the relevant sections within the rock arch in accordance with the excavation and support sequence.

For ease of modelling, the extensive depth of the tunnels was reduced to a thinner, denser layer which mimics the same overburden on the tunnels; thereby creating a constant stress field without simulating the stratigraphy.

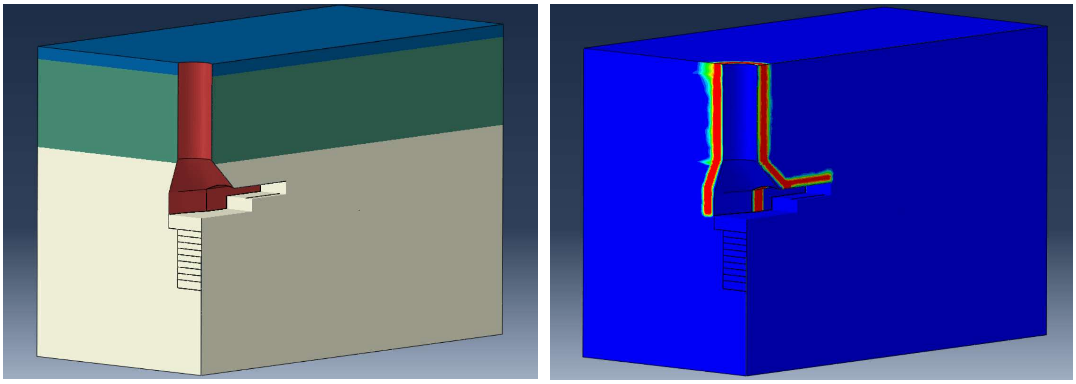


Figure 13: Breaking out and stepwise excavation and support of the MTS Station Chamber Bench. Stepwise activation of the bolt zone.

The deformation results were used to inform the trigger values in the monitoring plan. Monitoring trigger values are critical thresholds used to regularly assess the stability and safety of underground excavations.

The model predicted the maximum deformation of 31mm in the MTS Shaft Enlargement area and 28mm for the MTS Station Chamber at the end of construction (Figure 14). The end of construction stage covers the movements generated from the start of MTS Shaft Brow excavation to the final advance of the MTS Station Chamber Invert.

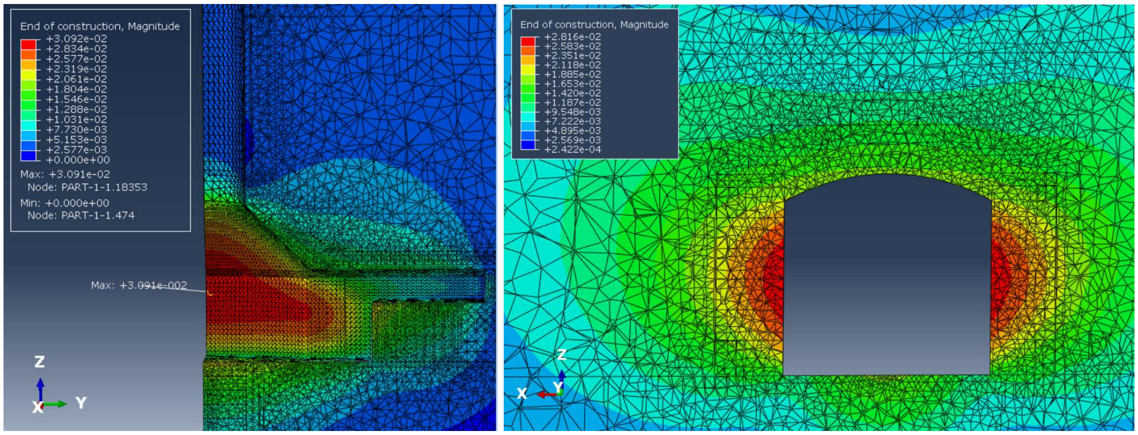
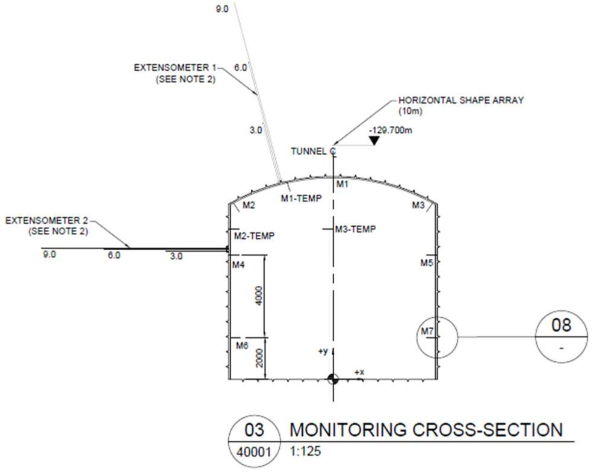


Figure 14: Deformations in the MTS Shaft and Station Chamber section, end of construction stage.

