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Analysing rock mass response to undercutting using real-time MPBX data in panel 0, Oyu Tolgoi mine

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ABSTRACT

It is widely acknowledged that undercutting is imperative to the success of a block cave. At Oyu Tolgoi, significant investment has been made in geotechnical instrumentation to facilitate understanding of the response of moderate to highly fractured rock mass to undercutting in a deep, high-stress environment. Approximately 488 multi-point borehole extensometers (MPBX) have been installed in Oyu Tolgoi Panel 0 footprint. Individual MPBX readings are fed into an integrated live data management platform, enabling real-time geotechnical assessments. These assessments provide insight into rock mass response to undercutting within various geotechnical and geological environments. The comprehensive instrumentation network facilitates proactive monitoring of ground conditions, which not only mitigates safety risks but also reduces production delays through scheduled rehabilitation. In addition to operational benefits, the data is used for back analysis, calibration of numerical modelling and validation of cave management rules.

Keywords: Oyu Tolgoi, Block Cave, Undercutting, Instrumentation, MPBX, Displacement

1 INTRODUCTION

Oyu Tolgoi (OT), located in the South Gobi region of Mongolia, ranks amongst the largest known copper and gold porphyry deposits globally. The site encompasses multiple orebodies, most notably Oyut, Hugo North and Hugo South. Hugo North is the first underground orebody to be mined at OT and measures approximately 280m in width, 2000m in length and 600m in ore column height. Given the scale of the orebody and the rock mass conditions (average Mining Rock Mass Rating of 40-65) block caving was chosen as the preferred mining method. Hugo North Lift 1 has been divided into four block caves, with Panel 0 the first in the sequence. Panel 0 undercutting began in February 2022 and completed in May 2024. To accommodate the deep and high stress conditions, the advanced undercutting technique was selected (Figure 1).

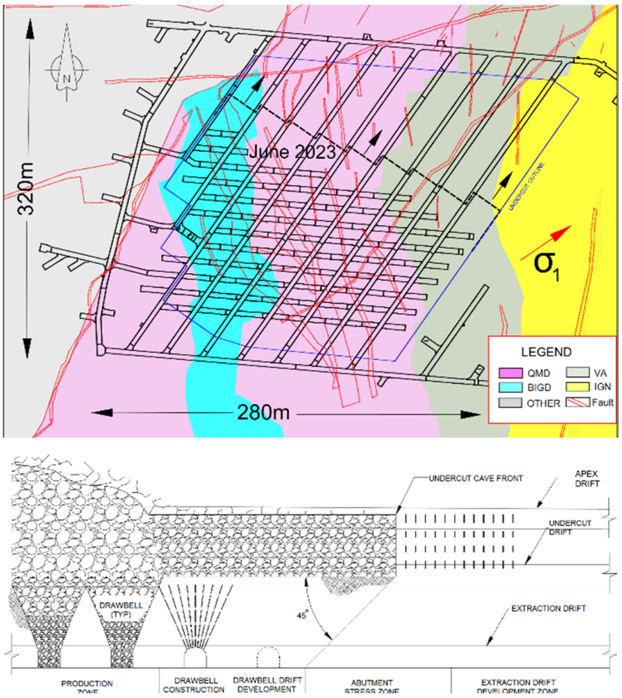

Figure 1 OT Panel 0 undercutting; plan (top) and section (bottom) view.

Panel 0 design parameters are shown in Table 1 below.

Table 1 OT Panel 0 Design Parameters

Parameter	Descriptions
EXL Depth	1300m
Footprint Size	Width ~320m Length ~280m
Level Spacing	APL/UCL - 22m UCL/EXL - 17m
Drawpoint Spacing	31m x 18m
UC Method	Advanced
UC Ring Profile	Narrow-Inclined (Big W)
UC Direction	~25°
UC Direction to σ_1	30°
EXL/UCL Drive Orientation to σ_1	20°
UC Face Orientation to Structure	>30° to major faults
UC Face Shape	Straight
UC Length	280m
UC Rate	2700m^2/month
UC Duration	3 years
UC Initiation and Direction	SW Initiation, South to North direction
UC Veranda and Destress Shadow	70m
UC Leads and Lags	±10m

**UC = Undercut, UCL = Undercut Level, APL = Apex Level, EXL = Extraction Level*

1.1 Multi-Point Borehole Extensometer (MPBX)

The International Society for Rock Mechanics and Rock Engineering (ISRM, 1979) classifies extensometers equipped with more than two anchorage points as multi-point borehole extensometers (MPBX) previously named multi-position borehole extensometer. These instruments are pivotal in measuring rock mass movement induced by various geological and engineering activities. This paper focuses on the displacement in rock mass surrounding underground excavations, influenced by stress changes associated with undercutting process.

Rock mass displacement monitoring in Panel 0 is performed using MPBX's with six anchor points positioned at depths of 0.8m, 1.5m, 2.5m, 4.0m, 7.0m, and 10m, and a reference head at the borehole collar (Figure 2).

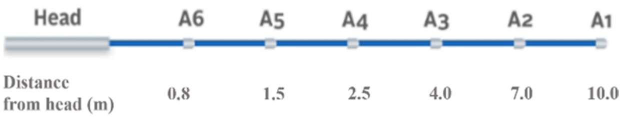

Figure 2 MPBX schematic with reference head and varied anchor depths.

This configuration is consistent throughout all MPBX installations across the footprint. Movement of each anchor point induces a measurable change in resistance across the fibreglass rods within the MPBX. This resistance variation is subsequently converted into a voltage difference relative to a standard reference voltage. Displacement is then quantified based on the ratio of these voltage readings. The installation process and detailed instrumentation specifications are readily available in the manufacturer's guide (MDT, 2018)

1.2 Panel 0 MPBX Configuration

A total of 488 MPBX's have been designed across Panel 0 extraction level. The typical instrumentation configuration in each monitoring area comprises of three MPBX's; one installed vertically in the intersection back, and one installed sub-horizontally (+5 degrees) in each opposing pillar sidewall (Figure 3). Although the three instruments are not located in the same ring, they are closely spaced at approximately 6 metres apart.

