

Pit slope optimisation through a deep oxide zone at Newmont Boddington gold mine

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Abstract

This paper comprises a case study of pit slope optimisation design and implementation through a deep oxide horizon sensitive to porewater pressure and adjacent to critical mine infrastructure. Successful completion of the optimised cutback allows additional width of mining within the underlying hard rock orebody, adding approximately 260 koz Au and 30 Mlb Cu to ore reserves. Preliminary ground investigations identified elevated porewater pressure within weak in situ oxide material. Initial slope stability assessments indicated challenges in achieving design. A combination of slope geometry changes, detailed hydrogeological assessments, and proactive slope drainage and buttressing initiatives coupled with monitoring controls during excavation are used to safely achieve an optimised pit shell design. The deep oxide slope is located adjacent to the main conveyor corridor carrying ore from the primary crusher to the processing plant and a section of haul road running along the pit crest. Additional care was therefore required during the planning and implementation stage of the project to ensure there was no impact to mine operations.

Slope geometry changes include local batter/berm reconfiguration and an overall composite angle slope profile to take advantage of available strength in upper unsaturated oxides while removing weight at the top of the slope. Drainage measures included progressively boxing out in situ oxide material in 20 m-wide panel segments below design berms and replacing them with free-draining hard rock mine waste. Buttressing comprised of mine waste rockfill to help stabilise oxide batter faces and add additional weight in the lower half of the slope. Monitoring mainly relied on prisms and vibrating wire piezometer arrays installed along the critical design section used to assess slope stability. Hold points were used during excavation/construction to assess stability using updated pore pressure data. The implementation stage was therefore able to take advantage of predicted/realised pore pressure reductions to inform subsequent deeper excavation as mining progressed.

Keywords: *slope stability, optimisation, cutback, assessment, pore pressure, VWP, oxide*

1 Introduction

This paper describes work related to designing and implementing a pit slope optimisation project at the Newmont Boddington gold mine located approximately 120 km south of Perth, Western Australia. The Boddington operation is one of Australia's highest-producing open pit gold mines, producing over 700 koz of gold during 2022. The operation is currently advancing three open pits through upper zones of saprolite and saprock, and lower zones of hard rock. The current cutback in the S05 pit is projected to extend the pit depth to over 650 m.

The S05 pit cutback expands the older S04 pit and is divided into two cutbacks, the S05A and the S05B. The S05A cutback has been underway since 2017, while the S05B cutback was initiated in 2022. Both cutbacks are now progressing simultaneously, with operations in each area sharing the S05A pit north wall. Optimisation of the S05B cutback added approximately 260 koz Au and 30 Mlb Cu above the base case reserve design.

Site infrastructure includes the run of mine and primary crushers (PCs) on the western side of the open pits and the processing mill on the eastern side. A conveyor corridor exists between the north and south pits, linking the PCs to the mill, and runs approximately 40 m beyond the planned pit boundary of the S05B pit. The conveyor is responsible for delivering ore feed to the mill. For this reason, a heightened level of attention

was provided during the design stage when planning the extent of the S05B cutback in proximity to the conveyor corridor. The intention was to ensure an appropriate low level of risk due to the importance of maintaining ore feed while also maximising ore recovery in the pit. Figure 1 shows the location of the pit, cutbacks and nearby infrastructure.

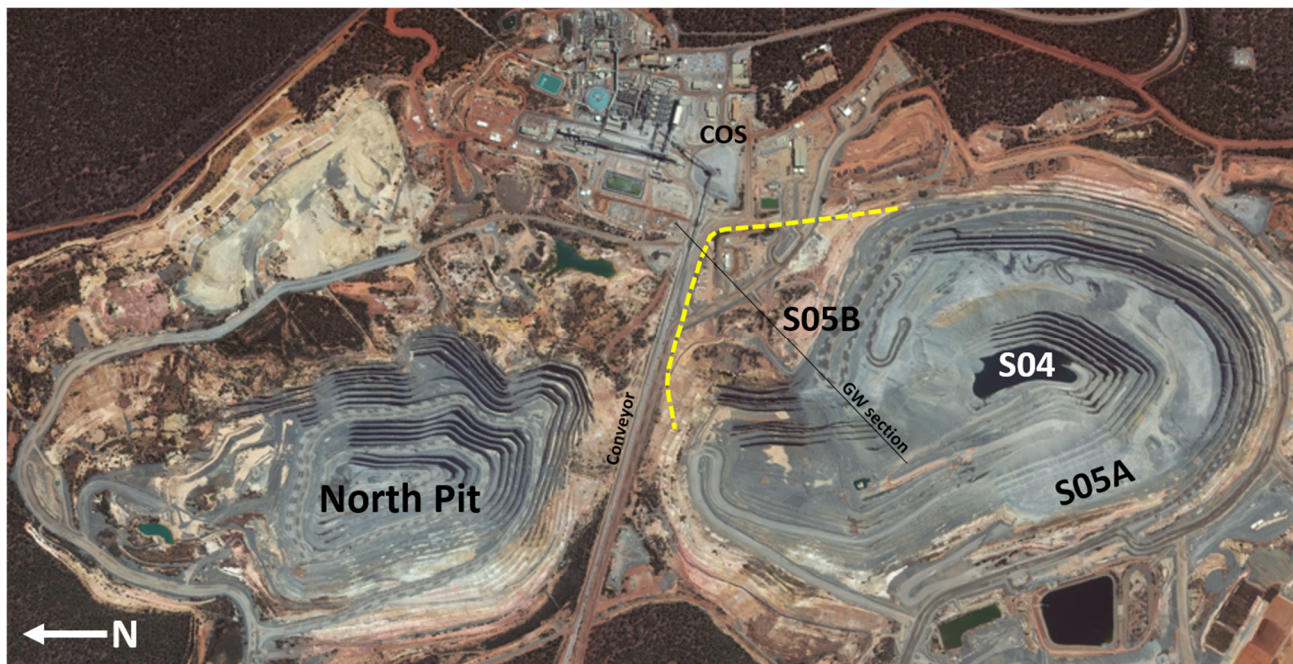


Figure 1 Location of S05B cutback relative to the S04 and S05A pits (S05B perimeter at the dotted yellow line)

The presence of a saturated oxide horizon greater than 60 m-deep in the top northeast area of the pit meant that ore recovery in underlying hard rock was governed by achievable slope geometry within the oxide horizon. Pit slope angles were initially relaxed to compensate for the weak saturated material. Pit slope optimisation was achieved by modifying the slope geometry through oxides, sequencing the construction of slope strengthening and drainage solutions, and introducing controls related to predicted/monitored pore pressure reduction during excavation.

2 Background and context

The Boddington gold mine orebody is a large low-grade deposit that is mined out using successive open pit cutbacks. The long life of the mine allows time to gain knowledge of ground conditions from excavation exposures, plan and execute additional ground investigation, and perform relevant studies within a broad time frame. The S05B cutback study commenced in 2017. While the hard rock study progressed relatively quickly, it became apparent that additional focus was required to address slope stability concerns within the zone of deep saturated oxide material. Figure 2 shows the thickness and location of oxide material below the initial topographical surface prior to commencement of the S05B cutback.