These results were used to verify the proposed monitoring trigger values and revise the monitoring plan and sections drawings.



MONITORING - TRIGGER VALUES (mm)		
MONITORING BOLT NO.	AMBER TRIGGER VALUES	RED TRIGGER VALUES
M1 (M1-TEMP^{1})	20 (10^{1})	25 (15^{1})
M2 (M2-TEMP^{1})	20 (10^{1})	25 (15^{1})
M3 (M3-TEMP^{1})	20 (10^{1})	25 (15^{1})
M4	30	35
M5	30	35
M6	30	35
M7	30	35
EXTENSOMETER 1	25	30
EXTENSOMETER 2	30	35
SHAPE ARRAY	20	25

Figure 15: Monitoring cross-section and trigger values - MTS Station Chamber.

6.3.2 Roadway Junctions

In response to site requests to remove the requirement for 4m long Flexi bolts in smaller roadways, DSP carried out a review of the supporting capacity of the initially designed system. The assessment included 3D finite element analysis of the roadway junctions considering the shorter 2.4m bolts and spared concrete as permanent support.

The 3D FE analysis, including the excavation sequence of the roadway junction was carried out using FE software Abaqus.

Following the Bischoff and Smart methodology [1], the bolts were represented as a rock arch placed above the tunnel lining. The bolt length was reduced by the distance of the spacing and reduced further by a resistance factor of 1.1, in accordance with BS EN 1997-1:2004 [2].

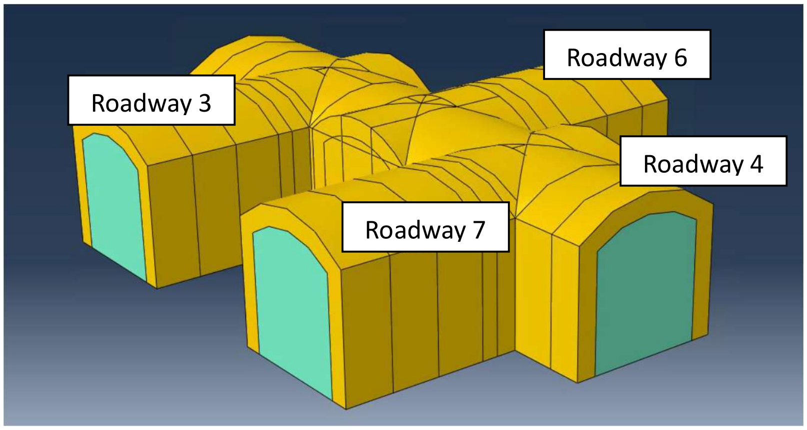


Figure 16: Rockbolts modelled as rock arches.

The modelled excavation sequence mimicked site conditions. First, excavation of Roadway 3 was carried out. Second, Roadway 7 followed by Roadway 4 which was excavated from right to left and last Roadway 6.

In line with BS EN 1997-1:2004 [2], strength reduction factors were applied to the characteristic ground parameters. In order to determine where and how the failure zone would occur the sprayed concrete lining, the bolt zone and ground, to a distance equivalent to one time the diameter of the tunnel, was converted to plastic analysis. The remaining ground strata remained as elastic to enable a quicker computational time.

As the factored parameters constrain the stresses in the lining and bolt zone to the factored parameters of the different materials, a successful convergence of results shows that the specified bolt zone is sufficient for the roadway junction.

Stresses and deformations within the ground and rockbolt zone as well as in the sprayed concrete lining have been assessed in the model. The generated compressive and tensile stresses were low in the crown. Pillars of compression were more predominant around the openings (Figure 17). However, the stresses remained within the compressive strength of the sprayed concrete and the confined rock zone. The model showed expected deformations ranging from 20mm to 28mm at the junction interfaces (Figure 18).

DSP's team was able to confirm additional Flexi bolts were not required for the support of smaller roadways. This helped to improve constructability while maintaining safety of the design.