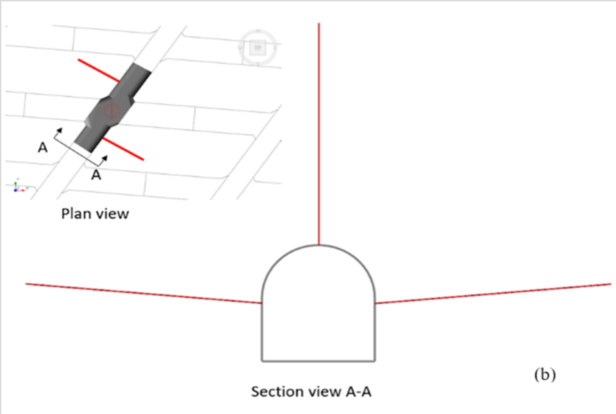

Figure 3 Typical MPBX configuration (section view).

The installation of MPBX's is split into two phases: before-undercut and after-undercut (Figure 4).

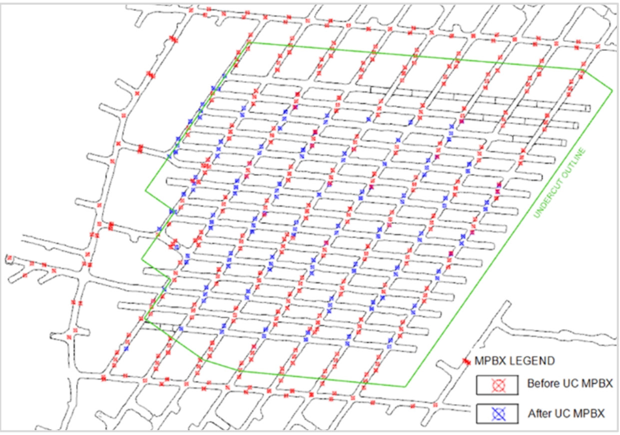

Figure 4 Panel 0 EXL MPBX installation sequence before(red) and after(blue) undercutting.

Following development of the extraction drives, and prior to the commencement of undercutting, half of the MPBX's are installed in alternating pillars across the footprint. The purpose of these instruments is to monitor deformation associated with undercutting. It is a requirement for all MPBX's in this phase to be installed across the footprint prior to the undercut starting. The after-undercut phase of MPBX installation occurs systematically across the footprint trailing behind the undercut face. These instruments are installed in the alternating pillars where the before-undercut instrumentation skipped. The intent of this phase of instrumentation is for long term monitoring of rock mass deformation and stress changes due to cave growth. Additional MPBX's are installed in the extraction level rim drives around the cave footprint periphery.

The before-undercut instrumentation locations have been strategically designed to enable monitoring of extraction level intersections and pillars during undercut stages: undercut advance, drawpoint (DP) drive development, and drawbell (DB) opening (**Error! Reference source not found.**).

Figure 5 MPBX positions, back (a) and wall (b), with respect to undercutting (UC face advance, drawpoint (DP) drives development, and drawbell (DB) opening) stages.

Integrating the MPBX instrumentation into an automated data collection system significantly improves the capability of evaluating rock mass response to undercutting and stress redistributions associated with the onset of caving. Adjacent to the MPBX holes, small boreholes are drilled to accommodate radios for signal transmission to the Geotechnical Data Acquisition (GDA) system. The installed MPBX units record data hourly as programmed into the smart link devices. This data is then transmitted via radio to the GDA and archived in a database. A comprehensive description of this system layout and integration is outlined by Moorcroft et al. (2022).

The Panel 0 MPBX network installed before undercutting facilitates an understanding of stress redistribution associated with undercutting through rock mass displacements. This paper aims to utilize real-time MPBX data to address the following research objectives:

1. Assess the practical benefits and concerns associated with implementing an automated data acquisition system and real-time data collections.

2. Examine the current methodology for illustrating (contouring) MPBX monitoring data during the undercutting phase.

3. Investigate rock mass displacement behaviours across different undercutting stages.

4. Analyse distinctions in the orientations and depths of rock mass displacements.

2 ANALYSIS

2.1 Displacement Contouring

Displacement contours have proven to be a valuable tool for OT Geotechnical Engineers, enabling swift identification of displacement hotspots and the ability to effectively communicate these issues with other departments. To make the contours, the following methods were tested: Multi-Quadric, Inverse Distance, Gaussian, Linear, Cubic, Quintic, and Thin Plate. The impact of applying different methods and parameters compared to the observation value illustrated in Figure 6.

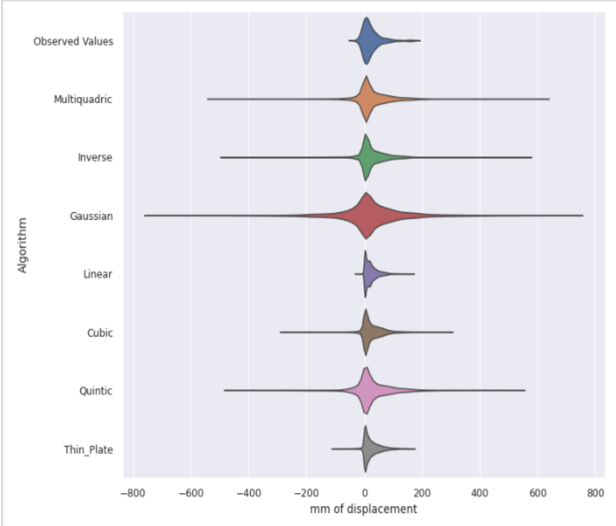

Figure 6 Violin plot demonstrating variance of modelled displacements when applying different methods.

There were inherent trade-offs between robustness and computing costs amongst all methods. The Radial Basis Function (RBF) Interpolator (Toit, 2008) method showed robustness and could run unsupervised when the Linear algorithm was applied. Experimentation revealed that, considering the geometric intricacies and data variability, the Multi-Quadric, Gaussian, and Quintic algebraic methods resulted in interpolated values deemed unlikely. These methods significantly over- and under-estimated displacement. Among the tested, the linear method emerged as the most favourable approach. The Linear method, although demonstrating performance comparable to Thin Plate, possessed a distinct advantage in its simplicity and ease of explanation.