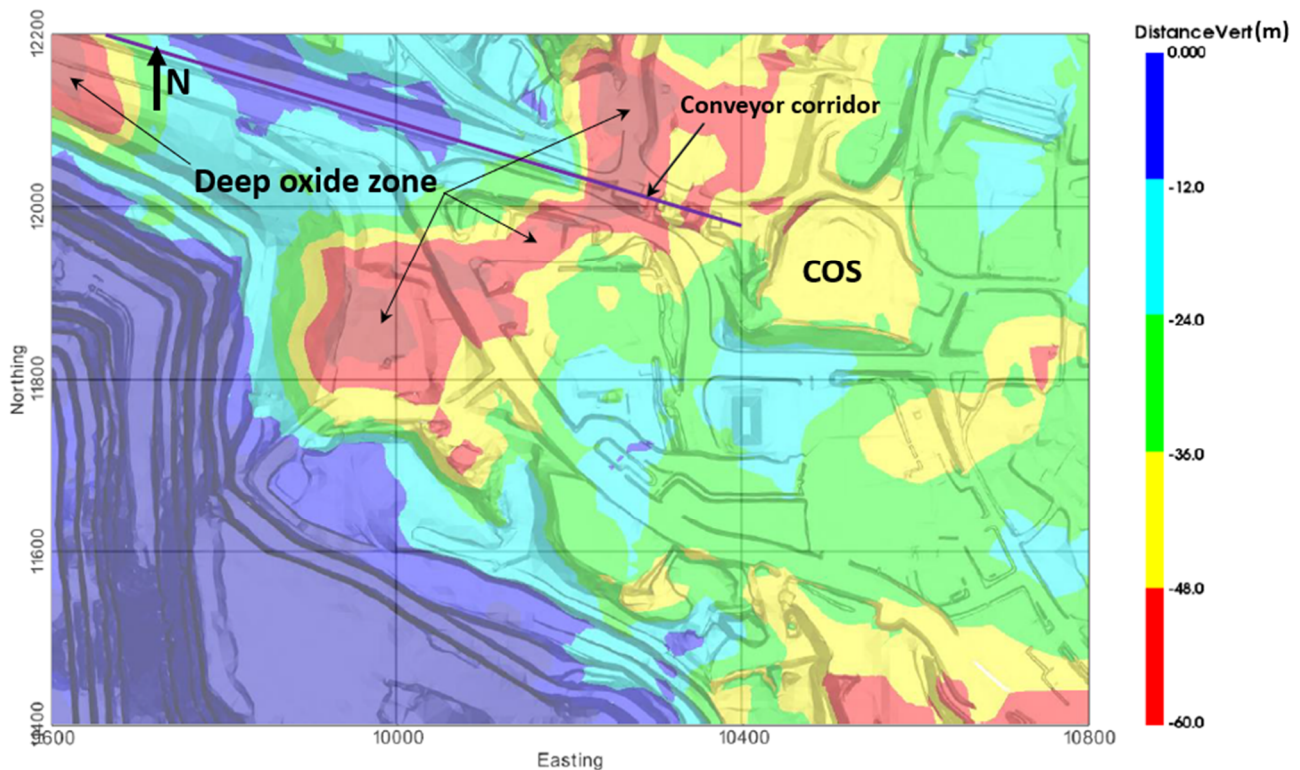


Figure 2 Thickness of oxide material below initial topography prior to commencement of cutback

Several consultants were engaged to conduct ground/hydrogeological investigations and provide design recommendations. These studies led to the construction of hydrogeological and geotechnical models focusing on the weak oxide profile. Potential drainage and slope stability recommendations included:

- Advanced depressurisation of the oxides using a vertical borehole depressurisation system.
- Flattening the design slope angle to compensate for the degree of saturation.
- Installation of soil nails to reinforce the oxide slopes.

Once the oxide study was progressed to a greater degree, an impasse remained and the project was then advanced within the Boddington geotechnical team. This facilitated better coordination within Newmont teams. The change in structure also provided a better opportunity for seamless transition of project goals, objectives and construction controls to the operations team during the implementation phase.

The economic incentive for optimising the S05B pit design within the oxide zone is to provide access to additional ore in the lower hard rock sections of the cutback. Figure 3 shows a cross-section through the proposed cutback, the ore block model and potential pit profiles dependent on upper oxide slope designs.

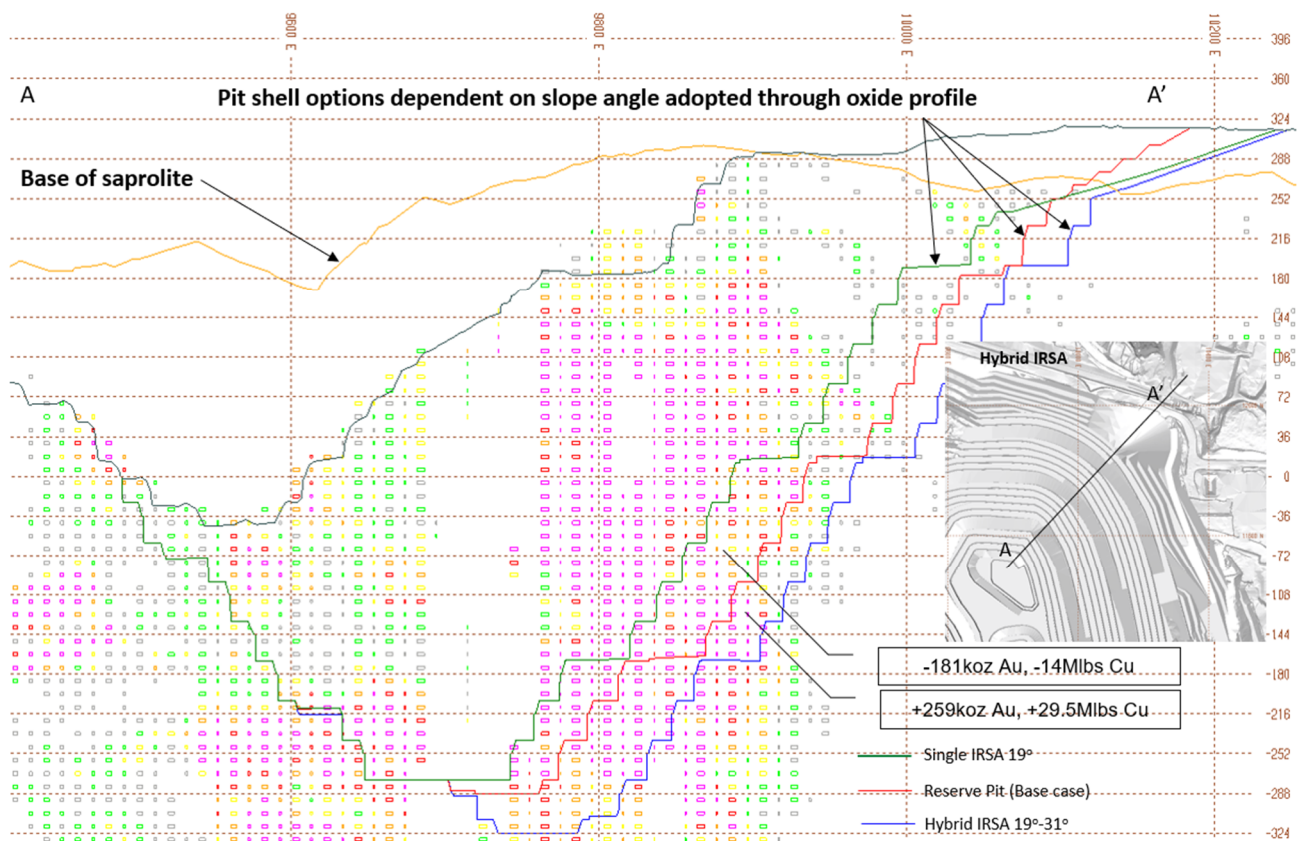


Figure 3 Section through the S05B cutback showing block model and potential pit designs

3 Geology

Geology within the S05B cutback area consists of the following lithological units starting from ground surface:

1. Made ground (excavated and replaced oxide material).
2. Saprolite.
3. Saprock/transition.
4. Hard rock (diorite/andesite/dolerite).