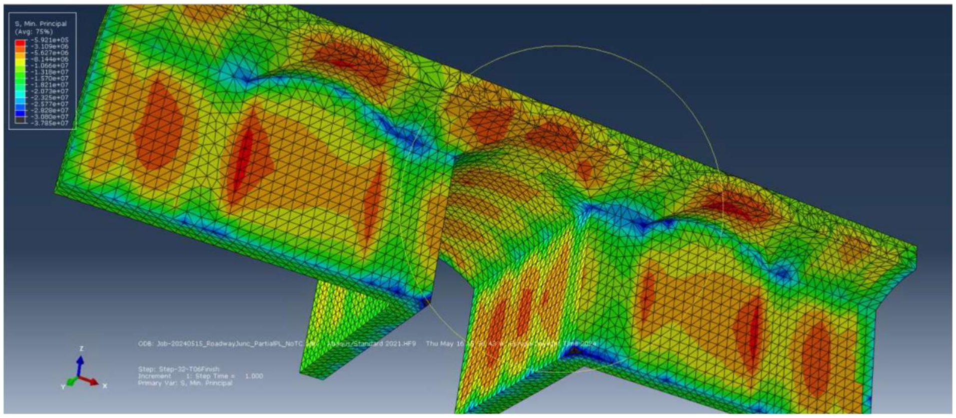


Figure 17: Compressive stresses in the rockbolt zone. Compressive stress constrained to 30.8MPa (confined rock strength).

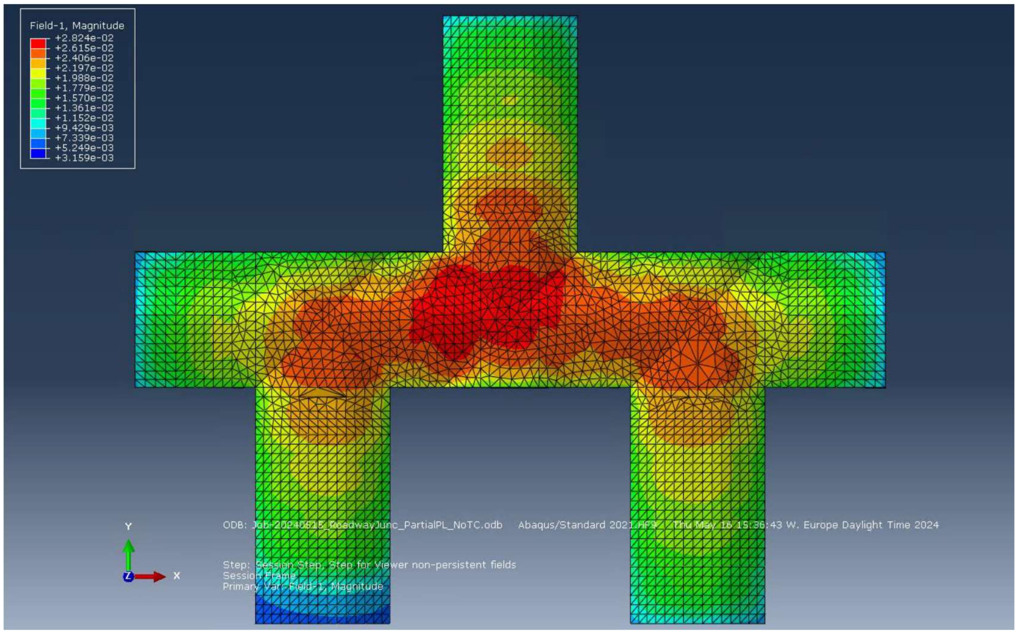


Figure 18: Deformations in the sprayed concrete lining. Viewing the sprayed concrete lining zone from above.

6.3.3 Rock pillar between MTS Station Chamber and Conveyor Tail End Chamber

As a part of the interface study, Dr. Sauer & Partners carried out an assessment of the rock pillar between the MTS Station Chamber designed by DSP and the MTS Conveyor Tail End Chamber designed by others. 3D FEA has been applied to model the Chambers, considering the excavation of both structures.