Ensuring that end-users comprehend the applied processing to their data significantly enhances the likelihood of them placing trust in the outcomes and any decisions derived from it (Joshi, 2018). Kriging was considered but ultimately dismissed. During the preplanning of the undercut, it was anticipated that the stress field might undergo changes, potentially leading to alterations in spatial trends respective to the undercut area (Butcher, 2000). This, in turn, would necessitate the recalculation of the variogram. Given the desired update cadence every 4 hours, this Kriging method was ultimately rejected.

2.2 Displacement patterns during undercut stages

To ensure an accurate assessment, this review only focused on instrumentation subjected to similar stress environments and episodes. MPBX's installed around the cave footprint periphery were deliberately omitted from the analysis due the assumption that abutment stresses during cave growth may mask the observable influence of undercutting. Individual MPBX's included and excluded from this review are illustrated below in Figure 7.

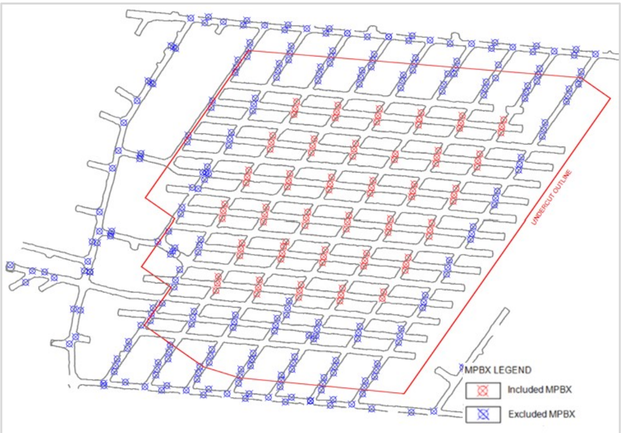

Figure 7 MPBX's included (red) in and excluded (blue) from the analysis.

This paper focuses on MPBXs that provided continuous measurements throughout the entire undercut stage. Instrumentation lacking complete data sets was excluded, typically due to MPBXs being broken, damaged, or temporarily turned off due to proximal firings. Although operational damage and failures pose significant challenges for MPBX monitoring, necessitating considerable maintenance, reinstallation, and calibration work, addressing these issues is beyond the scope of this paper. Additionally, MPBX reading anomalies related to environmental factors such as temperature were negligible because temperature fluctuations in OT underground are relatively low.

For each instrument, displacement curves were created to observe the relationship between MPBX readings (displacement) and distance to the undercut front. The distance between an individual instrument and the undercut front was measured directly along the strike of the extraction drive. Positive values indicate that the undercut has not passed over the individual MPBX location, and negative values indicate the undercut has passed over (Figure 8Figure 8.

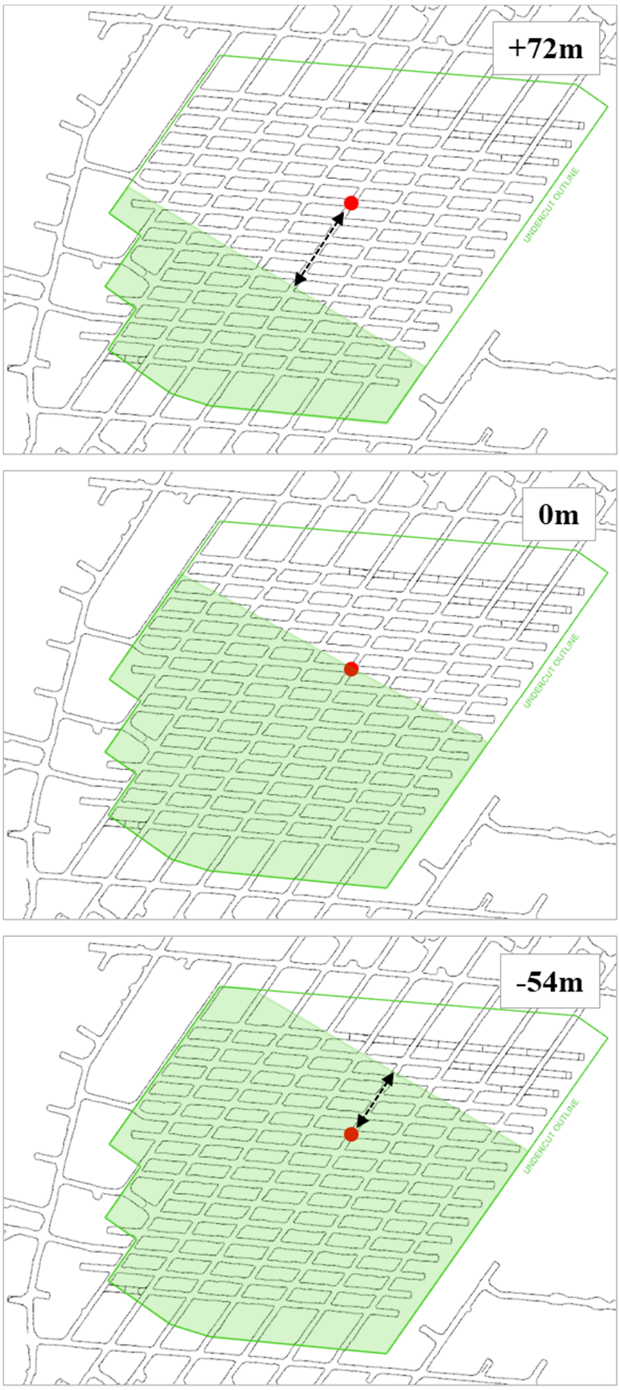

Figure 8 Methodology of measuring undercut face distance to MPBX position.

Displacement curves from continuous MPBX measurements throughout the entire undercut stage provided insights into the rock mass response to undercutting, highlighting three deflection points: initial displacement, rapid displacement, and return to stationary (**Error! Reference source not found.**). This displacement trend was consistent across MPBX instruments, allowing for analysis of the displacement contributions from each undercut stages. Undercut stages, previously illustrated in Figure 5, including undercut advance, drawpoint drive development, and drawbell openings, were overlaid on the displacement curves to observe the influence of these stages on displacement. (**Error! Reference source not found.** and Figure 11).