Digital 3D geological surfaces were developed by the site geology team using drillhole data from geological exploration, ore control and geotechnical investigation drilling. Figure 4 is a model of the upper portion of the S05B cutback developed using Rocscience Slide3™ showing the location and extent of geological materials. Figure 4 also identifies the eastern and western portions of the S05B cutback. The vertical thickness of the saprolite in the eastern portion is up to approximately 60 m thick. The north pit void is shown in proximity to the western portion of the S05B cutback. Some variability in the location of the base of saprolite and the top of saprock was noted, and some conservatism was incorporated into the geological model to accommodate this variance.

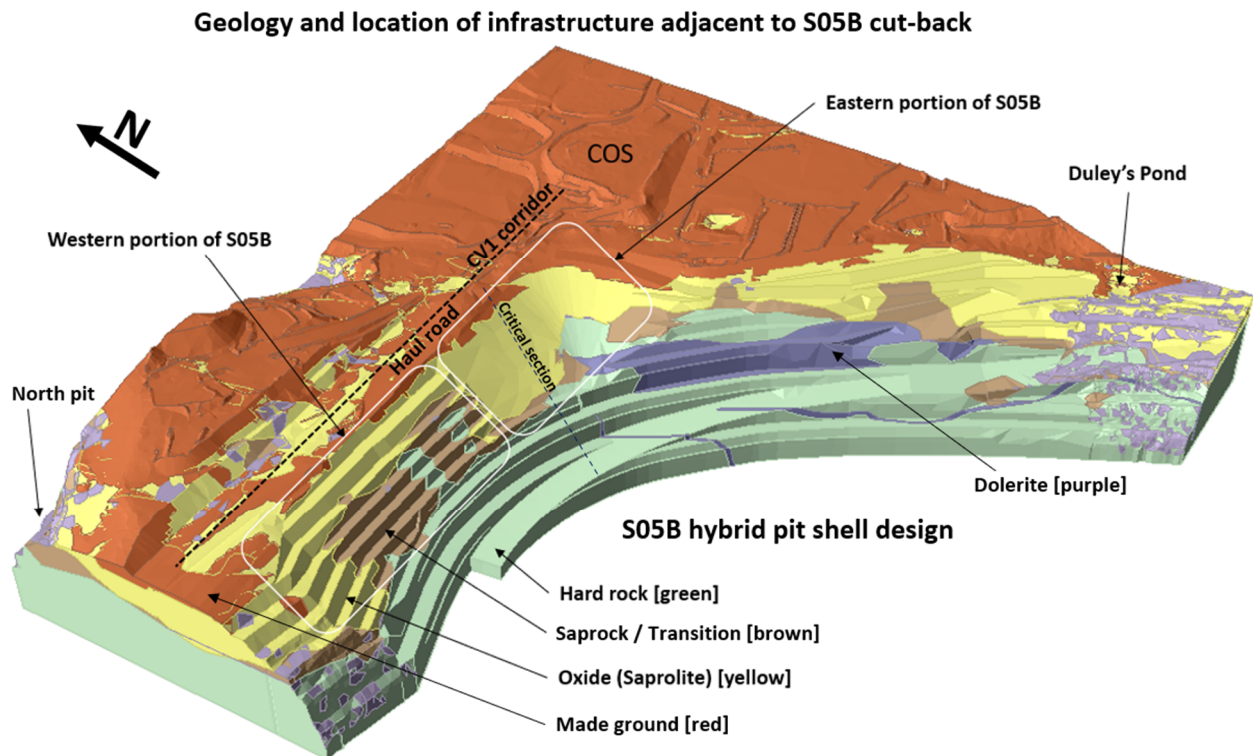


Figure 4 Upper S05B cutback showing distribution of geological materials and site infrastructure

4 Hydrogeology

The hydrogeological model was developed in stages through implementation and interpretation of groundwater monitoring. Early stage development of the hydrogeological model was done by installing vibrating wire and standpipe piezometers across the S05B oxide footprint. Monitoring results indicated relatively high groundwater in the northeast, diminishing towards pit exposures to the south and west (Red Creek Water Solutions 2018). A model of the phreatic surface was developed using acquired data (Absolute Geotechnics 2019) and is presented in Figure 5. The location of the groundwater (GW) section is as shown in Figure 1. The interpreted phreatic surface was used in preliminary slope stability assessments.

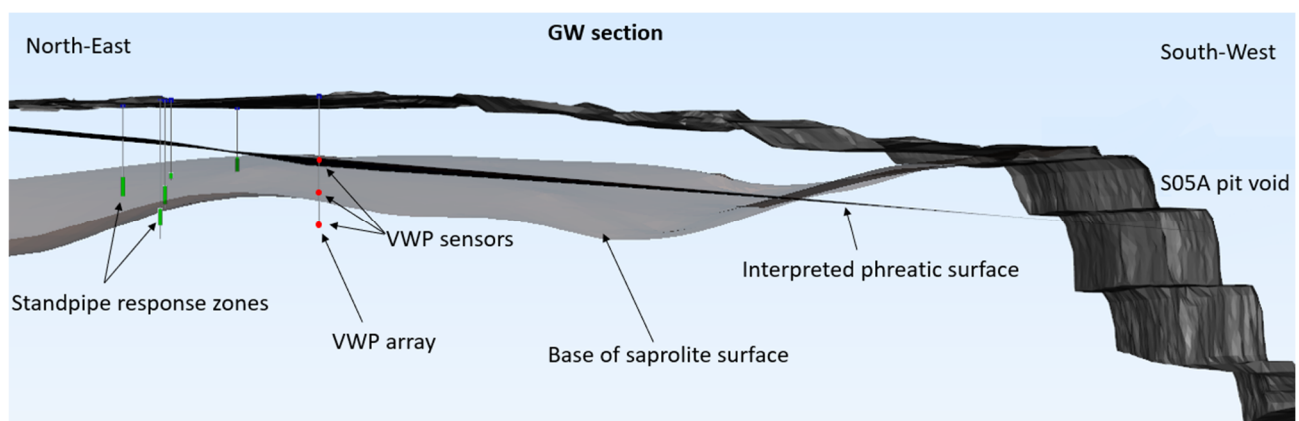


Figure 5 Groundwater (GW) section showing the location of monitoring instruments and the initial interpreted phreatic surface

Additional groundwater assessment was undertaken during follow-up studies due to the critical nature of elevated pore pressure on slope stability. Follow-up work included installation of additional multi-sensor vibrating wire piezometer (VWP) arrays in strategic locations, installing trial vertical drains nearby, and undertaking falling head tests during and after drilling. Testing included recording pore pressure responses

in nearby VWP arrays. VWP monitoring results indicated the presence of underdrainage near the base of the saprolite material (Fluid Potential 2021). An internal hydrogeology specialist (M McGann) was engaged to interpret permeability within the saprolite material. Using available data, pore pressure isolines were developed to represent current and future predicted pore pressure distributions at various stages of excavation. Figure 6 presents a critical section developed in Rocscience Slide2™ showing a modelled excavation in the dry upper portion of the slope. Nearby monitoring fixtures are presented alongside, resulting interpreted pore pressure isolines based on available data.