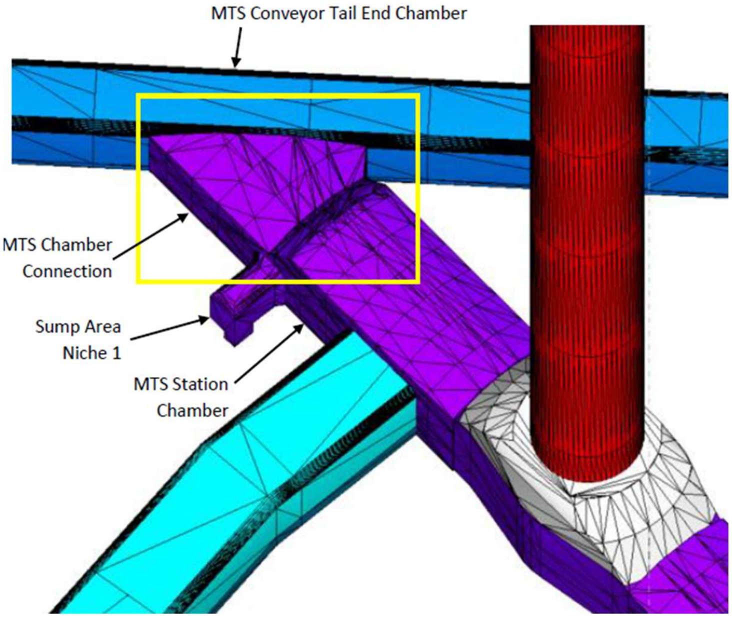


Figure 19: Rock pillar assessment zone of interest shown in yellow.

The MTS Station Chamber (North Heading) is constructed up to a temporary headwall approximately 3 to 14 metres away from the MTS Conveyor Tail End Chamber. It is assumed that the MTS Conveyor Tail End Chamber will be excavated at a later stage followed by the MTS Chamber connection in-between.

This sequence will produce a rock pillar between the two chambers as indicated in Figure 20. This pillar has been assessed by considering the average stress increase in a zone of half a tunnel diameter around the pillar (blue dashed line).

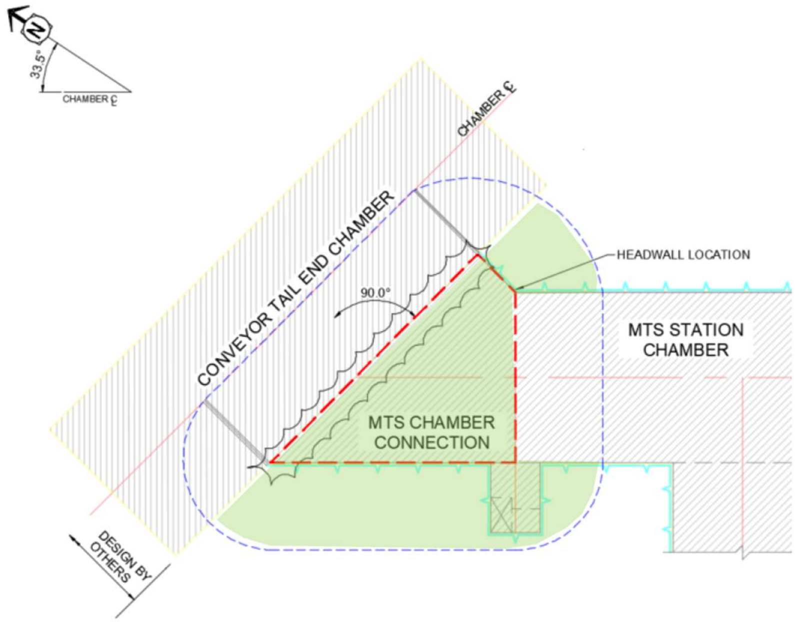


Figure 20: MTS Station Chamber, Conveyor Tail End Chamber, and the Pillar between the chambers (red dashed line).

To determine where and how a failure zone would occur, the bolt zone of the MTS Station Chamber was converted to plastic analysis, while the overburden, the ground and the sprayed concrete lining remained elastic. No rock bolt zone was modelled for the MTS Conveyor Tail End Chamber.

The following modelling stages were implemented in this interface study:

1) Stepwise excavation and support of the MTS Station Chamber's top heading and benches,
2) Wished-in-place excavation of the MTS Conveyor Tail End Chamber, as shown in Figure 21.