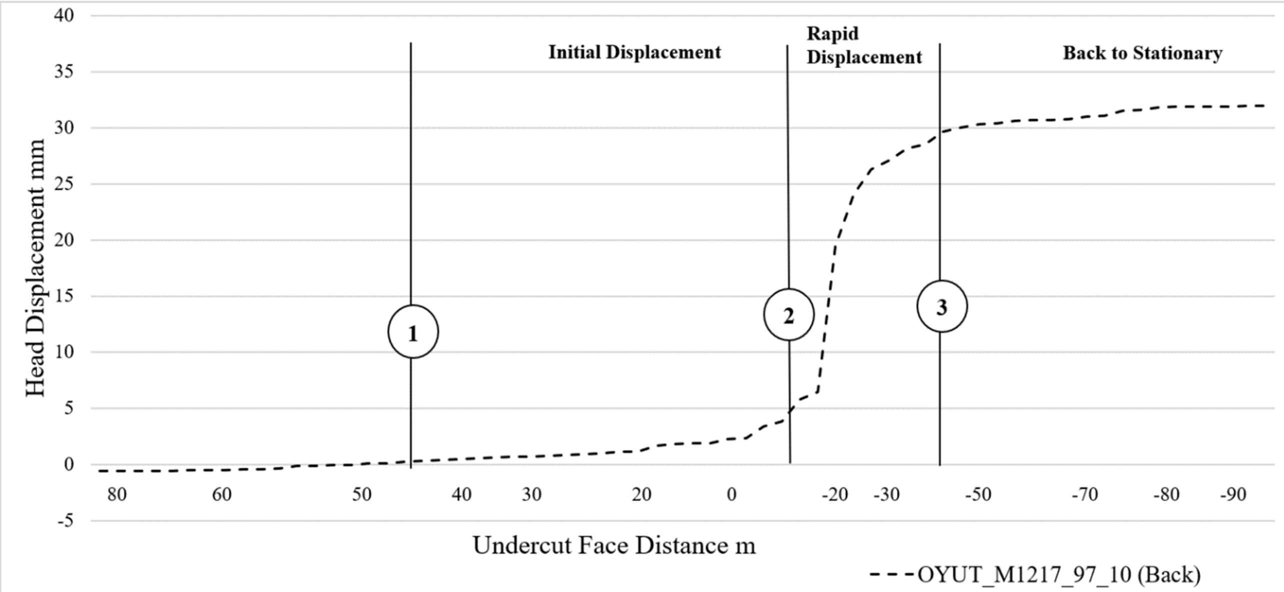

Figure 9 **Example of MPBX displacement curve showing relationship between displacement and distance to undercut face.**

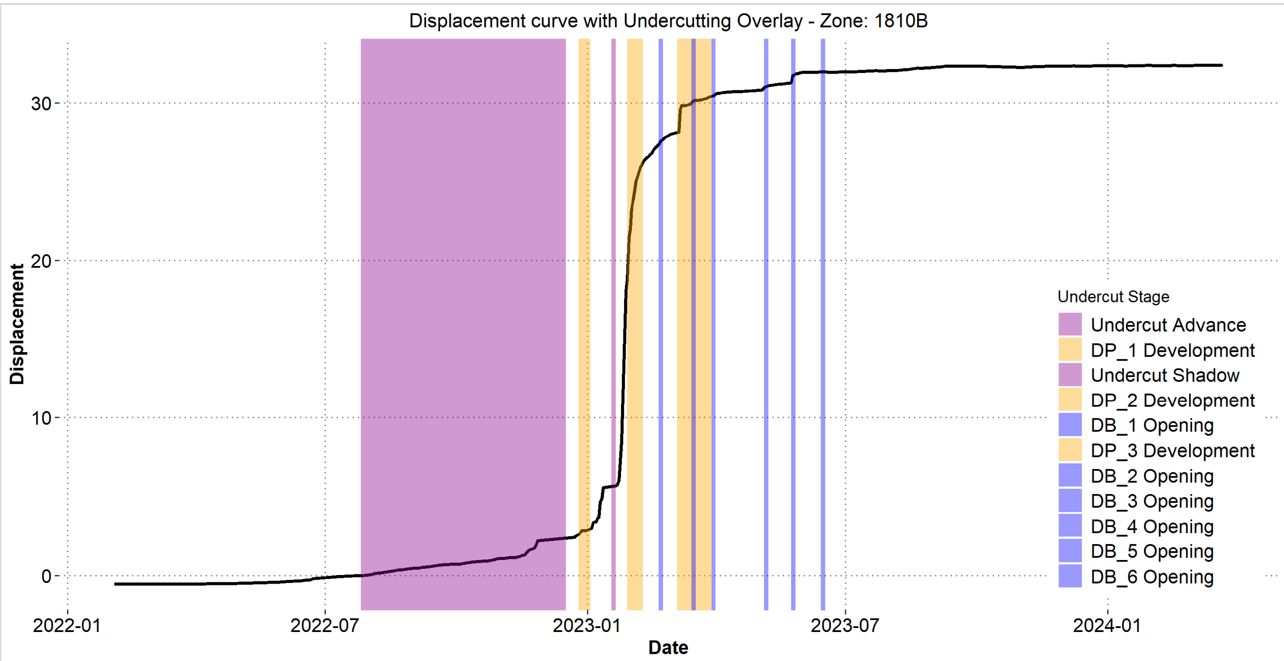

Figure 10 **MPBX displacement curve with respect undercut stages for a vertical instrument installed in extraction level drive backs.**