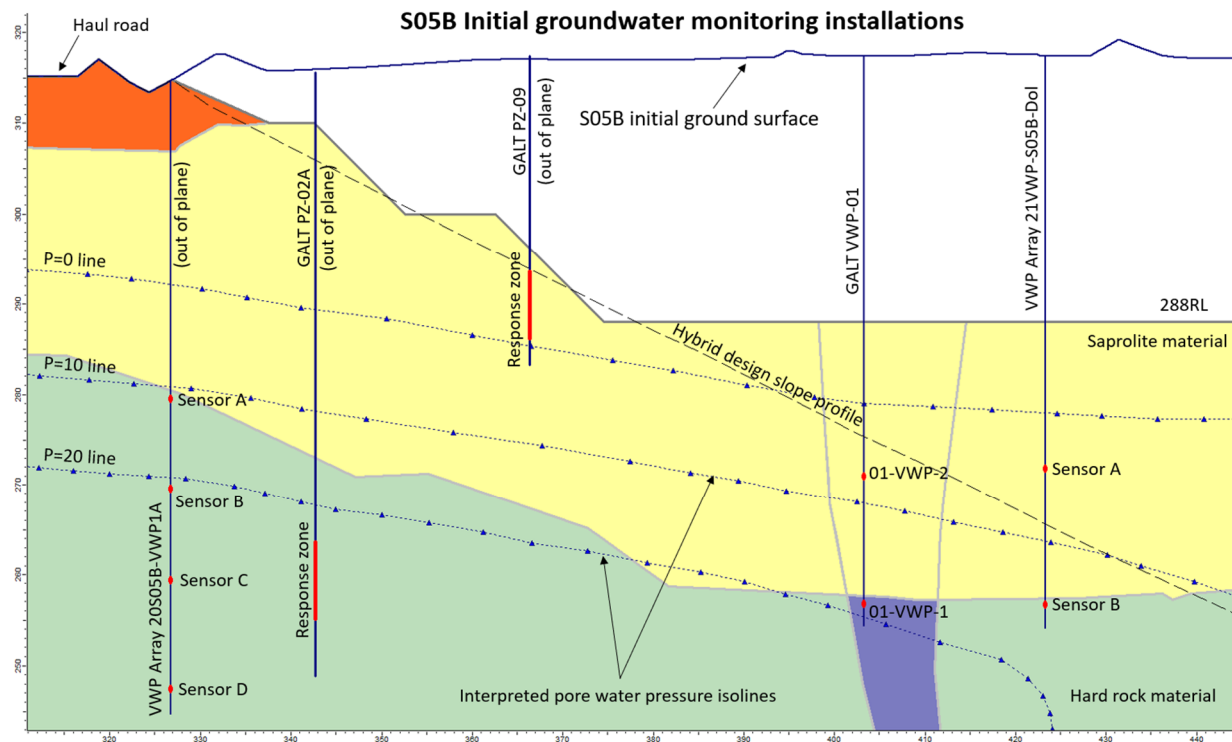


Figure 6 Section through a deep oxide zone showing initial pore pressure distribution and groundwater monitoring fixtures

5 Material parameters

The critical material identified in this study was saprolite, due to its relative weak strength and increased sensitivity to pore pressure. Determination of engineering properties of the saprolite material was done via laboratory testing of samples identified during ground investigations. Previous investigation of saprolite material on a site-wide scope had been done in 2012 by SRK. A supplemental ground investigation in 2018 focused specifically on the S05B oxide horizon, with reporting performed by Absolute Geotechnics in 2019. Data specific to the S05B area provided the greatest amount of confidence and was therefore given the greatest weighting when evaluating and assigning engineering properties.

Testing undertaken consisted of the following:

- Consolidated undrained (CU) triaxial.
- Atterberg limit.
- Particle size distribution.
- Moisture content.
- Density.
- Multistage direct shear.
- UCS (underlying saprock/hard rock).

Atterberg limit results indicate classification as medium to high plasticity silt, although the average sub-2 μm fraction in particle size distribution testing was above 20%. Calculated ‘activity’ of the saprolite soil (plasticity index/clay content %) indicates predominantly ‘inactive’ to ‘normal’ soils based on Skempton’s activity index, suggesting predominant kaolinite and illite clay minerals (Skempton 1953).

Triaxial testing was performed on 12 samples recovered from triple tube coring and undertaken on each sample in three stages. Determination of effective stress (c') and phi parameters was achieved by assessing a trendline through a P-Q plot of the CU triaxial test data. The amount of available test data provided a suitable degree of confidence in the parameters derived using this method without applying any corrections. Atterberg limit and CU triaxial test results (P-Q plot) are presented in Figure 7.

The optimisation solution incorporates rockfill material used to construct buttress and drainage features. Dolerite rockfill recovered during mining was used due to it being the heaviest material available. A bulking factor was applied when assigning loose bulk density.

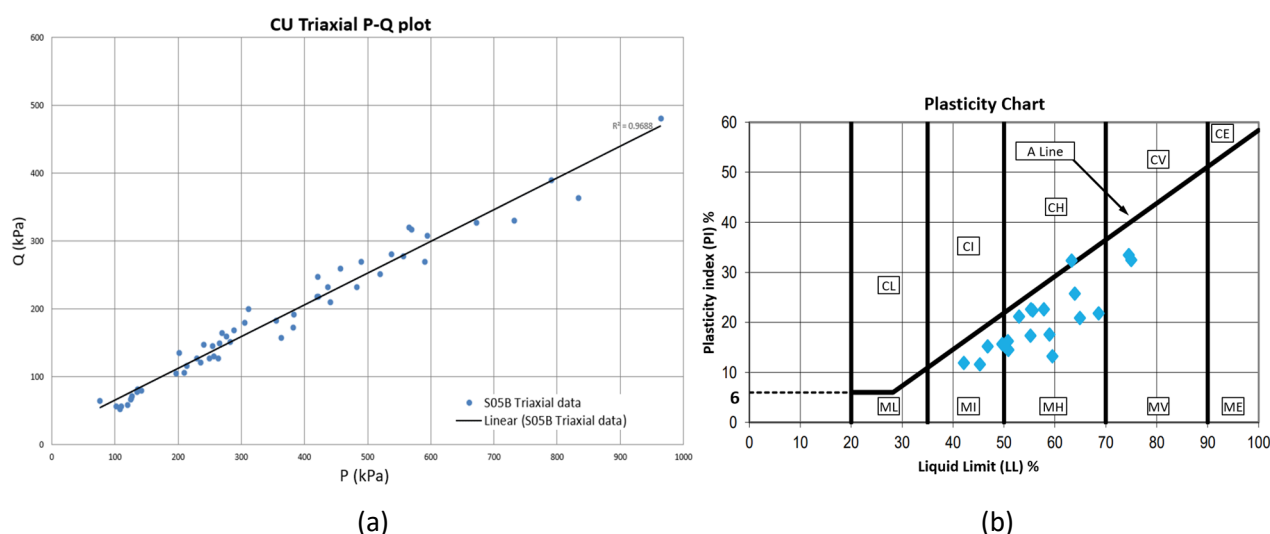


Figure 7 (a) P-Q plot of 2012 and 2018 CU triaxial results; (b) Atterberg limit results for S05B samples (Absolute Geotechnics 2019)

6 Approach to the optimisation process

Conducting follow-up study work within the site-based geotechnical team meant there was increased opportunity for interactions and communication with various departments at the mine, including hydrogeology, planning and operational teams. This promoted a better understanding of the different levers that were available within the operation and was important to the success of the project.