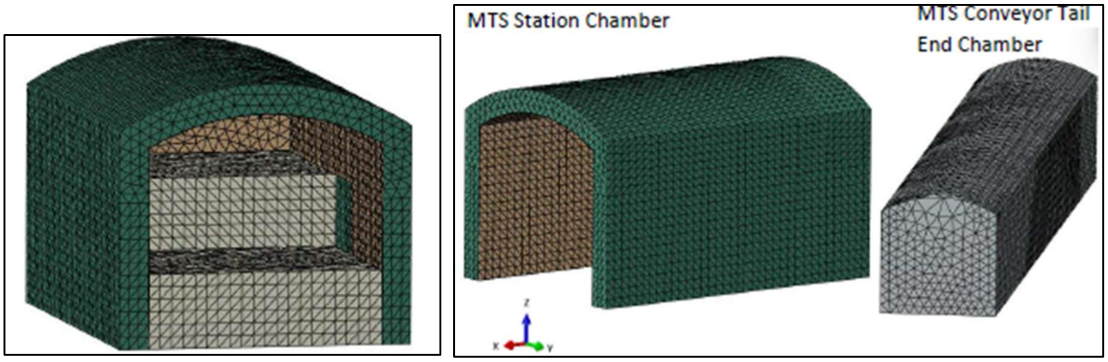


Figure 21: a) Stepwise excavation of the MTS Station Chamber; b)MTS Station Chamber & Conveyor Tail End Chamber interface.

The rock pillar compressive stresses were constrained to remain below the ground strength to identify the areas which exceed these limits. Figure 22 presents the vertical and horizontal stresses of the rock pillar between the chambers.

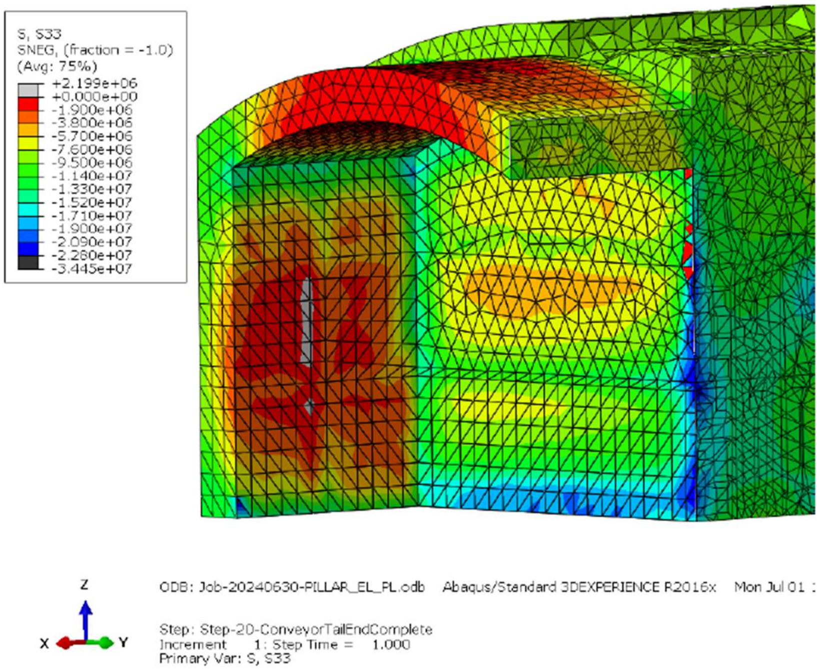


Figure 22: Vertical stresses (in Pa) of the pillar behind the MTS Station Chamber temporary headwall.

The calculation and analysis of this design interface study has confirmed that there were no indications of rockbursts at the rock pillar after tunnelling. The stresses remained within the acceptable limits, therefore there was no impact due to interface with the MTS Conveyor Tail End Chamber and no additional ground support was required for the MTS Station Chamber.

7 Instrumentation & Monitoring

This section describes how the FEA analysis results helped to predict and define the trigger values and what instrumentation was used for monitoring on site.

7.1 FEA Predictions

Monitoring trigger values are typically derived from numerical simulations using FEA software such as Abaqus (3D) and Phase2 (2D). As described in more detail in Section 6, the predictive process involves simulating excavation sequences, analysing stress redistribution, and determining deformation limits to establish trigger values for monitoring instrumentation.

Phase2 is a 2D software suitable for uniform geological conditions and preliminary design assessments. The model is typically calibrated with the empirical data, comparing numerical outputs with past excavation performance or empirical methods.

Abaqus enables a comprehensive 3D analysis of underground excavations by capturing complex geometries, anisotropic material behaviours, and three-dimensional stress-strain interactions, which makes it more suitable for complex analyses. It allows to extract deformation, stress, and strain data to determine critical thresholds.