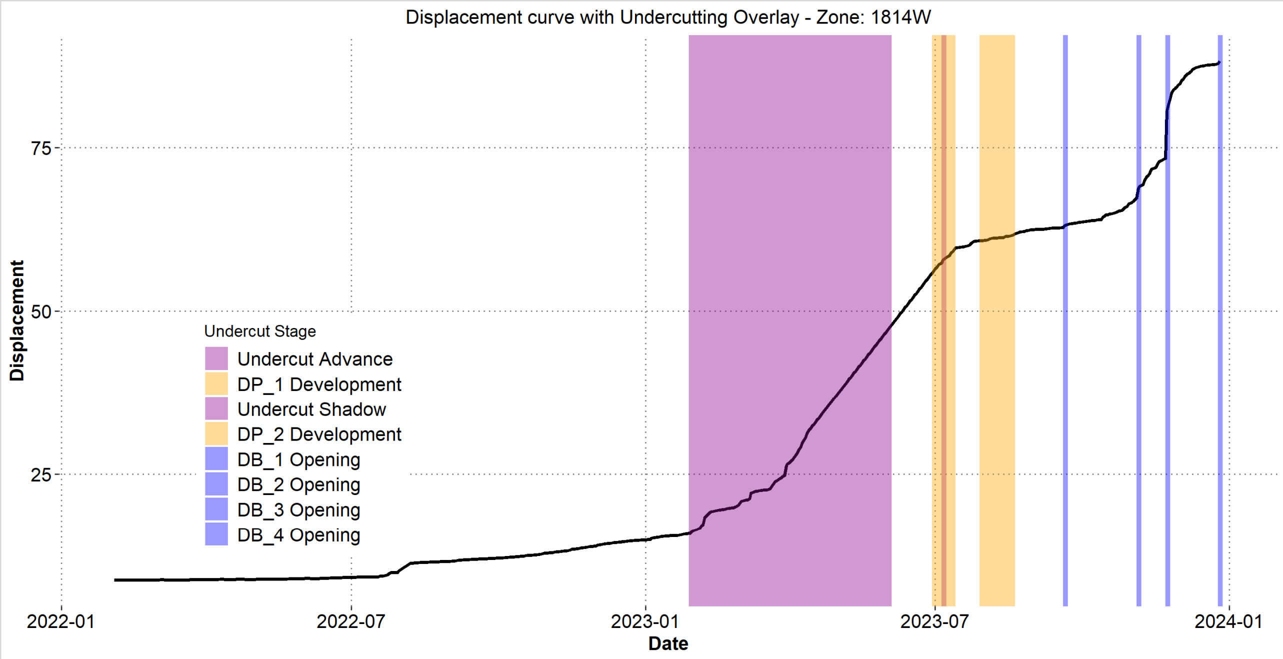

Figure 11 MPBX displacement curve with respect to mining activities for a horizontal instrument installed in extraction level pillars.

2.3 Depth of Displacement

Variations in movement across the MPBX anchors were used to analyse the depth of displacement in Panel 0. Utilising the 'back to stationary phase' from the displacement curves, the displacement ratio at various depths (anchors) was examined (Figure 12).

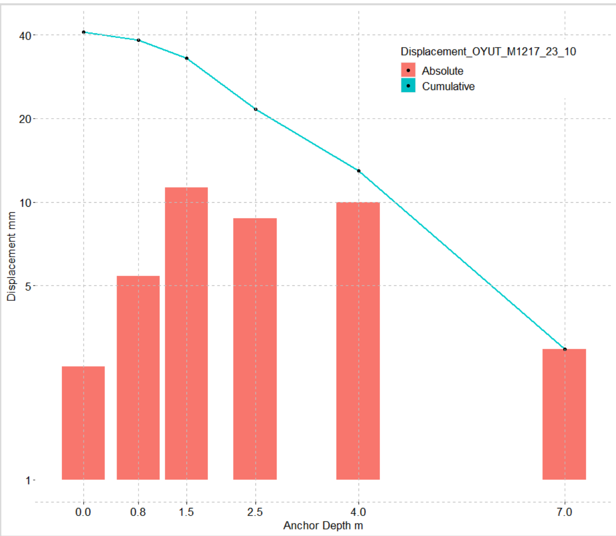

Figure 12 Depth of displacement by anchor depth.

This illustrated the variance in displacement between each anchor and the trend of displacement from the deepest anchor to the MPBX head or excavation surface. The variance in depth of displacement was also compared across different geological units and instrument positions (vertical vs horizontal).

3 RESULTS AND DISCUSSION

3.1 Vertical and Horizontal Displacement

As previously mentioned, the typical instrument configuration in each monitoring area comprises of three MPBX's; one installed vertically in the intersection back, and one installed sub-horizontally in each pillar sidewall.

Data from across the footprint has shown that MPBX's installed horizontally typically experience initial displacement, rapid displacement and return to stationary states earlier than instrumentation installed vertically. In general, horizontal displacement initiates approximately 75m from the undercut front, increases rapidly at around 30m, then returns to a stationary state approximately 20m behind the undercut front. Vertical displacement initiates approximately 35m from the undercut front, experiences a significant jump as the undercut front comes above the MPBX, and returns to a stationary state approximately 35m behind the undercut front (Figure 13**Error! Reference source not found.**).

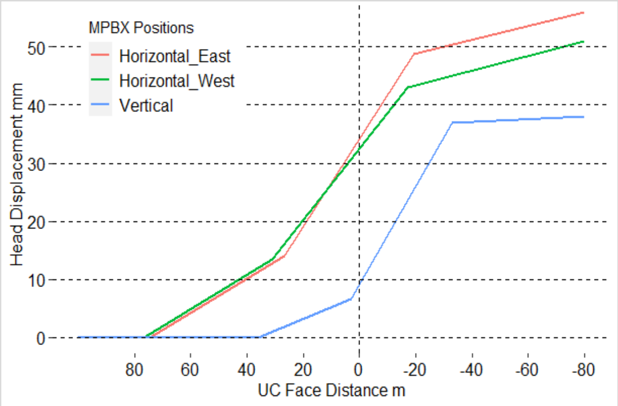

Figure 13 Horizontal vs vertical displacement during undercutting.

The instrumentation also highlights that deformation tends to plateau approximately 20-40m behind the undercut front. Given that the designed veranda length is 70m, this indicates that drawpoint development and drawbell opening are occurring in a destressed zone, as per the advanced undercut methodology. Once the undercut is finished, this data can be used to calibrate the veranda length for future panels.

The data highlights that majority of rock mass deformation occurs as the undercut front passes over instrumentation. Figure 14 illustrates the displacement contributions across different undercut stages. This implies that the high stress zone just ahead of the undercut front is the primary contributing factor of rapid displacement. It also validates the advanced undercutting methodology as it shows that developing extraction level pillars once the undercut passes over is the most feasible sequence.