The optimisation process focused on understanding the design constraints and main drivers governing slope stability, which were assessed to be:

- Material strengths.
- Pore pressure distribution within the slope.
- Geomorphology and location of geological contacts.
- Perceived constraints related to nearby mine site infrastructure.

An important aspect of the optimisation process was having the time and imagination to develop and test potential strategies using stability modelling. Equally important was having agency to challenge and effect changes to perceived constraints. Communicating with different teams onsite was crucial to gaining acceptance of proposed strategies that included:

- Reducing weight at the top of the slope by lowering the haul road level adjacent to the pit crest.

- Reducing the overall slope angle by locally narrowing the haul road that runs along the crest.
- Implementing variable width berms to locally accommodate ground conditions.
- Locally changing the generic sequencing of bulk material excavation in the pit.

Significant additional engineering solutions included the following:

- Introducing composite inter-ramp angles to take advantage of site conditions.
- Developing a rockfill buttress solution to strengthen the slope progressively during excavation.
- Developing a slope drainage solution to help reduce transient pore pressures and infiltration, and accelerate the mining schedule.
- Planning and implementing a suitable monitoring system to inform excavation activity.
- Developing hold points, initiated when excavation reached specific levels.
- Using monitoring data to qualify stability assessments required for the release of hold points.
- Adopting an observational method during excavation.

The observational method has been described by Powderham & O'Brien (2020) as a powerful technique that maximises economy while adequately addressing safety. It is an approach that is often well suited to projects related to ground engineering. Feedback loops using monitoring during the execution stage of the project are employed to inform relevant actions.

6.1 Optimisation of the western section of S05B

The base case pit shell design of the western section of the S05B cutback left a relatively narrow skin of oxide along the slope profile. This caused an issue with not being able to achieve the required Factor of Safety during stability assessments due to the weakness, and local saturation, of the saprolite material. This was resolved by the mining engineer at an early stage in the study by relocating the pit shell design slightly to the north and thereby mining out the weak material. This meant that only a marginal amount of additional stripping within the oxides was required to help gain access to additional hard rock ore lower in the pit. Although a large vertical extent of saprolite exists on the far western side of the planned cutback, reduced local groundwater levels meant more stable slopes.

6.2 Optimisation of the eastern section of S05B

The eastern section of the S05B cutback required additional attention mainly due to saturated ground conditions. Several rounds of iterative slope design were performed to gain an understanding of how different potential slope geometries impacted stability. These included performing 3D slope stability assessments using the Rocscience Slide3™ software and 2D assessments using Rocscience Slide2™ software. An interpreted phreatic groundwater surface was initially used in stability models and then replaced with porewater pressure grids in order to better represent hydrogeological conditions.

6.2.1 3D limit equilibrium modelling

The 3D limit equilibrium (LE) software was used to help determine the most appropriate critical section to bring forward into 2D LE design. Functionality within the 3D model meant that interpreted potential slip surfaces take into consideration geological features behind the slope face. For example, stronger and more competent geology may exist closely behind the slope face in certain areas, whereas other areas may be affected by deep and pervasive weak material. Once a critical area of the slope is determined using the 3D LE assessment, a cross-section can easily be exported to assess further in 2D. Figure 8 shows an example of 3D LE analysis output, cross-section generation within Slide3™ and the variable surface of an assessed slip surface.

Although the 3D model proved useful to help identify weak areas of the slope, the increased complexity made it more difficult to effect changes to the model. For this reason, it was more practical to work with the 2D model when changing the pit shape and manipulating groundwater and pore pressure.

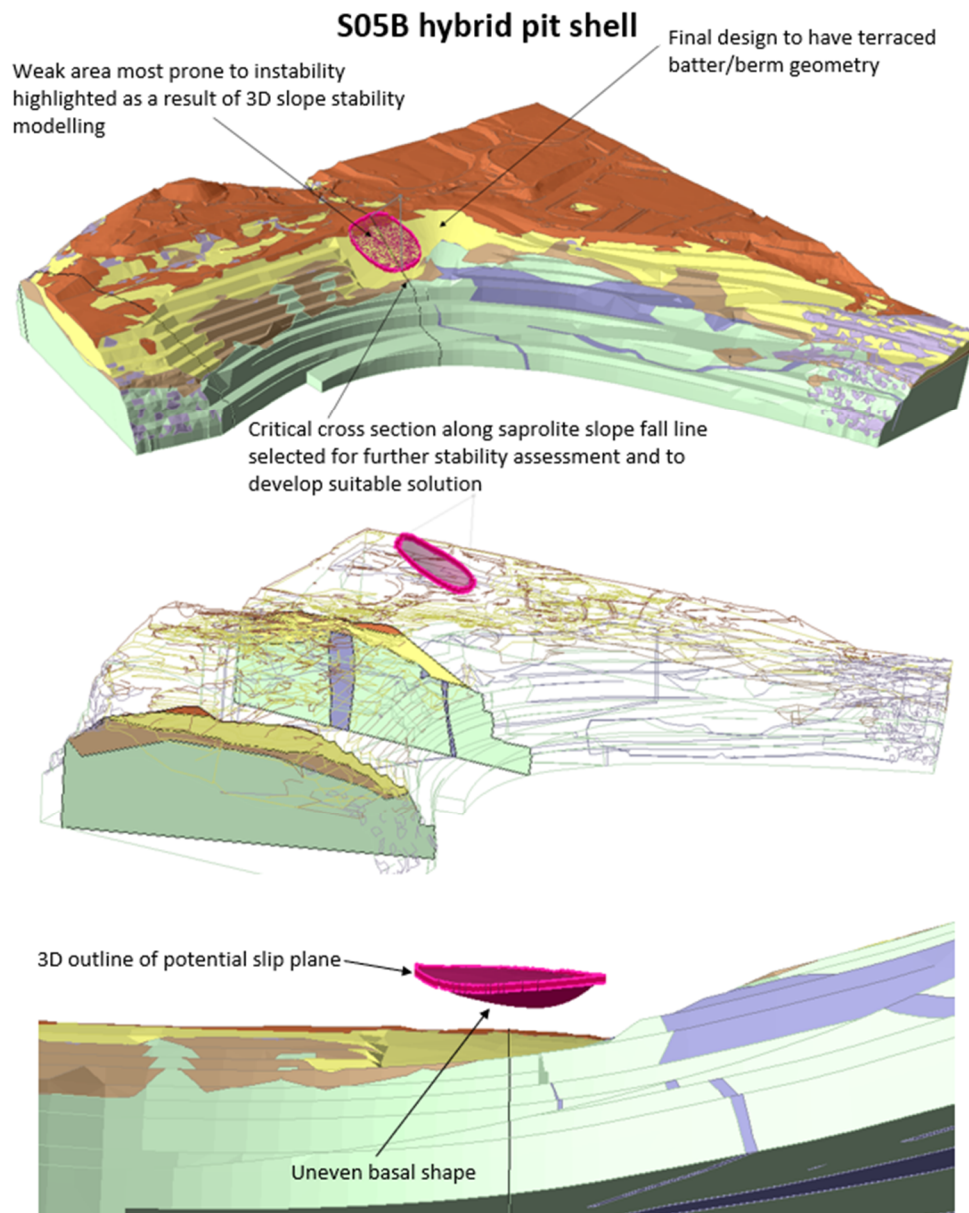


Figure 8 Slide3™ model output showing (a) Location of critical section; (b) Cross sections; (c) The uneven basal shape of a potential slip plane

6.2.2 2D limit equilibrium modelling

The versatility of the 2D modelling environment enabled different geometries, buttressing and drainage strategies to be developed and tested relatively easily. An important part of the ideation and modelling process was to consider whether solutions were practical and achievable during excavation using available machines and skill sets. In this case, discussions with operations and planning personnel were key to communicating what was being proposed and to gain feedback on capabilities during excavation/construction.