By analysing the numerical results, the DSP team could predict displacement limits, stress redistributions, and plastic zone formations, which informed the selection of monitoring trigger values.

From both 3D and 2D analyses, trigger values for field monitoring instruments were determined by defining allowable deformations, based on predicted displacements as well as sensitivity analysis, which included running parametric studies to account for variability in geological conditions.

Trigger values were so defined that the amber trigger is the predicted movement from the FE analysis and the red trigger is set 1.25x above the amber trigger, which is below the ultimate state limit and allows sufficient time to verify predictions against the ongoing construction stage using as-built monitoring data.

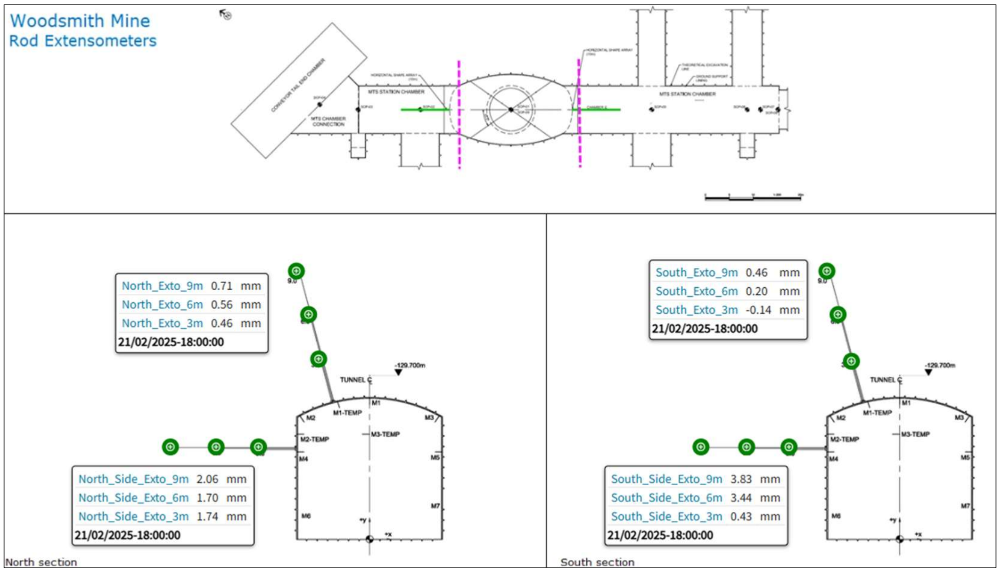
7.2 Monitoring Trigger Values

Monitoring trigger values are essential safety thresholds used in underground excavations to assess stability and mitigate risks. These values are determined using FEA software, which simulates the excavation process, predicts stress redistribution, and estimates deformations. Once construction begins, monitoring equipment such as extensometers, inclinometers, shape arrays, pressure cells, total stations and monitoring prisms continuously record real-time deformation and stress changes. The predicted values from FEA are then compared with as-built data. This allows the designer to confirm the accuracy of the design models. If necessary, construction and excavation sequences can be adjusted to ensure safety and stable ground conditions on site.

7.3 DATATYS

Once excavation commenced, real-time monitoring data was collected from instrumentation installed within the shaft and roadways. DSP's Design Representative on site reviewed the data on a weekly basis and compared it to the predicted values from the FE analysis. If deviations were to occur beyond acceptable limits, adjustments could be made to the excavation sequence, support design, or construction method. This real-time validation process allowed DSP to refine the numerical models and ensure excavation safety and stable conditions throughout the entire construction.

One of the key responsibilities of the DSP's Design Representative on site was the review of monitoring data collected via SOCOTEC's DATATYS system. This specialised platform was used for real-time geotechnical and structural monitoring. DATATYS connected to extensometers and shape arrays installed within the excavations (Figure 23 & Figure 24).



North_Exto_9m	0.71	mm
North_Exto_6m	0.56	mm
North_Exto_3m	0.46	mm
21/02/2025-18:00:00		

North_Side_Exto_9m	2.06	mm
North_Side_Exto_6m	1.70	mm
North_Side_Exto_3m	1.74	mm
21/02/2025-18:00:00		

South_Exto_9m	0.46	mm
South_Exto_6m	0.20	mm
South_Exto_3m	-0.14	mm
21/02/2025-18:00:00		

South_Side_Exto_9m	3.83	mm
South_Side_Exto_6m	3.44	mm
South_Side_Exto_3m	0.43	mm
21/02/2025-18:00:00		

Figure 23: Rod extensometers installed at the MTS Station Chamber - extract from the DATATYS system.