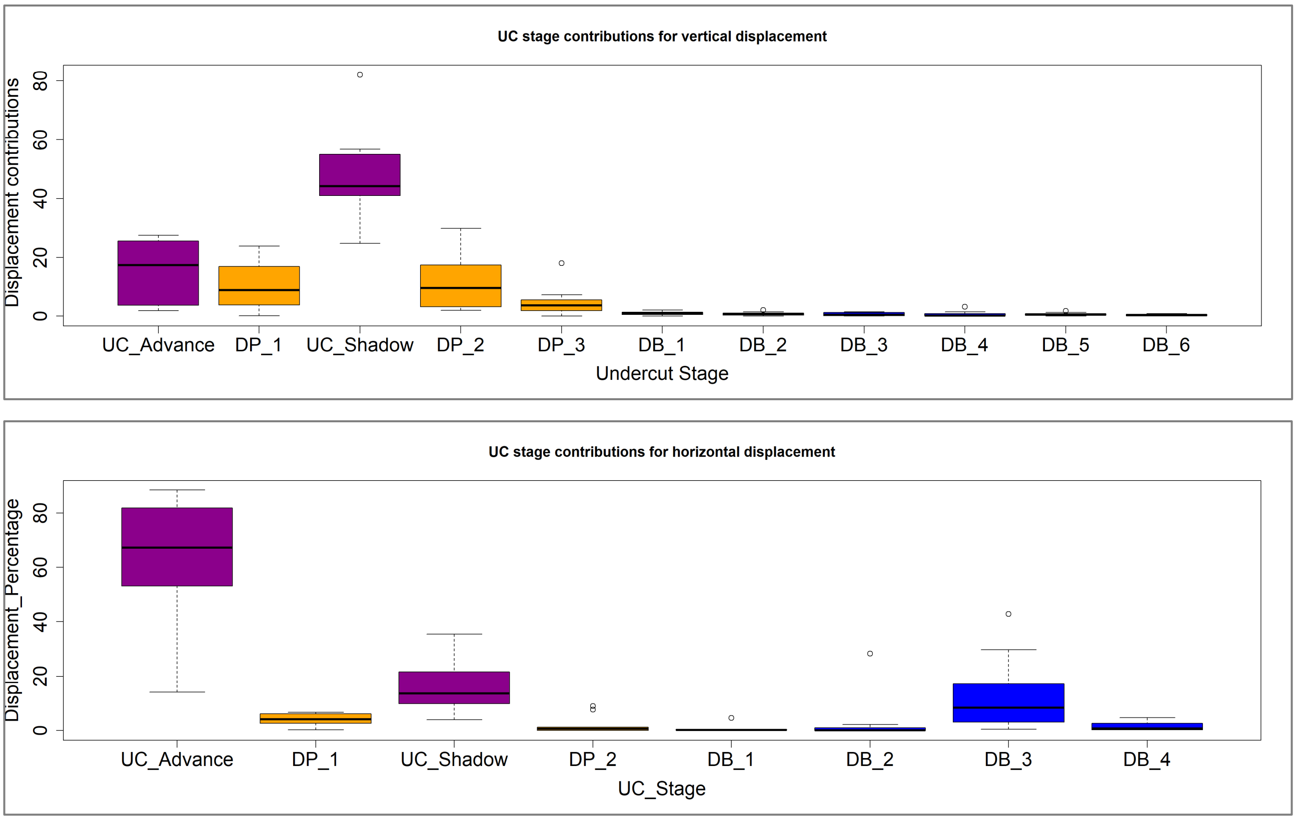

Figure 14 Vertical (Top) and Horizontal (Bottom) displacement percentages across different undercut stages.

Rock mass displacement with respect to drawpoint drive development and drawbell opening was analysed. It's worth nothing that instrumentation installed in the extraction drives are not equal distances from both drawpoint development and drawbells, and thus direct comparisons between displacement values during these undercut stages is not recommended. However, the displacement rates during these mining activities provided insight into rock mass response to mining.

MPBX data highlights more vertical displacement than horizontal displacement during drawpoint drive development, presumably due to the opening of large intersection spans (Figure 15).

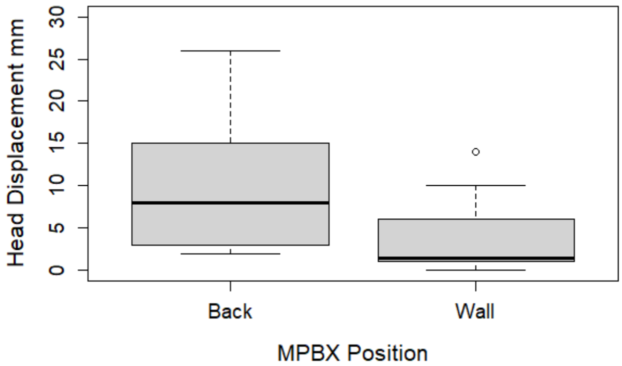

Figure 15 Horizontal vs vertical displacement during drawpoint drive development.

Conversely, more horizontal displacement than vertical displacement was observed during drawbell opening (Figure 16). This is likely a result of the drawbell firing decreasing the pillar size and thus increasing the stress on the pillar.

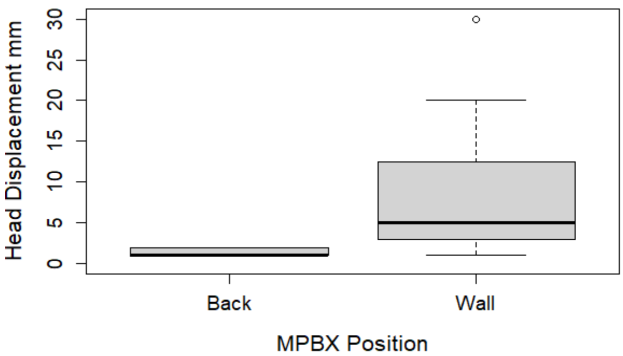

Figure 16 Horizontal vs vertical displacement during drawbell opening.