In order to satisfy spatial constraints and the required design acceptance criteria, multiple incremental changes were assessed prior to determining an appropriate final design. These steps involved implementing the optimisation solutions listed in Section 6. A cross-section of the resulting design geometry is presented

in Figure 9. Initial drainage measures shown in Figure 9 were considered as trenched and backfilled features with out of plane trenching at select intervals daylighting along the slope face.

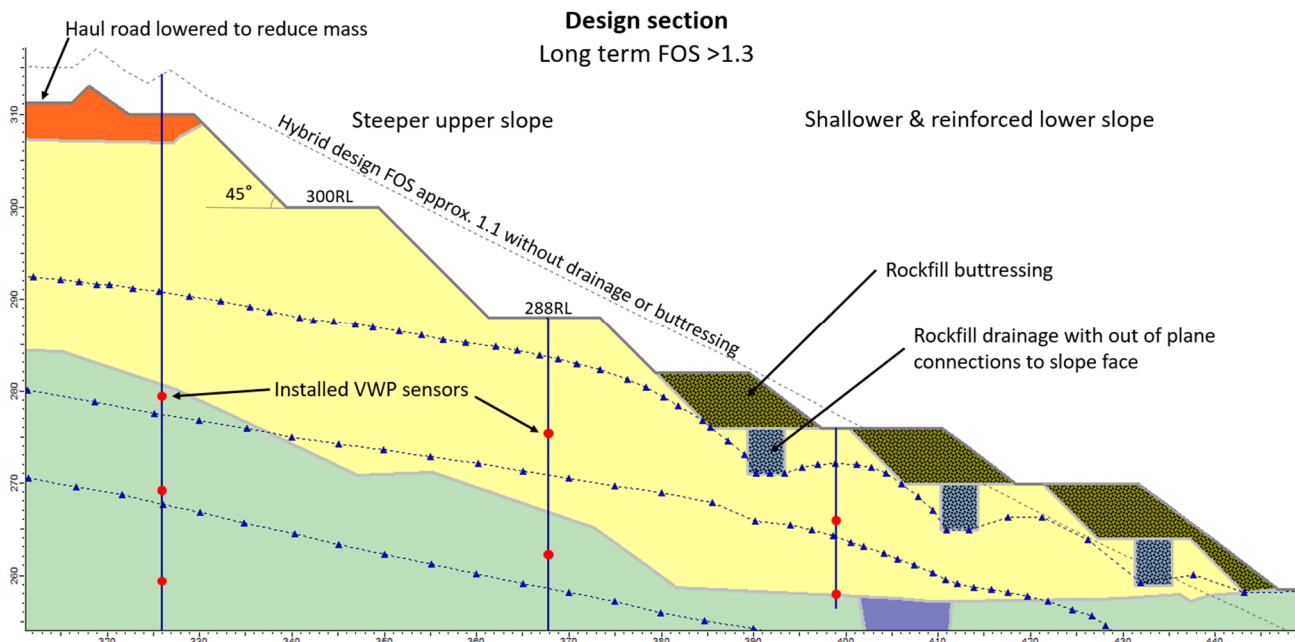


Figure 9 Design section showing buttressing, drainage measures and the location of VWP sensors

Assessments of short-term construction case scenarios were a crucial aspect of the evaluation process since these addressed slope conditions at critical time intervals during excavation. Pore pressure distributions required reinterpretation for each scenario considered. Some example construction case scenarios are presented in Figure 10.

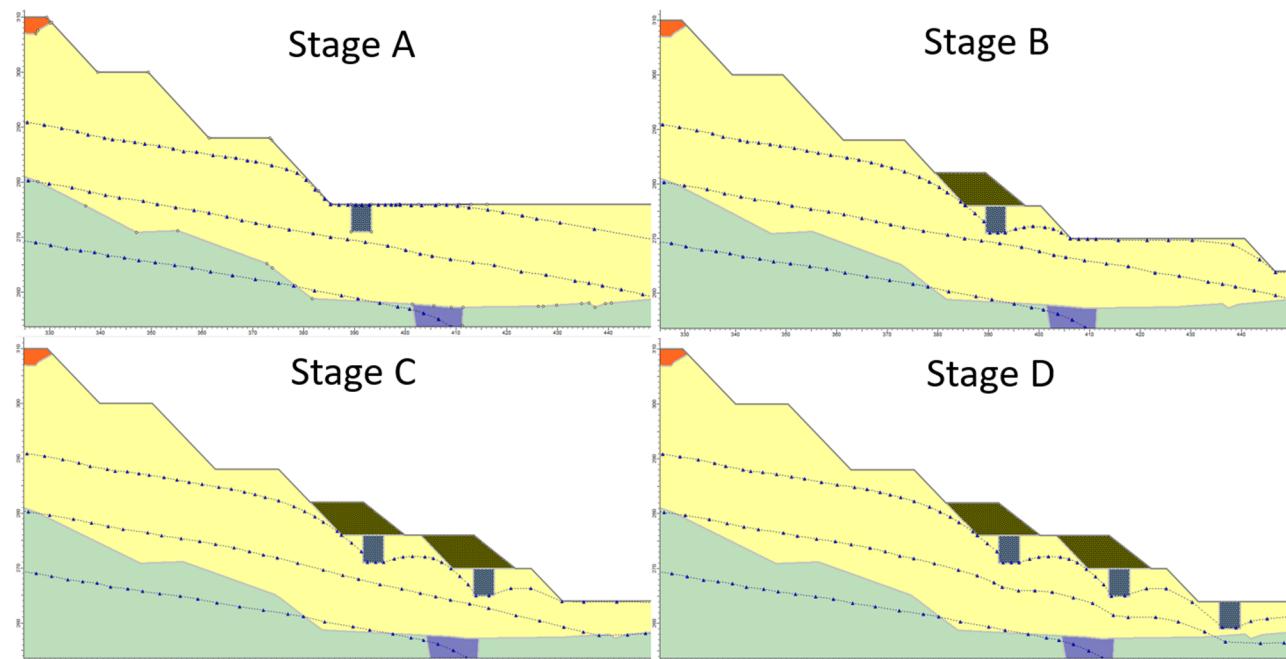


Figure 10 Selected examples of models developed to evaluate different stages of construction

The modelling exercise helped to define the strategy of excavating the slope. Half-height benches (6 m) were introduced to help implement drainage features and allow time for depressurisation. This also allowed for increased incremental buttressing and the addition of resistive weight in the lower portion of the slope.