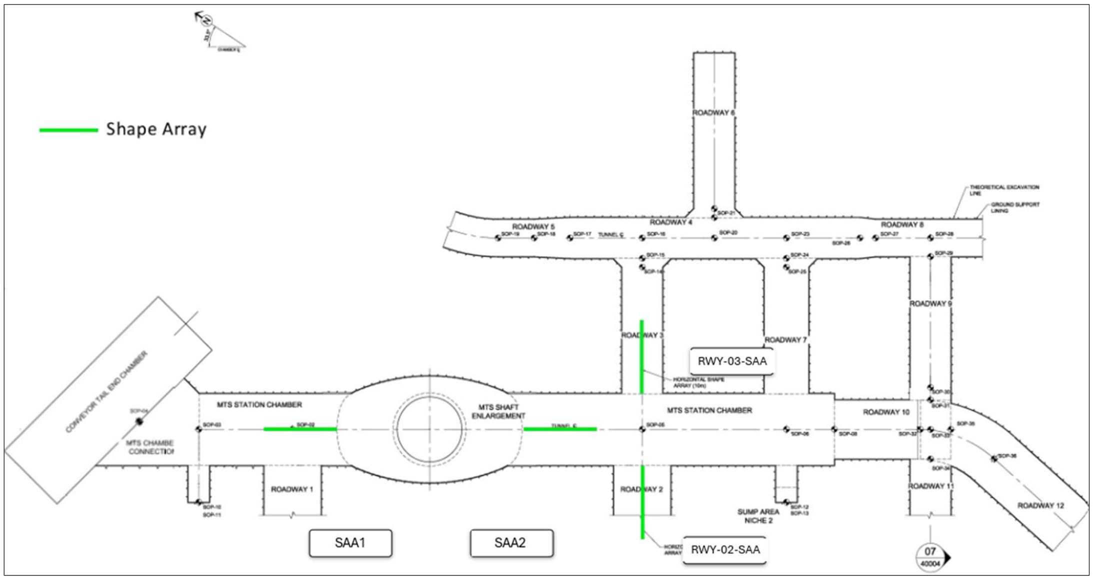


Figure 24: Shape arrays installed in the MTS Station Chamber and roadways - extract from the DATATYS system.

In most cases, the monitoring values recorded by DATATYS remained well below the predetermined trigger values, confirming the stability of the ground and ground support. On the few occasions when trigger values were exceeded, a meeting was held with the Mine Owner and the Contractor to investigate the data further. In such instances, deformations were often surveyed manually to verify the reliability of the DATATYS readings. In all cases where trigger values were exceeded, the cause was attributed to equipment failure, malfunction or drilling in the proximity of monitoring instrumentation, rather than actual structural movement. The verified deformations within the shaft and roadways stayed well below the predicted values (Figure 25).