3.2 Displacement and Rock Mass Strength

Using rapid displacement values from the three deflection points (initial displacement, rapid displacement, back to stationary), analysis was conducted to examine the relationship between displacement and Rock Mass Rating (RMR). Figure 17 below shows displacement categorised by in-situ RMR (Laubscher & Jakubec, 2001) during the rapid displacement phase on the displacement curve.

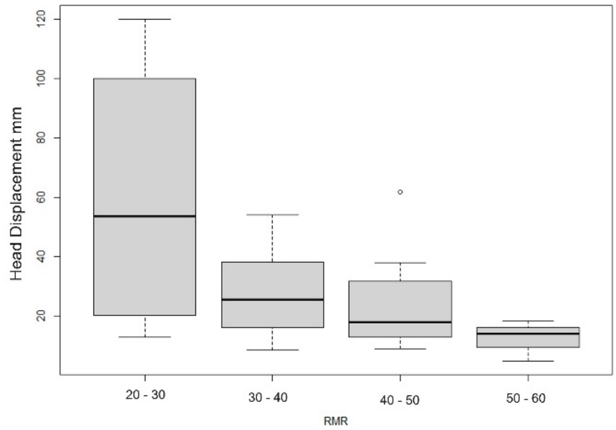

Figure 17 MPBX displacement categorised by RMR value.

As expected, higher displacement was observed in weaker rock mass, indicated by early onset of deformation and delays returning to the 'back to stationary' phase on the displacement curve. This was further confirmed when depth of displacement was compared by geological properties. There was not a significant relationship observed between lithology and depth of displacement, which is unsurprising given the similar rock mass strengths across the footprint. Within the weaker fault zones however, MPBX's moved uniformly up to a depth of 7m (Figure 18). This aligns with observations underground where rockmass deformation is predominantly observed throughout fault zones.

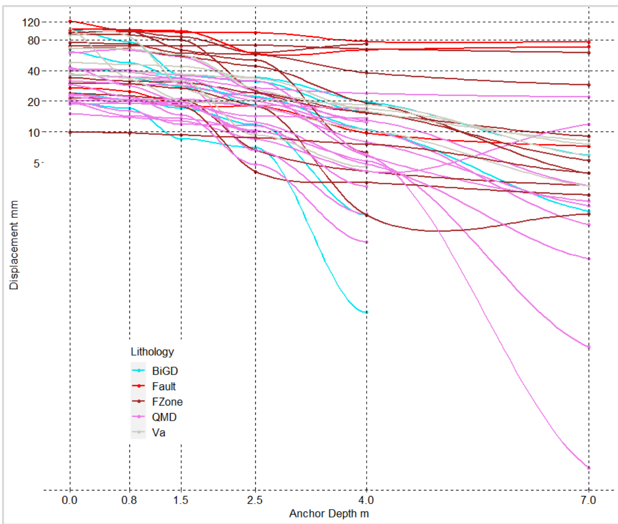

Figure 18 Depth of displacement categorised by lithological unit.

Depth of displacement was also compared by installed location; backs (vertical), sidewalls (horizontal) and within fault zones. Horizontally installed MPBX's displayed slightly larger displacement overall however most of this occurred at shallower depths near the excavation surface. Vertical MBPX's typically displayed uniform movement across all anchors, similar to trends observed in instrumentation installed within fault zones (Figure 19).

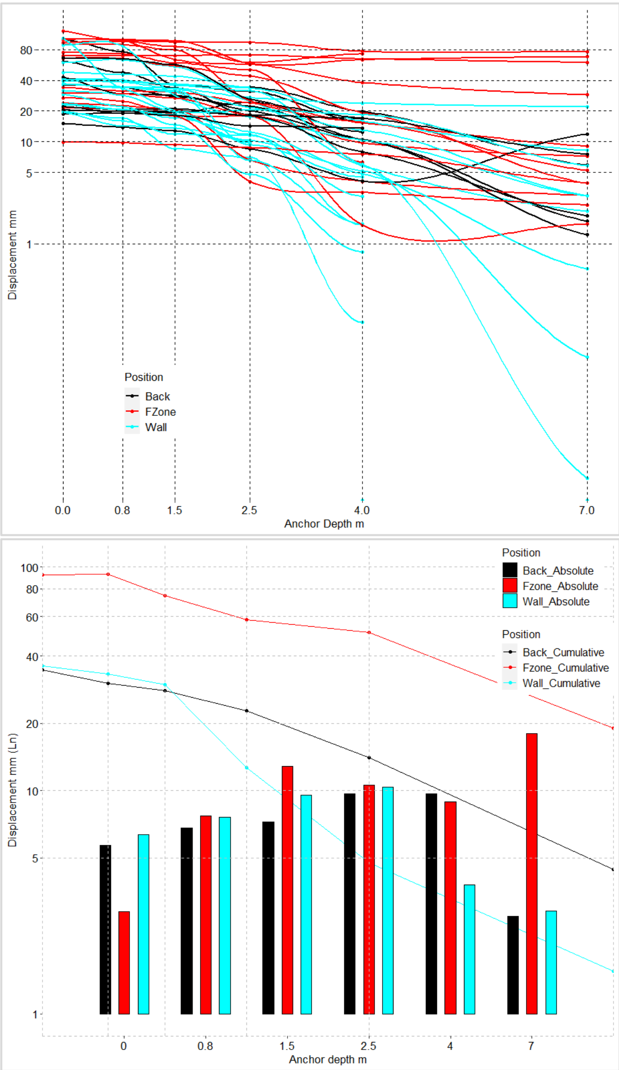

Figure 19 Depth of displacement categorised by install location for individual instruments values (top) and mean values (bottom).

MPBX readings were validated by comparing values to those obtained through observational borehole camera surveys. There were limited locations across the footprint where boreholes were within close enough proximity to instruments that they could be compared. Of the boreholes available for review, those drilled within close proximity to horizontal MPBX's confirmed that failure was in fact occurring at very shallow depths (<0.5m). When comparing observed failure and anchor displacement, fracturing increased at 18-23mm displacement, with failure observed when anchor movement exceeds 27mm within few indicative locations.