Stability modelling was also undertaken to evaluate the potential implications of blast-induced vibrations on slope stability. This was done by gathering and interpreting vibration data from existing geophones located onsite. Seismic loading was then incorporated into the modelling software.

Stability of the final reinforced slope is predicted to increase over time as pore pressures continue to reduce within the slope as a result of excavation. As a measure of comprehensive evaluation, a sensitivity analysis was also undertaken to evaluate potential silting up of drainage features in the future and what effect this might have on slope stability.

7 Construction controls

Validation of modelling undertaken during design was implemented as a form of control during excavation. Hold points were selected at particular stages of excavation, and verification was done using data from installed georeferenced instrumentation. Up-to-date pore pressure data from VWP arrays was used to update LE stability models and compare results with design predictions. Hold points were then released once the required Factor of Safety was achieved.

Predetermined hold points were presented and discussed with the mine planning department, and a construction document outlining all controls and requirements was developed and communicated to all parties involved prior to starting excavation below the phreatic surface. Single points of contact were established within the planning and geotechnical teams to communicate the results of hold point evaluations and provide approvals to proceed with the subsequent phases of construction.

Further discussion with the planning department reinforced the fact that once a hold point was released, the sequencing of excavating the next stage would play a key role in allowing additional time for pore pressure to dissipate. Therefore, purposeful mine scheduling was highlighted as a tool to help limit potential delays.

8 Monitoring

Various types of monitoring played a role in enabling success of the project. Groundwater monitoring, in particular, played a key role both leading into the design phase (as described in Section 4) and during the excavation phase. The following monitoring was undertaken during the excavation stage:

- Visual monitoring during daily inspections.
- Unmanned aerial vehicle flights/video capture.
- VWP porewater pressure monitoring.
- Survey prism monitoring (robotic total station).

Locations of monitoring instrumentation are presented superimposed on a georeferenced object file (OBJ) photogrammetry image of the area of the cutback shown in Figure 11.

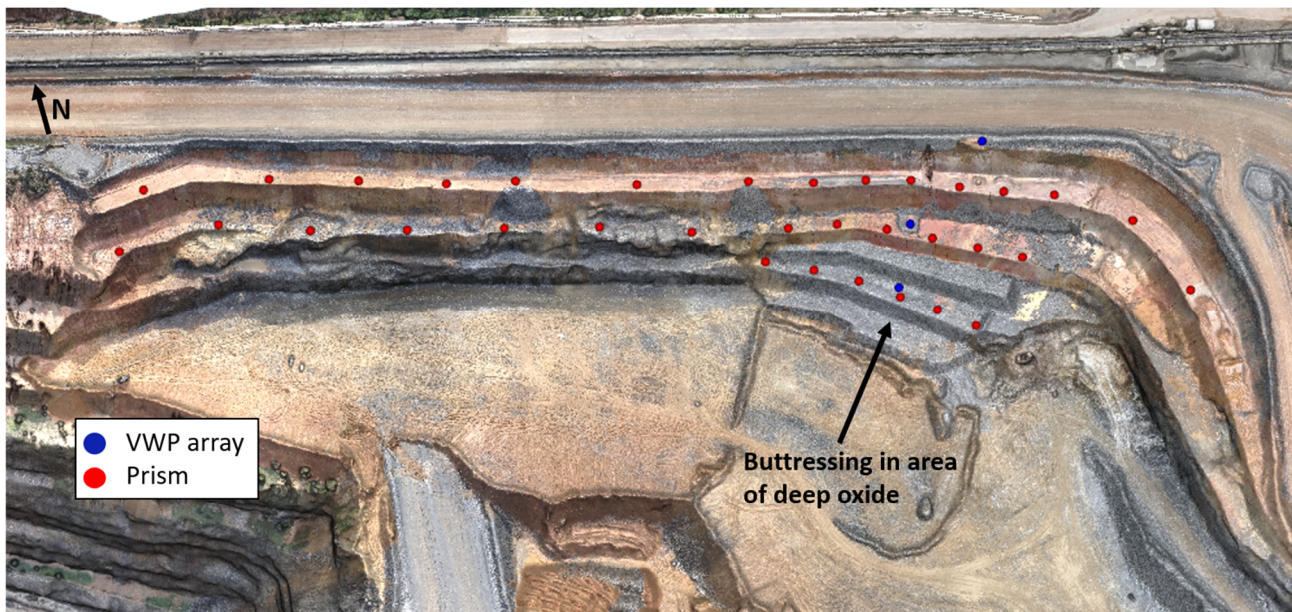


Figure 11 Monitoring instrumentation within the area of the cutback

Vertical multi-sensor VWP arrays were installed in diamond rig and D65 rig drillholes targeting the deepest sections of oxide, and in specific areas of the ground profile, in order to gain a good understanding of the pore pressure distributions. VWP arrays installed during excavation targeted predetermined locations in proximity to the critical design section to provide the most relevant data. The installation process also provided an opportunity for additional confirmation of ground conditions at chosen locations. VWP sensors were attached to data loggers at the surface which have the ability to relay data via telemetry back to systems in the office. Data loggers with long-life lithium batteries were chosen as these are simple, self-contained and effective. Installation of the VWP arrays was done using a cement-bentonite grout mix pumped through a tremie pipe with a screw pump. The bentonite grout mix followed guidance according to Durham Geo Slope Indicator (2013) for hard soils. The holes were filled from the bottom up, ensuring consistent encapsulation. An example of VWP monitoring data is presented in Figure 12, which also shows influence factors.

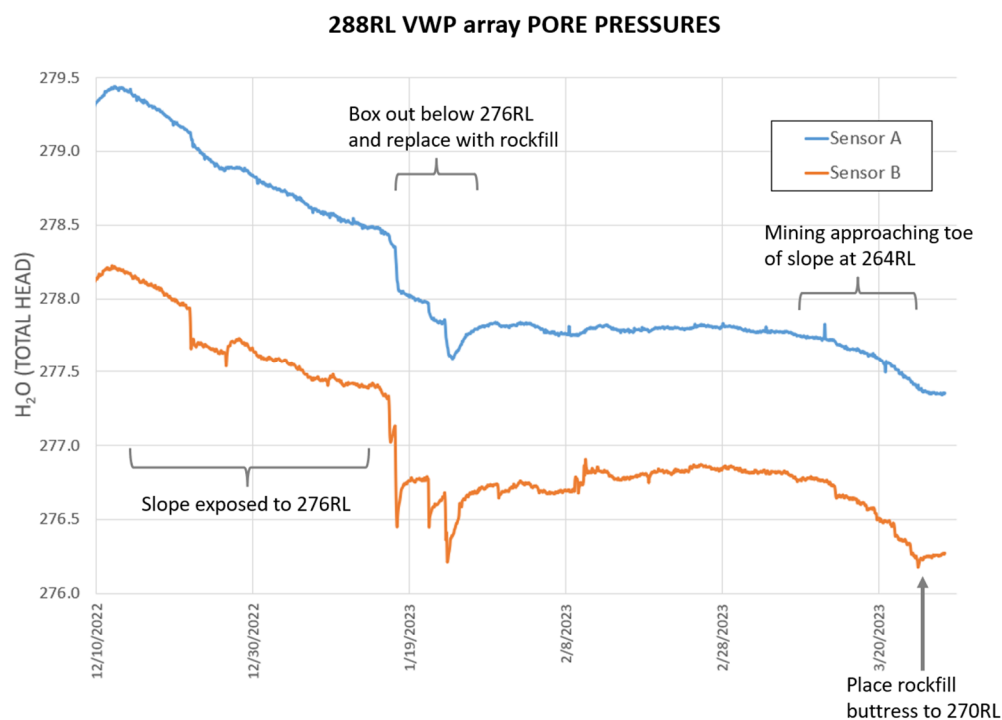


Figure 12 Example of falling VWP pore pressure readings during excavation

9 Construction stage – providing guidance during excavation

Being present and able to provide additional input and guidance during the execution stage of the project enabled further benefit to be realised. A number of construction methodologies were discussed in additional detail, leading to improved constructability. These included the following:

- Amending the drainage solution to boxout and replace whole berm widths rather than using a trench configuration. This led to an improved result overall, including the encouragement of a better drainage result and also a more effective slope stability solution. The resulting change is presented in the design section in Figure 13. Excavation was in sequential 20 m sections. An example of a 20 m section to be excavated/filled is shown in Figure 14. The procedure of excavation of the oxide and replacement with rockfill was stipulated to occur within a 24-hour period to help ensure stable slopes.
- Changes to the proposed geometry of excavation sequence stages were proposed by the mine planning team and were able to be assessed by the geotechnical team to determine suitability. In some cases, proposed changes proved acceptable and were approved.
- Controlled advanced removal of the oxide material and replacement with rockfill to help promote drainage.

The drainage measures adopted during the construction phase helped to reduce pore pressures below predicted levels at hold points. Hold points were therefore able to be released without requiring additional time for pore pressures to reduce further. As a result, there was no significant impact to the mining schedule.

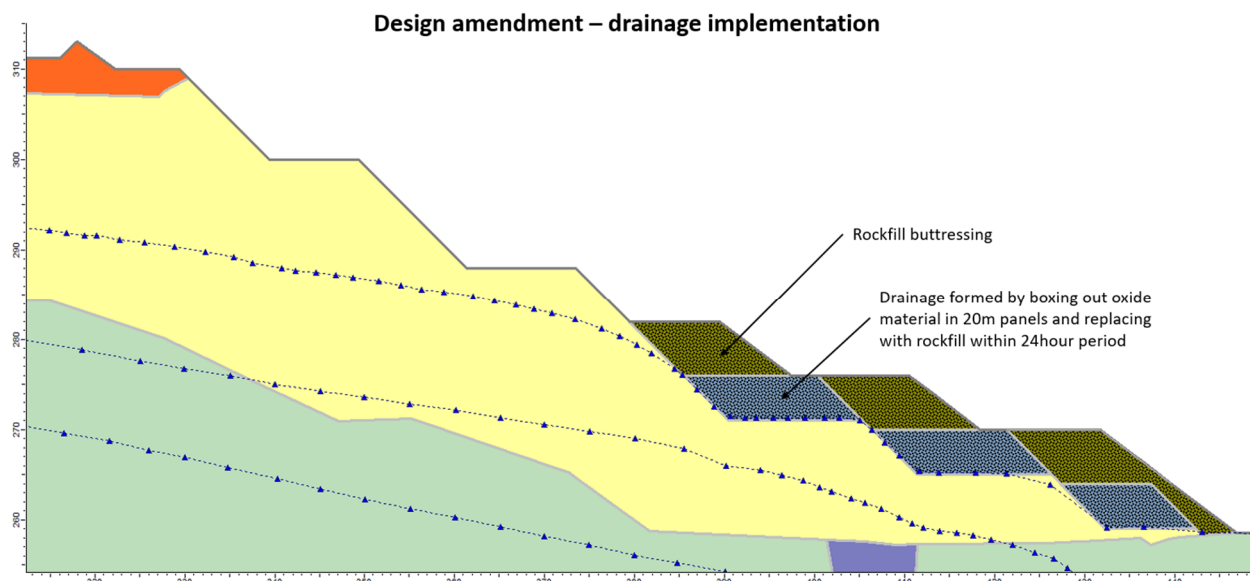


Figure 13 Example of falling VWP pore pressure readings during excavation

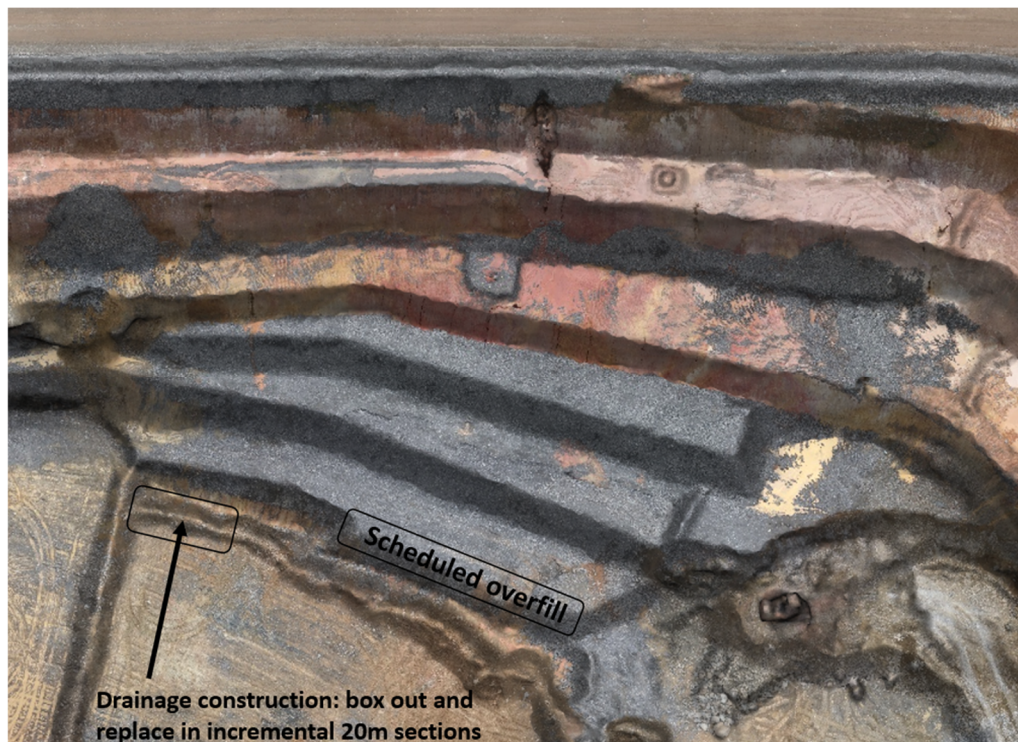


Figure 14 Example of an area to be boxed out and where overfill was placed to promote drainage and stability

10 Conclusion

Despite apparent roadblocks to achieving a favourable outcome, a suitable solution was able to be developed by leveraging ideation, coordination and communication with involved parties on the mine site. The result was a combined team effort between geotechnical, mine planning and operational departments to successfully achieve an optimised pit shell and gain access to additional ore reserves safely and without impacting nearby infrastructure. The cutback has currently reached the base of the deep oxide and has progressed without significant mishap.

Acknowledgement

The author would like to acknowledge and thank those who were involved in the early stages of this work and also the broader Newmont Boddington team, whose support and collaboration helped drive the project to success.

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