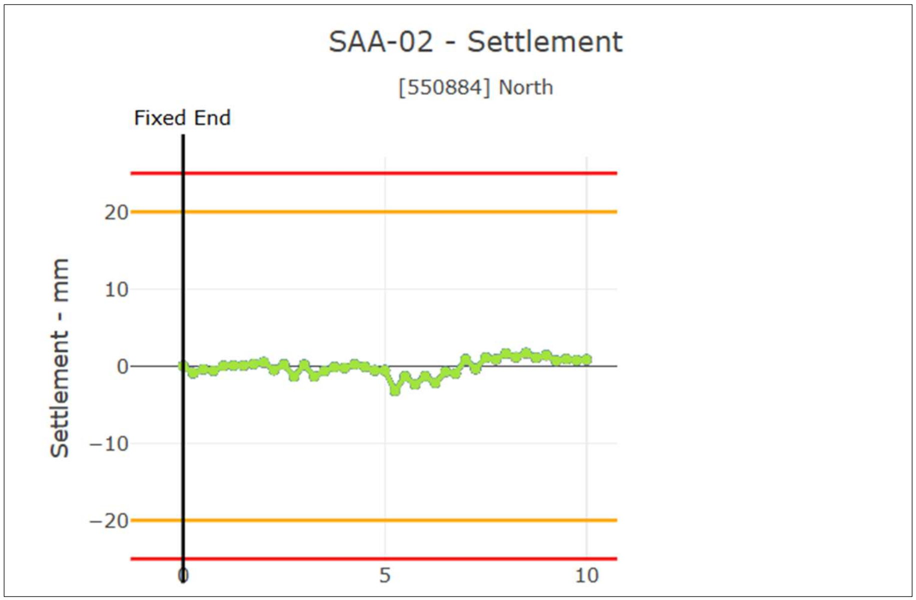


Figure 25: Extract from the DATATYS showing minimal settlements recorded by the shape array above the MTS Station Chamber.

By integrating numerical modelling with field monitoring, underground construction could be managed proactively, reducing geotechnical risks and ensuring compliance with safety thresholds.

8 Client, Design and Construction Teams Collaboration

At the Woodsmith Mine, collaboration between the Mine Owner, the EPCM, the Contractor and DSP Design Team has been key to ensuring a safe and structurally sound design and construction process. A central element of DSP's role was the application of Finite Element Analysis in the design of the MTS level structures. This provided a detailed understanding of the ground behaviour and support requirements. By using advanced FEA modelling, DSP facilitated collaboration between all parties during the design development. This approach helped eliminate, reduce, and control foreseeable geotechnical risks while providing essential, data-driven insights to the Mine Owner, the EPCM and the Construction Team.

A key aspect of DSP's involvement during construction was managing Technical Queries (TQs) related to ground support and raised by the Contractor. DSP utilised FEA simulations to validate the contractor's proposed design changes, ensuring that any adjustments maintained structural integrity and safety of the works. By integrating computational analysis into the TQ review and response process, DSP provided evidence-based solutions, minimising uncertainties and ensuring smooth and uninterrupted construction progress.

DSP was responsible for the FEA-driven engineering and design of the MTS Shaft Inset, incorporating temporary and permanent ground support solutions optimised for prevailing site conditions. On-site, DSP played a critical role in ensuring that execution aligned with the FEA-verified designs, continuously reviewing site data and updating the design where necessary. The DSP's Design Representatives on site ensured satisfactory completion of the works by inspecting and observing construction activities, verifying and validating the design intent and by maintaining continuous communication with all involved parties. This included real-time monitoring of instrumentation data, adapting designs based on new geotechnical insights, and refining ground support strategies using FEA outputs.

Through frequent workshops, open communication, and prompt validation of TQs through FEA modelling, as well as through DSP's presence on site to visually inspect and assess the response of the rock and support to mining, DSP ensured that the project met the Mine Owner's requirements with a safe, robust, and constructible design. DSP's proactive, analysis-driven approach effectively integrated design and construction, enhancing risk management and optimising engineering solutions for a safer and more efficient build.

9 Conclusion

The design and construction of the Woodsmith Project's MTS Shaft Inset and horizontal development presented challenges in ensuring underground safety of the works while maintaining constructability and efficiency of the design. Through a combination of advanced numerical modelling, risk assessment, and continuous collaboration between design and construction teams, effective solutions were implemented to mitigate the geotechnical risks.

The application of FEA played a pivotal role in optimising the ground support system, validating excavation sequences, and setting monitoring trigger values. The integration of 2D and 3D FEA assessments enabled a comprehensive understanding of the ground behaviour, allowing for proactive design adjustments that enhanced safety and long-term stability. By employing both Phase2 and Abaqus software, the DSP team was able to evaluate critical structures such as the MTS Shaft brow connection, roadway junctions, and rock pillar stability.

The iterative design approach, facilitated by real-time monitoring, ensured that predicted deformations and stresses remained within acceptable limits. This dynamic method enabled swift responses to technical queries, optimising excavation strategies while upholding safety standards.

Furthermore, the collaboration between the Mine Owner, EPCM, Designer, and Contractor was instrumental in managing evolving site conditions. Regular workshops, technical discussions, and data-driven decision-making contributed to the successful adaptation of design solutions to real-world challenges, minimising risks and improving overall constructability.

By leveraging innovative FEA modelling techniques, and a comprehensive instrumentation and monitoring strategy, the Woodsmith Project has set a benchmark for mine construction safety in challenging conditions. This project underscored the importance of integrating advanced numerical analyses with practical construction methodologies, ensuring both safety and efficiency in complex mining environments.

10 References

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