It is important to note that MPBX's have a limited capacity to measure rock mass movement greater than their length, 10 metres in this case. If the movement zone is particularly extensive and surpasses the length of the MPBX, true deformation should be verified by a collar survey or 3D scan measurement of total drive convergence.

3.3 Displacement Contouring

Whilst individual MPBX readings provide beneficial insight into localised deformation, contour maps offer a broad overview of displacement concentrations derived from real-time monitoring data. An example of Panel 0 MPBX contour mapping is shown in Figure 20. Gaps present in the contour maps represent areas where instruments were offline for maintenance during that plotted time period.

When reporting on MPBX contours, it is imperative to consider when the instruments were installed with respect to the undercutting phase. When reporting total cumulative displacement, data from MPBX's installed before the undercut commenced should not be mixed with data from MPBX's installed once the undercut has passed over. Instrumentation installed once the undercut has passed over will not show undercut induced deformation, and thus "dilutes" the historical data set. Both sets of data are useful and serve a purpose, but it is vital for users to be aware of their application. It is worth mentioning that this is only applicable when reviewing total cumulative displacement. When reviewing daily rates, both sets of instruments (before-undercut and after-undercut) can be reviewed together.

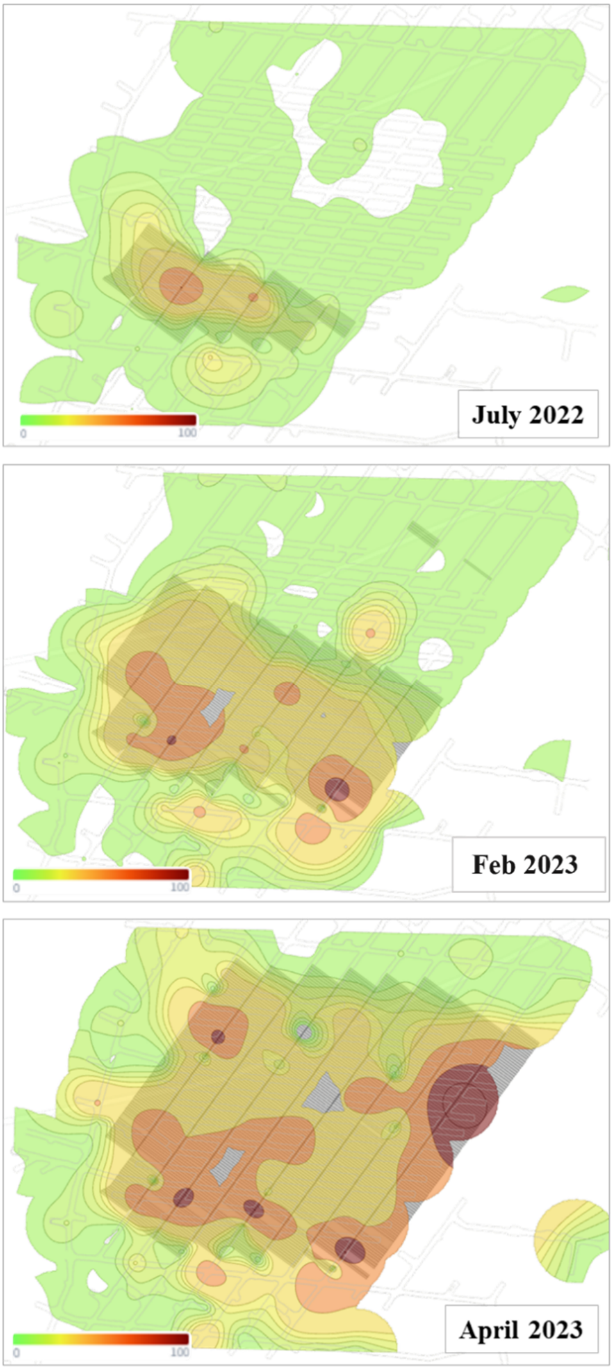

Figure 20 Panel 0 MPBX contour mapping throughout various stages of undercutting.

Implementing real-time MPBX contouring has highlighted the following key findings:

1. Contours facilitate the visualisation of deformation trends across individual instruments. With conventional software, instrumentation can only be reviewed at an individual level. Having the ability to link all instruments together highlights emerging trends and risk areas.
2. Contours efficiently present large quantities of data within a limited space. There is a substantial amount of data associated with 488 MPBX's reporting hourly readings. Having the integrated real-time platform removes the human workload and allows more time for analysis.
3. Contours enable a thorough analysis of multiple variables by integrating additional layers of data. Having the ability to overlay MPBX data on top of mine designs, undercut rings and drawbells enables clearer identification of relationships between displacement and mining activities.
4. Contours enable insight into the rate and magnitude of deformation through a time-stepping function. The ability to see displacement changes through time in relation to undercut ring firings has made identifying deformation relationships significantly easier.
5. Contours facilitate streamlined reporting and clear communication for those without prior geotechnical knowledge. Communicating risk and justifying early rehab has been made easier through the sharing of contour plots, which are easier to understand than traditional raw data.

4 CONCLUSION

Oyu Tolgoi's impressive network of 488 MPBX's installed in Panel 0 extraction level facilitates invaluable real-time rock mass monitoring. The comprehensive network offers early insight into rock mass deformation and provides the opportunity for significant in-depth analysis to be completed. In Panel 0, displacement typically peaks as the undercut front passes over instrument locations. In general, there is an increase in vertical displacement during drawpoint development and an increase in horizontal displacement during drawbell opening. Both the magnitude and the depth of displacement display a clear correlation with rock mass strength, with weaker rock mass exhibiting more deformation.

It can be beneficial to understand failure mechanisms by drilling additional boreholes at the same locations as the MPBX, allowing for measurements from anchors at different depths to be compared.

At this current stage of Panel 0 production, displacement across the extraction level footprint has been within acceptable limits, generally not exceeding 50mm. This is likely a testament to appropriate mine design and sequencing, a robust ground support system, and strict adherence to cave management rules such as undercut rates and lead-lags. Having such a comprehensive instrumentation network has not only facilitated proactive monitoring of ground conditions, but also validated geotechnical design and cave management rules. It has proven valuable to all phases of the mine design process; from studies to execution and will likely continue to be implemented in future caves at Oyu Tolgoi.

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